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## **Mapping New Iron oxide copper-gold (Iocg) Mineral Systems In Brazil: The Vale Do Curaçá And Riacho Do Pontal Copper Districts**

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**Abstract:** New interpretation of IOCG mineral systems in Brazil is proposed based on integration of geophysical, geological and geochemical data. At a continental scale, the Riacho do Pontal and Vale do Curaçá Districts flanking high-speed tomography images control on a broad scale as well as the Carajas IOCG Province in Brazil. On the northern edge of the São Francisco Craton, two copper districts were studied in Brazil and represent two new frontiers in mineral exploration. The Vale do Curaçá Copper District is situated in the interior of the craton, whereas the Riacho do Pontal Copper District is situated along its border. The Caraíba Mine and associated mineralization at the Vale do Curaçá District are related to Paleoproterozoic hydrothermal processes. However, the mineralization located in the Riacho do Pontal has been identified as dominantly Neoproterozoic.

More recently, new papers have been published regarding both districts that increased knowledge of copper mineralization and led to their characterization as IOCG deposits. Regional magnetic and gravimetric surveys were analyzed to interpret the geological, structural and metallogenetic characteristics of the Riacho do Pontal and Vale do Curaçá Copper Districts. The Vale do Curaçá Copper District is located in a high gravimetric NS domain. It is 110 km in length and 22 km in width and shows a strong wavelength gravity high (up to -40 mGal). The ore in the Caraíba mine has a density greater than 3.13 g/cm<sup>3</sup> in contrast to the sterile rocks with a density of less than 2.98 g/cm<sup>3</sup>.

The gravimetric signature of the Riacho do Pontal Copper District is mainly characterized by a NW-SE Bouguer anomaly low (down to -45 mGal). Geologically, these areas are related to the gneiss outcrops of Sobradinho Remanso and the southern portion of the Riacho Seco Complex. The four occurrences of the Riacho do Pontal Copper District are situated on these regional low-gravity domains.

3D models obtained with Geosoft VOXI Earth Modeling inversion show that the Caraíba mine is intrinsically related to the high magnetics associated with gravity anomaly highs. The ore bodies are subvertical and probably controlled by a stretching lineation.

MVI magnetic and gravity inversion shows two main NNW prospective trends. Trends I and II have a sigmoidal shear shape. These trends are positioned in the contact zone between domains with high magnetic (SI>0.005) and gravimetric anomalies (>-10.000 mGal) and show a contrast in density and magnetite content. Trend I is 60 km in length and 7 km in width; hosts the Caraíba, Surubim and Vermelho mines and other deposits; and is the most important trend for hosting IOCG deposits in the Vale do Curaçá District.

The results obtained from the magnetic inversions conducted in the region of the Pontal do Pontal show weak magnetic anomalies along a NW-SE trend. The magnetic linear discrete features are related to shear zones. These NW-SE features overlap older and deeper NE-SW features of the São Francisco cratonic root.

**Keywords:** 3d data integration; iocg; paleoproterozoic; gravimetric and magnetic; riacho do pontal; brazil

## 1. Introduction

Iron oxide copper-gold (IOCG) deposits have been described as world-class deposits that show their metallogenetic footprint in different tectonic settings with variable volumes of associated alteration (POLLARD et al., 2018; HITZMAN et al., 1992; BARTON, 2014; GROVES et al., 2010). On a global scale, IOCG deposits are strongly controlled by shear system zones and occur associated with high concentrations of magnetite and/or hematite. Frequently, the geometry and structural control of mineralized trends are related to secondary structures, transpression sites and orebody plunges along stretching lineations (O'DRISCOLL, 1985; HITZMAN, 2000; GROVES et al., 2016). Magnetic and gravity anomalies related to ore zones have led explorers to use them as an effective exploration tool to find new IOCG deposits (HAYWARD et al., 2016; SMITH, 2002; CLARK et al., 2013; CLARK, 2014).

The geological features of the IOCG deposits are distinct and show the variable intensity of hydrothermal processes, and they are hosted by sheared rocks with different ages and composition (LINDENMAYER, 1981; LINDENMAYER, 1982; HUHNS; NASCIMENTO, 1997; REQUIA et al., 2003; TALLARICO et al., 2005; DREHER et al., 2008; MONTEIRO et al., 2008a, 2008b; TEIXEIRA et al., 2010b; XAVIER et al., 2010, 2012; MELO et al., 2016; HUHNS and SILVA, 2018). The flow of fluids and hydrothermal alteration are channeled mainly along the regional shear zones (HOLDSWORTH; PINHEIRO, 2000; GROVES et al., 2016; POLLARD et al., 2018). The array of shear zones is responsible for the sigmoidal "S-shape" of Carajás Province and Vale do Curaçá District (HOLDSWORTH; PINHEIRO, 2000; LINDENMAYER, 1982).

In northeast region of Brazil new IOCG districts were mapped on the north border of the São Francisco Craton. The Vale do Curaçá copper District is situated in the interior of the craton, whereas the Riacho do Pontal District is situated on its border, termed Riacho do Pontal Mobile Belt (LINDENMAYER, 1982; SILVA et al., 1996, TEIXEIRA et al., 2010a; HUHNS et al., 2014; JULIANI et al., 2016; GARCIA et al., 2018; HUHNS and SILVA, 2018). Potassium and calcic-ferrie hydrothermal alteration processes were described as related to copper mineralized zones (TEIXEIRA et al., 2010b; GARCIA, 2013; GARCIA et al., 2018; HUHNS et al., 2014). The Caraíba Mine and associated mineralization at the Vale do Curaçá District are related to paleoproterozoic hydrothermal processes (ca. 2.0 Ga; TEIXEIRA et al., 2010b; GARCIA et al., 2018). However, the mineralization in the Riacho do Pontal Copper District has been characterized as dominantly Neoproterozoic (HUHNS et al., 2014; HUHNS and SILVA, 2018; Figure 2.1). Both Vale do Curaçá and Riacho do Pontal Copper Districts can be considered among the most important prospects for host IOCG deposits in Brazil. However, few studies have shown the structural control of these deposits and the relationship with regional magnetic and gravity signatures.

The IOCG Districts and provinces and their relationship with the Brazilian and West African cratons and mobile belts are shown in figure 2.1

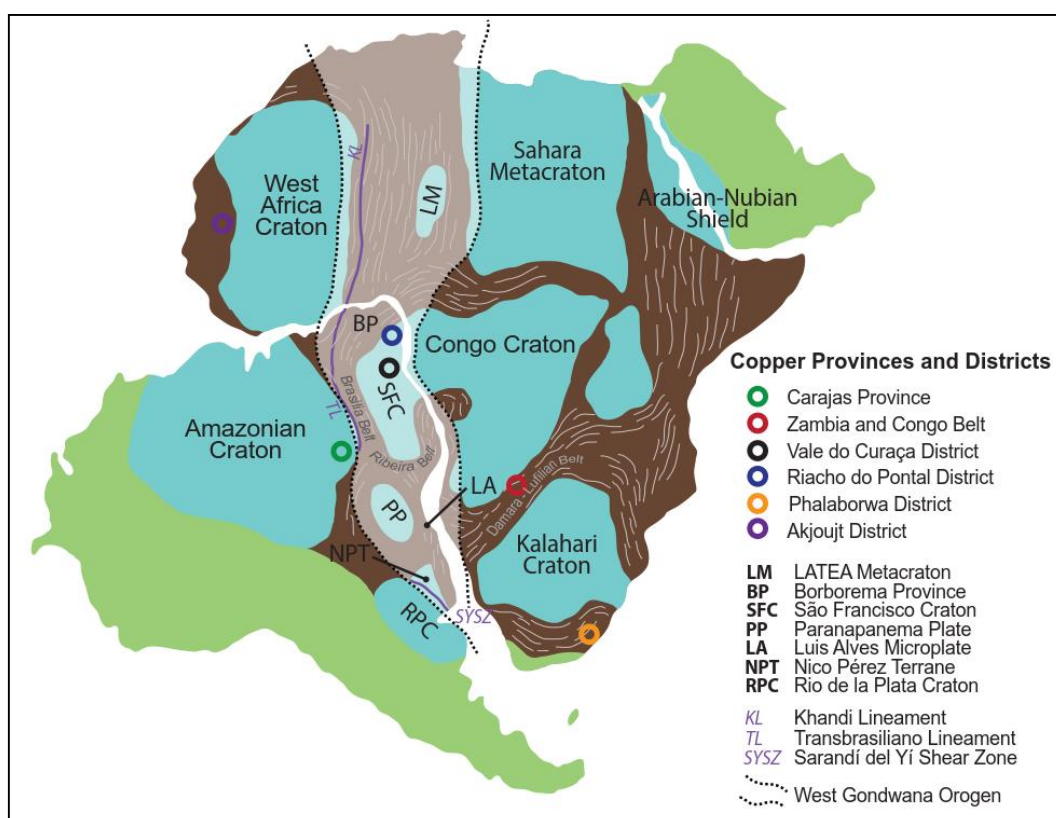


**Figure 2.1** IOCG Provinces and Districts situated in Brazil and Africa: main crustal blocks and Neoproterozoic orogenic belts in South America and Africa, including locations of the West Gondwana Orogen (Modified after GRAY et al., 2008; LIÉGEOIS et al., 2013; BRITO NEVES; FUCK, 2014; GANADE et al., 2016). See text for further explanation.

The IOCG Provinces and Districts situated in Brazil and Africa are situated mainly in border of crustal blocks and in Neoproterozoic orogenic belts. There are at least three main IOCG copper districts/Provinces with different ages: a) Carajás Province (2.72 Ga and 2.5 Ga); Vale do Curaçá District (2.0 Ga) and c) Neoproterozoic (0.75 – 0.57 Ga) Districts such as Riacho do Pontal and Phalaborwa District (Figure 2.1).

The main goal of this study was to understand the tectonic setting of these two copper districts, their tectonic evolution and the relationship with the mineralization event. Are these districts situated at the same crustal level? What are the main structural controls of mineralization at the Curaçá and Riacho do Pontal Districts? What is the meaning of the endowment of these mineralization's for other mobile belts situated along the border of São Francisco Craton?

## 2. Brazilian IOCG Districts and Tomography Maps

Craton edges are known to be characterized by a thin lithosphere and are strongly tectonized zones creating transtensional or transpressional sites along translithospheric faults (BEGG et al., 2009). These major shear zones or fault zones are frequently used for melt introduction into the crust. A series of iron-oxide-copper deposits (IOCGs) including world class Olympic Dam at Gawler Craton and other cluster of deposits within Eastern rocks of Mount Isa inlier of Australia are related to the presence of large intrusive provinces (LIPs) that contain a considerable presence of intrusive felsic rocks (PIRAJNO; BAGAS, 2008; McPhie et al., 2011; PIRAJNO; HOATSON, 2012; HITZMAN, 2000; GROVES et al., 2016). In the Carajás Mineral Province sheared felsic intrusive rocks has been reported that could represent fragments of large intrusive provinces (Lips) ranging from 2.74 Ga to 2.55 Ga in age (HOLDSWORTH; PINHEIRO, 2000; POLLARD et al., 2018; GRAINGER et al., 2008).

Integration of geophysical, geological, and geochemical data on the crust and mantle has generated a map of lithospheric that have shown that approximately 70% of the existing subcontinental lithospheric mantle (SCLM) may be of Archean origin. The inference is that most preserved Proterozoic crust overlies Archean SCLM that has been variably refertilised and metasomatised by mantle melts associated with convergent margin and mantle plume processes (BEGG et al., 2009; GRIFFIN et al., 2008).

