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ARTICLE

Geology of the Riacho do Pontal iron oxide copper-gold (IOCG) prospect, Bahia, Brazil: hydrothermal alteration approached via hierarchical cluster analysis

Geologia do prospecto de óxido de ferro-cobre-ouro de Riacho do Pontal, Bahia, Brasil: análise hierárquica de clusters aplicada à definição da alteração hidrotermal

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ABSTRACT: The Riacho do Pontal prospect is situated on the border between the Borborema Province and the São Francisco Craton, in Bahia state. It comprises rocks polydeformed during the Neoproterozoic. The prospect area includes migmatites and gneissic rocks intruded by several sin- to post-tectonic granites. Structural analysis indicates a strong relationship between the development of ductile to brittle-ductile shear zones and associated hydrothermalism. The main tracts of high-strain rate are represented by the Riacho do Pontal (north) and Macururé (south) shear zones. Several copper occurrences have been mapped within the Riacho do Pontal prospect along secondary shear zones. In these areas, the gneissic rocks were affected by intense hydrothermal alteration. Hierarchical cluster analysis permitted the identification of the main hydrothermal mineral associations present in these rocks, which resulted from potassic (biotite) and sodic-calcic (amphibole-albite) alteration, in addition to silicification and iron alteration (hematite). These hydrothermal alteration types are similar to those typically found in iron oxide copper-gold deposits developed at intermediate crustal levels. Hematite-quartz-albite-chalcopyrite-pyrite hydrothermal breccias host the highest-grade copper ore (chalcopyrite-pyrite-chalcocite) zones. The spatial relationship between copper deposits and shear zones improves the metallogenic potential for copper of the Borborema Province and has important implications for mineral exploration in the region.

KEYWORDS: Riacho do Pontal; Borborema Province; copper mineralization; IOCG type deposits; hierarchical cluster analysis.

RESUMO: *O prospecto Riacho do Pontal, situado no limite entre a Província Borborema e o Cráton do São Francisco, no Estado da Bahia, consiste de rochas polideformadas durante o Neoproterozoico, incluindo gnaisses e migmatitos cortados por granitos sin- a pós-tectônicos. A análise estrutural indicou forte relação entre o desenvolvimento de zonas de cisalhamento dúcteis a rúpteis-dúcteis e hidrotermalismo associado, que se vincula especialmente a dois corredores principais de deformação, representados pelas zonas de cisalhamento Riacho do Pontal, ao norte, e Macururé, ao sul. Diversas ocorrências cupríferas foram mapeadas na área do prospecto Riacho do Pontal ao longo de zonas de cisalhamento secundárias. Nessas áreas, os gnaisses foram afetados por intenso hidrotermalismo. Análise hierárquica de clusters permitiu a identificação das principais associações de minerais hidrotermais dessas rochas, formadas devido à alteração potássica (biotita) e sódico-cálcica (anfibólio-albita), além de silicificação e formação de hematita hidrotermal. Esses tipos de alteração hidrotermal são semelhantes aos caracterizados em depósitos de óxido de ferro-cobre-ouro desenvolvidos em níveis crustais intermediários. Brechas hidrotermais com associação de hematita-quartzo-albita-calcopirita-pirita hospedam o minério de mais alto teor constituído por calcopirita-pirita-calcocita. O reconhecimento da relação espacial entre depósitos de cobre e a instalação de zonas de cisalhamento expande o potencial metalogenético para cobre da Província Borborema, com importantes implicações para a exploração mineral na região.*

PALAVRAS-CHAVE: *Riacho do Pontal; Província Borborema; mineralização de cobre; depósitos do tipo IOCG; análise hierárquica de clusters.*

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INTRODUCTION

The Riacho do Pontal prospect is located in the southern portion of the Borborema Province (Brito-Neves 1975, 1983; Almeida *et al*. 1976), near the contact with the northern section of the São Francisco Craton (Almeida 1977; Fig. 1), in Bahia state. In this region, in the 1970's, during the mineral exploration boom of this region, the focus on the research of 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) prevailed and several copper occurrences were recognized.

