

# THE IRON OXIDE COPPER-GOLD DEPOSITS OF THE CARAJÁS MINERAL PROVINCE, BRAZIL: AN UPDATED AND CRITICAL REVIEW

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**Abstract** - The Carajás Mineral Province, northern Brazil, represents an Archaean cratonic block that contains the world's largest known concentration of large-tonnage IOCG deposits (e.g., Sossego, Salobo, Igarapé Bahia/Alemão, Cristalino, Alvo 118, Igarapé Cinzento/Alvo GT46). These deposits are hosted by 2.76 to 2.73 Ga metavolcano-sedimentary units, 2.70 to 2.65 Ga gabbro/diorite, granitoids and porphyry dykes, within brittle-ductile and ductile shear zones. Geochronologic data suggest that formation of the Carajás IOCG deposits may possibly be linked to three metallogenic events: ~2.74, 2.57 and 1.8 Ga.

In general, the Carajás IOCG deposits display a hydrothermal alteration sequence characterised by early sodic and sodic-calcic assemblages, followed by potassic alteration, magnetite-(apatite) formation, chloritic, copper-gold mineralisation and hydrolytic alteration. Tourmaline is particularly common in deposits hosted by metavolcano-sedimentary units (e.g., Salobo and Igarapé Bahia/Alemão). The development of fayalite, garnet and sillimanite represents higher temperature alteration assemblages of some deposits hosted in ductile shear zones, such as Salobo and Igarapé Cinzento/Alvo GT46. Silica and carbonate alteration are important in deposits formed in brittle-ductile conditions (e.g., Sossego and Alvo 118).

Extensive zones of scapolite alteration (>20 km<sup>2</sup>) represent sodic alteration around IOCG deposits (e.g., Sossego), reflecting high salinity and buffered activity gradients in Cl in the early regional hydrothermal fluids. Metal leaching from the host rocks was probably enhanced by the high salinity of fluids, driven by heat from the intrusive episodes recorded in the Carajás Mineral Province. As a consequence, geochemical ore signatures defined by the Fe-Cu-Au-REE-(U-Y-Ni-Co-Pd-Sn-Bi-Pb-Ag-Te) association is variably developed in the Carajás IOCG deposits, and strongly dependent upon the chemistry of the leached host rocks.

Fluid inclusions in ore-related minerals point to a fluid regime in which hot brine (>30 wt.% NaCl<sub>equiv.</sub>) solutions, represented by salt-bearing aqueous inclusions, were progressively cooled and diluted by lower temperature, low-salinity (<10 wt.% NaCl<sub>equiv.</sub>) aqueous fluids. This mixing process was likely responsible for a trend of salinity and temperature decrease (>550 to <300°C), accompanied by an *f*O<sub>2</sub> increase towards the mineralisation stages. This process tends to favour the predominance of hematite-bornite in more oxidised deposits (e.g., Alvo 118) over magnetite-chalcocopyrite (e.g., Sossego).

Extensive fluid-rock interactions, possibly involving basinal/evaporite and magmatic fluid components, resulted in <sup>18</sup>O-enriched fluids ( $\delta^{18}\text{O}_{\text{fluid}} = 5$  to 15‰), typical of most Carajás IOCG deposits. In addition, calculated fluid isotopic compositions for shallow-emplaced deposits, such as Sossego and Alvo 118 ( $\delta^{18}\text{O}_{\text{fluid}} = -5.2$ ‰,  $\delta\text{D}_{\text{fluid}} = -35$ ‰, at 300°C), also reinforce the importance of the significant, structurally-controlled influx of meteoric fluids for ore deposition related to high fluid pressure release and brecciation. Chlorine and boron isotopes, combined with Cl/Br - Na/Cl systematics, strongly suggest that fluid regimes responsible for the formation of the Carajás IOCG deposits involved a significant contribution from residual evaporative fluids (e.g., bittern fluids generated by seawater evaporation) that may have mixed with magma-derived brines.

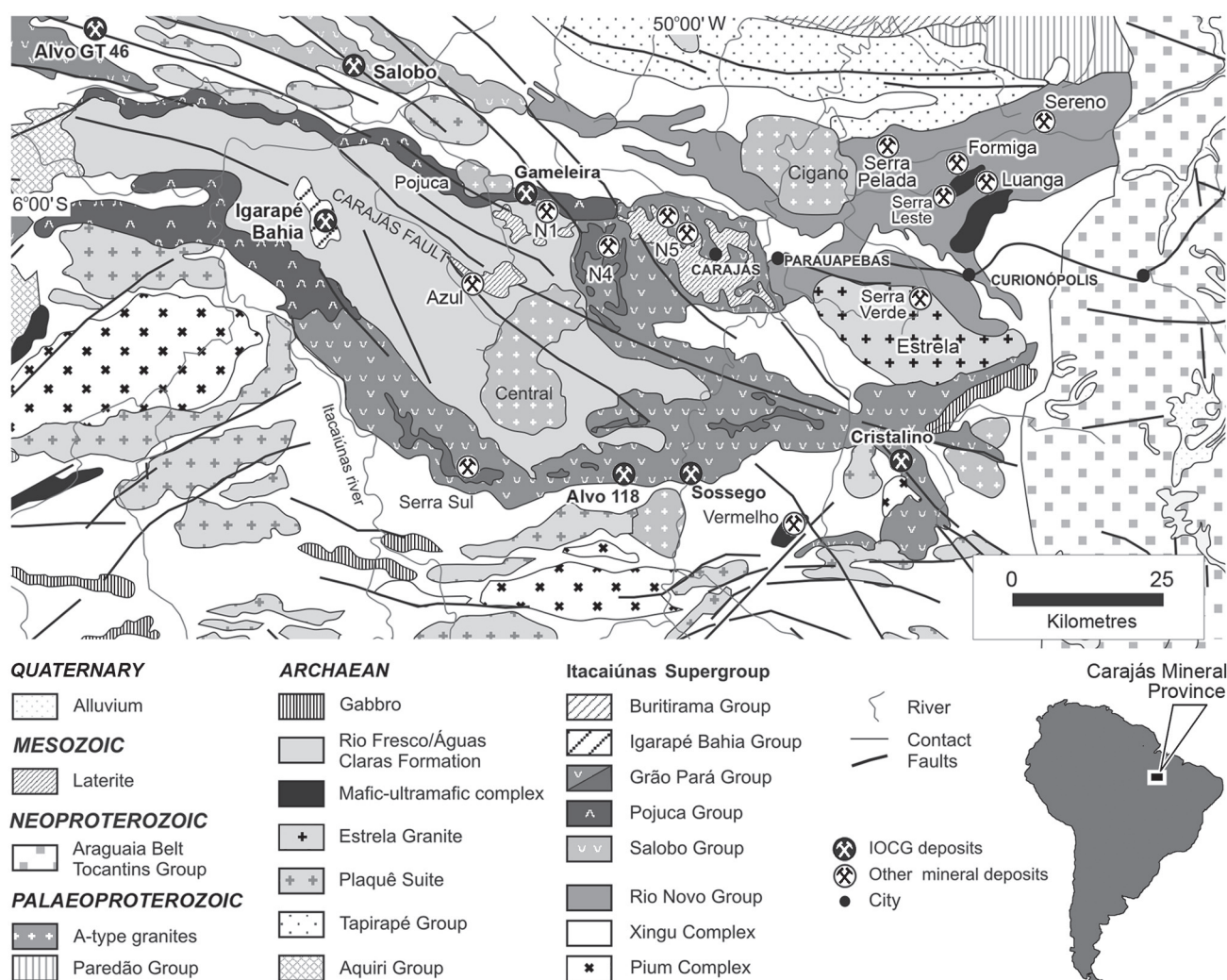
Sulphur isotope compositions for the Carajás IOCG deposits vary from values close to that expected for a mantle source (e.g.,  $\delta^{34}\text{S} = 0 \pm 1$ ‰ at Salobo) to <sup>34</sup>S enriched values (>7‰) in deposits in which contribution of meteoric fluids was significant, reflecting distinct physico-chemical conditions or input of heavy sulphur from surficial reservoirs.

## Introduction

The iron oxide-copper-gold (IOCG) deposits of the Carajás Mineral Province (CMP) are located in the south-eastern portion of the Amazon Craton, northern Brazil. They have recently assumed a degree of economic significance since Vale, the former Companhia Vale do Rio Doce (CVRD), brought the first of these world-class deposits, *Sossego* (245 Mt @ 1.1 wt.% Cu, 0.28 g/t Au; Lancaster *et al.*, 2000), into production in 2004. Others of the known IOCG deposits in the province are planned to commence operations sequentially in the near future, depending upon the performance of international commodity prices.

These include *Salobo* (789 Mt @ 0.96 wt.% Cu, 0.52 g/t Au, 55 g/t Ag; Souza and Vieira, 2000), *Cristalino* (500 Mt @ 1.0 wt.% Cu; 0.3 g/t Au, Huhn *et al.*, 1999), *Igarapé Bahia/Alemão* (219 Mt @ 1.4 wt.% Cu, 0.86 g/t Au; Tallarico *et al.*, 2005), *Gameleira* (100 Mt @ 0.7 wt.% Cu; Rigon *et al.*, 2000), *Alvo 118* (170 Mt @ 1.0 wt.% Cu, 0.3 g/t Au; Rigon *et al.*, 2000) and several IOCG prospects and deposits that are currently under investigation, including, *Igarapé Cinzento/Alvo GT46*, *Castanha*, *Bacaba*, *Jatobá*, *Visconde*, and *Serra Dourada*.

Most of the known IOCG deposits of the CMP are located along, or near, regional shear zones that define the contact between the metavolcano-sedimentary units of the



**Figure 1:** Simplified geological map of the northern part of the Carajás Mineral Province (Itacaiúnas Shear Belt) and location of the main ore deposits (modified from Docegeo, 1988; CPRM, 2004).

Itacaiúnas Supergroup (~2.76 Ga) and basement rocks of the Xingu Complex (~3.0 Ga). The Cinzento shear zone, in the northern sector of the province, hosts the Salobo and Igarapé Cinzento (also known as Alvo GT46) deposits. The southern sector is defined by a 60 km-long, east-southeast-striking shear zone, along which Alvo 118, Sossego and Cristalino occur, together with several other minor deposits (e.g., Castanha, Bacaba, Jatobá, Visconde, Serra Dourada) and a number of barren massive magnetite bodies.

As for major examples of IOCG class deposits elsewhere in the world (Hitzman, 2000; Pollard, 2000; Williams *et al.*, 2005), much controversy remains over genetic models for those of the CMP. Most of the models proposed have reinforced the importance of Archaean (~2.75 to 2.57 Ga) granitoid intrusions for the establishment of magmatic-hydrothermal systems (Réquia *et al.*, 2003; Tallarico *et al.*, 2005; Villas *et al.*, 2006; Neves *et al.*, 2006; Pollard, 2006; Grainger *et al.*, 2008), while deep-seated formational/metamorphic solutions (with possible magmatic components), and meteoric-hydrothermal fluids have also been invoked for the genesis of the CMP IOCG systems (Rosa, 2006; Monteiro *et al.*, 2008a). Alternatively, syngenetic volcanic exhalative and sub-sea-floor replacement models have also been proposed, particularly for the Salobo and Igarapé Bahia/Alemão deposits (Lindenmayer, 1990; Villas and Santos, 2001; Dreher, 2004; Dreher *et al.*, 2008). In addition, recent studies provide strong evidence for the involvement of

marine evaporitic fluids in the IOCG hydrothermal systems of the CMP, reinforcing the role of non-magmatic brines in the genesis of these deposits (Xavier *et al.* 2008a).

In this context, this review aims to update and summarise the available data for the best known IOCG deposits of the CMP, including their main geologic attributes, hydrothermal alteration types and fluid characteristics, in an attempt to unravel the evolution of these palaeo-hydrothermal systems, and assess possible fluid and salinity sources and mechanisms of ore deposition.

## The Carajás Mineral Province

The Carajás Mineral Province is located in the southeastern part of the Amazon Craton, one of the largest cratonic areas in the world. This province is divided into three tectonic blocks: (1) the southern Inajá granite-greenstone terrane (or Pau D'Arco Shear Belt); (2) the Rio Maria greenstone terrain (Huhn *et al.*, 1988); and (3) the northern Itacaiúnas Shear Belt (Araújo *et al.*, 1988).

In the Itacaiúnas Shear Belt (Fig. 1), the Archaean basement includes tonalitic to trondhjemitic gneiss and migmatite of the Xingu Complex (2974±15 Ma; Machado *et al.*, 1991) and granulite of the Pium Complex. In the latter, SHRIMP zircon ages of 3002±14 Ma and 2861±12 Ma are considered to respectively represent the parental magmatic rock and the granulite facies metamorphism, (Pidgeon *et al.*, 2000).



The basement rocks are overlain by metavolcano-sedimentary units of the Rio Novo Group (Hirata *et al.*, 1982) and the 2.76 to 2.73 Ga Itacaiúnas Supergroup (Wirth *et al.*, 1986; Docegeo, 1988; Machado *et al.*, 1991; Trendall *et al.*, 1998; Krymsky *et al.*, 2002; Galarza *et al.*, 2003; Pimentel *et al.*, 2003; Tallarico *et al.*, 2005), which comprise variably deformed, lower greenschist to amphibolite facies metamorphosed basic and felsic volcanic rocks, iron formations, and clastic sedimentary rocks (Wirth *et al.*, 1986; Hirata *et al.*, 1982; Docegeo, 1988; Machado *et al.*, 1991).

The *Itacaiúnas Supergroup* is divided into the Igarapé Salobo, Igarapé Pojuca, Grão Pará, Igarapé Bahia and Buritirama groups (Docegeo, 1988). The *Igarapé Salobo Group* hosts the Salobo IOCG deposit, and consists of paragneiss, amphibolites, quartzites, meta-arkoses and metamorphosed iron formations. The *Igarapé Pojuca Group* (2732±3 Ma, U-Pb zircon; Machado *et al.*, 1991) contains greenschist to amphibolite facies metamorphosed rocks, represented by basic meta-volcanics, pelitic schists, amphibolites and iron formations. This group hosts both the Pojuca copper-zinc and the Gameleira IOCG deposits (Galarza and Macambira, 2002). The *Grão Pará Group* comprises greenschist facies metamorphic units, including meta-basalts, felsic meta-volcanic rocks and iron formations that form the giant Carajás iron deposits. Greenschist facies meta-volcanic, meta-pyroclastic and meta-sedimentary rocks, including iron formations, define the *Igarapé Bahia Group*, which is overlain by the *Buritirama Group*, a meta-sedimentary sequence composed of quartzites, mica schist, carbonate schist, calc-silicate rocks, manganiferous marble and goudites. The former group hosts the Igarapé Bahia/Alemão IOCG deposit, and the latter the Buritirama Mn ores.