Seismic tomography has been used to understand the global geodynamic framework by several authors (GRIFFIN et al., 2013; BEGG et al., 2009; BEGG et al., 2010). The application of seismic tomography images shows that boundaries of cratonic zones and discontinuities in subcontinental lithospheric mantle (SCLM) are physically favorable for the ascension of magmas (GRIFFIN et al., 2008; GRIFFIN et al., 2013). The authors have shown that preserved cratonic regions (SCLM) can be mapped as areas presenting a high seismic velocity. At a global scale, it has been shown that smaller volumes of magmas directly originating from the mantle are positioned at the craton limit. Worldwide diamond, platinum-group elements (PGE), Ni-Cu-(PGE) and copper porphyry and IOCG deposits are situated along cratonic edge and can be related with tectonic evolution of Sub-Continental Lithospheric Mantle - SCLM (GRIFFIN et al., 2013; BEGG et al., 2010; CZARNOTA et al., 2013).

Seismic tomography produces maps with relative variation in the velocity of P and S waves with reference to a known model. Basically, the arrival time of the waves is measured and compared to the expected times, showing the signature of the mantle up to a depth of 500km (GRIFFIN et al., 2013). A Broad Regional Seismic Tomography Image from Central East Brazil region shows the Carajás Province, Vale do Curaçá and Riacho do Pontal IOCG districts are concentrate along prominent trans-lithospheric structures, particularly on the flanks of highs domains (Figure 2.2). Domains of high velocity anomaly can represent ancient blocks of metasomatized subcontinental lithospheric mantle (SLCM) within a discrete mantle lithosphere domain flanked by major faults (BEGG et al., 2010; GRIFFIN et al., 2013).

The IOCG Carajas Province, Vale do Curaçá and Riacho do Pontal Copper districts are located in the transition zone between domains of high and low velocities (Figure 2.2), reflecting refertilisation of the subcontinental lithospheric mantle (SCLM) and or a higher temperature. They have been found along cratonic edges and can be related with tectonic evolution of SCLM. Ore deposits typically concentrates along prominent trans-lithospheric structures, particularly in lower-velocity regions or on the flanks of high-velocity regions (GRIFFIN et al., 2013; BEGG et al., 2010). In this context, the large areas flanking high speed tomomography image that already control in a broad scale Carajás IOCG Province and Riacho do Pontal and Vale do Curaçá Copper Districts in Brazil should be evaluated in more detailed in further works (Figure 2.2).

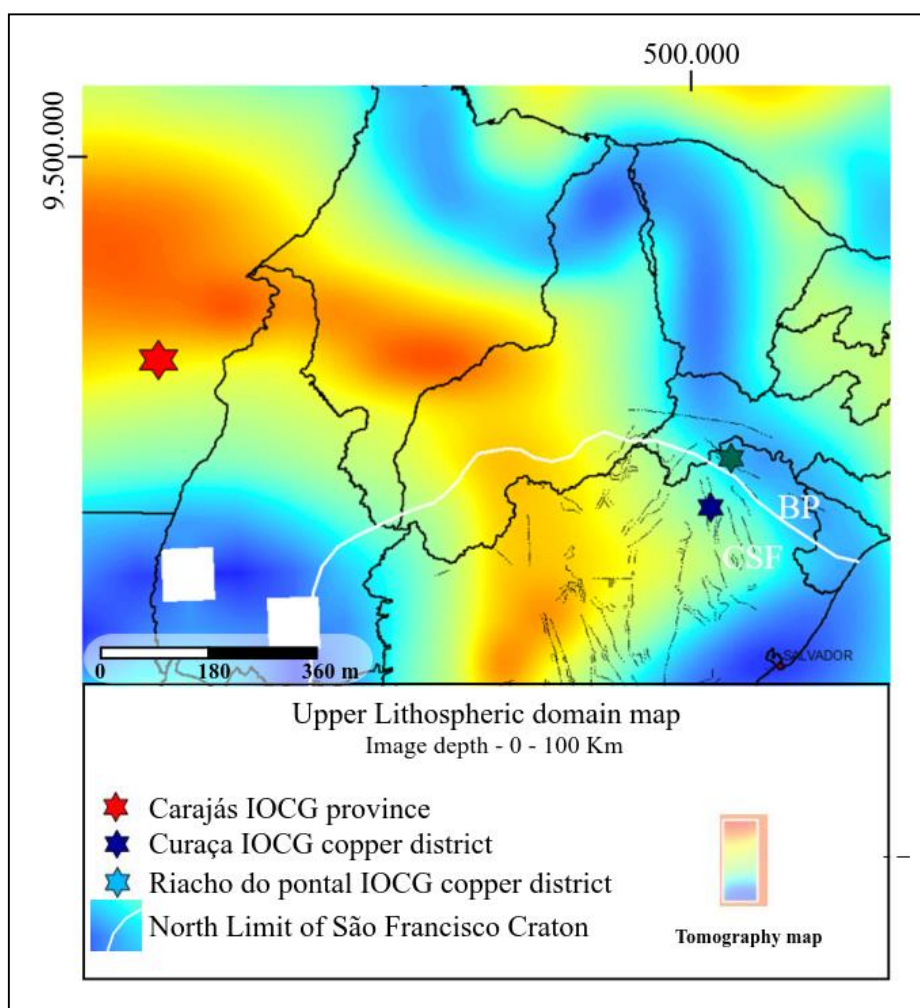


**Figure 2.2** - Seismic Tomography Image showing the Carajás IOCG Province, Riacho do Pontal and Vale do Curaçá Copper districts at Brazil. The high zones (in red) in tomographic map represents high velocity domains that represents microcontinental blocks (mantle lithosphere domain). They are flanked by low velocity domains that represents lower velocities that reflect refertilisation of the SCLM and/or a higher temperature along fault zones. Frequently, deposits concentrate along prominent trans-lithospheric structures, particularly in lower-velocity regions (blue) or on the flanks of highs (Courtesy of BEGG, 2010).

### 3. Geological Setting

Geologically, the Vale do Curaçá copper District consists mainly of rocks belonging the Itabuna-Salvador-Curaçá Orogen (ISCO). The ISCO is located east of the Gavião and Jequié blocks and west of the Serrinha Block (Figure 2.3); it is an 800-km-long belt of high metamorphic grade granulitic rocks from the Archaean to the Paleoproterozoic. These rocks were deformed and metamorphosed due to the collision of the Gavião, Jequié and Serrinha blocks (PADILHA; MELO, 1991; BARBOSA; 1990; BARBOSA; DOMINGUEZ, 1996; TEIXEIRA et al., 2010b). The Itabuna-Salvador-Curaçá Orogen (ISCO) is a Rhyacian to Orosirian orogenic belt resulting from the collision of Archaean blocks in the range of 2.0 to 2.2 Ga. (BARBOSA; SABATÉ, 2004; TEIXEIRA et al., 2010a). It was followed by deformation, with high metamorphic grade and syntectonic granites (OLIVEIRA et al., 2004). Shrimp U/Pb ages of 2695 ± 12 Ma were obtained in granulitic rocks at the Caraíba Complex (TEIXEIRA et al., 2010b) and 2072 Ma for the metamorphic event (OLIVEIRA et al., 2004).

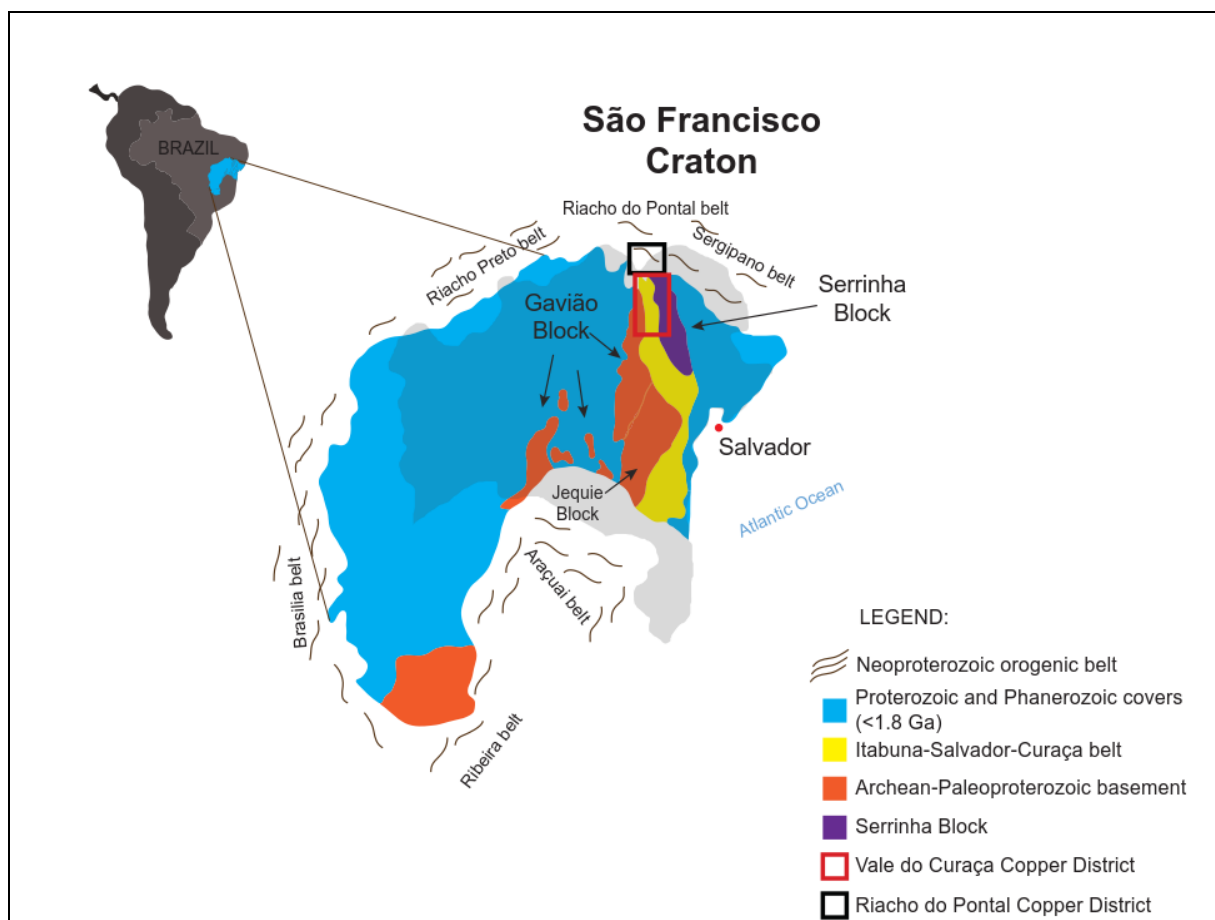


**Figure 2.3** Geological map of the São Francisco Craton (SFC) showing the Vale do Curaça and Riacho do Pontal Copper Districts. Both are situated on the northern edge of the SFC in contact with Borborema Province.

The Riacho do Pontal Copper District is situated in the southern portion of Borborema Province. It is one of three belts situated on the northern border of the São Francisco Craton, which are the Riacho Preto, Riacho do Pontal and Riacho Preto belts (Figure 2.3). This area has been characterized as the Brasiliano collisional zone (from 0.75 to 0.57 Ga) developed during the convergence of the Neo- to Mesoproterozoic terrains of Borborema Province with the São Francisco Craton (ALKMIM et al., 1993). The suture is marked by a negative positive pair of strong gravimetric anomalies. The positive peak corresponds to the lower crustal lift of the Borborema Province, and the negative corresponds to nappes pushed towards the Craton (OLIVEIRA, 2008). This geophysical limit coincides with the occurrence of basal-ultrabasic rocks belonging to Neoproterozoic arch complexes (SÁ, 1994). According to Oliveira (2008), it is possible to observe that the supracrustal bands of the Riacho do Pontal and Sergipana bands were placed allochthon with displacements on the order of 30 to 60 km over the São Francisco Craton (SÁ et al., 1992). This overlapping structure is observed in both magnetic and gravimetric data, with the truncation and displacement of old NS structures occurring along the border between these two tectonic compartments. According to Sá et al (1992), the collisional event was overprinted by transcurrent shear zones.