The possibility of copper deposits associated with iron oxides in the Borborema Province, similar to those of the iron oxide copper-gold deposits (IOCG deposits; Hitzman *et al*. 1992; Hitzman 2000), was emphasized only in more recent studies, such as those conducted by Maas *et al*. (2003) and Machado (2006), in the Orós-Jaguaribe Belt, and by Huhn *et al*. (2011), in the Cariri region. These studies related the occurrence of copper deposits, associated with quartz-hematite breccias in the region bounded by the towns of Mandacaru, São Julião, Fronteiras, and Pio IX (Piauí state) and Campos Sales (Ceará state), to the economically important IOCG deposits; these have previously been identified in Brazil in notably large deposits from the Carajás region (Huhn & Nascimento 1997; Xavier *et al.* 2008; Monteiro *et al*. 2008; Grainger *et al*. 2008; Groves *et al*., 2010). Additionally, the Riacho Seco Copper Project of the Companhia Baiana de Pesquisa Mineral (CBPM), located in the nearby area of the Riacho Seco town, is located within shear zone and hosted in biotite-garnet mylonites, revealing important structural control for this mineralization. The research and mineral assessment conducted by CBPM dimensioned a reserve of 5 Mt with an average grade of 0.8% Cu for this deposit.

The geological context of the Riacho do Pontal prospect comprises migmatites and gneissic rocks intruded by sin- to post-tectonic granitoids. The copper occurrences, however, are spatially related to shear zones. The important structural control may be similar to that reported in other areas of the Borborema Province (Huhn *et al*. 2011).

This study focuses on the geological characterization and definition of the structural positioning of the Riacho do Pontal prospect. Additionally, hierarchical cluster analysis permitted the identification of hydrothermal alteration associations and their comparison with those typical of IOCG deposits, aiming to contribute to the definition of new regional metallogenic and prospective criteria for copper research in the NE of Brazil.

REGIONAL GEOLOGICAL SETTING

The Borborema Province (Fig. 1) is characterized by significant plutonism, important regional-scale shear zones and evolution through the junction of tectonostratigraphic crustal blocks of the Archean to Paleoproterozoic gneissic-migmatitic basement (Massive Median), and supracrustal units represented by Proterozoic metasedimentary and metavolcanic rocks (folded belts or supracrustal belts; Brito-Neves 1975, 1983; Almeida *et al*. 1976; Santos & Brito-Neves 1984; Santos *et al*. 1997; Angelim *et al*. 1997).

The studies conducted by Jardim de Sá *et al.* (1992) and Jardim de Sá (1994) evidenced complexities and heterogeneities indicating that the Borborema Province comprises domains of distinct evolution juxtaposed by shear zones, but with records of deformation and magmatism related to the Brasiliano Orogeny.

Santos (1996) introduced the model of lithostratigraphic terrains for the Borborema Province, postulating that it was formed by the agglutination of large crustal fragments juxtaposed during the Early Neoproterozoic Cariris Velhos and the Late Neoproterozoic Brasiliano orogenies.

Based on its spatially well-defined geological attributes, the Borborema Province has been divided into three distinct zones, namely northern, transversal and southern (Santos *et al.* 1997; Brito-Neves *et al.*, 2000, among others). The expressive regional lineaments of Patos, at north, and Pernambuco, at south, delimit the central segment of the province, represented by the Transversal Zone (Fig. 1), which configures a rectangular area (Jardim de Sá 1994; Brito-Neves *et al.* 2005).

Oliveira & Medeiros (2000) and Oliveira (2008) contributed to the evolution of the tectonostratigraphic terrain concept in the Borborema Province based on gravimetric and magnetic data interpretation. According to Oliveira & Medeiros (2000), regardless of the evolutionary models adopted, the division of the province into five major tectonic blocks is consensual and includes: 1) Médio Coreaú, 2) Ceará (or Cearense); 3) Rio Grande do Norte; 4) Transversal Zone or Central and 5) South or External (Fig. 1).