Differing interpretations of the available geological, geochemical and isotopic data for the Grão Pará mafic rocks has produced controversy regarding the tectonic environment. According to Olszewski *et al.* (1986), these rocks clearly differ from those of most Archaean greenstone belts, modern MORB, IAB and hot-spot basalts, and were deposited on continental crust in a tectonic environment similar to many modern continental extensional basins. However, according to Zuchetti (2007), the meta-basalts of the Grão Pará Group have a calc-alkaline magmatic affinity and geochemical characteristics typical of subduction zone and continental arcs, with evidence of crustal contamination. A similar depositional setting has been proposed by Dardenne *et al.* (1988), Meirelles and Dardenne (1991), Silva *et al.* (2005) and Lobato *et al.* (2005). Alternatively, Araújo and Maia (1991) considered deposition in a pull-apart basin formed during the Archaean ductile stage of development of the Itacaiúnas Shear Belt.

The Rio Novo Group and the Itacaiúnas Supergroup were in turn overlain by a low-grade metamorphosed sedimentary sequence, that includes conglomerate (with iron formation, quartzite and siltstone clasts, within a foliated quartz-sericite matrix), sandstone (locally manganese-rich), dolomitic marble (with lenses of talc-chlorite-rich rocks), carbonaceous siltstone and sericitic quartzites (Tallarico *et al.*, 2000). This unit, known as the *Rio Fresco Group* (Docegeo, 1988) or the *Águas Claras Formation* (Nogueira, 1985; Araújo *et al.*, 1988), was deposited in a shallow-marine to fluvial environment. Dating of detrital zircon in sandstones (2681±5 Ma; Trendall *et al.*, 1998) and meta-gabbro sills (2645±12 Ma and 2708±37 Ma; Dias *et al.*, 1996; Mougeot *et al.*, 1996) constrains the age of the Águas Claras Formation to the Archaean.

The complex structural evolution of the Carajás Archaean units has been attributed to the development of regional east-west trending, steeply dipping fault zones, that show evidence of several episodes of reactivation (Holdsworth and Pinheiro, 2000). The Itacaiúnas sinistral, transpressive, strike-slip ductile shear zone was formed at 2.85 to 2.76 Ga. Dextral transtension led to the development of the Carajás and Cinzento strike-slip fault systems between 2.7 and 2.6 Ga. A sinistral, transpressive regime, which evolved at about 2.6 Ga, resulted in moderate to strong deformation of the rocks immediately adjacent to the Carajás and Cinzento fault systems (Holdsworth and Pinheiro, 2000).

Widespread syntectonic, 2.76 to 2.74 Ga alkaline granites, including the Estrela, Plaqué, Planalto and Serra do Rabo complexes, intrude the Itacaiúnas and Rio Novo metavolcano-sedimentary sequences (Dall'Agnol *et al.*, 1997; Avelar *et al.*, 1999; Barros *et al.*, 2001, 2004). A calc-alkaline monzogranite dated at 2688±11 Ma (Barros *et al.*, 2001) and at 2668±100 Ma (Silva *et al.*, 2005), indicates possible volcanic-arc magmatism, as well as thin tabular porphyry bodies of dacitic to rhyolitic composition (2645±9 Ma and 2654±9 Ma, Pb-Pb SHRIMP; Tallarico, 2003), which are also recognised in the province. Late Archaean peralkaline, meta-aluminous granitic magmatism occurs locally throughout the CMP, but is only represented along the Cinzento shear zone by the Old Salobo (2573±2 Ma; Machado *et al.*, 1991) and the Itacaiúnas granites (2560±37 Ma; Souza *et al.*, 1996). Other Archaean intrusions include the Vermelho, Onça, Jacaré-Jacarezinho and Luanga (2763±6 Ma, Machado *et al.*, 1991) mafic-ultramafic layered complexes, as well as 2.76 to 2.65 Ga gabbro dykes and sills (Galarza *et al.*, 2003; Pimentel *et al.*, 2003).

Extensional events in the Palaeoproterozoic (*ca.* 1.88 to 1.87 Ga) were accompanied by widespread emplacement of within-plate A-type, alkaline to sub-alkaline granites (e.g., Serra dos Carajás, Cigano, Pojuca, Young Salobo, Musa, Jamon, Seringa, Velho Guilherme and Breves; Machado *et al.*, 1991; Dall'Agnol *et al.* 1994, 1999a,b, 2005; Macambira and Lafon, 1995; Teixeira *et al.*, 2002; Tallarico *et al.*, 2004) and dyke swarms.

Felsic magmatism within the CMP may have extended into the Meso- and Neoproterozoic, although less well developed, represented by an alkali-rich leucogranite dyke with a U-Pb SHRIMP age of 1583±7 Ma (Pimentel *et al.*, 2003) in the Gameleira deposit area, and the *ca.* 600 Ma Formiga granite (Grainger *et al.*, 2008). The province was also affected by other magmatic events, reflected by late undeformed dolerite, diorite, and gabbro dykes of unknown ages.

## The Carajás IOCG Deposits

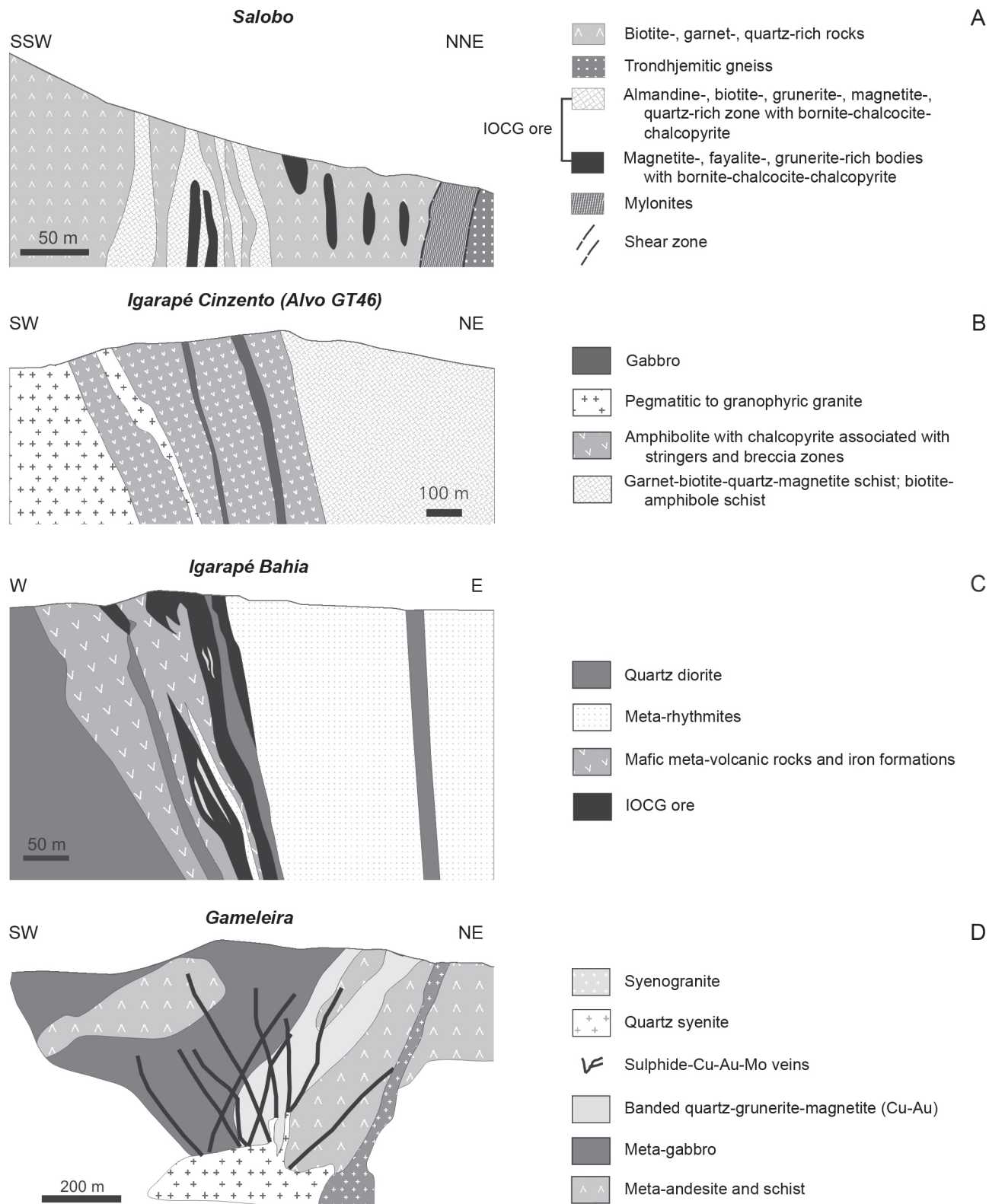
### Northwestern Sector

**Salobo:** The Salobo deposit was discovered in 1977 and contains estimated reserves of 789 Mt of ore @ 0.96% Cu, 0.52 g/t Au and 55 g/t Ag (Souza and Vieira, 2000). This deposit is hosted by the Salobo Group that belongs to the Itacaiúnas Supergroup, in tectonic contact with trondhjemitic gneiss of the Xingu Complex (Lindenmayer, 2003). These units have been strongly deformed by the 2.7 Ga Itacaiúnas and 2.5 Ga Cinzento ductile shear zones (Machado *et al.*, 1991; Holdsworth and Pinheiro, 2000), and are crosscut by the 2.57 Ga syn-tectonic Old Salobo and the 1.88 Ga Young Salobo granites (Lindenmayer, 1990, 1998). The development of the shear zones resulted in a widespread and penetrative, sub-vertical, northwest-striking

mylonitic foliation in the rocks of the Salobo deposit area, with the exception of the Young Salobo granite and late dolerite dykes (Réquia *et al.*, 2003).

The dominant lithology in the Salobo deposit area is a biotite-garnet-quartz-rich rock, first defined as meta-greywacke (Lindenmayer, 1990) and reinterpreted as a hydrothermally altered dacite (Lindenmayer, 2003). Host rocks also include amphibolite, metamorphosed banded iron formation and quartzite (Fig. 2A). The ore

forms structurally-controlled, steeply dipping, irregular, lens-shaped and massive replacement bodies, generally associated with magnetite-rich rocks (10 to >50% magnetite) with Mn-almadine, grunerite (Figs. 6A, B), Cl-rich hastingsite, fayalite, schorlitic tourmaline, Fe-biotite, allanite and quartz (Réquia *et al.*, 2003). The ore zone corresponds to the massive garnet-biotite-fayalite-grunerite rock which generally contains >50% magnetite with minor graphite and fluorite, and the foliated, granoblastic,



**Figure 2:** Geological cross-sections of the IOCG deposits from the northwestern sector of the Carajás Mineral Province. **A** Salobo (modified from Vieira *et al.*, 1988; Lindenmayer *et al.*, 1990; Villas and Santos, 2001); **B** Igarapé Cinzento (DOCEGEO in Silva *et al.*, 2005); **C** Igarapé Bahia (Soares *et al.*, 1999); **D** Gameleira (Pimentel *et al.*, 2003).



almandine-biotite-grunerite-plagioclase-quartz rock which carries 10 to 50% magnetite, as shown on Fig. 2A, extending into the adjacent biotite-garnet-quartz schists (Viera *et al.*, 1988). These rocks have been interpreted as iron formation, which have been metamorphosed to pyroxene-hornfels facies (Lindenmayer, 1990; Villas and Santos, 2001). Similar, structurally disrupted 'iron formations' extend intermittently over tens of kilometres of strike length throughout the district (Siqueira and Costa, 1991). Alternatively, these magnetite-rich rocks might be the product of extreme iron and potassic hydrothermal alteration at high-temperatures (>550°C) of andesitic-basalt and dacite of the Salobo Group (Lindenmayer, 2003). In the latter alternative, high temperature hydrothermal alteration would have overprinted rocks that were previously deformed and mylonitised. In addition, widespread chlorite alteration (<370°C), accompanied by the formation of calcite, epidote, albite, sericite and quartz, followed by the generation of greenalite, fluorite and uraninite, was also described in the deposit (Lindenmayer and Teixeira, 1999; Lindenmayer, 2003).

The lens-shaped and massive replacement orebodies are distributed over a strike length of 4 km, width of 100 to 600 m, and have been recognised to a depth of 750 m below the surface (Souza and Vieira, 2000). They are parallel to planar S-C structures along the main southeast trend of the shear zone, and commonly exhibit plastic flow textures, recrystallisation, mylonitisation and brecciation (Lindenmayer, 1990; Lindenmayer and Teixeira, 1999; Siqueira and Costa, 1991). In this context, episodes of ore remobilisation during development of the shear zone cannot be ruled out (Siqueira, 1996). The copper-gold mineralisation in the massive replacement orebodies comprises large quantities of magnetite (Fig. 7a) with disseminations of bornite, chalcocite and chalcopyrite (Lindenmayer, 1990; Réquia *et al.*, 1995), associated with covellite, molybdenite, cobaltite, safflorite, native gold and silver. Late veins with chalcopyrite, calcite, epidote, quartz and fluorite, controlled by Riedel shear structures, are also present at Salobo (Lindenmayer 2003; Siqueira, 1996; Réquia *et al.*, 2003).

**Igarapé Cinzento (Alvo GT 46):** The Igarapé Cinzento IOCG deposit (Fig. 2B) is mainly hosted by metavolcano-sedimentary units (meta-basalts, meta-andesites and banded iron formations) of the Grão Pará Group, gabbro-diorite and calc-alkaline granitic rocks (monzogranite, quartz-monzonite and quartz syenite;  $2668 \pm 100$  Ma; Sm-Nd method; Silva *et al.*, 2005). Deformation and metamorphism of mafic volcanic and intrusive protoliths ( $2686 \pm 87$  Ma; Sm-Nd method; Silva *et al.*, 2005) produced foliated hornblende- or cummingtonite-bearing amphibolite. Along the contact with granitic rocks, the amphibolites display a metamorphic halo characterised by the crystallisation of garnet and tourmaline. Grunerite is also developed in iron formation bodies within the amphibolite when they occur close to granite contacts.

Mylonitic sillimanite-garnet-microcline gneiss also occurs within the Igarapé Cinzento area. This lithology has been considered to have resulted from the deformation and metamorphism of granitic rocks, as supported by geochemical studies (Silva *et al.*, 2005).

Intense potassic and iron-rich hydrothermal alteration produced biotite-, biotite-cummingtonite- and garnet-biotite-amphibole-quartz-magnetite-rich rocks. These lithologies, which may represent the product of hydrothermal alteration of the metavolcano-sedimentary units of the Grão Pará, have lenses of least-altered iron formations and

amphibolites and are crosscut by granite injections. The development of actinolite, chlorite, albite, silica, sericite, epidote and carbonate alteration have also been recognised at the deposit (Silva *et al.*, 2005). Apatite, tourmaline and allanite are common in the hydrothermally altered rocks.

The orebodies are controlled by north-northeast-trending brittle-ductile faults that crosscut the Cinzento shear zone. The mineralisation occurs associated with breccia zones and consists of chalcopyrite, bornite, covellite and chalcocite, associated with magnetite along mylonitic foliation planes in hydrothermally altered rocks. Stringers and veins are also associated with magnetite-rich zones within granite and amphibolite. Molybdenite, parisite, xenotime, thorite, larsenite and cassiterite are subordinate phases in the Igarapé Cinzento ore assemblage (Silva *et al.*, 2005).