Along the northern edge of the São Francisco Craton, two fertile districts have been characterized to host copper mineralization: Vale do Curaça and Riacho do Pontal copper districts. More recently, new papers have been published regarding both districts that increased knowledge of copper mineralization, leading to the recognition of these deposits as

IOCG deposits (LINDENMAYER, 1982; SILVA et al., 1996, TEIXEIRA et al., 2010a; HUHNS et al., 2014; JULIANI et al. 2016; GARCIA et al., 2018; HUHNS and SILVA, 2018 ). Only in the last 10 years have new high- resolution airborne geophysical surveys been completed which has motivated new exploratory campaigns in these districts. Despite the increase in new geological information, the low tax of discoveries is still mainly due to the absence of systematic and modern exploratory surveys and by the low density of exploration drilling used in all of past activities.

#### 4. Paleoproterozoic Vale do Curaçá Copper District

Since the beginning of the last century, the Vale do Curaçá Copper District has been the focus of intense geological activity. During the 1970's, a mineral exploration boom occurred in this region. The focus of the exploration program was copper in volcanic-hosted massive sulfide mineralization (VMS or VHMS; FRANKLIN et. al., 1981; BARRIE; HANNINGTON, 1999) in greenstone belts and copper mineralization hosted in mafic-ultramafic layered complexes (DELGADO; SOUSA, 1975; LINDENMAYER, 1982). These exploration activities led to the discovery of the Caraíba mine and a series of copper deposits and occurrences in the Vale do Curaçá District. Approximately 300,000 meters of drilling were executed in the entire mining district (FRÁGUAS, 2013).

The Vale do Curaçá Copper District occupies an area of approximately 2000 km<sup>2</sup>, and it among the most important mining districts in Brazil. Approximately three hundred copper occurrences have been mapped. The District encloses the Caraíba copper mine with total reserves of 42,4 MT @ 1.71% Cu (MENDONÇA et al., 2018). The most important copper deposits at Vale do Curaçá are those the Surubim, Vermelhos, Arapuã, Sussuarana, and Pirulito (ROCHA, 1999; TEIXEIRA et al., 2010a).

The geology of the Curaçá District comprises Tanque Novo and Caraíba Complexes. The Tanque Novo Complex consists of Bom Despacho, Arapuã, Surubim and Bogó Gneissic rocks (LINDENMAYER, 1981) consisting mainly of feldspathic quartz gneiss, cordierite-garnet-biotite gneiss, amphibolite, and magnetite (quartzite)-rich rocks (LINDENMAYER, 1981; TEIXEIRA et al., 2010b). The Caraíba Complex contains tonalite to granodiorite bodies. A series of mafic-ultramafic bodies were individually intruded into the supracrustal rocks. These rocks have undergone episodes of deformation, metamorphism and related granitic intrusion. The Caraíba mine ultramafic bodies were dated at  $2580 \pm 10$  Ma G.a (U-Pb-SHRIMP; OLIVEIRA et al., 2004) (Figure 2.4).

Shear zones have been mapped along the Curaçá District and are often marked by intense biotite rich rocks related to mylonitic rocks. These zones are characterized by two phases of progressive deformation (SILVA et al., 2007; ROCHA, 1999): a) The first phase (D1) represents transpressive thrust structures showing vergence to the west. The associated metamorphism was in the amphibolite to granulite facies. b) The D2 phase was related to directional shear zones with closed N-S isoclinal folds and penetrative vertical shearing structures. Kinematic studies indicate that D1 was overprinted by sinistral strike-slip shear zones (SILVA et al., 1996; TEIXEIRA et al., 2010a). These shear zones were responsible for the positioning of mylonitized granites and the intense fluid flux. The shearing process destroyed the preexisting fabric. The main mineralization event in the Vale do Curaçá District occurred between 2050 and 2010 Ma (TEIXEIRA et al., 2010a; GARCIA et al., 2018).

Pioneering studies emphasized orthomagmatic processes for the genesis of copper mineralization and its polycyclic and complex structural control (LINDENMAYER, 1981; LINDENMAYER, 1982; SILVA et al., 1996). Maier e Barnes (1999) noted the unusual aspects of this deposit compared to those of typical magmatic origin, such as the following: a) the sulfides are represented by bornite and chalcopyrite; b) a large amount of magnetite representing 50 wt.% of the ore; c) high Cu/Ni ratio (~ 40); and d) orthopyroxenites with abundant biotite related to shear zones. The importance of metasomatic processes in the genesis of deposits was initially suggested by Rocha (1999) and more recently confirmed by Teixeira et al (2010b), who proposed the analogy of the deposits of the Vale do Curaçá Copper District are analogous to IOCG deposits. In spite the primary origin for part of the copper mineralization at the Curaçá Copper District, the copper system can any

host rocks at varying depths and there are strong structural criteria (pressure shadow, SC structures) showing the epigenetic nature of mineralization is related to shear events (D2). The great majority of the host rocks are orthogneiss and gabbro-noritic within the Vale do Curaçá Copper District.

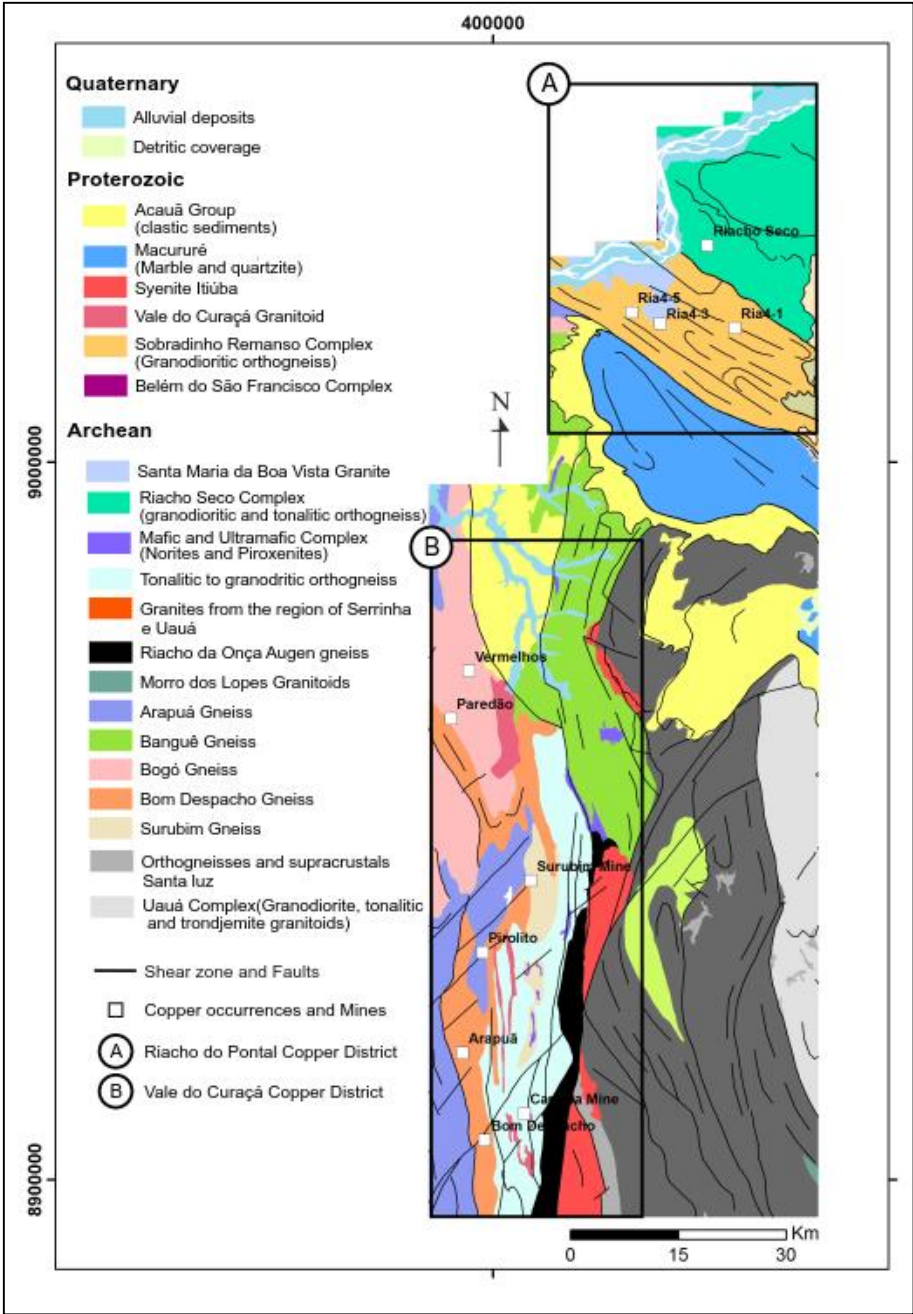


**Figure 2.4** Regional geology of the north border of the São Francisco Craton, showing the Vale do Curaçá and Riacho do Pontal Copper Districts. Modified after Delgado e Souza (1981), Misi e Teixeira (2008), Teixeira et al. (2010a e b) and CBPM (2011).

The geology of the Caraíba Mine is well marked by the contact between the orthogneiss (G2) and mafic-ultramafic rocks. Frequently, biotite has been mapped along NS contacts. The supracrustal are banded gneiss, diopsidite, forsterite marbles, granitiferous mafic granulite, biotite-schist and iron formations (LINDENMAYER, 1982).

The Caraíba orebody is hosted mainly in mafic-ultramafic complexes. Rocha (1999) and (TEIXEIRA et al., 2010b) recognized an expressive hydrothermal process related to copper ore zones. In more recent papers, a new interpretation shows an early orthomagmatic mineralization that was overprinted by an iron oxide-copper-gold system (TEIXEIRA et al., 2010b; GARCIA et al., 2018). The footprint of the Caraíba mineralization is related to a 2.0 Ga epigenetic event (GARCIA, 2013; GARCIA et al., 2018). A series of new copper occurrences crosscutting different types of host rocks including the basement of the mafic-ultramafic complex has been characterized along the Itabuna-Salvador-Curaçá Belt. Studies conducted by Silva et al (1985, 1996, 2007) found evidence of the control and structural complexity at the Caraíba mine.

The ore minerals are chalcopyrite, bornite and chalcocite, usually associated with magnetite. Intercumulus crystals of disseminated chalcopyrite, bornite and magnetite, grown in the interstices of pyroxenes and amphiboles constitute primary (magmatic) mineralization. Hydrothermal mineralization is associated with the following alteration assembly: biotite, microcline, epidote, chlorite, magnetite and quartz (GARCIA, 2013). Ore often occurs as veining or hydrothermal breccia, sometimes as massive or a “jaguar-like” breccia ore. Magnetite occurs commonly in equilibrium with spinel and ilmenite and exhibits replacement by chalcopyrite, bornite and ilmenite, especially when the host is biotite mylonite.

## 5. Neoproterozoic Riacho do Pontal Copper District

More than twenty copper occurrences have been described in the Riacho do Pontal region. Geologically, these occurrences are dominantly positioned in the zone of contact between Borborema Province and the San Francisco craton. This area is a small slab of the Brasiliano collisional zone (from 0.75 to 0.57 Ga in age) developed during the convergence of Neo- to Mesoproterozoic terrains with the São Francisco Craton (ALKMIN et al., 1993). Copper occurrences are structurally controlled by shear zones (Figure 2.4). Ria4 (1, 3 and 5) occurrences and Riacho Seco Deposit are the main copper occurrences in this district.