The contact of the Borborema Province with the northern portion of the São Francisco Craton (Fig. 1) is represented by the fronts of the Brasiliano nappes, where the studied region is positioned. This area is characterized as a Brasiliano collisional zone (0.75 – 0.57 Ga) developed during the convergence of Neo- to Mesoproterozoic terrains due to a tangential tectonic event with a transpressive component and mass transport towards the São Francisco Craton (Alkmin *et al*. 1993).

According to Oliveira (2008), this region shows an aeromagnetic pattern characterized by dominantly shallow sources, defined by positive linear axes oriented towards E-W, with amplitude lower than 100 nT and short wavelength (10 km), intercalated with negative linear and ellipsoidal

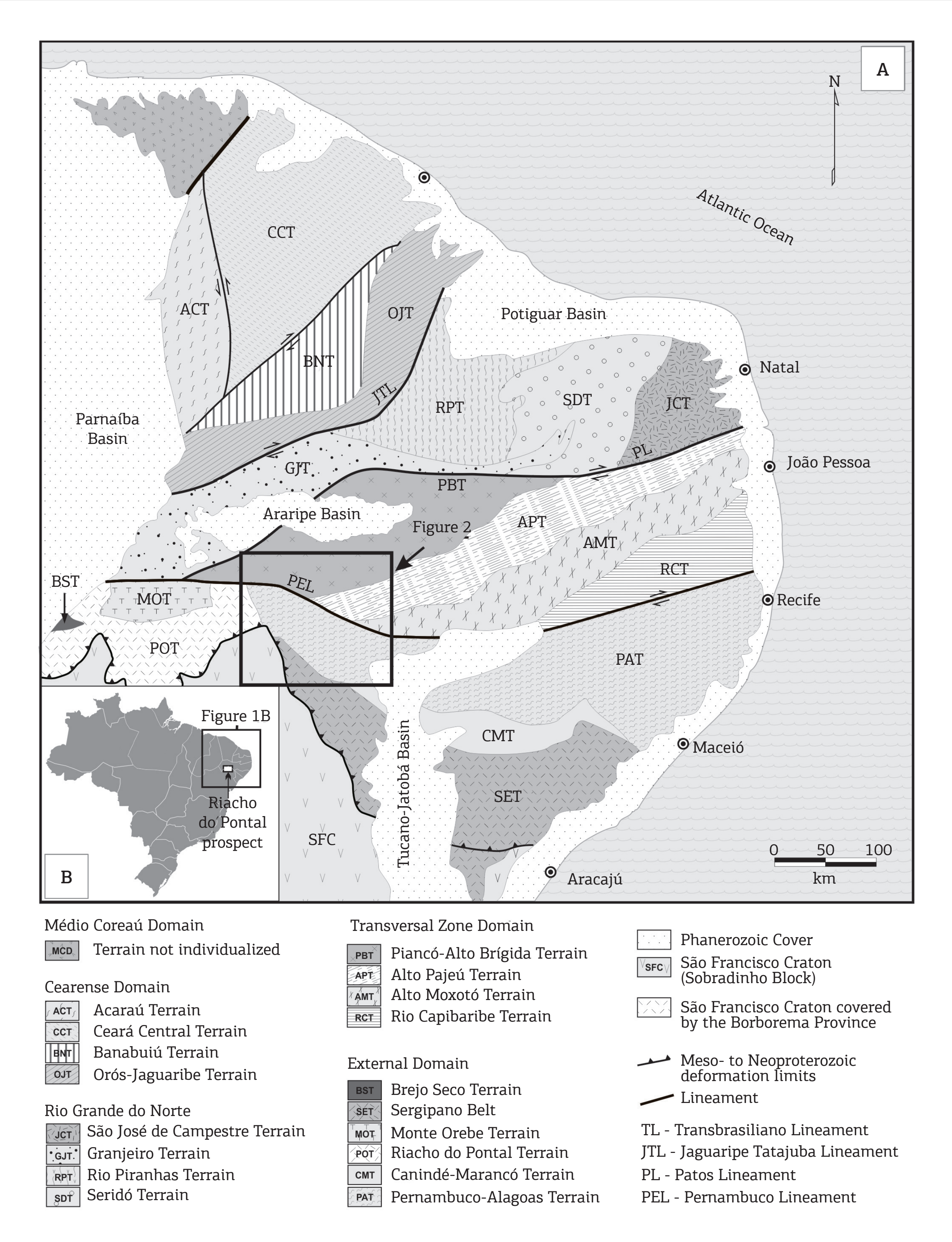

Figure 1. (A) location of the Borborema Province in the NE region of Brazil. In the figure, the Riacho do Pontal prospect is located in the northern limit of the Bahia state; (B) partitioning of the Borborema Province in tectonostratigraphic terrains, according to Gomes (1998).

axes that are truncated by linear anomalies in the NE-SW direction. This gravimetric residual signal is superimposed on a regional positive anomaly with 200 km of wavelength and 60 mGal of amplitude. The regional anomaly is interpreted as the response of a crustal structure that underwent a collisional process. In this case, a tectonic shift caused the elevation of a dense mantle wedge in the lower crust below the São Francisco Craton due to the crustal overload.