**Igarapé Bahia/Alemão:** This deposit occurs in a small erosional window, and is hosted by rocks of the Igarapé Bahia Group, considered to be a lower greenschist facies metamorphosed unit of the Archaean (*ca.* 2.75 Ga) metavolcano-sedimentary Itacaiúnas Supergroup (Docegeo, 1988). The upper part of the deposit comprises a 100 to 150 m thick gossan-laterite zone from which significant amounts of gold (>60 t; Tallarico, 2003) were mined by Vale, up to 2003. Below the base of oxidation, the deposit contains hypogene copper-gold mineralisation with estimated reserves of 219 Mt @ 1.4% Cu and 0.86 g/t Au (Tallarico *et al.*, 2005).

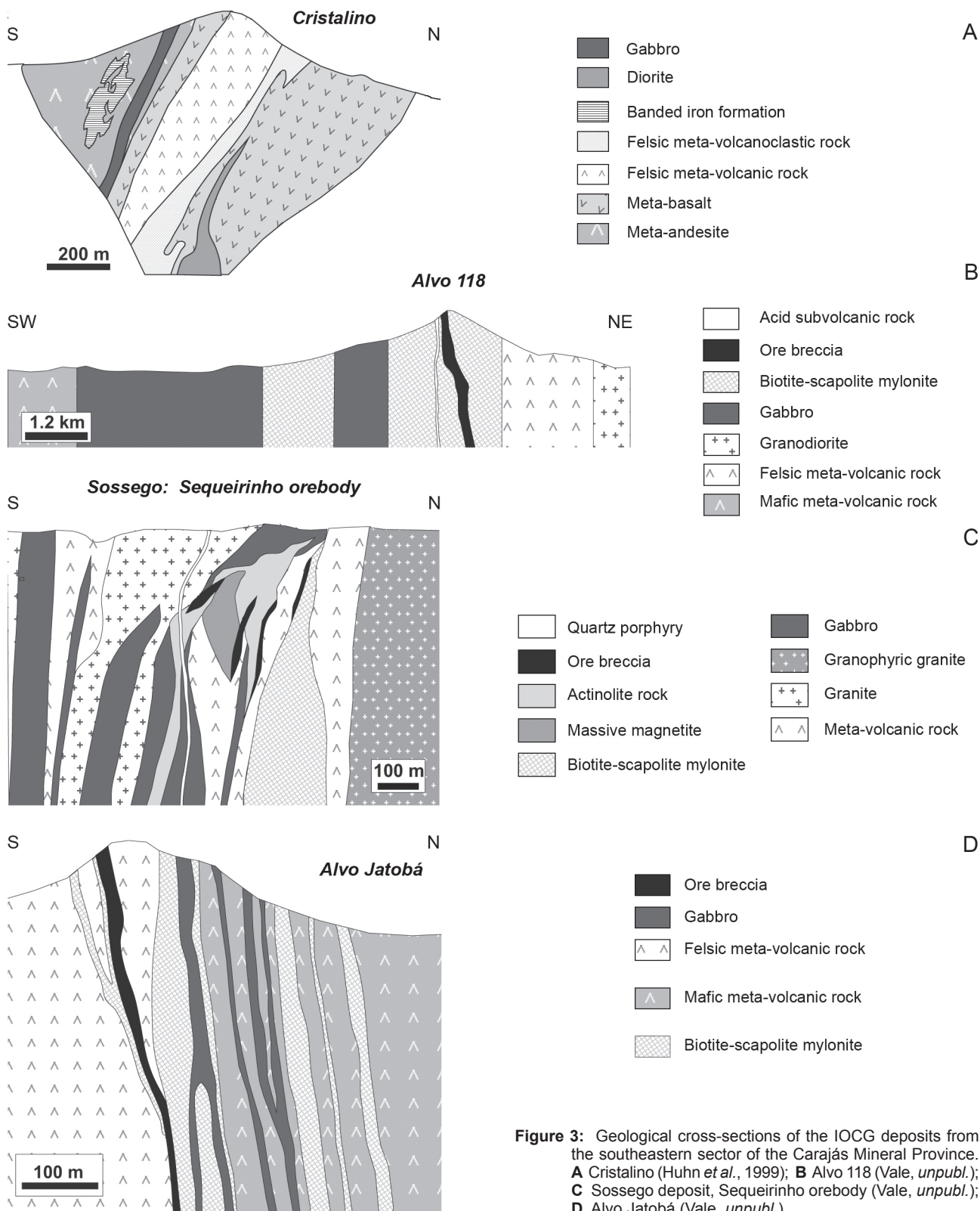
The copper-gold mineralisation at the Igarapé Bahia/Alemão deposit is hosted by a hydrothermally altered breccias developed at the contact between the footwall mafic volcanics (with associated BIF and hyaloclastite), and a dominantly coarse to fine-grained metasedimentary sequence in the hanging wall (Fig. 2C). The breccia unit defines a semicircular body at surface, having a shape similar to a ring complex with a diameter of approximately 1.5 km. The breccia unit occurs as a 2 km long by 30 to 250 m thick series of fault dislocated bodies on the southern, northeastern and northwestern sections of this structure, dipping steeply (~75°) outwards, nearly concordant with the metavolcanic-sedimentary wallrocks (Tallarico *et al.*, 2005). A set of un-metamorphosed 2.75 to 2.65 Ga quartz diorite (Galarza *et al.*, 2002) and dolerite dykes ( $2579 \pm 7$  Ma; Tallarico *et al.*, 2005) crosscut the orebodies, the host metavolcano-sedimentary sequence and the overlying clastic metasedimentary sequence of the Águas Claras Formation/Rio Fresco Group.

The breccia has gradational contacts with its wallrocks, and is made up of polymictic, usually matrix-supported clasts, composed mainly of coarse, angular to rounded basalt, BIF (Fig. 7B) and chert derived from the footwall unit (Lindenmayer *et al.*, 1998; Dreher *et al.*, 2008). The breccia contains disseminated to massive chalcopyrite and bornite (Figs. 7H, E and I) with varying concentrations of magnetite, chlorite, carbonate, amphibole, biotite, apatite, tourmaline and quartz within the matrix. Ferropyrrosmalite (Tazava *et al.*, 1999) and scapolite (Althoff *et al.*, 1994) were also recognised within the breccia matrix. Hydrothermal alteration assemblages are dominated by chlorite in weakly mineralised zones (e.g., Furo Trinta and Acampamento Sul orebodies in the south and northeast respectively), whereas strongly mineralised zones (e.g., Acampamento Norte orebody in the northwest) contain abundant Fe-rich alteration minerals (magnetite, siderite, Fe-amphibole, stilpnomelane; Dreher *et al.*, 2008). The so-called Alemão deposit (Barreira *et al.*, 1999; Ronzê *et al.*, 2000), situated immediately northwest of Igarapé Bahia, represents a particularly magnetite-Cu-Au-enriched, down-faulted

segment of the Acampamento Norte orebody. Resources for Alemão have been quoted as 170 Mt @ 1.5% Cu and 0.8 g/t Au (Cordeiro, 1999). According to Santos (2002), the Alemão segment consists of a concordant, almost vertically dipping, mineralised fragmental rock body, about 500 m long and up to 250 m thick.

Several generations of late mineralised veins crosscut the ore breccia, and are composed of variable concentrations of chalcopryite, pyrite, quartz, calcite, chlorite and fluorite. These veins commonly display open space - filling textures (e.g., comb).

**Gemeleira:** The Gemeleira IOCG deposit (Fig. 2D) represents the eastern extension of the Pojuka Cu-Zn-Au deposit. Both are hosted by biotite, and garnet-biotite schists, interpreted as meta-andesite (2719±80 Ma, Sm-Nd method;  $\epsilon Nd_t = -1.4$ ) of the Pojuka Group, within the Itacaiúnas Supergroup, and by cogenetic meta-gabbro (2757±81 Ma;  $\epsilon Nd_t = -0.8$ ; Pimentel *et al.*, 2003). Within the Gemeleira deposit area, these rocks are crosscut by two types of granitoids (Lindenmayer *et al.*, 2001): (1) an older quartz-syenite to alkali-feldspar syenite, which has been correlated with the 1.87 Ga Pojuka granite, and



**Figure 3:** Geological cross-sections of the IOCG deposits from the southeastern sector of the Carajás Mineral Province. **A** Cristalino (Huhn *et al.*, 1999); **B** Alvo 118 (Vale, *unpubl.*); **C** Sossego deposit, Sequeirinho orebody (Vale, *unpubl.*); **D** Alvo Jatobá (Vale, *unpubl.*).

(2) a younger alkali-rich syenogranite dated at 1583 Ma (Pimentel *et al.*, 2003).

The host meta-andesite and meta-gabbro have undergone potassic alteration represented by biotite, with associated uraninite, allanite and tourmaline in subordinate amounts. Almandine, quartz and albite, with subordinate titanite, ilmenite, magnetite, scapolite, tourmaline and apatite are also recognised in the hydrothermally altered meta-volcanic rocks (Lindenmayer *et al.*, 2001). The copper-gold ore at Gameleira is dominantly composed of: (1) sulphide-rich veins and breccias cutting meta-andesite and meta-gabbro and (2) sulphides associated with a banded quartz-grunerite-magnetite rock, interpreted as a wide-banded hydrothermal vein (Lindenmayer *et al.*, 2001). The sulphide-rich veins are younger and comprise quartz, green biotite, albite, chalcopryrite and bornite, with minor allanite, apatite, uraninite, fluorite, tourmaline, muscovite, chlorite, molybdenite, cobaltite, Co-pentlandite, carbonate and gold. Interestingly, the ore in the banded quartz-grunerite-magnetite rock contains chalcopryrite and minor bornite, pyrite, cobaltite, pentlandite and gold, but lacks molybdenite.

### **Southeastern Sector**

**Cristalino:** The Cristalino deposit (Fig. 3A) is hosted by mafic to felsic volcanic rocks overlain by a brecciated iron formation. These rocks are metamorphosed to greenschist facies and intruded by 2.74 Ga diorite, quartz-diorite and granite (Huhn *et al.*, 1999). Silicification is synchronous with mylonitisation, followed by sodic (albite and scapolite) and potassic (biotite and microcline) alteration. These alteration assemblages are replaced by amphibole (hastingsite, actinolite and grunerite) and magnetite, and subsequently overprinted by extensive ore-related chlorite, accompanied by epidote, apatite, allanite and tourmaline (Huhn *et al.*, 1999).

Copper-gold mineralisation is associated with quartz-carbonate breccias (Fig. 7C), vein-stockworks, and to a lesser degree, as disseminations in meta-volcanic and intrusive rocks. The mineralisation consists of chalcopryrite, pyrite, magnetite, marcasite, bravoite, cobaltite, millerite, vaesite and gold, with subordinate hematite, bornite, covellite, chalcocite, molybdenite and sphalerite (Huhn *et al.*, 1999).

**Sossego:** The Sossego deposit (Fig. 4) occurs along an east-southeast-striking regional shear zone that defines the southern contact between the 2.76 Ga Itacaiúnas Supergroup and the ~3.0 Ga basement tonalitic to trondhjemitic gneisses and migmatites of the Xingu Complex. Granite, granophyric granite, gabbro intrusions and late dacite porphyry dykes intrude both the Xingu Complex basement and the Itacaiúnas metavolcanic rocks in the deposit area. Although the ages of these rocks are still uncertain, a Pb-Pb zircon age of  $2734 \pm 4$  Ga for a biotite-hornblende granite and a U-Pb zircon age of  $2765 \pm 39$  Ga for a tonalite-trondhjemite (Sardinha *et al.*, 2004) close to the deposit area, are currently considered the best estimates. In addition, the Palaeoproterozoic Rio Branco granite intrusion crosscuts the hydrothermally altered volcanic and intrusive rocks in the deposit area. This field relationship, together with the lack of hydrothermal alteration and mineralisation of the granite, indicate it was emplaced much later than the formation of the copper-gold ore at Sossego.

In the Sossego deposit area, shear deformation is represented by metre- to centimetre-wide mylonitic zones, marked by intense silica alteration. This shearing is regionally crosscut by north- and northwest-striking faults, and by a dextral system of transcurrent brittle-ductile east-west to northeast-southwest-striking, subvertically dipping faults (Fig. 4), which appear to control part of the mineralised zones (Morais and Alkmim 2005). Rocks in the immediate footwalls of these faults are intensely mylonitised and display biotite-tourmaline-scapolite and silica alteration.

Two major groups of orebodies, separated from each other by a major high angle fault, are defined at the Sossego deposit: (1) Sequeirinho-Pista-Baiano and (2) Sossego-Curral. The Sequeirinho and Sossego orebodies represent the bulk of the deposit, respectively contributing 85% and 15% of the ore reserves.

The orebodies have distinct styles of hydrothermal alteration, which likely reflect both different host rocks (granite, granophyric granite, gabbro, and felsic metavolcanic rocks with minor lenses of meta-ultramafic rocks) and palaeodepths of formation. The deeper portions of the deposit, mainly represented by the Sequeirinho orebody (Fig. 3C), have undergone regional sodic (albite-hematite) and actinolite-rich sodic-calcic alteration (Fig. 6C). The latter is commonly associated with massive magnetite bodies enveloped by apatite-rich actinolite (Fig. 6D). Spatially restricted zones of potassic (biotite and potassic feldspar) alteration overprint the sodic-calcic assemblage and grade outward to chlorite-rich zones (Fig. 5). At higher structural levels, represented by the Sossego-Curral orebodies, early albitic and subsequent sodic-calcic alteration are poorly developed, whereas potassic alteration assemblages mark the onset of the mineralisation, and grades laterally outward to a widespread zone of chlorite and late hydrolitic alteration (sericite-hematite-quartz-chlorite-calcite) assemblages (Carvalho *et al.*, 2005; Monteiro *et al.*, 2008a, 2008b).

These different orebodies commonly form breccia bodies (Fig. 7E) where copper-gold mineralisation was first precipitated with accompanying potassic alteration, and more importantly, with a later assemblage of calcite-quartz-chlorite-epidote-allanite-titanite-(hematite). Chalcopryrite, which is the main ore mineral, occurs in association with pyrite, gold (Fig. 7K), siegenite (Fig. 7L), millerite, Pd-melonite, hessite, cassiterite, sphalerite, galena, molybdenite, thorianite and monazite. The Fe-Cu-Au-Co-Ni-Pd-REE association represents the geochemical signature of the ore at the Sossego deposit and possibly reflects the chemistry of the host rocks leached by hot hydrothermal fluids.

**Alvo 118:** The Alvo 118 deposit (170 Mt @ 1.0 wt.% Cu, 0.3 g/t Au), together with Sossego and Cristalino, lies on a steeply-dipping, east-southeast-striking, 60 km-long shear zone, close to the contact between the Itacaiúnas Supergroup metavolcano-sedimentary sequence (~2.76 Ga) and the basement Xingu Complex (~3.0 Ga; Fig. 7). Along this structure, mafic and felsic metavolcanic rocks attributed to the Grão Pará Group (Itacaiúnas Supergroup), together with granite, gabbro and porphyry dyke intrusions, comprise the main hosts to the copper-gold mineralisation. The ages of crystallisation of the granite intrusion and the porphyry dykes have been estimated at  $2743 \pm 3$  Ma and  $2654 \pm 9$  Ma, respectively, via SHRIMP II  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages determined on zircon grains (Tallarico, 2003).