Hydrothermal alteration zones have been identified in the Riacho do Pontal District (HUHN et al., 2014). Hydrothermal alteration led to a pervasive calcic-potassic and calcic-ferric overprint of the host gneisses and migmatites. Early stage sodic hydrothermal is distal in relation with areas with calcic-potassic and potassic-ferric alteration with higher strain rate. The hydrothermal alteration process led to a replacement of metamorphic minerals of banded gneiss by hydrothermal assemblage. These hydrothermal minerals are spatially connected to penetrative shear deformation, LS tectonite and stretching lineation (HUHN and SILVA, 2018). Pyrite, hematite, chalcopyrite and chalcocite are related to ore zones. Magnetite can occur as associated ore minerals, constituting less than 1% of this paragenesis (GARCIA et al., 2018).

The Riacho do Pontal Belt was overprinted by two main shearing events: a) D1-Thrust shear zones with convergence towards the North, representing a series of NW parallel structures related to hydrothermal alteration and mineralization; and b) D2-Dextral strike slip shear zones related to multiple reactivation that are responsible for strong shearing of paragneissic and orthogranitic rocks. Both events were related to transpressive structural regimes.

## 6. Data and Methods

### 6.1. Geophysical Dataset

The gravimetric data are part of the ground gravimetric database provided by the Brazilian National Geological Survey (CPRM) and are used to interpret the studied area. The database includes part of the data used by Oliveira (2008) in his works in the northwest region of Bahia. The survey was

performed with a LaCoste & Romberg gravity gauge (model G-939), spaced 5 to 10 km between stations (OLIVEIRA, 2008). The work was carried out between 2005 and 2007.

The magnetic and radiometric databases were acquired from the Riacho Seco and Andorinhas Survey (CBPM, 2001). The data were acquired with flight and control line spacing of 500 m and 10,000 m in the NS and EW directions, respectively, at a constant height of 100 m. The plane was flown for a total of 48,641 linear kilometers.

The seismic tomography world database and maps used in present paper are property of Minerals Targeting International Pty Ltd ("MTI"), and comprise the GLAM Product (GRIFFIN et al., 2013; GRIFFIN et al., 2013). It takes part of a global data compilation comprising many geoscientific datasets, including gravity, magnetics, seismic tomography, crustal seismic profiles, magnetotellurics, geology, isotope geochemistry and geochronology. The product is one of the first systematic attempt to map the Sub Continental Lithospheric Mantle (SCLM) including details of mantle evolution and the trans-lithospheric architecture (GRIFFIN et al. 2008; GRIFFIN et al., 2013).

## 7. Geological Data and Drilling

During data integration, the Brazilian Geological Survey (CPRM) geological map was used as a base map. In addition, regional profiles were conducted along secondary roads, and 300 geological points were established. Geological sections were developed aiming at a structural understanding of the area. Six drill holes were made totaling 1800 m. Of the four holes drilled in the Riacho do Pontal project area, three were analysed, but drill hole RCB-RIA4-DH00001 was only analysed to 63m depth. Drill holes were targeted for geochemical and surface geology.

## 8. Petrophysical Studies

The petrophysical data were obtained from drill holes and surface rocks using a magnetic susceptibility and rock device (GDD Instrumentation). This database provided susceptibility ( $\text{SI} \times 10^{-3}$ ), volume rock density ( $\text{g/cm}^3$ ) and electrical resistivity ( $\text{ohm.m}$ ). Magnetic susceptibility was measured using a KT10 PLUS S/C susceptibility meter, and volume rock density was measured by vacuum-saturating the samples. Electrical resistivity was measured on samples with water under vacuum and left to sit for 24 h using a frequency analyzer. Overall, 33 samples were collected from drill holes PCB-RIA4-DH001 (14 samples) and PCB-RIA4-DH-002 (19 samples) of the Riacho do Pontal Target. The samples represent the following units: a) biotite-quartz-mylonite; b) quartz-amphibole-biotite-mylonite; c) quartz-magnetite-biotite-mylonite; and d) biotite mylonite. In total, 15 surface rocks from the Caraíba and Surubim mines' ore zones were analyzed. Biotite-magnetite-chalcopyrite mylonite was sampled from both mines.

## 9. Inversion

Gravimetric and magnetic data were gridded using the Geosoft Oasis Montaj minimum curvature algorithms. A 3D inversion of the VOXI-MVI type magnetic data was employed from the grids of the total magnetic field, in which it was possible to illustrate the geometry of the magnetic anomalies and highlight the magnetic pathways along shear zones. The inversion by the MVI magnetization vector allowed for the possibility of magnetic field data, recovering the direction of magnetization and amplitude for each magnetic domain in the survey area (ELLIS; WET, 2012).

The Oasis Montaj platform and the D Inversion VOXI packages were used to process the data (ELLIS and WET, 2012). The model used was unconstrained in both magnetic and gravimetric data. For the elaboration of gravimetric modeling, topographic maps with the same cell size (125 m) were used (LI; OLDENBURG, 1996). However, the geologic information including petrophysical properties, surface geology, structural interpretation and the gridded geophysical interpretation was used qualitatively in the 3D modeling.

The interpretation of potential-field data was used to prospect for IOCG deposits. IOCG mineral system ore bodies are usually related to magnetic and dense rocks. The IOCG ore bodies were modeled using potential-field data.

## 10. Results

### Gravimetric and Magnetic Interpretation.

Studies of the geophysical signature IOCG deposits has shown the effectiveness of integration of the geophysical data with physical property measurements and geologic observations have lead to a new understanding of the geometry of the deposit and potential for host metasomatic system (HAYWARD et al., 2016; WILLIAMS, 1994; POLLARD et al., 2018; ESDALE et al., 2003; AUSTIN et al., 2012; AUSTIN et al., 2014). In Brazilian IOCG Provinces and districts, a detailed understanding of the geophysical signatures of mines and deposits and hydrothermal alteration has been rarely published.

Regional magnetic and gravimetric surveys were analyzed to interpret the geological, structural and metallogenetic characteristics of the Riacho do Pontal and Vale do Curaçá Copper Districts. The Vale do Curaçá and Riacho do Pontal Districts were integrated using the ground gravimetric data from the northern portion of the São Francisco Craton, showing that the copper mineralization was set in different gravimetric domains (Figure 2.5a). Location of regional gravity stations are illustrated in Figure 2.5b. A total of 60 stations were used in present study.

The Vale do Curaçá Copper District is located in a high gravimetric N-S domain. It is 110 km in length and 22 km in width and shows a strong wavelength gravity high (up to -40 mGal). The following geological units are related to this high gravimetric domain: the Bom Despacho gneiss, Surubim Gneiss, Banguê gneiss, mafic and ultramafic complex and tonalitic to granodioritic orthogneiss. The Caraíba, Surubim and Vermelhos mines and a series of copper occurrences are situated along this high-gravity domain. This high-gravimetric region should be exhaustively explored using all exploration methods to identify new deposits and add new reserves to the Caraíba mine.

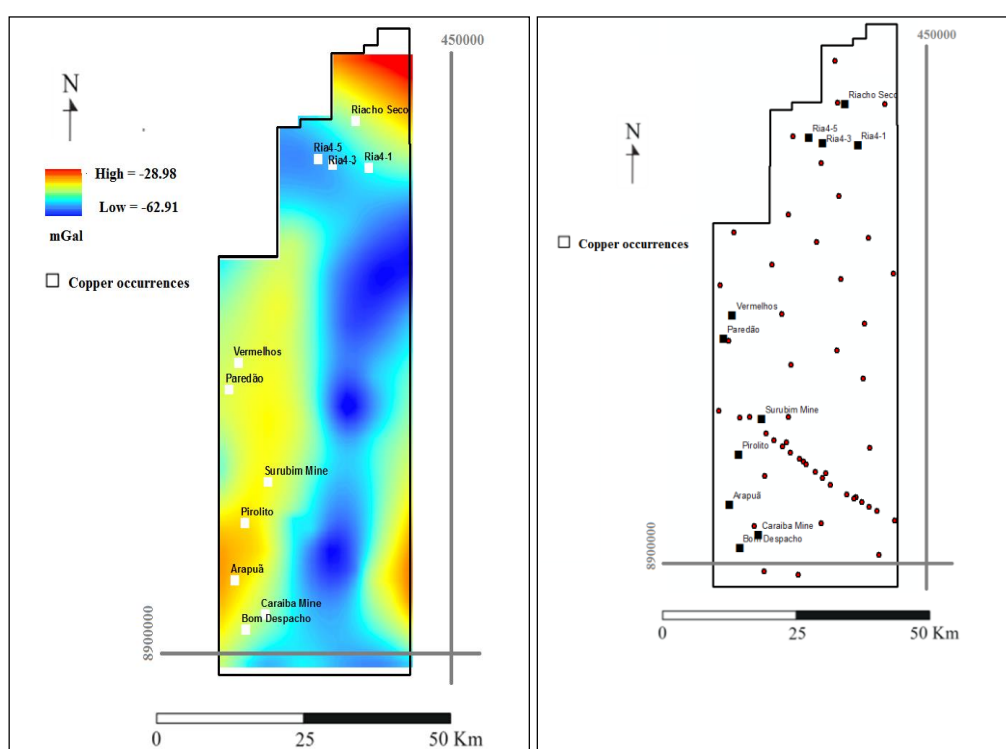


**Figure 2.5** a) Bouguer gravity anomalies on the northern border of the São Francisco Craton. Vale do Curaçá District copper occurrences are situated on zones with high gravity anomaly (up to -40 mGal). On the other hand, copper occurrences in the Riacho do Pontal District belt are located in low gravimetric domains (down to -45 mGal); b) Location of regional gravity stations.

The ore in the Caraíba mine has a density greater than 3.13 g/cm<sup>3</sup> in contrast to the sterile rocks with density less than 2.98 g/cm<sup>3</sup> (FREITAS, 2016). The gneissic-granite, mylonitic and pyroxenite have an average density respectively of 2,78 g/cm<sup>3</sup>, 3,1 g/cm<sup>3</sup> and 3,3 g/cm<sup>3</sup>. Caraíba and Surubim mines was sampled from ore zones and shows density ranging from 3,5 to 4.35 g/cm<sup>3</sup> (Figure 2.6).

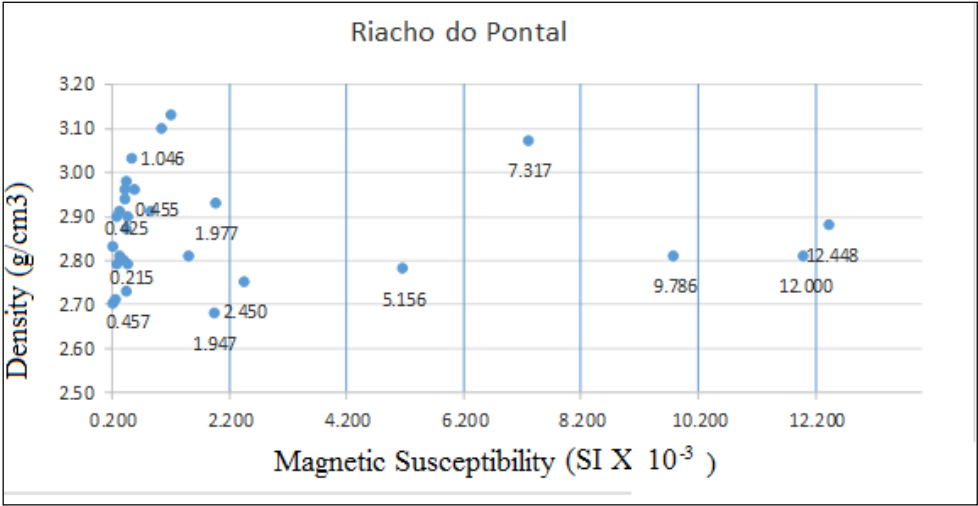
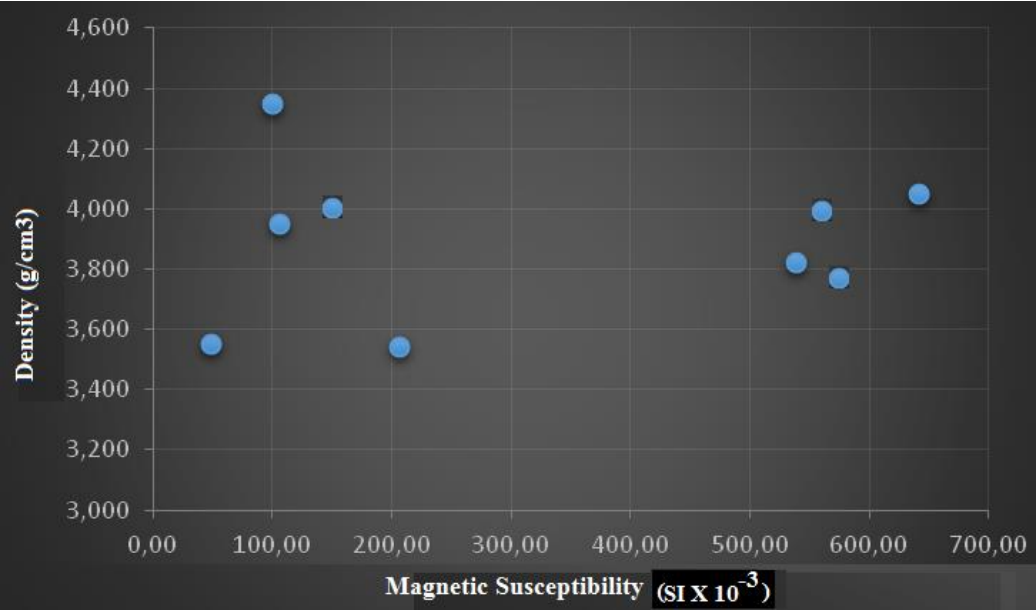