The Riacho do Pontal prospect is located between the Sobradinho Block of the São Francisco Craton (Fig. 1) and the Sergipano Belt (Fig. 2). The latter is considered as the outcome of collision between the Pernambuco-Alagoas Massif and the São Francisco Craton during the Neoproterozoic assembly of West Gondwana (Bueno *et al.* 2009). The Sobradinho Block consists predominantly of garnet-biotite gneiss, garnet-mica schists, phyllites, quartzites, and marbles intercalated with lenticular ultramafic bodies. The U-Pb dating between 980 and 1199 Ma in detrital zircon crystals in metasedimentary rocks of this region indicates that protoliths of these rocks were deposited prior to the Brasiliano Orogeny (Oliveira *et al.* 2006). Granitoids cut through the area and have been divided into two groups: the pre-collisional granites (e.g. 628 ± 12 Ma Camará tonalite; U-Pb SHRIMP zircon age) and the 584 to 571 Ma syn-collisional granites (e.g. Angico and Pedra Furada granites; U-Pb TIMS titanite ages; Bueno *et al.* 2009).

The Sergipano Belt (Fig. 2) is represented by the Estância and Macururé groups. Muscovite-garnet-biotite schists and muscovite quartzite represent the main lithotypes of the Macururé Group. In the Estância Group, dolomitic rocks intercalated with calcitic marble predominate.

From a structural stand point, two major regional NW-SE, sub-parallel, regional shear zones are characterized in the Riacho do Pontal prospect area, and these are the Riacho Seco (RSSZ) and the Macururé (MSZ) shear zones. These shear zones are geometrically related to the tectonic movement of the Sergipano Belt basal thrust (SBT), which has vergence towards south. Figure 2 shows the regional position of these structures in contact with the São Francisco Craton.

METHODS

Geological mapping and structural analysis in the area of the Riacho do Pontal prospect have been carried out and integrated