The felsic and mafic meta-volcanic and intrusive rocks have been subjected to the following sequence of alteration, observed progressively inwards towards the ore zones: (1) an early, but restricted, sodic phase, represented by albite and scapolite; (2) a potassic assemblage, dominated by biotite or microcline, and accompanied by the formation of magnetite (Fig. 6E); (3) pervasive and widespread chlorite, spatially associated with the copper-gold mineralisation (Figs. 6F and 7D); and (4) local post-ore quartz-sericite alteration (Torresi, 2008).

The copper-gold mineralisation developed during brittle deformation that resulted in the formation of breccia bodies and vein stockworks, with open-space filling textures composed of quartz, calcite, fluorite, apatite, allanite and Y-bearing phosphates (e.g., britholite and xenotime). The ore assemblage (Fig. 7J) is generally composed of chalcopyrite (80 vol.%), bornite (5 vol.%), hematite (10 vol.%), magnetite (5 vol.%) and minor to trace amounts of native gold, chalcocite, galena, sphalerite, cassiterite and Bi-Te-Au-Ag minerals (e.g., stutzite and petzite; Torresi, 2008).

The geochemical signature of the Alvo 118 ore is characterised by Fe-Cu-Au-(Te-Ag-Pb-Sn)-P-F-REE, and differs from the Sossego IOCG ore by the absence of Co-Ni-Pd-bearing phases and the presence of F (Bortholoto, 2007; Xavier *et al.*, 2008b). Unlike the other IOCG deposits of the Carajás Mineral Province, the Alvo 118 ore is enriched in HREEs, which are concentrated in apatite and in an Al-poor, Be-B-HREE silicate of the gadolinite group, which have never been reported in IOCG systems elsewhere in the world (Xavier *et al.*, 2008b).

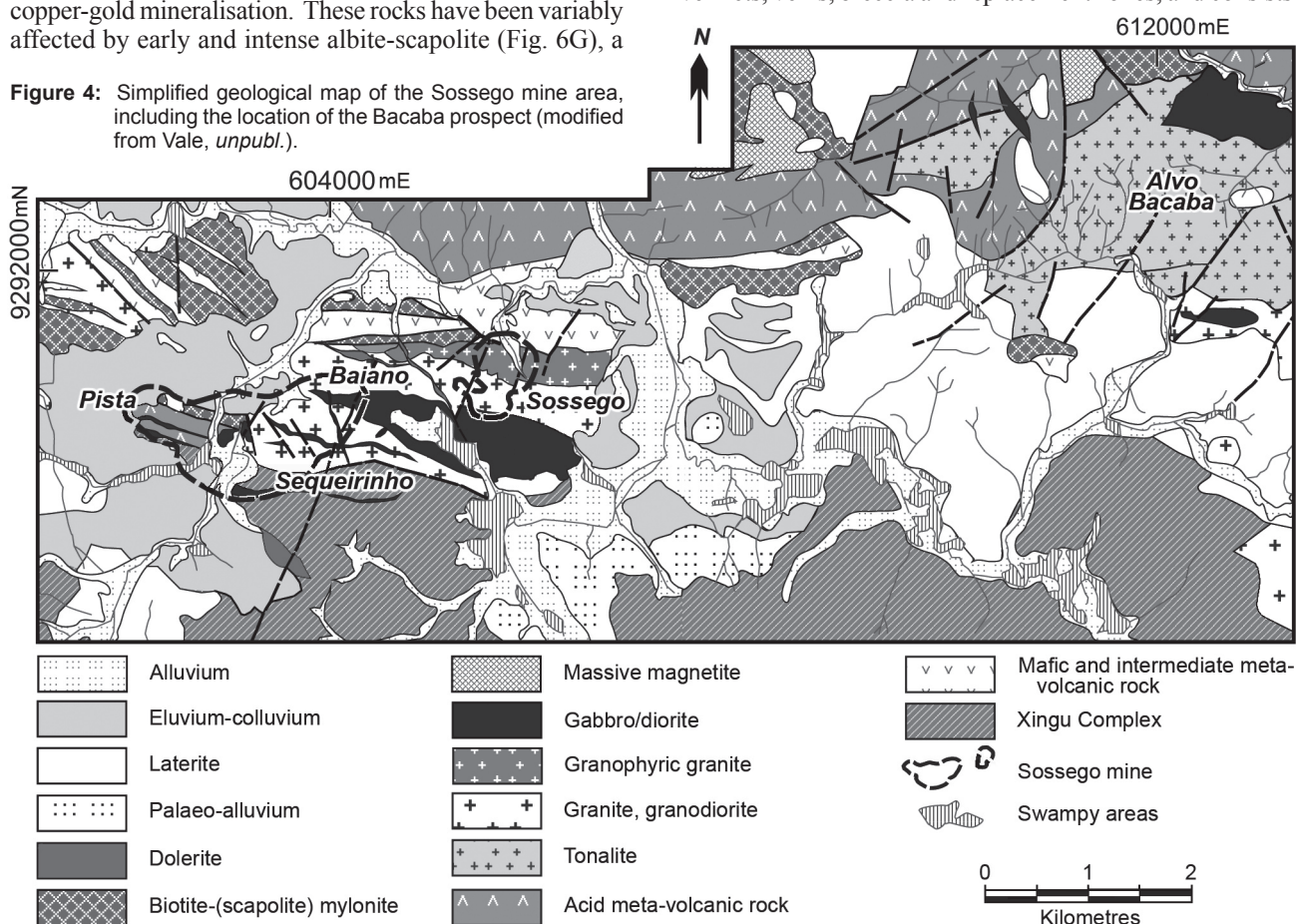
**Bacaba, Castanha and Jatobá Prospects:** The Bacaba prospect is located 7 km northeast of the Sossego mine, where granite and gabbro are the main hosts to copper-gold mineralisation. These rocks have been variably affected by early and intense albite-scapolite (Fig. 6G), a

potassic phase with a predominance of potassium feldspar-magnetite and/or biotite-magnetite (Fig. 7F), magnetite formation, and later chlorite and sericite alteration (Augusto *et al.*, 2008). This alteration sequence is similar to that described at Sossego, except for the higher abundance of scapolite at Bacaba. The copper mineralisation was late, and spatially related to potassic (with potassic feldspar) and chlorite alteration. Ore and gangue minerals include chalcopyrite, galena, bornite, chalcocite, melonite, hessite, altaite, magnetite, hematite, uraninite, cassiterite, ferberite, allanite, apatite, monazite and cheralite, which confer a Cu-Fe-Ni-Te-Ag-Pb-U-Sn-W-REE-Th-P geochemical signature to the ore.

The Castanha and Jatobá prospects in the northern and northeastern sectors of the Sossego mine (Fig. 3D) respectively, are mainly hosted by rhyolitic to dacitic meta-volcanic rocks and gabbro (Pestilho and Monteiro, 2008). As at Bacaba, intense scapolite development has been recognised in these prospects, being mainly represented by metre-wide (>10 m) marialitic scapolite ( $\pm$ magnetite and fluorite) veins and alteration halos (Fig. 6H). Scapolite in the halos replaces pre-existing igneous feldspar, while in the altered host rocks, disseminations of scapolite occur as deformed and rotated porphyroblasts with pressure shadows.

Fracture-controlled potassic alteration assemblages with Ba-rich potassium feldspar, magnetite and allanite, overprint scapolite. Pervasive potassic alteration, with >50 vol.% biotite and magnetite ( $\pm$  quartz, microcline, scapolite, hastingsite, tourmaline and zircon), also forms alteration zones along the mylonitic foliation, particularly in the gabbro. The potassic alteration was followed by chlorite with associated calcite, quartz, apatite, allanite and epidote that accompanies copper mineralisation. The ore occurs in veinlets, veins, breccia and replacement zones, and consists

**Figure 4:** Simplified geological map of the Sossego mine area, including the location of the Bacaba prospect (modified from Vale, *unpubl.*).



of chalcopyrite, pyrite, sphalerite, millerite, vaesite and Pd-melonite. At the Castanha prospect, pyrrhotite (Figs. 7G and 7M) and subordinate pentlandite occur in the ore breccia matrix (Pestilho and Monteiro, 2008).

## Ages of IOCG-forming Events

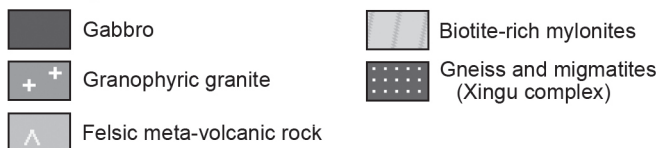
Available geochronologic data for IOCG deposits of the CMP are still scarce, and not sufficiently precise to confirm that all these deposits are genetically linked (Fig. 8). In general, geochronologic data yielded by Pb-Pb systematics reflect older ages (~2.7 Ga), and have collectively suggested metal sourced from the Itacaiúnas Supergroup units, and genetic relationships with the emplacement of syntectonic alkaline granites (e.g., 2.74 Ga Planalto granite) and/or of ~2.75 to 2.65 Ga gabbro-diorite bodies. More robust and precise geochronologic data, including U-Pb SHRIMP II dating on zircon and monazite, and Re-Os on molybdenite, have pointed to an important metallogenic event at 2.57 Ga (Réquia *et al.*, 2003; Tallarico *et al.*, 2005), which has been related to Late Archaean magmatism. Nevertheless, the Old Salobo and Itacaiúnas intrusives are the only two examples of 2.57 to 2.56 Ga granites (Machado *et al.*, 1991; Souza *et al.*, 1996) in the CMP. Except for the former that occurs at the Salobo IOCG deposit, no clear spatial association between IOCG deposits and granitic magmatism of this age has been demonstrated in the province.

In addition, dating of ore-related minerals has given different ages, even in a single deposit. At Salobo, the stepwise Pb leaching technique applied to chalcocite, tourmaline, chalcopyrite and magnetite yielded respective  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages of  $2705 \pm 42$ ,  $2587 \pm 150$ ,  $2427 \pm 130$  and  $2112 \pm 12$  Ma (Tassinari *et al.*, 2003). The oldest of these was correlated with the formation of the copper-gold mineralisation, while the 2.58 and 2.42 Ga ages are related to the tectonic reactivation of shear zones. The youngest was attributed to the emplacement of the ~1.88 Ga Young Salobo granite (Tassinari *et al.*, 2003). Re-Os dating of molybdenite yielded ages of  $2576 \pm 8$  and  $2562 \pm 8$  Ma that have also been interpreted as the timing of mineralisation, and synchronous with the ~2.57 Ga Old Salobo granite emplacement (Réquia *et al.*, 2003).

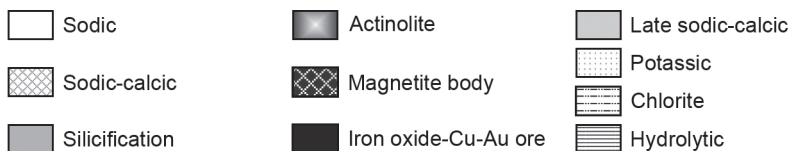
Re-Os dating on molybdenite crystals from veinlets hosted by amphibolite and granite from the Igarapé Cinzento deposit gave respective ages of  $2711 \pm 9$  and  $2554 \pm 8$  Ma (Silva *et al.*, 2005), considered to represent molybdenite formation, genetically linked to monzogranite emplacement ( $2668 \pm 100$  Ma; Sm-Nd method; Silva *et al.*, 2005). However, the mineralisation age for this IOCG deposit was defined by Ar-Ar on biotite at  $1809 \pm 6$  and  $1845 \pm 5$  Ma (Silva *et al.*, 2005).

**Figure 5:** Schematic cross-section of the Sequeirinho and Sossego orebodies, showing the distribution of hydrothermal alteration zones, and average temperatures and oxygen isotope compositions of the hydrothermal fluids involved in each alteration stage (Monteiro *et al.*, 2008a, 2008b).