**Figure 2.6** Graphic relationship between magnetic susceptibility and density (g/cm<sup>3</sup>) at (a) the Vale do Curaçá District (Caraíba and Surubim mines) and (b) the Riacho do Pontal Copper District.

The gravimetric signature of the Riacho do Pontal Copper District is mainly characterized by a NW/SE Bouguer anomaly low (down to -45 mGal). Geologically, these areas are related to gneiss outcropping in the Sobradinho Remanso and South portion of the Riacho Seco Complex. The Riacho do Pontal Copper District occurrences are situated along these regional low-gravity domains. The less or unaltered rocks have a typical density of 2.7-2.78 g/cm<sup>3</sup>, and that of more strongly altered rocks is 2.75-3.1 g/cm<sup>3</sup> (Figure 2.7). The NW Bouguer low-gravity anomaly of Riacho do Pontal District represents geologically the collisional suture between the cratonic block and the Riacho do Pontal mobile belt.

The northeast portion of the Riacho do Pontal Copper District is characterized by a positive gravimetric anomaly (down to -40 mGal). It comprises the foliated orthogneissic rocks of the Riacho Seco Complex. The Riacho Seco copper occurrences are situated in the contact zone between this domain of high gravimetry and the low gravimetric domain. Biotite-garnet rich rocks along shear zones host a series of small copper occurrences at this site.

The TMI data were reduced to the magnetic north pole using magnetic inclination of -20° and declination of -22.31°. It was applied the upward continuation filter to 1000 m (Figure 2.7) for reducing the noise of data and better delineation of deep magnetic structures. The magnetic footprints of the Vale do Curaçá and Riacho do Pontal Copper Districts are quite distinctive. Copper occurrences situated in the Vale do Curaçá District are associated with linear magnetic anomalies situated on the west portion of the Itabuna-Salvador-Curaçá Belt (Figure 2.7). On the other hand, the copper deposits located in the belt of the Riacho do Pontal Copper District are located in zones without or with very weak magnetic anomalies.

The NNW-trending magnetic signature of the Vale do Curaçá Copper District is anastomosed, and it has been overprinted by at least two cycles of shearing. The copper occurrences and mines in this district, including areas of strong hydrothermal processing, are associated low-amplitude magnetic anomalies (TMI) of from ~24,000 to ~25,700 nT (Figure 2.7).

The magnetic trends ( $SI > 0.005$ ) are juxtaposed with shear structures and faults with different magnetism intensities (Figure 2.6). The Caraíba mine situated in the central-west portion of the Itabuna-Salvador-Curaçá Belt and recognized as the most fertile trend is more magnetic ( $SI > 0.009$ ) than are mines located in the eastern portion. Geologically, the regional magnetic trends are related to more intense metamorphic granulitic processes overprinting geological units: the Bom Despacho Gneiss, the Surubim, Banguê and tonalitic to granodioritic orthogneiss. Late NE-SW shear zones are quite common crosscutting N-S early magnetic trends. The ore zones from Caraíba and Surubim mines have a range of magnetic susceptibility from  $30 SI \times 10^{-3}$  to  $700 SI \times 10^{-3}$ .

In the Riacho do Pontal Copper District, the copper occurrences (Riacho do Pontal and Riacho Seco) are not related to high magnetic anomalies. The Riacho do Pontal and Riacho Seco occurrences are hosted, respectively, in gneiss of the Sobradinho Remanso and Riacho Seco Complexes. These rocks are pervasively hydrothermally altered, and their magnetic signature shows values of magnetic intensity (TMI < ~24,000 nT). These host rocks have a range of magnetic susceptibility going from  $0.2 SI \times 10^{-3}$  in less altered rocks to  $12.2 SI \times 10^{-3}$  in more hydrothermalized rocks. At a regional scale, the NW-SE magnetic trends overlap older and deeper NE-SW features related to São Francisco Craton.

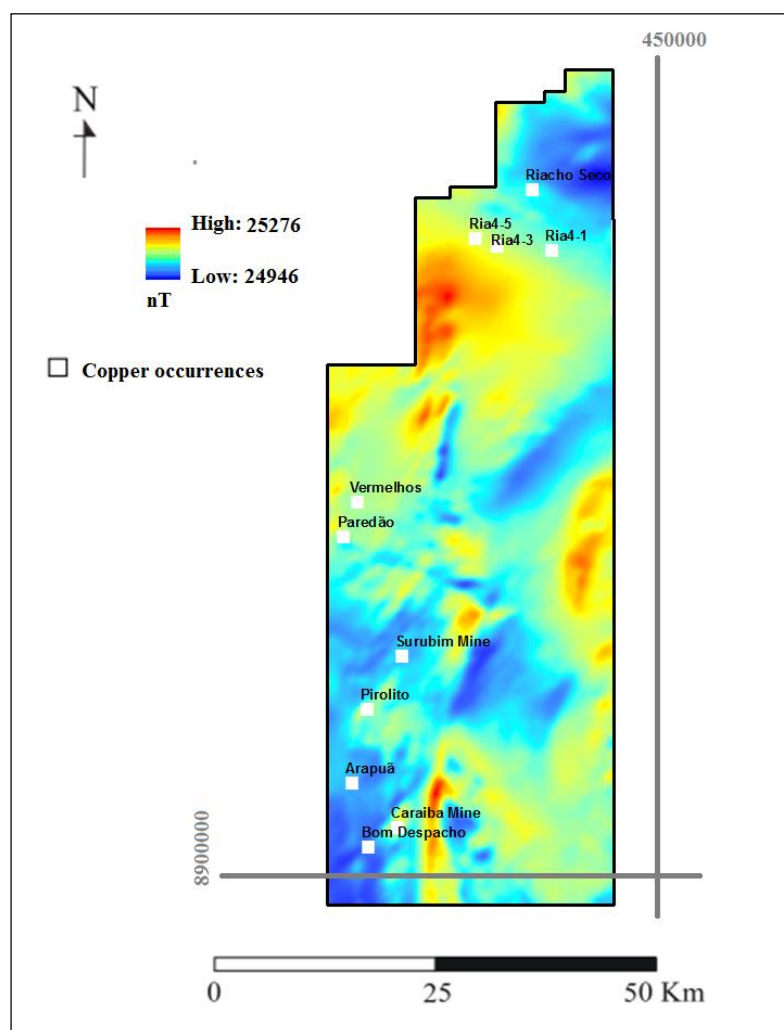


**Figure 2.7** – a) The TMI-RRP map of the northern portion of the Sao Francisco Craton, outlining the Riacho do Pontal and Vale do Curaçá Copper Districts. The magnetic signatures of the two districts are markedly different. In the Vale do Curaçá Copper District, there are well-delineated NS trends continuous for approximately 100 km, and the intensity of magnetic anomalies goes from ~24,000 to ~25,700 nT. On the other hand, in the Riacho do Pontal copper district, the NW magnetic trends are discrete, and the anomalies are weaker (<24,000 nT);.

It were used different filter with the following enhancement methods: total horizontal derivative, ASA, tilt angle, THDR of the tilt angle, TDX , and balanced total horizontal derivative (Ferreira et. al, 2013, Castro et. al. 2015). The anomalies generated by these methods enhance the main magnetic structures. However, The tilt angle of the total horizontal derivative (TAHG) transform (Ferreira et al. 2013) were used to identify the structural-magnetic framework. This transform is an edge detection method, being less sensitive to variations in the depth of the sources (Ferreira et al. 2013). Strong and continuous peaks, making the magnetic structures easier to recognize, represent the magnetic anomalies in the TAHG map (Figure 2.8). The TAHG map shows the most important structural trends mapped in the field. The major structures are deep (> 10km) and can reach the SLCM and can be used as a channel for percolation of hydrothermal fluids and magmas.

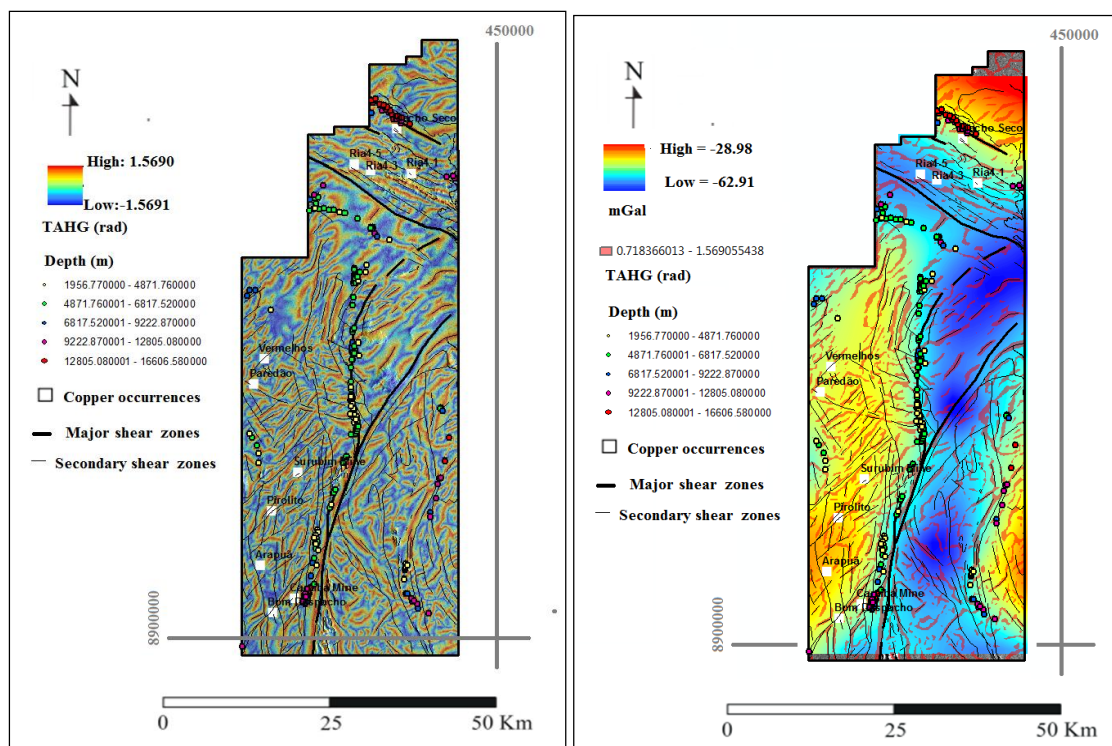


**Figure 2.8** – (a) TAHG map represents tilt angle of horizontal gradient. This transform is an edge detection method (Ferreira et al. 2013). Strong and continuous peaks, making the magnetic structures easier to recognize are mapped in the TAHG. Euler deconvolution solutions (colored circles, SI = 0) overlap the TAHG map, showing that more important and deep Structures at Vale do Curaçá District structure are situated in the central portion of the area. At Riacho do Pontal District TAHG map shows strong NW magnetic anomalies near of Riacho Reco copper occurrence; (b) Bouguer gravity map and major and secondary shear structures. Euler solution are situated along major shear zones and on border of high gravity anomalies on both Copper Districts.