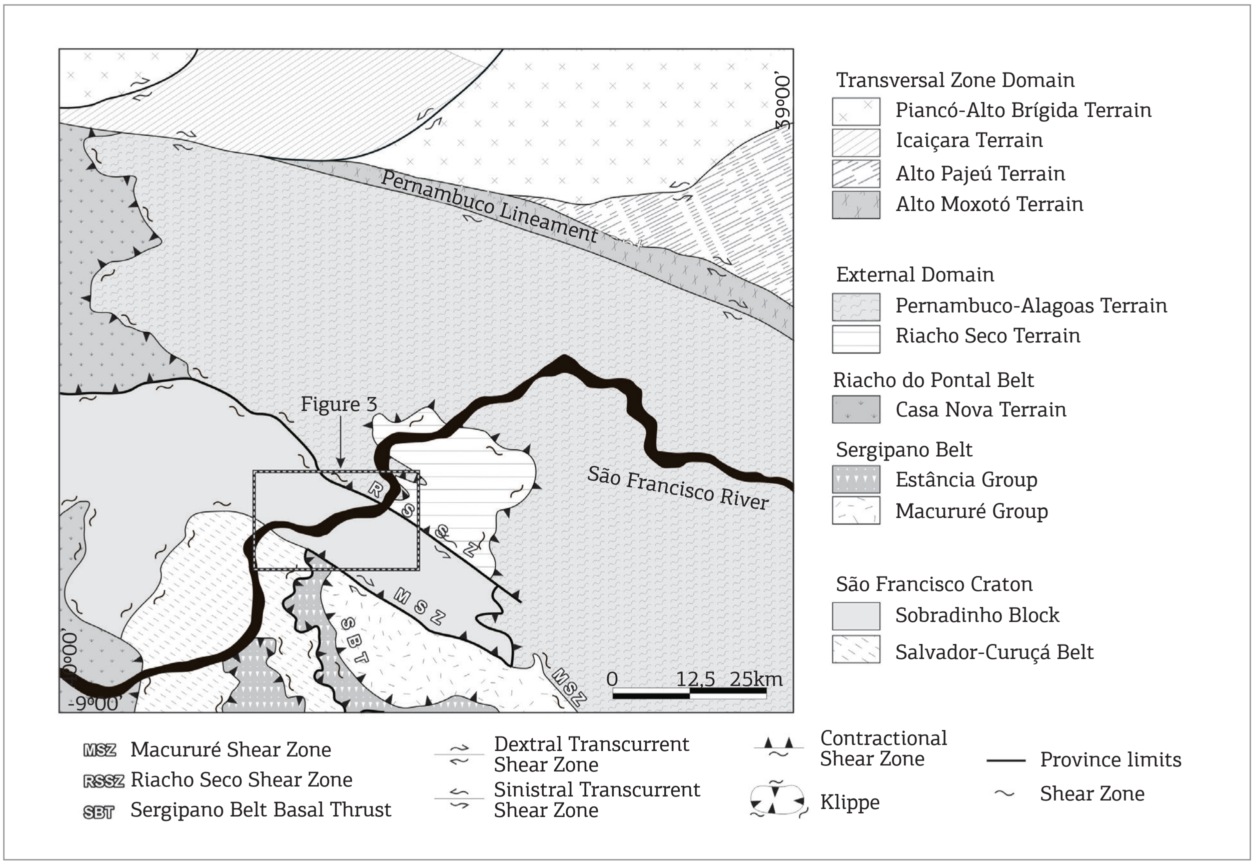

Figure 2. Geological map of the Riacho do Pontal Belt region, showing the location of the Riacho do Pontal prospect between Riacho Seco and Macururé shear zones, according to Gomes (1998).

with information from detailed drill core logging. Petrographic studies under transmitted and reflected light and using Energy Dispersive X-ray Spectrometry (EDS) coupled with Scanning Electron Microscope (SEM) permitted the characterization of hydrothermal mineral and ore assemblages. Hierarchical cluster analysis for 34 variables applying cluster method and cluster rule (Ward 1963) were performed aiming the identification of diagnostic hydrothermal mineral associations.

GEOLOGICAL SETTING OF THE RIACHO DO PONTAL PROSPECT

Figure 3 shows the local setting in the Riacho do Pontal prospect area. The central portion of the Riacho do Pontal prospect is predominantly characterized by gneisses, migmatites and tonalites of the Sobradinho Remanso Complex (Fig. 3). This complex is intruded by syn-collisional granites (Bueno *et al.* 2009). Locally, the rocks are mylonitized, forming L-S tectonites. At the south of the Sobradinho Remanso Complex, rocks belonging to the Macururé Group, represented by dolomitic marble and subordinated quartzites, are recognized.

The geological units mapped in the area of the belt are generally oriented according to a major NW-SE trend, although, locally, it is possible to recognize a NE-SW orientation generated by late tectonic events that affected the region.