### Lithologies



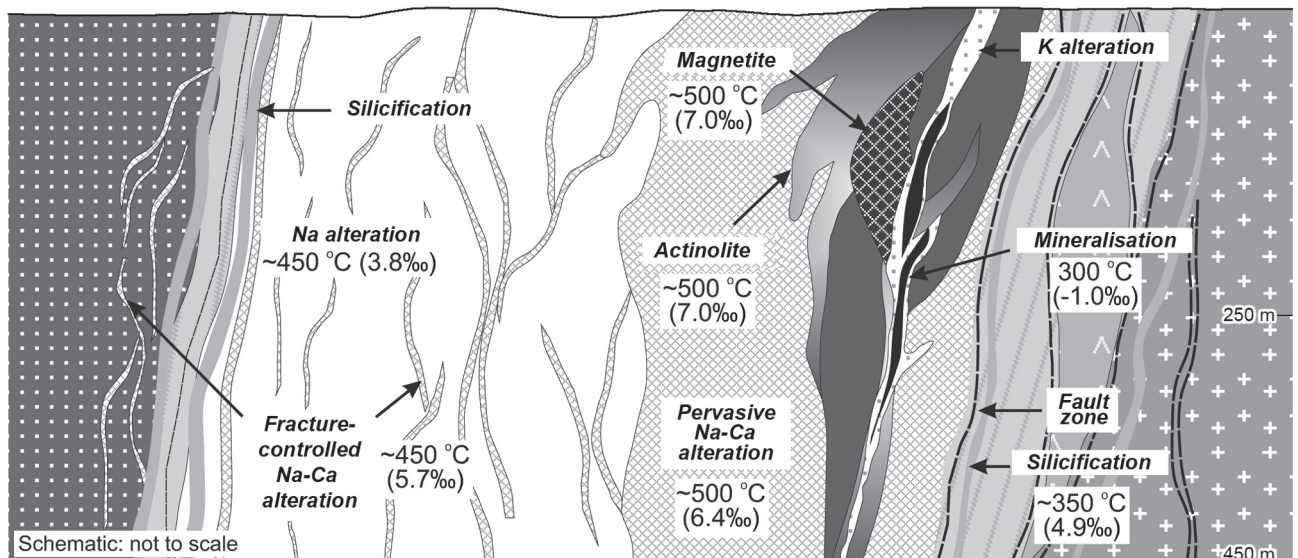
### Main alteration types



S

SEQUEIRINHO

N



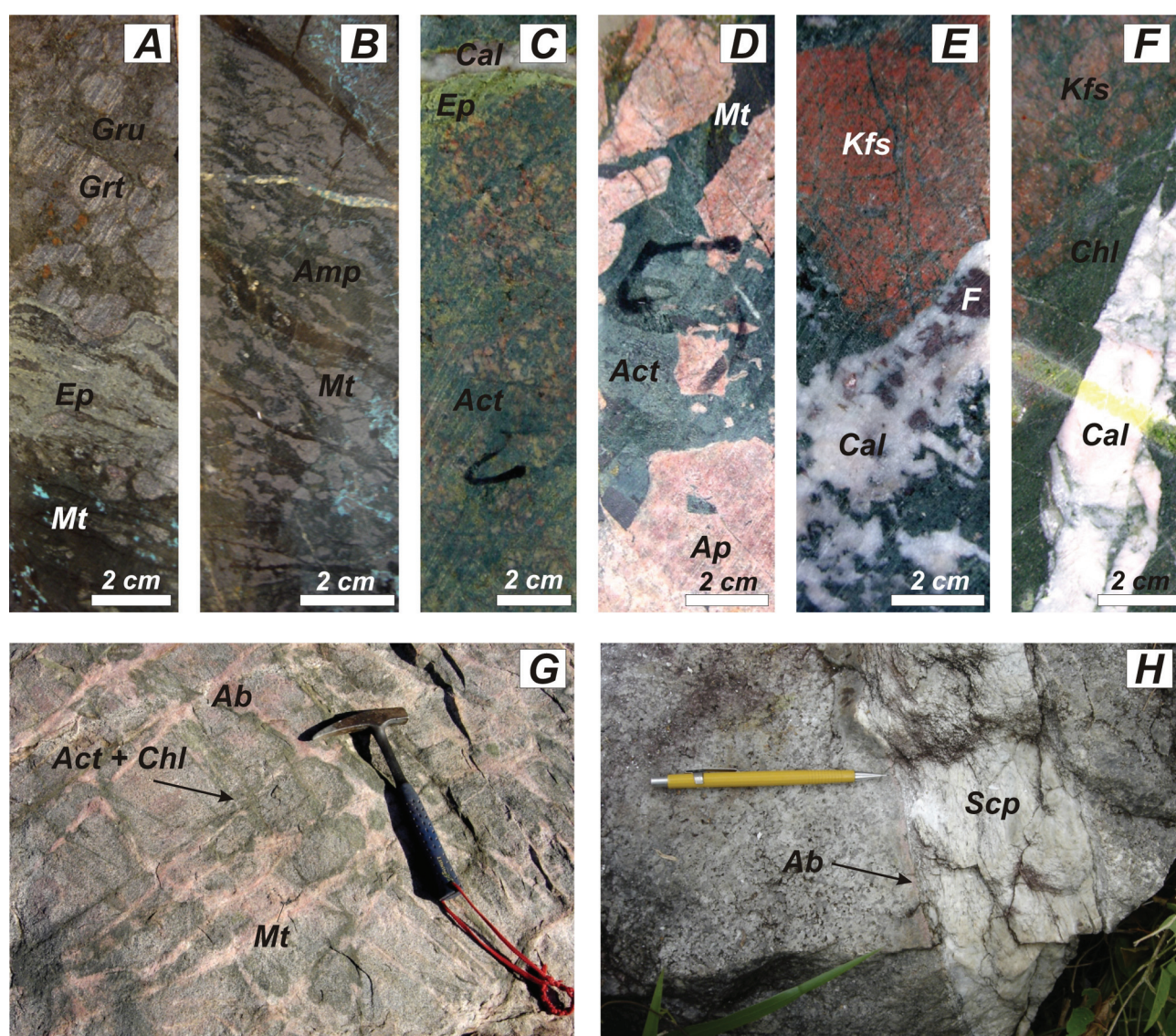


Pb-Pb dating of chalcopyrite from the main copper-gold ore of the Igarapé Bahia IOCG deposit yielded ages of  $2764 \pm 22$  and  $2772 \pm 46$  Ma (Galarza *et al.*, 2002), whereas U-Pb SHRIMP II dating of monazite gave an age of  $2575 \pm 12$  Ma (Tallarico *et al.* 2005). The latter is similar to Re-Os ages for Salobo, being then related to the same Late Archaean magmatic event.

At Cristalino, chalcopyrite and pyrite gave a  $2719 \pm 36$  Ma Pb-Pb age (Soares *et al.* 2001), similar to those of the Planalto granite ( $2747 \pm 2$  Ma; Pb-Pb on zircon) and diorite ( $2738 \pm 2$  Ma; Pb-Pb on zircon, Huhn *et al.*, 1999) that occur in the deposit area. Disturbed  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  spectra of amphibole, spatially associated with the ore at Sossego, suggest a minimum alteration age of 2.3 to 2.2 Ga (Marschik and Leveille, 2001). Pb-Pb dating of massive ore from the Sequeirinho orebody gave  $2530 \pm 25$  Ma and  $2608 \pm 25$  Ma ages (Neves *et al.*, 2006), whereas a Sm-Nd isochron age of  $2578 \pm 29$  Ma was obtained from samples of the Sequeirinho ore breccia (Neves, 2006). These ages were

interpreted to be the result of either partial isotopic resetting, or the time of mineralisation related to hydrothermal fluid circulation along the main shear zones (Neves, 2006). Moreover, Pb-Pb dating of the ore breccia from the Sossego orebody resulted in an age of  $1592 \pm 45$  Ma (Neves, 2006), which was explained by isotopic resetting. However, its association with magmatic or thermal events recognised in the CMP is contentious.

Molybdenite from the Gameleira IOCG ore gave a  $2614 \pm 14$  Ma Re-Os age (Marshick *et al.*, 2002). Pb-Pb dating of whole rock ore samples indicated ages of  $2245 \pm 29$  Ma, whereas  $2419 \pm 12$ ,  $2217 \pm 19$  and  $2180 \pm 84$  Ma were obtained from chalcopyrite grains (Galarza and Macambira, 2002). Biotite associated with pervasive potassic alteration at Gameleira, was dated by Ar-Ar at  $1734 \pm 8$  Ma (Pimentel *et al.*, 2003). In addition, a Sm-Nd isochron (MSWD = 0.83) age of  $1839 \pm 15$  Ma with  $\epsilon_{\text{Nd}}$  of -9.2, was obtained for the main mineralisation stage (quartz-grunerite-sulphide-gold veins) at Gameleira. The strongly negative



**Figure 6:** Main hydrothermal alteration types recognized in the IOCG deposits of the Carajás Mineral Province. **A** High-temperature alteration from the Salobo deposit with garnet, grunerite, and magnetite overprinted by epidote. Malachite occurs associated with magnetite and represents replacement of chalcopyrite; **B** Magnetite and amphibole in Salobo drill-core cut by late carbonate vein (upper part); **C** Sodic-calcic alteration typical of the Sequeirinho orebody (Sossego deposit), overprinted by late epidote and calcite; **D** Apatite-rich actinolite from the Sequeirinho orebody; **E** Potassic alteration represented by orthoclase, overprinted by chlorite and cut by calcite-fluorite veins from the Alvo 118 deposit; **F** Chloritisation and calcite veins from Alvo 118; **G** Regional fracture-controlled sodic (albite-magnetite) and sodic-calcic alteration (actinolite and chlorite); **H** Marialitic scapolite vein crosscutting granodiorite in the vicinity of the Sossego deposit. **Mineral abbreviations:** Ab = albite; Act = actinolite; Ap = apatite; Cal = calcite; Chl = chlorite; Ep = epidote; F = fluorite; Grt = garnet; Gru = grunerite; Kfs = potassium feldspar; Mt = magnetite; Scp = scapolite.

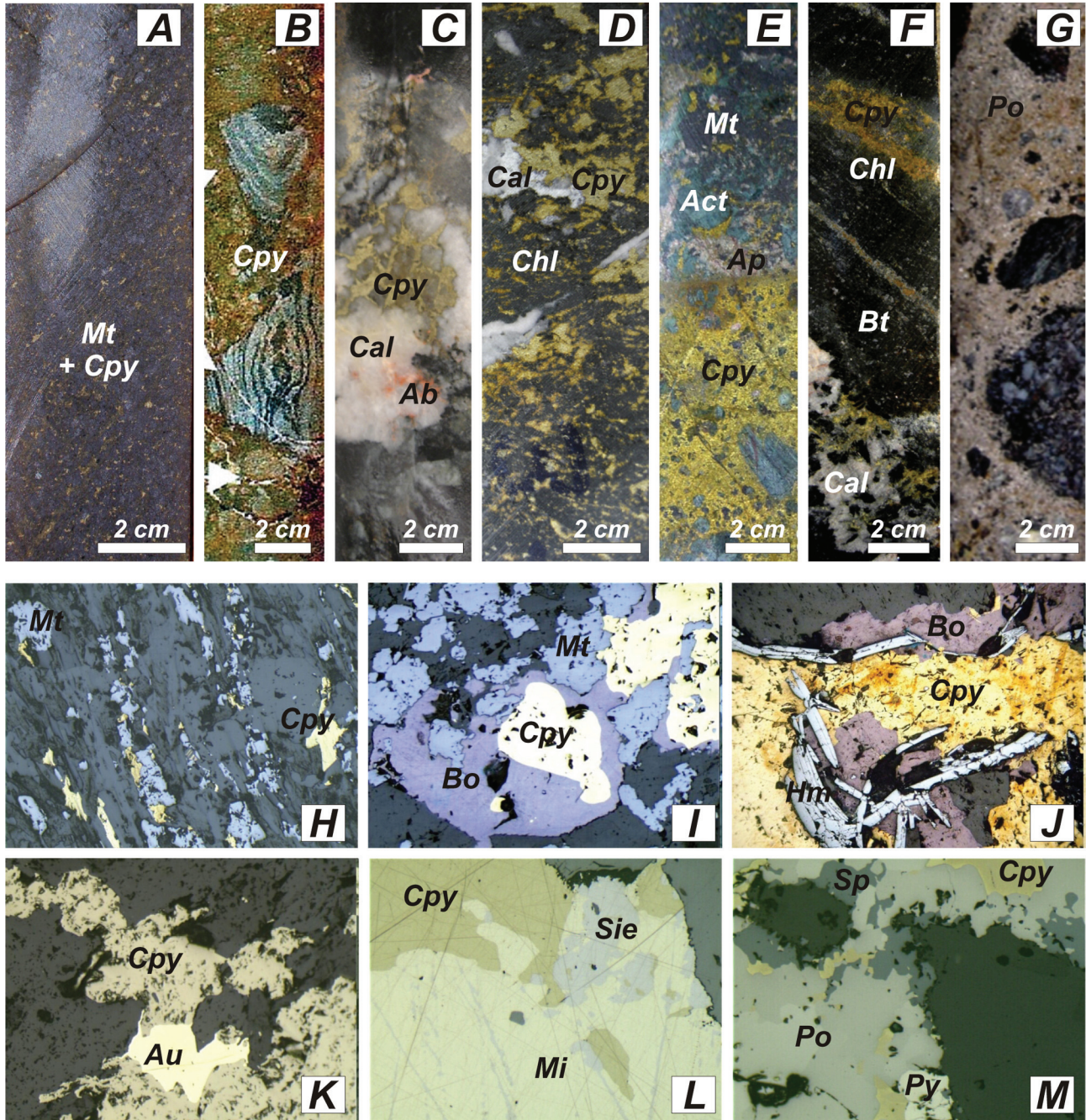


$\epsilon\text{Nd}_t$  value for the sulphide-rich veins suggests, according to Pimentel *et al.* (2003), that the original fluids underwent an intense interaction with, or were derived from, igneous rocks with an Archaean Nd isotopic signature.

SHRIMP II U-Pb dating on xenotime from massive and vein ore of the Alvo 118 deposit yielded ages of  $1869 \pm 7$  and  $1868 \pm 7$  Ma, respectively (Tallarico, 2003). These Palaeoproterozoic ages have been considered as evidence

of a distinctly separate metallogenic event, post-dating that associated with the main Carajás IOCG deposits (Grainger *et al.*, 2008).

These age differences could reflect partial resetting of the isotopic systems, provoked by tectonic reactivation along the Carajás and Cinzento strike slip systems and/or Archaean and Palaeoproterozoic granitic activity recognised throughout the evolution of the Amazon Craton (Fig. 8).



**Figure 7:** Ore - representative samples from IOCG deposits of the Carajás Mineral Province and related paragenesis. **A** Salobo ore, composed of magnetite and disseminated chalcopyrite; **B** Ore breccia from Igarapé Bahia, with chalcopyrite in the matrix supporting fragments of banded iron formation; **C** Mineralised volcanic rock from the Cristalino deposit, with chalcopyrite associated with calcite and albite; **D** Alvo 118 ore, composed of chalcopyrite, calcite, quartz, and chlorite; **E** Ore breccia from the Sequeirinho orebody (Sossego deposit), with chalcopyrite surrounding magnetite, actinolite and apatite clasts; **F** Biotite-scapolite mylonite from the Bacaba prospect, cut by veins with chalcopyrite, calcite and coarse-grained biotite; **G** Castanha ore breccia, with pyrrhotite dominant, surrounding fragments of the host metavolcanic rock; **H** Magnetite and chalcopyrite along the mylonitic foliation defined by chlorite orientation, in weakly mineralised breccia from the Igarapé Bahia deposit (reflected light); **I** Characteristic ore paragenesis of the Igarapé Bahia deposit with magnetite, chalcopyrite and bornite (reflected light); **J** Association of hematite, chalcopyrite and bornite from the Alvo 118 deposit (reflected light); **K** Gold inclusion in chalcopyrite from the Sossego deposit (reflected light); **L** Siegenite and millerite associated with chalcopyrite in the Sossego ore breccia (reflected light); **M** Pyrrhotite, pyrite, chalcopyrite and sphalerite in the Castanha mineralisation (reflected light). **Mineral abbreviation:** Ab = albite; Act = actinolite; Ap = apatite; Au = native gold; Bo = bornite; Bt = biotite; Cal = calcite; Chl = chlorite; Cpy = chalcopyrite; Hm = hematite; Mi = millerite; Mt = magnetite; Po = pyrrhotite; Py = pyrite; Sie = siegenite; Sp = sphalerite.



## Nature of Hydrothermal Fluids

### Fluid Inclusion Evidence

Four types of fluid inclusions were involved in the formation of the Carajás IOCG systems: (I) highly saline (35 to 70 wt.% NaCl<sub>equiv.</sub>) brines, represented by halite-bearing or multi-solid aqueous inclusions ( $T_{ht} = 570$  to  $250^{\circ}\text{C}$ ); (II) lower temperature (generally  $<200^{\circ}\text{C}$ ) aqueous fluids with salinities varying from  $<5$  up to 30 wt.% NaCl<sub>equiv.</sub>, represented by two-phase inclusions; (III) low-salinity ( $<6$  wt.% NaCl<sub>equiv.</sub>) aqueous-carbonic ( $\text{CO}_2 \pm \text{CH}_4$ ) fluids ( $T_{decrep.} \geq 250^{\circ}\text{C}$ ); and (IV) single-phase carbonic ( $\text{CO}_2 \pm \text{CH}_4$ ) fluids. The hot saline brines (type I) and the cooler lower salinity aqueous fluids (type II) are ubiquitous in IOCG deposits from the CMP, although  $\text{CO}_2$ -rich fluids (types III and IV) have only been identified in deposits from the northwestern sector of the province (e.g., Igarapé Bahia, Salobo, and Igarapé Cinzento).