### 3D Gravimetric and Magnetometric Inversions

Magnetic inversion was performed at the Vale do Curaçá Copper District. The magnetization vector inversion (MVI) process used in this study considers that the anomalous magnetic signal observed on the surface is associated not only with susceptibility contrasts but also with the direction of the field magnetization, which allows one to verify the presence of remanence. It was not used as a constraint parameter in the inversion model.

The interpretation of magnetic and gravity 3D models was obtained with the Geosoft VOXI Earth Modeling inversion solution using mainly the magnetization vector inversion (MVI) technique. The input used the total field of magnetometry and gravimetric data. Applying the VOXI MVI 3D magnetic inversion over the Vale do Curaçá Copper District shows a series of magnetic trends aligned N-S, dipping 75 to 85 degrees East (Figure 2.9). These magnetic belts are imbricated by the overlap of at least two episodes of shearing (D1 and D2).

The Caraíba mine is controlled by NNW-trending subvertical shear zones, showing an anastomosing shape in both the horizontal and vertical directions. A series of subparallel N-S shear structures have been active and responsible for multiple reactivation events. N-S shearing magnetic zones are related to thrust shear zones (D1) with convergence to the West, and are overprinted by strike slip faults. The D1 and D2 events have controlled the distribution of hydrothermal alteration and mineralization. The NE-SW late shear zones are subvertical.

MVI (Geosoft VOXI) was used to ran the inversion of magnetic and gravimetric data at Vale do Curaçá Copper Districts. At the Caraíba mine, the host rocks are mafic granulite, granulitic orthogneiss and a mafic complex lens. These rocks were overprinted by sodic and potassic hydrothermal alteration. Hydrothermal alteration and magnetic anomalies are related to the NNW and NE-SW structural trends (Figure 2.9).

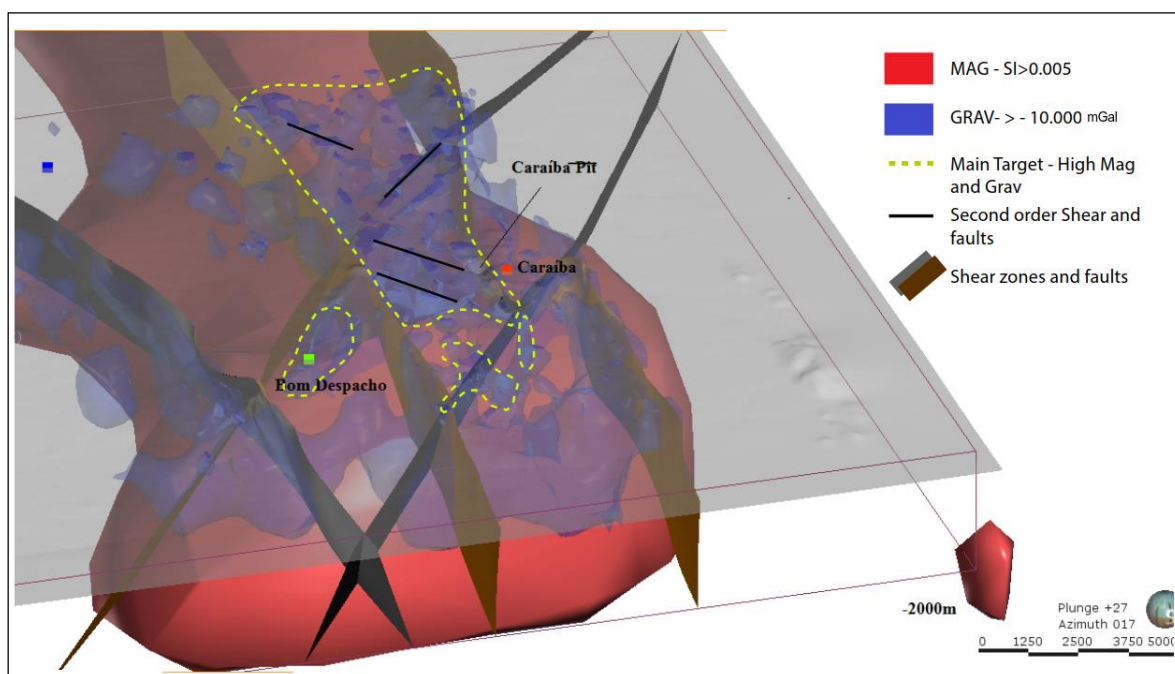


**Figure 2.9** - Draping structure and MVI magnetic and gravimetric inversion onto the terrain surface surrounding the Caraíba mine (Curaçá Copper District). In the Vale do Curaçá District, it is possible to observe a series of subparallel N-S magnetic trends. Most anomalies are related to geological units represented by the mafic granulites and granulitic orthogneiss. Some magnetic anomalies are related to the N-S and NE-SW structural trends. The Caraíba Mine bodies are strongly related to a magnetic and gravimetric N-NS trend,  $SI > 0.005$ , with gravimetric anomalies  $> -10,000$  mGal. Dashed red area represents main target with more potential to host new IOCG orebodies at the Caraíba Mine.

The Caraíba Mine bodies are strongly related to magnetic and gravimetric NNW trends having  $SI > 0.005$  and with gravimetric anomalies  $> -10,000$  mGal (Figures 2.9 and 2.10). The Caraíba mine and Paredão occurrence have a strong relationship with magnetic anomalies. The other occurrences along the Vale do Curaçá District are not related directly with high gravimetric and magnetic anomalies.

The Caraíba mine is related to magnetic and gravity anomalies along N-S trending shear zones. The host rocks are granulitic orthogneiss and ultramafic bodies. The mine is situated about 1 km from the N-S shear zone that was displaced by NW-SE shear zones. Sodic and potassic hydrothermal alterations are mapped along the N-S and secondary NE shear zones. In 3D tectonic settings, the mine is intrinsically related to high magnetics associated with a gravimetric anomaly (Figure 2.10). The orebodies are oriented in a subvertical direction and are controlled by a stretching lineation.

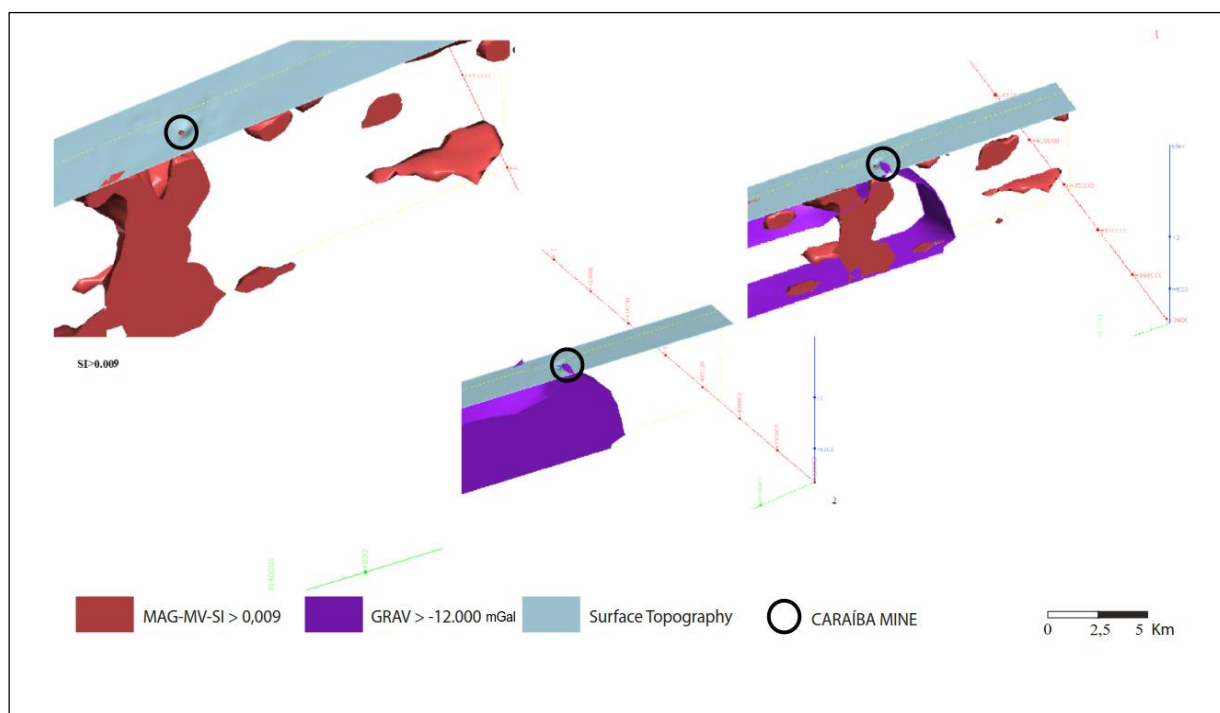


**Figure 2.10** – 3D gravity and magnetic inversion integrated at the Caraíba mine. The Caraíba mine is strongly related to magnetic and gravity anomalies. The potential continuity in depth of ore zones related with magnetic and gravity anomalies is quite promising and should be investigated in further work.

3D magnetic and gravity inversions shows two main NNW prospective trends, both with a sigmoidal shear shape. These trends are positioned in the zone of contact between domains with high magnetic ( $SI > 0.005$ ) and gravimetric anomalies ( $> -10,000 \text{ nT}$ ) and show a contrast in density and magnetite content. Trend I is 60 km in length and 7 km in width, hosts the Caraíba, Surubim and Vermelho mines and other deposits and is the most important trend for host IOCG deposits in the Vale do Curaçá Copper District. Trend II is 35 km in length and 5 km in width. Geologically, these trends are hosted mainly along the contact between Surubim gneiss, tonalitic to granodioritic orthogneiss, and gabbro-norite and/or norite bodies (Figure 2.11).