Large deformation corridors are represented by the RSSZ and MSZ, which correspond to thrust faults with vergence to SW and important directional components. Secondary shear zones subparallel to these major lineaments were mapped in the area of the belt.

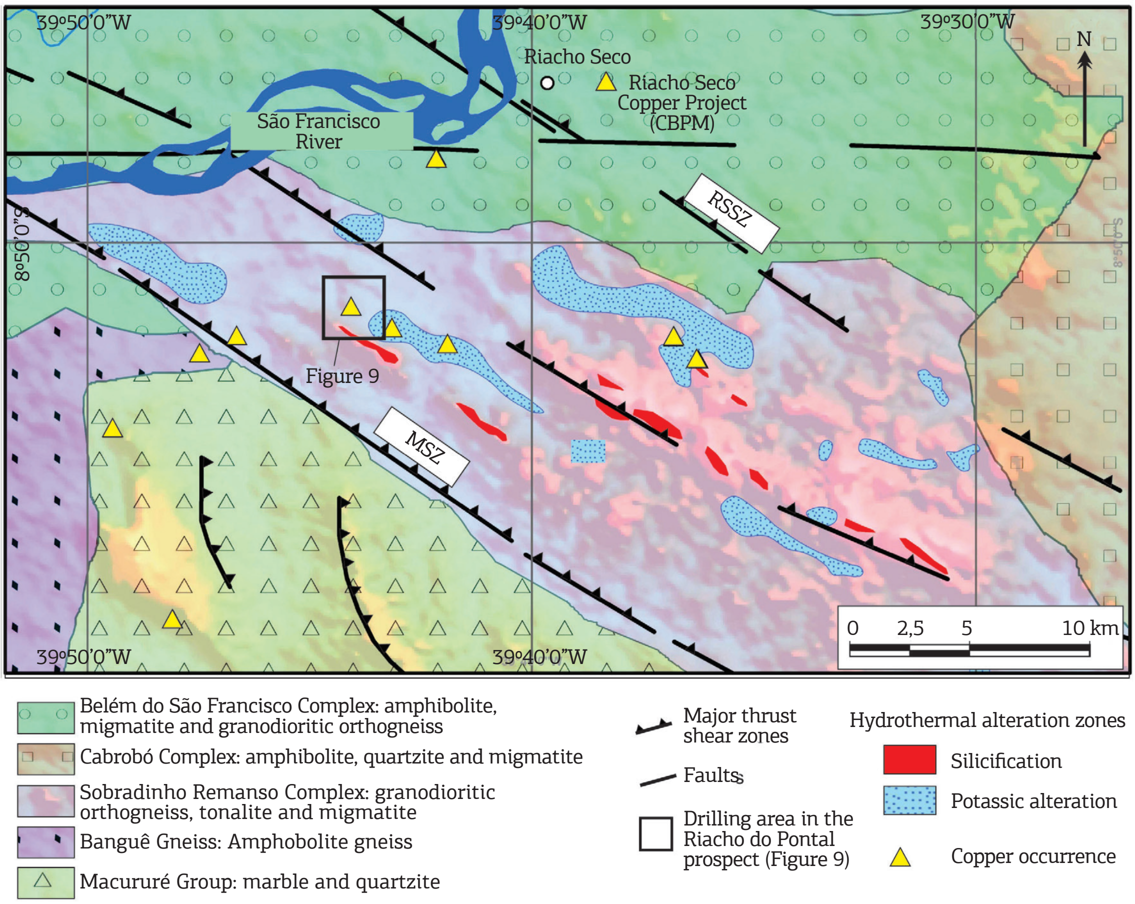

Figure 3. Geological map of the study area in the Riacho do Pontal Belt, modified from Oliveira et al. (2006), superimposed on a Topographic Digital Elevation Model. The map shows the location of the Riacho do Pontal prospect between the main Riacho Seco (ZCRS) and Macururé (ZCM) shear zones, the main lithotypes and most pervasive hydrothermal alteration zones, represented by potassic alteration in biotite-rich rocks and silicification zone.