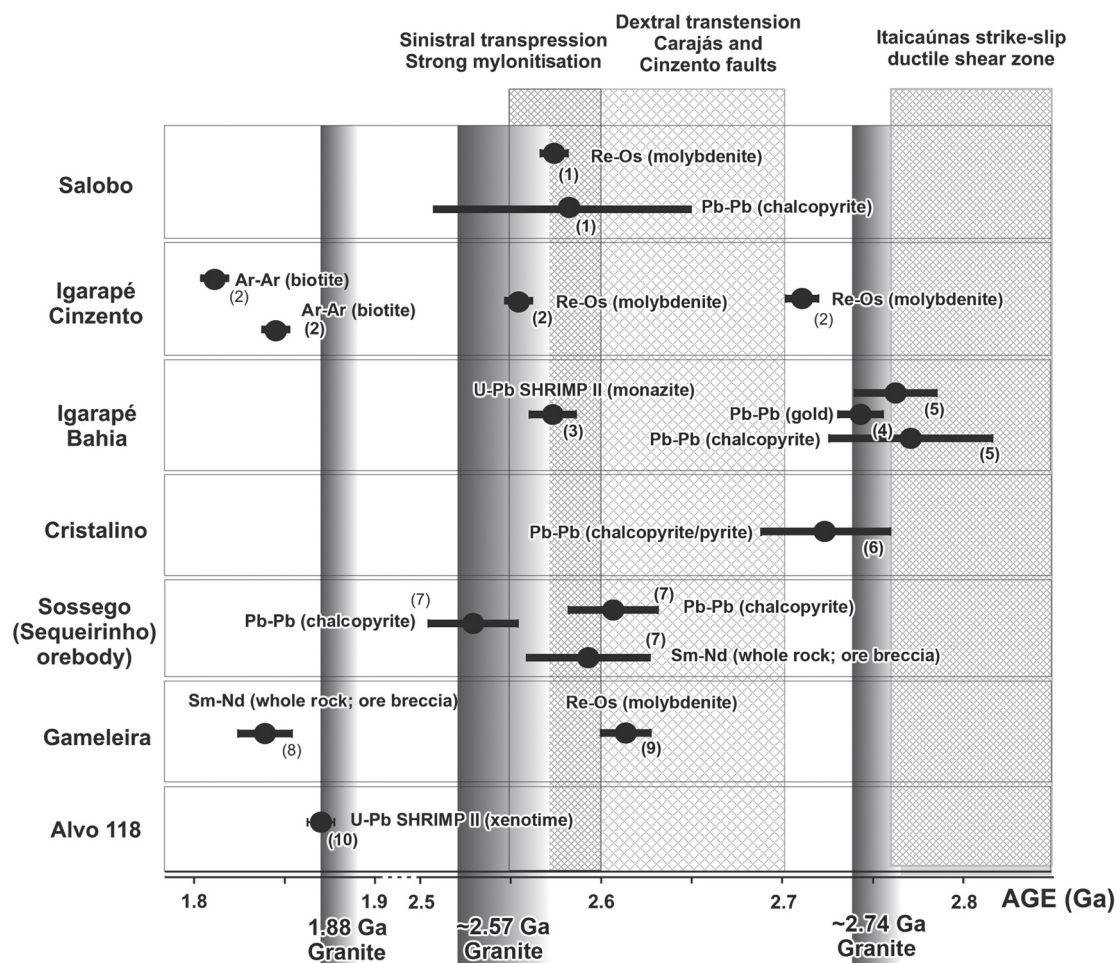
Fluid inclusions hosted in quartz from the Salobo ore zones are dominated by high temperature ( $173$  to  $485^{\circ}\text{C}$ ) type I aqueous brines (30.6 to 58.4 wt.% NaCl<sub>equiv.</sub>), and type II aqueous fluids with variable salinity (0.2 to 29.2 wt.% NaCl<sub>equiv.</sub>) and lower temperatures ( $140$  to  $270^{\circ}\text{C}$ ), that overprint early carbonic fluids (type IV; Réquia and Xavier, 1995). Late quartz veins and fluorite, on the other hand, mostly contain type II, and lesser type I aqueous fluids, and are devoid of carbonic inclusions.

At Igarapé Cinzento, type I saline fluids ( $\sim 35$  wt.% NaCl<sub>equiv.</sub>) commonly coexist with types III and IV  $\text{CO}_2$ -

bearing inclusions (Silva *et al.*, 2005). Type II fluids with relatively lower homogenisation temperatures ( $150$  to  $190^{\circ}\text{C}$ ) and variable salinity ( $0$  to  $>20$  wt.% NaCl<sub>equiv.</sub>), were considered to be later trapped phases that either progressively mixed with, or modified the earlier types I, III and IV (Silva *et al.*, 2005).

Fluid inclusions, trapped by quartz in the Igarapé Bahia breccia ore unit, indicate that high temperature ( $150$  to  $430^{\circ}\text{C}$ ) type I saline (32 to 45 wt.% NaCl<sub>equiv.</sub>) aqueous phases, together with  $\text{CO}_2 \pm \text{CH}_4$ -bearing types III ( $<6$  wt.% NaCl<sub>equiv.</sub>) and IV varieties, and lower temperature ( $100$  to  $190^{\circ}\text{C}$ ), lower salinity (16 to 24 wt.% NaCl<sub>equiv.</sub>) type II aqueous fluids, were involved in the mineralisation process (Almada and Villas, 1999; Lindenmayer, 1998; Althoff *et al.*, 2000; Dreher *et al.*, 2008). Type I aqueous brines (33 up to 60 wt.% NaCl<sub>equiv.</sub>;  $115$  up to  $519^{\circ}\text{C}$ ) and lower salinity (10 to 25 wt.% NaCl<sub>equiv.</sub>;  $99$  to  $192^{\circ}\text{C}$ ) type II aqueous fluids are the predominant inclusions in quartz from late, poorly mineralised veins at Igarapé Bahia (Dreher *et al.*, 2008). Type III aqueous-carbonic inclusions are rarely found in these veins.

Only types I and II fluid inclusions were described in quartz, fluorite and calcite ore veins at Gameleira (Ronchi *et al.*, 2000). Microthermometry data for type II fluids reveal homogenisation temperatures of between  $80$  and  $160^{\circ}\text{C}$  and salinity ranging from  $8$  to  $21$  wt.% NaCl<sub>equiv.</sub>. The homogenisation temperatures for the type I highly saline inclusions were in the range of  $200$  to  $400^{\circ}\text{C}$ . Similar to the veins at Igarapé Bahia, the occurrence of aqueous-



**Figure 8:** Summary of geochronologic data for IOCG deposits of the Carajás Mineral Province and the main recorded tectonic and magmatic events. Data sources: (1) Réquia *et al.* (2003); (2) Silva *et al.* (2005); (3) Tallarico *et al.* (2005); (4) Galarza *et al.*, (2002); (5) Galarza and Macambira (2003); (6) Huhn *et al.* (1999); (7) Neves (2006); (8) Marshick *et al.* (2002); (9) Pimentel *et al.* (2003); (10) Tallarico (2003).

carbonic (type III) and/or carbonic (type IV) inclusions is rare at Gameleira.

Fluid inclusion studies undertaken on ore breccia and vein quartz from the southeastern IOCG deposits revealed that types I and II fluid inclusions are dominant and CO<sub>2</sub>-bearing types absent. Both types I and II show similar homogenisation temperatures and salinity ranges at the Sequeirinho-Pista-Baiano and Sossego-Curral orebodies of the Sossego deposit (Rosa, 2006; Torresi, 2006; Carvalho, 2009). Overall, the combination of these microthermometric data point to the involvement of possibly three fluid types at this deposit: (1) hypersaline (>40 wt.% NaCl<sub>equiv.</sub>), hot (>500°C) brine; (2) a low temperature (~150°C), saline (11 to 31 wt.% NaCl<sub>equiv.</sub>) phase; and (3) low temperature (<250°C), low salinity (<11 wt.% NaCl<sub>equiv.</sub>) aqueous fluid (Carvalho, 2009). However, in sulphide-rich breccia quartz at Alvo 118, type II fluid inclusions are by far the most abundant (60 to 70% by volume) within individual populations, compared to the coexisting type I brines. Salinities and homogenisation temperatures for these type II fluid inclusions vary from 1.5 to 15 wt.% NaCl<sub>equiv.</sub>, and from 128 to 257°C (mean = 158°C), whereas values of between 33 and 41 wt.% NaCl<sub>equiv.</sub> and between 219 and 331°C (mean = 258°C) are typical of the less abundant type I inclusions at Alvo 118 (Torresi, 2008).

Microthermometric data, combined with SEM imaging and EDS analyses, reveal that both types I and II fluid inclusions from the IOCG deposits of the CMP contain mainly NaCl-CaCl<sub>2</sub>, although K-Fe-Mn chlorides may become important in the late mineralisation stage. Analyses by laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) conducted on individual type I inclusions from most deposits demonstrate that these high salinity inclusions are invariably Ca-dominated brines, containing more Ca than any other cation (Xavier *et al.* 2009). In addition to Ca, these brines contain percent level concentrations of Na and K and are strongly enriched in Ba, Sr and Mn. Most contain tens to hundreds of ppm of Pb and Zn. No high salinity inclusions analysed by LA-ICP-MS from any deposit contained significant Cu, indicating they represent either depleted ore fluids, or that the brines in inclusions from these deposits are not those responsible for supplying Cu to the hydrothermal system (Xavier *et al.*, 2009).

### Stable Isotope Evidence

The calculated  $\delta^{18}\text{O}_{\text{fluid}}$  of the ore-stage fluids at 485°C (temperature from fluid inclusions and isotope ratios from magnetite) for the Salobo deposit ranges from 6.6 to 12.1‰, with an average at 7‰ (Réquia and Fontboté, 2001). This isotopic signature for the mineralising fluids was interpreted by these authors as evidence of a magmatic origin.

At Igarapé Bahia, oxygen isotopic ratios in magnetite, quartz and siderite yield calculated temperature of 400°C and  $\delta^{18}\text{O}_{\text{fluid}}$  compositions varying from 5 to 16.5‰ for the ore-forming fluids (Dreher *et al.*, 2008). This interval is wider than those ( $\delta^{18}\text{O}_{\text{fluid}}$  = 0.7 to 9.4‰) estimated by Oliveira *et al.* (1998) and Tazava (1999) for the same deposit. The fluid regime would initially be dominated by  $\delta^{18}\text{O}$ -enriched fluids, either magmatic, or fluids that interacted with  $^{18}\text{O}$ -rich, probably sedimentary rocks, at high temperatures. The shift towards lower  $\delta^{18}\text{O}$  values may have been achieved by increasing the infiltration of cooler solutions into the system. This seems to be particularly the case in poorly mineralised late veins in which mixing with  $\delta^{18}\text{O}$ -depleted, meteoric fluids is evident (Dreher *et al.*, 2008).

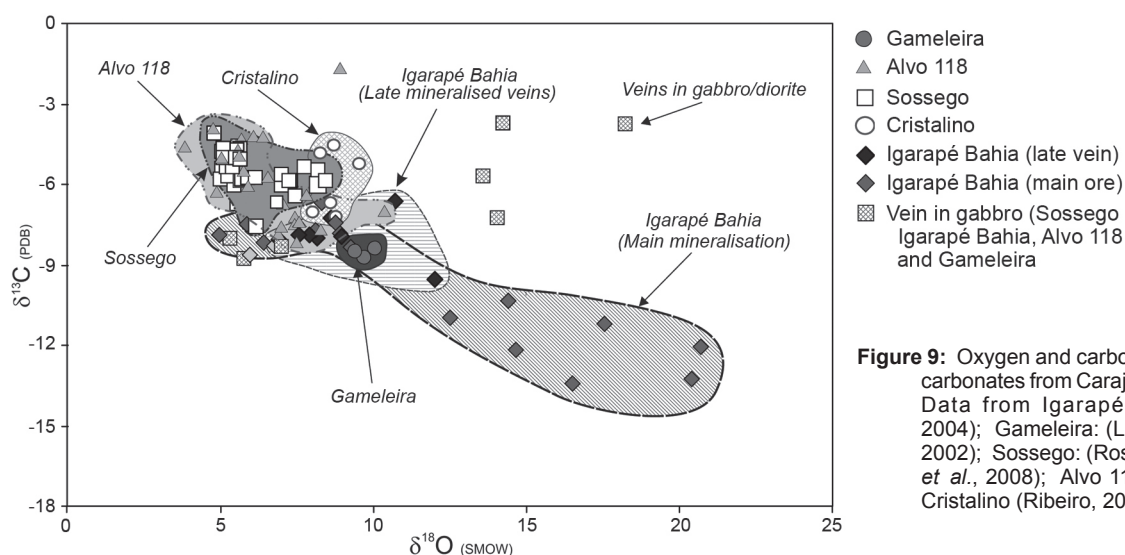
At Sossego, evolution of the hydrothermal system is reflected by a sharp temperature decline and decrease in  $\delta^{18}\text{O}_{\text{fluid}}$  outward from the most intense alteration. Zones with actinolite-magnetite-apatite, proximal to copper-gold mineralisation in the deep parts of the deposit (e.g., Sequeirinho-Baiano-Pista orebodies), were formed by high temperature (>550°C),  $^{18}\text{O}$ -enriched (6.9±0.9‰) fluids (Monteiro *et al.*, 2008a). Outwards from these zones, sodic-calcic and sodic alteration developed in the presence of fluids with  $\delta^{18}\text{O}_{\text{fluid}}$  values of 6.0±0.8‰ (500±25°C), and 3.6±0.6‰ (450±50°C), respectively. Paragenetically later copper-gold mineralisation in both deep parts of the deposit, and at higher structural levels (e.g., the Sossego-Curral orebodies) displays markedly lower temperatures (<300°C), and is characterised by the introduction of D-enriched (–35‰) and  $^{18}\text{O}$ -depleted (–0.4‰) hydrothermal fluids. The  $\delta\text{D}_{\text{fluid}}$  and  $\delta^{18}\text{O}_{\text{fluid}}$  values of early fluids that formed sodic-calcic alteration and actinolite-magnetite-apatite zones partially overlap the characteristic range for primary magmatic and low-temperature metamorphic waters. These same  $\delta^{18}\text{O}_{\text{fluid}}$  values could also have resulted from high temperature equilibration of deeply circulating basinal or formational/meteoric waters with the host rock units. Late fluids, however, have isotopic signatures similar to those of meteoric waters, possibly of low latitude coastal origin.

The oxygen isotopic composition of the ore-bearing fluids from Alvo 118 was estimated on the basis of  $\delta^{18}\text{O}$  values of calcite from ore breccia and veins for a temperature range of 250 to 350°C. These temperature values were constrained by fluid inclusion homogenisation temperatures and chlorite geothermometry, and as a consequence, are taken as minimum and maximum estimates, respectively. The ore breccia fluids have  $\delta^{18}\text{O}_{\text{H}_2\text{O}}$  values mostly between –0.8 and 4.7‰, with a few values in the range of 10.8 to 13.7‰.  $\delta^{18}\text{O}_{\text{fluid}}$  values of calcite in mineralised and barren veins respectively, range from 0.5 to 6.3‰ and from –1.8 to 6.2‰, being indistinguishable from the ore breccias, except for the heavier values of the latter (Torresi, 2008). The  $\delta^{18}\text{O}$  data suggest that strong interaction between the ore fluids and mafic and felsic volcanic and intrusive host rocks, may have generated  $^{18}\text{O}$ -enriched fluids that became progressively more depleted in  $\delta^{18}\text{O}$  by prolonged mixing with meteoric fluids.