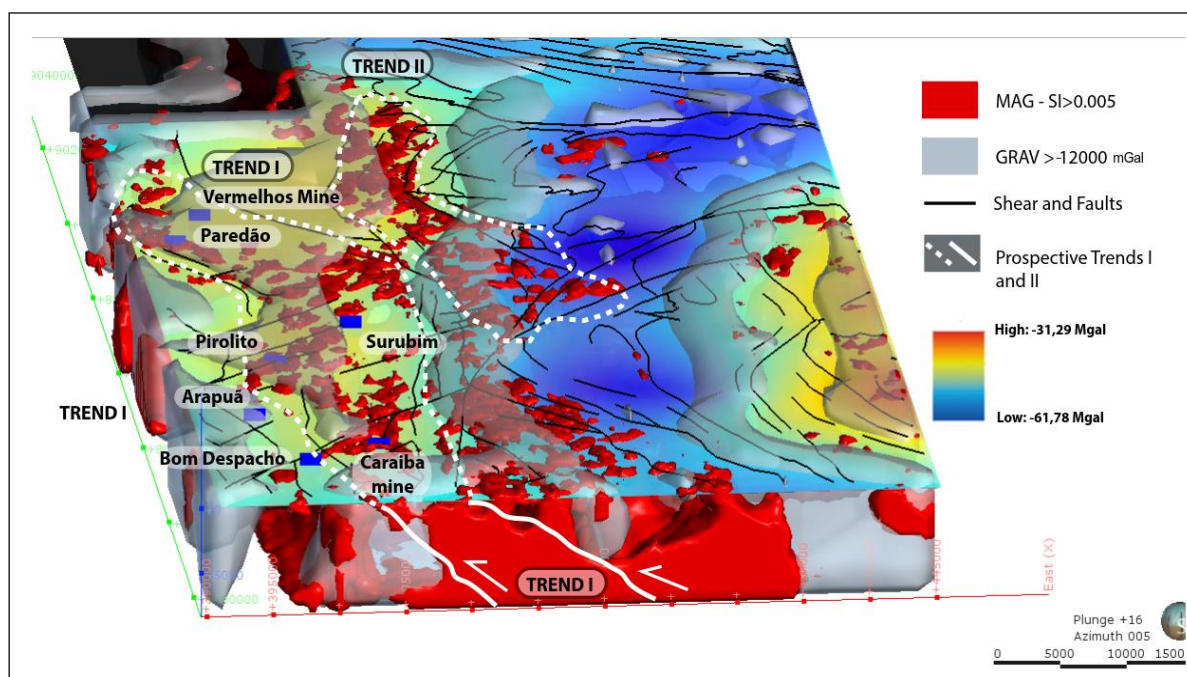


**Figure 2.11** The IOCG mineral system in the region of the Vale do Curaçá Copper District, in regional terms, shows two main porprospective trends. The trends are positioned in the contact zone between domains with high magnetic ( $SI > 0.005$ ) and gravimetric anomalies ( $> -10,000$  mGal) and show a contrast in density and magnetite content.

The Ria4 prospect and Riacho Seco deposit do not show correlation with magnetic anomalies. The occurrences of copper in the region are positioned at magnetic lows. This observation is explained by the fact that the mineralized zone is related to hematite zones and the content of iron oxide is low ( $< 2\%$ ). The exploration drilling program (Ria4-DH01) crosscut 32 m @ 1% copper (HUHN et. al 2014; HUHN and SILVA, 2018). The results obtained in the magnetic inversions conducted in the region of the Riacho do Pontal Copper District show weak magnetic anomalies along a NW-SE trend. The discrete linear magnetic features are related to shear zones. These NW-SE features overlap over older and deeper NE-SW features. However, analysis of the Riacho do Pontal District magnetic anomalies in 3D at the Riacho Seco deposit shows a low magnetic anomaly close to the surface and change in depth ( $> 400$  m) to an area with high magnetic signature, reaching up to 24,500 nT (Figure 2.12). The results allow for the possibility of a continuous model for follow up of the deposits as related to deeper magnetic anomalies.

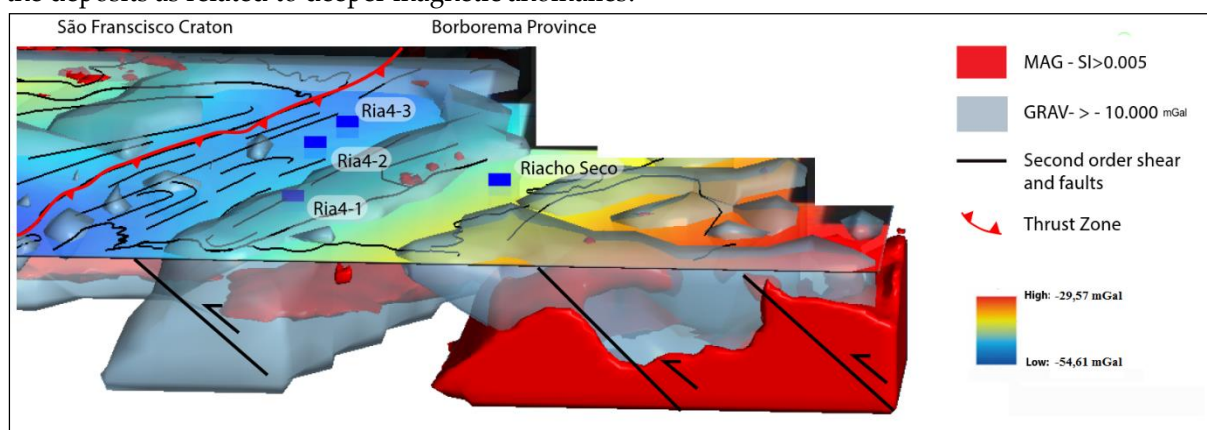


**Figure 2.12** The MVI magnetic gravimetric inversions in the region of the Riacho do Pontal Copper District. In the region of the Riacho Seco Deposit and the Riacho do Pontal prospects the magnetic and gravity anomalies are weaker (  $SI < 0.002$ ; Grav  $< -10,000$  mGal ) and deeper (  $> 1.5$  km).

## 11. Understanding Vale do Curaçá and Riacho do Pontal District IOCG Mineral Systems and Main Exploration Vectors for the Caraíba and Riacho do Pontal Districts

Understanding the IOCG systems at different scales allows tracing some parameters leading to the formation of districts or fertile provinces (GRAINGER et al., 2008; POLLARD et al., 2018; GROVES et al., 2016).

At a regional scale lithospheric major structures control the traps of IOCG mineralizing systems or heat-magmas, or the fluid flow is frequently evident in gravity and magnetic databases (CLARK, 2014).

Fertile provinces that lead to the formation of world class deposits require melting of subcontinental lithospheric mantle (SCLM) on the margins of cratons, which is responsible for magmatic ascension; associated high heat; and volatile flow (GRIFFIN et al., 2013; HOLDSWORTH; PINHEIRO, 2000). The deposits occur in long lived subparallel regional structures that have been focus of multiple reactivation events (SILVA et al., 1993; ROCHA, 1999; SILVA et al., 1996; TEIXEIRA et al., 2010a; HUHNE et al. 2014; HUHNE and SILVA, 2018). In the Riacho do Pontal and Vale do Curaçá Copper Districts structural interpretation shows that early thrust zones are reused several times and are overprinted by strike-slip shear zones (SILVA et al., 1993, SILVA et al., 1996).

Usually, a major shear system was responsible for the sigmoidal “SC-shape” of some provinces. Fractal patterns representing SC structures are systematically repeated from macro-scales to micro-scales. These structures are critical pathways for upward flux of fluids promoting the interaction between fluid-rock. Duplex, shear bands, and asymmetrical structures are quite common along the shear system. The structural controls and traps used for orogenic gold in shear zones are the same for IOCG deposits. The more important traps for host orebodies are: a) interconnection zones between “SC” structures; b) fractal second- or third- order “C” structures; c) bends along shear zones in both horizontal and vertical planes where high grade breccia are typically hosted; d) fault intersections that are highly favorable for host breccia ores, and e) ductile shear zones reactivated by late brittle faults that enrich older zones and can generate new mineralized bodies.

Hydrothermal alteration is characterized by early high temperature Na (albite) alteration (500-400 °C; POLLARD, 2006) to lower temperature K-Fe (<350 °C) alteration (TEIXEIRA et al., 2010b; HUHNE et al., 2014; JULIANI et al., 2016; Garcia et al., 2018; HUHNE and SILVA, 2018). High temperature albite alteration can be linked to a magmatic-hydrothermal systems (OLIVER, 2004; POLLARD, 2006; POLLARD et al., 2018). Iron is strongly soluble at high temperature and saline fluids and is caused by increasing of H<sup>+</sup> in the fluid system resulting in a more intense Fe fluxes (WILLIAMS, 1994). Thus, magnetite (hematite) bodies and/or disseminated magnetite (hematite) infill along shear zones.

Frequently, lithological boundaries between units with different competence are crucial for the hosting high deformation corridors. In this manner, zones of contact with competent rocks such as paragneiss, mafic granulite, granulitic orthogneiss and BIFs are usually traps for percolation of hydrothermal fluids related with shear zones. At Vale do Curaçá Copper District, only considering the epigenetic IOCG mineralization process, the host rocks are predominantly mafic and felsic granulitic rocks.

The ore bodies often assume a sigmoidal shape as they are often hosted in shear zones. However, pipe breccia zones along hydrothermal corridors can be found. Among the explanations for the evolution of IOCG systems is that they develop by direct melting of the SCLM and are positioned in shear zones initially as a pipe breccia reworked by shear deformation. Variation in the direction and dipping along the shear zones, both horizontally and vertically, acts as a structural trap for both hydrothermal breccias and pipe breccias. Typically, rich breccia zones are situated in a central hydrothermal system zone in transtensional structures.

Hydrothermal alteration is related to intermediate- to high-temperature fluids in the Riacho do Pontal and Vale do Curaçá Districts. The alteration halo extends from 1 km to 5 km in width, following the major shear zones. Sodic alteration is more distal and potassic, and calcic and ferric alterations are more proximal in both districts.. The southern deposits and Sussuarana, Caraíba and Surubim mines are related to deeper and high temperature sodic/potassic hydrothermal alteration, in contrast with the Vermelho deposit, in which hydrolytic alteration occurred in shallower zones in the IOCG hydrothermal system as initially described by Hitzman et al. (1992, 2000). Typically, a series of magnetic dipoles are linked to shear zones and hydrothermal halos.

More recently, a new generation of ore system exploration models has been developed to take advantage of the massive volume of data available to the exploration industry (LESHER et al., 2017; BARNETT; WILLIAMS, 2012). Improving exploration competitiveness is necessary with more sophisticated integration of different data sets. The challenge remains in decreasing the size of exploration areas and increasing the success rate of drilling programs (LESHER et al., 2017; COOKE et al., 2017). Thus, for the Vale do Curaçá and Riacho do Pontal copper districts, the main footprint that shows the ore system signature was recognized (Figure 2.13). The more important geological, structural, geochemical, mineralogical and petrophysical parameters of these copper districts are summarized below and illustrated on figure 2.13.

In 2D and 3D mapping, it is possible to verify the variation in these parameters with distance in the direction of the mines, deposits or occurrences. The increase and decrease in the intensity of these processes represent the vectorization of the IOCG systems studied.

### **The main footprint of IOCG Districts is as follows:**

#### *a) Riacho do Pontal District*

- Structural - increase in intensity of shearing and in density of structures in direction of secondary structures. The foliation tends to be vertical;
- Stream sediment and soil – Anomalies of Cu, Ni, Fe and La in stream sediment and Cu ( Ni, Ce and La) in soil;
- Low magnetic anomalies related with Kd- (kd-anomalous potassium)related to shear zones (HUHN and SILVA, 2018);
- Low magnetic anomalies (rich hematite related to ore zones).