Hydrothermal alteration affected the rocks along these shear zones, including notable potassic alteration and silicification (Fig. 3). In this region, approximately 30 copper occurrences are known. These are characterized by copper minerals disseminated in hydrothermally altered and tectonically deformed rocks. On surface, the oxidized zones contain malachite and azurite.

HYDROTHERMAL ALTERATION AND STRUCTURAL TRENDS IN THE RIACHO DO PONTAL PROSPECT

Along the Riacho Seco Shear Zone (ZCRS) and Macururé Shear Zone (ZCM) and secondary structures, hydrothermal alteration is identified in the region of the Riacho do Pontal prospect and strongly modified the host paragneissic rocks. Early hydrothermal sodic-calcic alteration is limited to small areas and distal in relation to areas of higher strain rate. It resulted mainly in the replacement of metamorphic minerals of banded gneiss (e.g. biotite) by hydrothermal amphibole.

Zones of albitization are important in the Riacho do Pontal prospect and may represent the result of evolution of the sodic-calcic alteration. They are characterized by the formation of hydrothermal albite associated with amphibole, garnet, apatite, and quartz. Commonly, mineral phases from these zones have been subsequently replaced by hydrothermal biotite and chlorite.

However, the most pervasive event is the proximal potassic alteration (Fig. 3) that was responsible for the origin of biotite-rich rocks, which are crenulated and have hydrothermal biotite along the foliation and in the microliths. Albite is also present in zones of potassic alteration together with quartz, apatite, and ilmenite. These biotite-rich rocks are recognized mainly along major deformation corridors.

The late silicification is evidenced by milky quartz-hematite veins (± fuchsite) of decametric scale up to 50 m thick, oriented according to the regional trend. These veins hold the topography, resulting in crests up to 250 m high and 150 m wide (Fig. 3). Late albite was also identified associated with quartz and hematite.

EVOLUTION TREND OF THE HYDROTHERMAL ENVELOPE

The hydrothermal alteration types that accompanied the deformation within the shear zones in the area of the Riacho do Pontal prospect can be grouped and hierarchized. Aiming to detect hydrothermal mineral associations, we performed the hierarchical cluster analysis for 34 variables, which represent samples collected from drill holes executed in the prospect. The results were obtained from the analysis of bore hole records, taking into account the different types of hydrothermal alteration minerals observed macroscopically, in SEM and petrographic studies. The cluster method initially considers each observation as a separate cluster and combines them until all observations belong to a general cluster.

The result of the hierarchical cluster analysis is illustrated in Figs. 4 and 5. Three groups of samples are highlighted: (1) 1, 5, 7, 8, 9, 10, 15, 16, 18, 19, 23, 24, 26, and 34; (2) 2, 3, 11, 14, 17, 20, 21, 22, 23, 27, 28, 29, 30, 31, 32, and 33; (3) 4, 6, 12 and 25. These three sets of clusters represent rocks that underwent similar hydrothermal alteration and can be geochemically correlated.

The three main groups of samples can be identified based on their hydrothermal alteration mineral associations related to early- (amphibole formation) and late-stage shear events (albitization and potassic alteration):

1. Sodic-calcic alteration (cluster I in Fig. 5): characterized by the presence of hydrothermal amphibole in association with plagioclase, chlorite, and ilmenite. The early development of an incipient mylonitic foliation was coeval with the hydrothermal amphibole formation (Figs. 6A to 6C, 7A and 7B) in distal zones;
2. Sodic alteration (cluster II in Fig. 5): associated with the formation of albite, which is related to hydrothermal biotite, amphibole, chlorite, garnet, apatite, and quartz (Fig. 6D). It is linked to zones with more intense alteration and pervasive mylonitization (Fig. 7C);
3. Potassic alteration (cluster III in Fig. 5): defined by the presence of hydrothermal biotite in association with albite, ilmenite, quartz, and apatite. These hydrothermal minerals are spatially connected to penetrative shear deformation, LS tectonite with linear (L) and planar (S) fabric, and have intense crenulation (Figs. 6F, 7C and 7F). Pyrite, hematite, chalcopyrite and chalcocite are common in this alteration stage (Figs. 6E, 6H and 7H), which represents the proximal alteration in relation to ore.