At the Castanha prospect, the temperature of mineralised vein formation was estimated at 355±10°C, using oxygen isotope fractionation between quartz-biotite and calcite-biotite pairs. At this temperature, the  $\delta^{18}\text{O}_{\text{fluid}}$  in equilibrium with calcite (4.6 to 7.3‰), quartz (5.8‰) and biotite (6.6‰) has a narrower variation than those values from the Sossego and Alvo 118 deposits (Monteiro *et al.*, 2007). Similar isotopic compositions have been estimated for the Bacaba ( $\delta^{18}\text{O}_{\text{fluid}}$  = 6.0‰) and Jatobá ( $\delta^{18}\text{O}_{\text{fluid}}$  = 5.9‰) prospects, at 350°C. These data indicate a limited contribution of  $^{18}\text{O}$ -depleted fluids, probably of meteoric origin, similar to that identified in the mineralisation stage of the Sossego and Alvo 118 deposits.

Comparison of stable isotope data of carbonate from IOCG deposits in the Carajás Mineral Province indicates narrow and roughly similar variations in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values for Sossego (Monteiro *et al.*, 2008a), Gameleira (Lindenmayer *et al.*, 2002), Cristalino (Ribeiro, 2008) and Alvo 118 (Fig. 9). On the other hand, the oxygen and carbon isotopic data for the ore breccia carbonate from Igarapé Bahia (Dreher *et al.*, 2008) show a widespread variation (Dreher, 2004). Carbonate from veins that crosscut gabbro/diorite in different deposits (e.g., Sossego, Alvo 118,





**Figure 9:** Oxygen and carbon isotopic data for carbonates from Carajás IOCG deposits. Data from Igarapé Bahia (Dreher, 2004); Gameleira: (Lindenmayer *et al.*, 2002); Sossego: (Rosa, 2006; Monteiro *et al.*, 2008); Alvo 118 (Torresi, 2008); Cristalino (Ribeiro, 2008).

Gameleira and Igarapé Bahia) have higher  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values that may reflect fractionation at low temperature. Except for gabbro-hosted vein carbonate that displays relatively higher  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  values, all other carbonate from ore zones define a continuous negative covariant trend between  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (Fig. 9), pointing to extensive fluid-rock interaction and/or mixing processes.

## Sulphur and Carbon Sources

The  $\delta^{34}\text{S}$  values of chalcopyrite and bornite in the Salobo deposit range from 0.2 to 1.6‰, implying a magmatic sulphur source (Réquia and Fontboté, 2001). A similar range of  $\delta^{34}\text{S}$  values (0.6 to 1.5‰) was reported for sulphides from the Cristalino deposit (Ribeiro, 2008). However,  $\delta^{34}\text{S}$  values have been verified over a wider range of -10.8 to 7.6‰ (Fig. 10) in other Carajás IOCG deposits, possibly reflecting variations in physical-chemical conditions ( $f\text{O}_2$ , T, pH) during ore deposition, different sulphur isotopic signatures of country rocks, or multiple sulphur sources for individual systems.

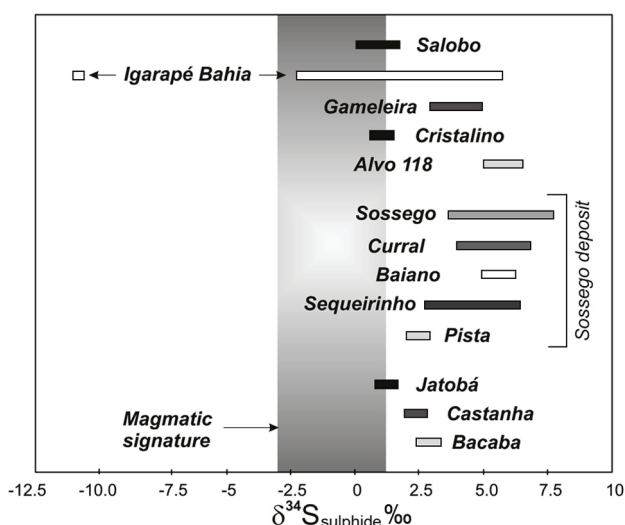
At Igarapé Bahia, the sulphur isotopic compositions of chalcopyrite from the ore breccia matrix and nodules within the hanging wall metasedimentary sequence are concentrated in the range of -2.1 to 5.6‰, with an outlier at -10.8‰ (Villas *et al.*, 2001; Dreher *et al.*, 2008). The clustering of  $\delta^{34}\text{S}$  values between 0 and 2‰ indicates that most sulphur is magmatic, either derived directly from a magmatic source or from non-magmatic fluids that leached sulphides from magmatic rocks. In addition, the extreme value of -10.8‰ indicates a limited contribution of reduced, biogenic sulphur (Dreher *et al.*, 2008). On the other hand,  $\delta^{34}\text{S}$  values of up to 5.6‰, suggest the participation of oxidised sulphur, which could be produced by inorganic, high temperature reduction of seawater sulphate, or of sulphate from a sedimentary source. Chalcopyrite from poorly mineralised veins however, shows a narrower range of  $\delta^{34}\text{S}$  values from -0.3 to 4.0‰ favouring sulphur sourced from magma or leached from magmatic rocks (Dreher *et al.*, 2008).

The orebodies of the Sossego deposit all show heavier sulphur ( $\delta^{34}\text{S} = 4.9 \pm 2.4$ ‰; Monteiro *et al.*, 2008) than expected for a mantle source ( $\delta^{34}\text{S} = 0 \pm 1$ ‰; Eldridge *et al.*, 1991). Sulphide  $\delta^{34}\text{S}$  values increase from 2.2‰ at Pista, up to 7.6‰ at the Sossego-Curral orebodies, pointing to a trend towards heavier isotopic values upwards in the system, closely related to a greater input of surficially derived fluids (Monteiro *et al.*, 2008a). Sulphur isotopic signatures for

Gameleira (2 to 4.8‰; Lindenmayer *et al.*, 2001; Marschik *et al.* 2002) and Alvo 118 ( $\delta^{34}\text{S} = 5.1$  to 6.3‰; Torresi, 2008) also differ from a mantle/magmatic source adding the possibility of heavier sulphur sources (e.g., evaporitic sulphate?) for the ore breccia and vein sulphides.

However, the IOCG prospects in the vicinity of the Sossego deposit, such as Castanha ( $\delta^{34}\text{S} = 1.7$  to 3‰), Bacaba ( $\delta^{34}\text{S} = 2.7$  to 3.5‰) and Jatobá ( $\delta^{34}\text{S} = 0.9$  to 1.8‰), show a narrower range of sulphur isotope compositions compared to the Sossego and Alvo 118 deposits. The occurrence of abundant pyrrhotite at Castanha for instance, implies that the mineralising fluid was in the  $\text{H}_2\text{S}$  stability field and the sulphide isotopic signatures may reflect the  $\delta^{34}\text{S}_{\text{SS}}$ . Thus, the source of sulphur in these prospects may be related to fluids derived from magma or leaching from igneous, including metavolcanic, rocks.

Carbon isotopic signatures ( $\delta^{13}\text{C} = -3.3$  to  $-13.4$ ‰) of carbonate from the Carajás IOCG deposits have been interpreted to be related to magmatic carbon sources (Oliveira *et al.*, 1998; Tazava, 1999; Lindenmayer *et al.*, 2001; Ribeiro, 2008; Dreher *et al.*, 2008), which would have  $\delta^{13}\text{C} \sim -5$ ‰ (Ohmoto, 1986). However, the average



**Figure 10:** Sulphur isotopic compositions of sulphides from Carajás IOCG deposits. Sources of data: Salobo (Réquia and Fontboté, 2001); Igarapé Bahia: (Tazava and Oliveira, 2000; Dreher, 2004; Dreher *et al.*, 2008); Gameleira: (Lindenmayer *et al.*, 2001; Marschik *et al.*, 2002); Cristalino: (Ribeiro, 2008); Alvo 118: (Torresi, 2008); Sossego: (Rosa, 2006; Monteiro *et al.*, 2008a); Jatobá, Castanha and Bacaba prospects: (Monteiro *et al.*, 2007).

$\delta^{13}\text{C}$  value of the crust is also about  $-5\text{‰}$ , which can be generated through diverse pathways and, as a consequence, this value cannot be unequivocally diagnostic of a mantle origin (Ohmoto and Goldhaber, 1997). The carbon signature of the Carajás deposits possibly reflects overall  $\delta^{13}\text{C}_{\text{CO}_2}$  values similar to those of the surrounding rocks.  $^{13}\text{C}$ -depleted signatures (e.g.,  $\delta^{13}\text{C} = -13.4\text{‰}$  in the Igarapé Bahia deposit; Dreher *et al.*, 2008) could also imply an organic carbon origin.

## Halogen Activities in the Hydrothermal Fluid

Chlorine-bearing mineral phases, such as hydrothermal biotite (up to 4 wt.% Cl), amphibole, apatite, scapolite and ferropyrsmalite have been described in the Carajás IOCG deposits, e.g., Igarapé Bahia (Zang and Fyfe, 1995; Tazava *et al.*, 1999; Tallarico *et al.*, 2000; Dreher, 2004), Salobo (Guimarães, 1987), Gameleira (Lindenmayer *et al.*, 2001), Cristalino (Huhn *et al.*, 1999) and Sossego (Villas *et al.*, 2005; Souza, 2007; Monteiro *et al.*, 2008b).

Further to this evidence that the Carajás IOCG mineralisation was formed in a Cl-rich environment, the chlorine/fluorine intercept [ $\text{IV}(\text{F}/\text{Cl}) = 7.3$  to  $7.9$ ], calculated from the composition of biotite from Sossego (Monteiro *et al.*, 2008b), suggests higher Cl/F ratios in the fluid than those associated with typical magmatic-hydrothermal systems, such as porphyry-copper deposits.

In addition, extensive scapolite zones represent early sodic alteration synchronous with shear zone development at Castanha, Jatobá and Bacaba (Pestilho and Monteiro, 2007; Monteiro *et al.*, 2007; Augusto *et al.*, 2008) and Serra Dourada (Villas *et al.*, 2006; Sousa 2008). Marialitic scapolite occurs in veins and replacement zones at these prospects, where it forms haloes, or alteration fronts, in granitic, volcanic and gabbroic rocks. Evidence of *in situ* replacement of evaporitic minerals was not observed in these areas. However, the occurrence of Cl-bearing marialite reflects both hypersalinity and buffered Cl-activity gradients in the hydrothermal fluids. These conditions could be related to limited introduction of meteoric water and dilution in the early alteration stages of the distal Castanha, Jatobá and Bacaba areas. Thus, scapolite zones in the Carajás Mineral Province could represent distal envelopes to major palaeo-hydrothermal IOCG systems.

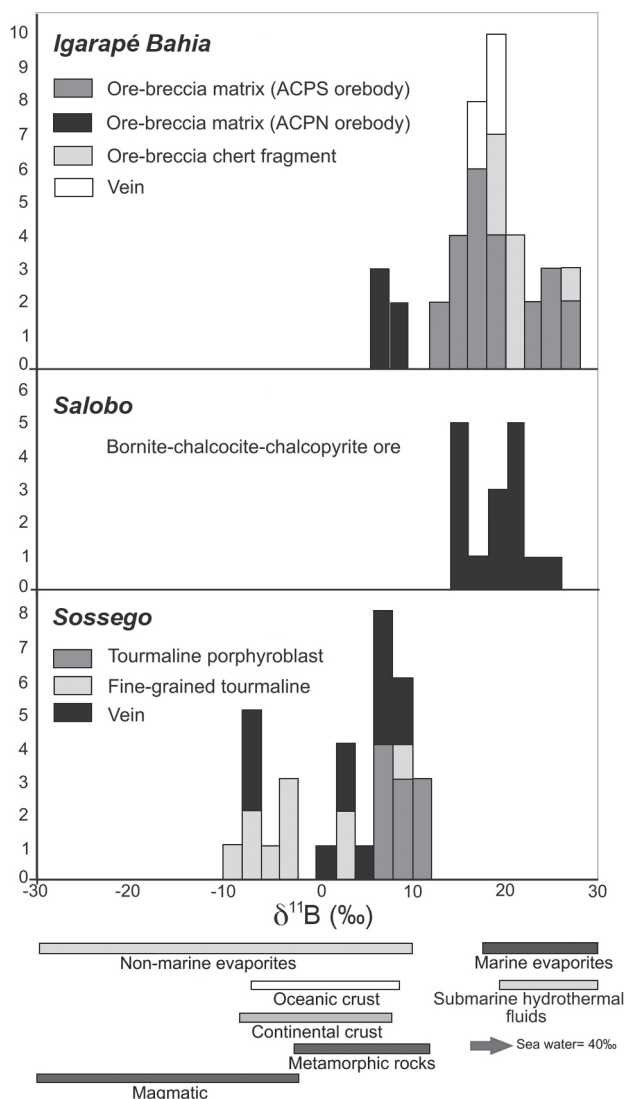
## Chlorine–Boron Isotopes and Cl/Br–Na/Cl Systematics

Chlorine isotope data, combined with Cl/Br ratios of fluid inclusions in quartz and calcite from the Sossego and Gameleira IOCG deposits, were first reported by Chiaradia *et al.* (2006).  $\delta^{37}\text{Cl}$  values of between 0 and  $2.1\text{‰}$ , and Cl/Br ratios of between 800 and 1500 are typical at Sossego (e.g., Sequeirinho and Sossego orebodies), although at Gameleira,  $\delta^{37}\text{Cl}$  values range from  $-0.6$  to  $0.3\text{‰}$  and Cl/Br ratios are  $\geq 4000$ . According to the same authors, these data indicate mixing of magmatic mantle-derived fluids and basinal brines to produce the Sossego IOCG fluids. Although Gameleira has been classified as a magmatic end member of the IOCG class of deposit (Lindenmayer *et al.*, 2001; Pimentel *et al.*, 2003), the high molar Cl/Br ratios and near  $0\text{‰}$   $\delta^{37}\text{Cl}$  values point to an important involvement of evaporitic fluids during the mineralising event (Chiaradia *et al.*, 2006).

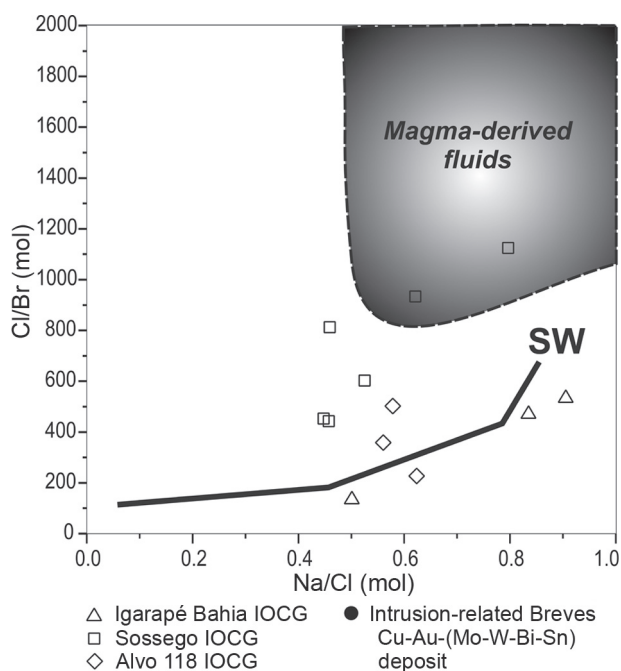
A boron isotope study of texturally different tourmaline from three IOCG deposits (Igarapé Bahia, Salobo and Sossego) was carried out by Xavier *et al.* (2008a) using

secondary ion mass spectrometry (SIMS). Values of  $\delta^{11}\text{B}$  from 14 to  $26.5\text{‰}$  for Igarapé Bahia and Salobo confirm the involvement of marine evaporites brines in the ore fluids (Fig. 11), while lower  $\delta^{11}\text{B}$  values from Igarapé Bahia (5.8 to  $8.8\text{‰}$ ) suggest these fluids may have also mixed with an isotopically different hydrothermal fluid, or one that had a mixed boron source. More variable and isotopically lighter boron in tourmaline from Sossego ( $-8$  to  $11\text{‰}$ ) is attributed to mixed sources, including light boron leached from felsic intrusive and volcanic host rocks, and heavy boron derived from marine evaporites.