#### *b) Vale do Curaçá District*

- The District of Vale do Curaçá is associated, regionally, with high gravimetric and magnetic associated with the portion west of the Itabuna-Salvador-Curaçá orogen;
- The IOCG mineral system in the Vale do Curaçá Copper District, in the regional context, shows two main magnetic trends.
- The Caraíba Mine bodies are strongly related to magnetic and gravimetric NNW trends having SI > 0.09 and with gravimetric anomalies < -10,000 mGal;
- Hydrothermal Alteration – An increase in the anomalies related to hydrothermal processes i) an distal sodic alteration; (ii) the mineralized zone is intensely related calcic-ferric alteration;
- Increase in Fe acinolite FeOt/Mg/MgO+FeOt) and Fe-Biotite (Fet/Mg) towards more hydrothermalized altered zones (Figure 2.12);

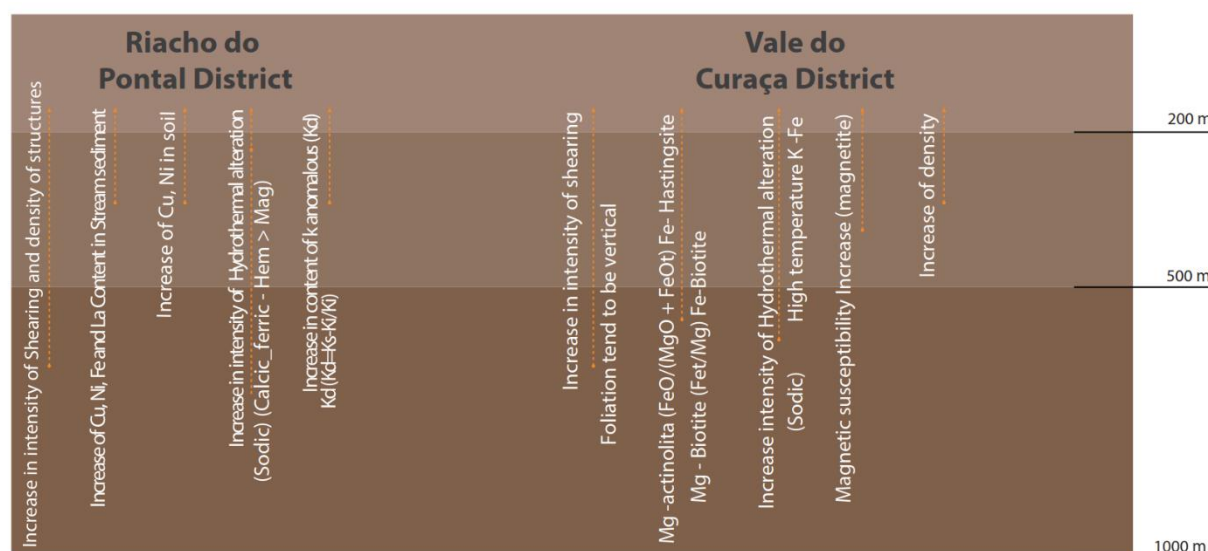


**Figure 2.13** The main geological geochemical, structural and geophysical vectoring illustrating the footprint of the Vale do Curaça and Riacho do Pontal Copper Districts.

The general hydrothermal zoning pattern for IOCG deposits is usually vertical, from magnetite-dominant at depth to hematite-dominant at shallower levels (HITZMAN et al., 1992; HITZMAN, 2000). Using this model, it is possible to interpret the Riacho do Pontal District as positioned in the shallowest portion of the IOCG system (Figure 2.12). In this way, additional work must be performed identifying deeper (or more eroded) areas of the IOCG system related to more magnetic and density areas (such as the Riacho Seco target).

However, a paradigm remains at the Vale do Curaça District that is not typical; selection of new targets that are not necessarily hosted in ultramafic rocks. The IOCG system can develop in any host rock at varying depths. A full understanding of the IOCG model for mining companies can greatly expand exploration in the district.

### Exploration Potential for Vale do Curaça and Riacho do Pontal Districts

Geophysical investigations have been conducted in different IOCG districts worldwide (AUSTIN; FOSS, 2012; AUSTIN., 2014; HAYWARD et al., 2016). Much of these studies have concluded that rocks despite having an unstable remaining magnetization have presented lower than expected given their high susceptibilities (HAYWARD et al., 2016).

The Carajas Province is one of the most important IOCG provinces in the world and shows a direct link between high temperature hydrothermal alteration and shear zones (e.g. Sequeirinho et al.; XAVIER et al. 2010; MONTEIRO et al., 2008a; POLLARD et al., 2018 ). At Salobo mine (1.112 Gt at 0.69 % Cu and 0.43 g/t Au; Vale 2012) calcic-sodic hydrothermal alteration was followed by iron-enrichment (almandine-grunerite-magnetite), potassic alteration with biotite, copper-gold ore formation, and later Fe-rich hydrated silicate alteration (MELO et al., 2016). Processing of gamma airborne data shows very well the increase potassic alteration along shear zones (COSTA, 2017). At Furnas deposit Leão-Santos et al (2015) show that mineralized magnetite hydrothermal alteration zone is very well defined by high magnetic susceptibility values (from  $200 \times 10^{-3}$  SI to  $900 \times 10^{-3}$  SI) and high density values (approximately  $3.4 \text{ g/cm}^3$  to  $3.8 \text{ g/cm}^3$ ). At Salobo mine there are a coincident relationship between magnetic anomalies and the magnetite-calcocite dense ore zone (COSTA, 2017). IOCGs in the Mont Isa Trend (Australia) is usually related with strong magnetic anomalies (e.g 7,000 nT at Ernsty Henry) and are coincident with gravity anomalies having the same source (AUSTIN; FOX, 2012). The shape of magnetic and gravimetric anomalies at Carajás Belt and Vale do Curaça District are often tabular bodies associated to ultramylonitic fabric (LEÃO-

SANTOS et al., 2015; HOLDSWORTH; PINHEIRO, 2000; GRAINGER et al., 2008; POLLARD et al., 2018; MONTEIRO et al., 2008 a).

The same strong relationship, between magnetic and gravimetric footprint have been described in the Vale do Curaçá Copper District (e.g. TEIXEIRA et al., 2010b; GARCIA et al., 2018). As highlighted by Corriveau et al. (2010a, 2011), the mapping of high-temperature calcic-iron alteration can define prospective trends at regional scale. Therefore, more intense exploration efforts at Vale do Curaçá District should be focused in targets related to K-magnetic alteration related to shear system. The Vale do Curaçá District is still an immature District and new high-resolution geophysical surveys should be applied to recognize new targets.

Garcia et al (2008) studying the deposits situated at Vale do Curaçá District has proposed a model of hydrothermal zoning for this IOCG System. At a deeper tectonic setting in the system, the hydrothermal ore is associated with sodic-potassic alteration at Caraíba, Surubim, and Vermelhos deposits. At shallow levels as described at Vermelho Deposit, the system is characterized by hydrolytic alteration (hematite, barite, sericite, and accessory phases as actinolite and chlorite) according to model proposed by Hitzman et al. (1992) and Hitzman (2000).

In the Gawler Craton which is one of the regions where the understanding between magnetic and gravimetric anomalies has been more extensively studied looking for IOCG deposits, it is possible to better mapping of the complexity and diversity of IOCG hydrothermal system. At the Gawler Range Craton the IOCG System is controlled by transition from magnetite-rich to hematite-rich and more dense areas that represent the best potential target for host IOCG deposits. In fact, the ore is situated in the transition between a strongly magnetic and gravimetric zone (POTTER et al 2013; HART; FREEMAN, 2004; BELPERIO et al., 2007; HAYWARD et al., 2016; HAYARD et al., 2016). The Carrapateena Deposit (POTTER et. al. 2013) is mainly related to hematite hydrothermal alteration (gravity high), with secondary relationship with magnetic high anomaly showing a small offset of higher gravity (2 mGal) and magnetic anomalies (200 nT). At Olympic Dam Mine (SKIRROW, 2014) a strong coincidence between magnetic highs (1600nT) that are related to geologic host and a secondary high magnetic related to IOCG system. At Gawler Range, the highest gravity anomalies are frequently related to barren magnetite alteration or associated with hematite rich breccia as Olympic Dam deposit (ESDALE et al., 2003).

Huhn et al (2014); Huhn and Silva (2018) have noted the Neoproterozoic IOCG Riacho do Pontal is related to k-hematite system. Some barren magnetite-amphibole outcrops have been mapped on north of the district, indicating that hydrothermal zoning may also exist on this belt, broadening its exploratory perspective. Huhn and Silva (2018) using fuzzy logic processing in a huge dataset have and select potential areas for host copper mineralization at the RIA4 project.

For example, in the Carajas Mineral Province, few occurrences shows sheared late hematite alteration but not related yet with rich ore zones (e.g. Salobo Deposit; MELO et al., 2016).

From the review of features related to IOCG deposits in the Gawler Range, there are the scientific and exploration challenge for the absence of deposits in Brazil situated in the transition zone between high magnetic and high gravimetric yet. Geologically the transition between magnetic and gravity highs represent evolution of hydrothermal alteration and a potential target for sulphide-bearing mineralization (HAYWARD et al., 2016; MCCAFFERTY et al., 2016). In tectonic settings where the gravity anomaly indicate high content of iron oxide, any offset between gravity and magnetic anomalies can reflect in the proportion of magnetite and hematite or less frequently the presence of pyrrhotite (NISBET et al., 2000). The main reason that one of the most sought-after geophysical sinature is not discovered yet at Brazil IOCG Province and districts is that these districts and other potential tectonic setting in Brazil remain fully under-explored and the geological setting is not mapped on the appropriate scale.

## Conclusions

Knowledge of the signature of IOCG deposits in Brazil shows that these deposits can be hosted in any type of rock, with different styles of hydrothermal alteration and at different depths.

The main conclusions obtained in the present study of the Riacho do Pontal and Vale do Curaçá copper districts are as follows:

1 - The Vale do Curaçá District is part of Paleoproterozoic Itabuna-Salvador-Curaçá orogen. It represents a collision event involving the Gavião, Jequié and Serrinha blocks in the Rhyacian to Orosirian transition (BARBOSA; SABATÉ, 2004). The Riacho do Pontal District is situated over a Neoproterozoic collisional zone;

2 - The Vale do Curaçá and Riacho do Pontal Copper Districts are hosted in different gravimetric domains. The Vale do Curaçá copper district is in a high gravimetric domain. It is 110 km in length and 22 km in width and shows a strong anomaly with a wavelength of up to -40 mGal. The Caraíba, Surubim and Vermelhos mines and a number of copper occurrences are positioned in this site;

3 - The gravimetric signature of the Riacho do Pontal District is mainly by a negative Bouguer NW-SE anomaly (below -45 mGal). This negative Bouguer anomaly represents the collisional suture between the cratonic block and the mobile belt Riacho do Pontal. The IOCG occurrences of the Riacho do Pontal District are located in these low gravimetric signature domains. The rocks, slightly altered, have a density of the order of 2.7-2.78 g / cm<sup>3</sup> and the rocks most strongly altered show density of 2.75-3.1 g / cm<sup>3</sup>;

4 - The magnetic signature of the districts of the Vale of the Curaçá and the Riacho do Pontal are quite distinct. Copper corridors in the Vale do Curaçá Copper District are associated with sigmoidal magnetic anomalies located in the western portion of the Itabuna-Salvador-Curaçá Orogen. On the other hand, the copper deposits located in the belt of the Riacho do Pontal District are situated in zones without or with the presence of very weak magnetic anomalies;

5 - MVI magnetic and gravity inversion shows two main NNW prospective trends. Trends I and II have a sigmoidal shear shape. These trends are positioned in the contact zone between domains with high magnetic (SI>0.005) and gravimetric anomalies (>-10,000 nT) and show a contrast in density and magnetite content. Trend I is 60 km in length and 7 km in width, hosts the Caraíba, Surubim and Vermelho mines and other deposits and is the most important trend for hosting IOCG deposits in the Vale do Curaçá District;

6 - The general hydrothermal zoning pattern for IOCG deposits is usually vertical, from magnetite-dominant to depth to hematite-dominant at upper levels. It is possible to interpret the neoproterozoic Riacho do Pontal District as positioned in the shallowest portion of the IOCG system. In this way, additional work must be performed by searching for deeper (or more eroded) areas of the IOCG system related to more magnetic and dense areas (targets on north portion of the Riacho Seco target);

7 - The large areas flanking high speed seismic tomography image that already control in a broad scale Carajás IOCG Province and Riacho do Pontal and Vale do Curaçá Copper Districts in Brazil should be evaluated in more detailed in further exploratory program;

8 - Regional results of this work enlarge the geological, structural and geophysical understanding of Riacho do Pontal and Vale do Curaçá IOCG districts. The use of a broader database of petrophysical data may improve the geophysical models elaborated in this work.

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