A more recent application of Cl/Br–Na/Cl systematics in fluid inclusions from the Carajás IOCG deposits (e.g., Sossego, Alvo 118 and Igarapé Bahia) has been performed by Xavier *et al.* (2009) using ion chromatographic analysis. Cl/Br and Na/Cl ratios of the fluid inclusions in the investigated deposits plot close to, and mostly above, the seawater evaporation curve (Fig. 12). Fluid inclusions from Igarapé Bahia and Alvo 118 have the closest Cl/Br and Na/Cl ratios to the seawater evaporation curve. In the case of the Sossego deposit, Cl/Br and Na/Cl ratios are intermediate between the seawater evaporation curve and the lower end range of magma-derived fluids. Furthermore,



**Figure 11:** Histograms of tourmaline boron isotope compositions (average uncertainty  $1\sigma = \pm 0.8\text{‰}$ ) from selected IOCG deposits of the Carajás Mineral Province (Xavier *et al.*, 2008). The range of boron isotopic compositions for various boron reservoirs in nature (Barth, 1993; Palmer and Swihart, 1996) are shown for reference.



**Figure 12:** Cl/Br and Na/Cl ratios of fluid inclusions from the Sossego, Alvo 118 and Igarapé Bahia IOCG deposits of the Carajás Mineral Province. The thick line labelled SW is the seawater evaporation curve, while the field limited by a dashed line represents magma-derived fluids (modified from Viets *et al.*, 1996).

the low Cl/Br ratios of Carajás IOCG fluids also rule out the dissolution of evaporites as the source of salinity. As bromine is not incorporated into the precipitating salts during seawater evaporation, the residual brine becomes Br-enriched and the Cl/Br ratios decrease (Viets *et al.*, 1996). Conversely, the dissolution of evaporitic salts result in fluids with Cl/Br ratios well above 20 000.

Collectively, chlorine–boron isotope data and Cl/Br and Na/Cl systematics provide compelling evidence for residual evaporative (e.g., bittern fluids) and magma-derived brines as the main sources of the highly saline fluids involved in the formation of the Carajás IOCG deposits. Nevertheless, marine evaporites have not yet been recognised in the province, although it is geologically feasible that they might have been deposited in the lower parts of the Itacaiúnas Supergroup, given the early rifting history of the basin, and subsequently destroyed by metamorphic or regional metasomatic events.

## Mechanisms of Ore Deposition

Irrespective of their origin, high-temperature, Cl-rich, highly saline fluids were probably responsible for the transport of metals as chloride complexes during the evolution of the Carajás IOCG hydrothermal systems. Hypersaline, neutral to weakly acidic and intermediate-reduced brines (magnetite stable) can transport thousands of ppm of Cu at 400°C (Liu and McPhail, 2005). Gold is also highly soluble at high temperature (>350°C) and/or high Cl-concentrations (Henley, 1973). If iron was also transported by this metalliferous fluid, magnetite formation could result in sulphate reduction favouring ore deposition. Ore deposition in this evolving system would require reduced salinities of the fluid, temperature decrease and an increase in reduced sulphur content.

A decrease in the chlorine content of the fluid might have been achieved either by fluid mixing and/or by loss of chlorine to minerals, as evidenced by chlorine incorporation

in amphibole, biotite, apatite and scapolite. A reduction in temperature during the ore stage is indicated by the mineral chemistry and stable isotope compositions of gangue minerals in most of the Carajás IOCG deposits. Fluid mixing between a high-temperature, hypersaline, intermediate oxidation state, metalliferous brine and oxidised meteoric-derived fluids has been clearly demonstrated, particularly for the IOCG deposits of the southeastern sector of the province (e.g., Sossego, Alvo 118) and considered the principal ore deposition mechanism.

## Concluding Remarks

The Carajás IOCG deposits share a number of similarities, including: (1) variable host lithologies, which in all cases include metavolcano-sedimentary units of the ~2.76 Ga Itacaiúnas Supergroup; (2) association with shear zones; (3) proximity to intrusions, which may be of different compositions (granite, diorite, gabbro, rhyolitic or dacitic porphyry dykes); (4) intense hydrothermal alteration, with the notable importance of proximal K-Fe alteration as microcline with associated magnetite, the local predominance of sodic (albite-scapolite) and sodic-calcic assemblages in deeper or distal zones, and ore-related, late stage chlorite and carbonates; (5) late sulphide precipitation; and (6) a wide range of fluid inclusion homogenisation temperatures (100 to 570°C) and salinities (0 to 69 wt.% NaCl<sub>equiv.</sub>).

Major differences between these same deposits include: (1) the presence of distinct hydrothermal alteration assemblages at specific deposits, such as the high temperature silicates (e.g., fayalite and almandine) at Salobo and Igarapé Cinzento in particular, which are absent at others; (2) ore mineral assemblages indicative of variable oxidation states of the source fluids (e.g., chalcopryrite-chalcocite-bornite at Salobo; chalcopryrite±chalcocite-digenite-covellite at Igarapé Bahia; chalcopryrite-pyrite at Sossego and Cristalino; pyrrhotite-chalcopryrite-pyrite at Castanha). The predominance of any one of these mineral associations in a specific IOCG deposit of the province is dependent upon a combination of factors such as crustal level, fluid sources, reactions along the fluid path and at the deposition site, temperature,  $fO_2$ ,  $fS_2$ , and pH of the fluid.

The Cristalino, Sossego and Alvo 118 deposits, together with the Castanha, Jatobá and Bacaba prospects within the southeastern sector of the CMP, are hosted by meta-volcanic rocks of the Itacaiúnas Supergroup, felsic intrusive rocks, gabbro and minor quartz-feldspar porphyry dykes. A similar sequence of hydrothermal alteration, characterised by sodic (albite and scapolite), sodic-calcic (actinolite), potassic (microcline and/or biotite), chlorite-bearing and hydrolytic (muscovite and hematite) assemblages, was recognised at all of these deposits. Extensive zones of scapolite alteration however, were only recognised at the Castanha, Jatobá and Bacaba prospects (Monteiro *et al.*, 2007). These scapolite-rich zones are represented by replacement fronts and metre-scale veins, and indicate high salinity and buffered activity gradients in chlorine of the early hydrothermal fluids, with very limited influx of externally-derived diluted fluids.

Copper-gold mineralisation was invariably introduced in the late stages of all of the IOCG systems of the province, generally controlled by subsidiary brittle or brittle-ductile structures. Despite the generally similar characteristics shared by the IOCG deposits of the southeastern part of the CMP, important differences may be recognised at



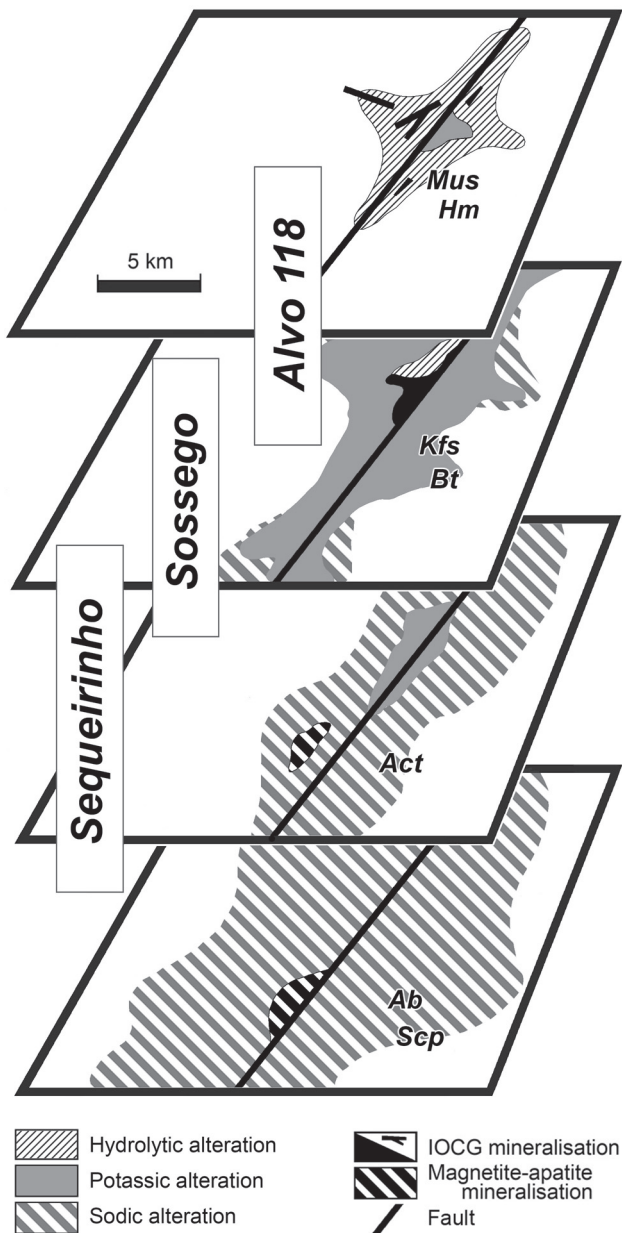
the deposit scale. At Sossego, for instance, the alteration surrounding the Sequeirinho orebody is dominantly sodic-calcic, whereas at the Sossego orebody, it is potassic and chloritic (Monteiro *et al.* 2008a). These variations in hydrothermal alteration are indicative of fluid/rock interactions at different structural levels, in which the Sequeirinho orebody represents deeper portions, and the Sossego orebody the upper parts of the same palaeosystem (Fig. 13). The latter shares several similarities with the shallowly emplaced Alvo 118 deposit, in particular the predominance of potassic and chloritic alteration.

Despite evidence for a common evolution of the Carajás IOCG deposits, dating of ore-related minerals has revealed different ages, even in a single deposit (e.g., Igarapé Bahia, Gameleira, Salobo; Réquia *et al.*, 2003; Tallarico *et al.*, 2005; Pimentel *et al.*, 2003). A temporal relationship between the widespread Archaean

magmatism (~2.74 Ga) and the Carajás IOCG deposits has been indicated, notably at the Cristalino deposit (Huhn *et al.*, 1999a, b). Robust geochronologic data also points to an important metallogenic event at 2.57 Ga (Réquia *et al.*, 2003; Tallarico *et al.*, 2005; Grainger *et al.*, 2008). However, there is a lack of a clear spatial association between the IOCG deposits and magmatism of this age in the province, except at Salobo. Thus, despite the importance of magmatism in providing heat and fluids for the development of extensive hydrothermal systems, the available geochronologic data may not be necessarily related to an individual magmatic event. Alternatively, the ages may be the result of a long-term history of isotopic resetting due to the development and/or reactivation of Archaean ductile or ductile-brittle shear zones and/or Palaeoproterozoic anorogenic magmatism.

Overall, the fluid inclusion data points to trends in fluid evolution that have consistently involved highly saline (35 to 70 wt.% NaCl<sub>equiv.</sub>) and hot metalliferous brines, and lower temperature (generally <250°C) aqueous fluids of low to intermediate salinity, with or without the participation of aqueous-carbonic (CO<sub>2</sub>±CH<sub>4</sub>) and carbonic fluids. CO<sub>2</sub>-bearing fluid inclusions were only reported at the Salobo, Igarapé Bahia and Gameleira deposits (Réquia and Fontboté, 2001; Ronchi *et al.*, 2001; Dreher, 2004) in the northwestern sector of the province. The lower temperature (<250°C) aqueous fluids predominate in the mineralisation stage of most of the Carajás IOCG deposits. This fluid likely represents influx of surficially-derived meteoric water, which might have been channeled within the regional faults. The ore precipitation was marked by a sharp temperature decrease in all IOCG deposits to below 300°C. The transition from a dominantly brittle-ductile to a brittle structural regime and cooling of the system favours the influx of oxidised meteoric-derived fluids, which were of fundamental importance to enhance the efficiency of copper deposition. Thus, copper deposition might be related to collapse of the early hydrothermal system, controlled by fluid flow in regional shear zones, followed by the influx of meteoric fluids under hydrostatic, brittle conditions.

Stable isotope data have not provided unambiguous evidence for the involvement of magma-derived fluids in the formation of the Carajás IOCG deposits. Although  $\delta D_{H_2O}$  and  $\delta^{18}O_{H_2O}$  values of hydrothermal fluids partially overlap the characteristic range for primary magmatic waters, these isotopic signatures are also typical of low-temperature metamorphic waters. In addition, these same  $\delta^{18}O_{H_2O}$  values could also have resulted from high temperature equilibration of deeply circulating basinal or formational/meteoric waters with the host rock units (Monteiro *et al.*, 2008a). Extensive fluid-rock interaction, possibly involving basinal/evaporite and magmatic fluid components, could result in  $^{18}O$ -enriched fluids ( $\delta^{18}O_{fluid} = 5$  to 15‰) characterised in most Carajás IOCG deposits. On the other hand, chlorine and boron isotopes, combined with Cl/Br–Na/Cl systematics, strongly suggest that the fluid regimes responsible for the formation of the Carajás IOCG deposits had a significant component of residual evaporative fluids (e.g., bittern fluids generated by seawater evaporation) that may have mixed with magma derived brines (Chiaradia *et al.*, 2006; Xavier *et al.*, 2009). Although heavy  $\delta^{11}B$  values (>10‰) for ore-related tourmaline represents indirect evidence of a marine evaporite contribution to the hydrothermal system, Cl/Br and Na/Cl ratios rule out the dissolution of



**Figure 13:** Distribution of hydrothermal alteration zones in IOCG deposits from the southeastern sector of the Carajás Mineral Province, and relationship with structural level, based on the model of Hitzman (2000) and Hitzman & Valenta (2005). Mineral abbreviations: Ab = albite; Act = actinolite; Bt = biotite; Kfs = potassium feldspar; Hm = hematite; Mus = muscovite; Scp = scapolite.

evaporite-bearing units via metamorphism, or interaction with hydrothermal fluids, as the source of salinity.

Sulphur isotope compositions in the Carajás IOCG deposits vary from values close to that expected for a mantle source ( $\delta^{34}\text{S} = 0 \pm 1\text{‰}$ ) at Salobo to  $\delta^{34}\text{S}$  enriched values ( $>7\text{‰}$ ) in deposits in which the contribution of meteoric fluids was significant, such as Sossego and Alvo 118, reflecting distinct physico-chemical conditions, or input of heavy sulphur from surficial reservoirs.

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