In addition, silicification and late hematitization are represented by veins and veinlets with quartz-hematite ± fuchsite (Fig. 7G). This phase of hydrothermal alteration was not sampled for the present study.

Studies using EDS coupled with SEM in hydrothermal alteration zones I (early and distal sodic-calcic alteration), II (sodic alteration) and III (late proximal potassic alteration) showed the following characteristics: (a) increase in potassium towards the later alteration stages; (b) consumption of FeO from the initial to the intermediate hydrothermal alteration zone; (c) process of albitization responsible for the increase of Na_2O to the most advanced

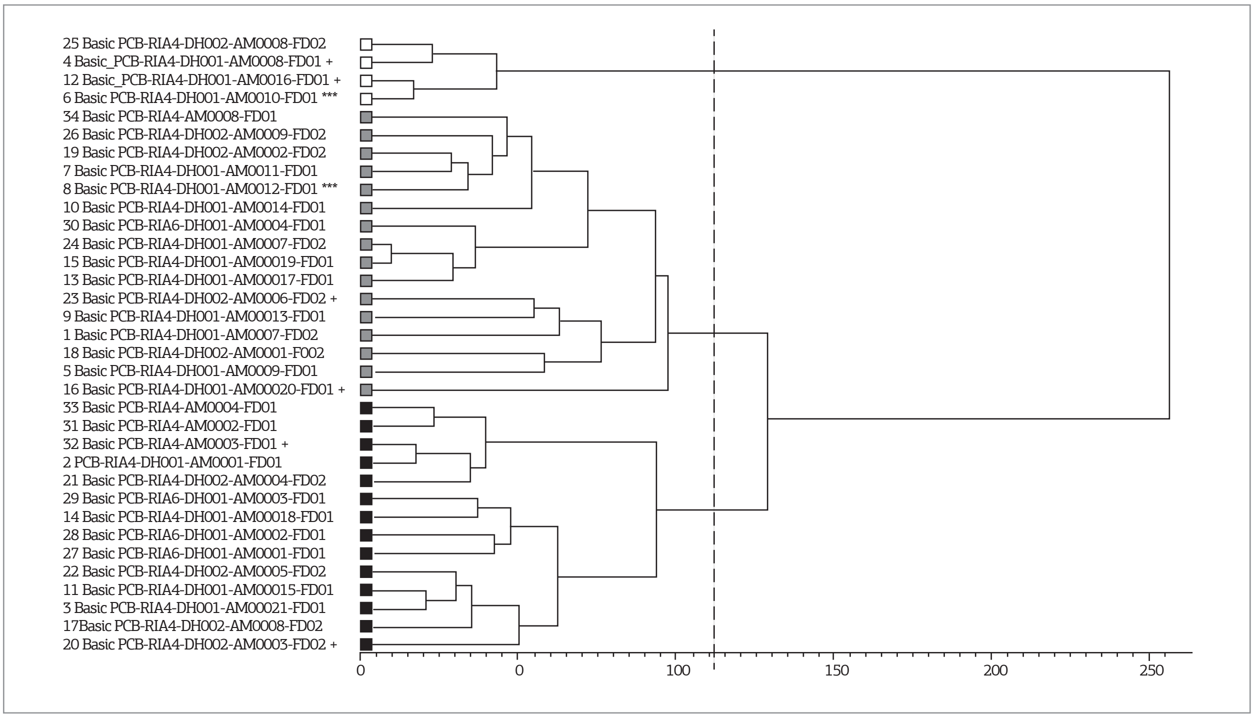

Figure 4. Diagram of hierarchical clustering calculated for the analytical results of 34 samples (variables) related to hydrothermal alteration zones identified in the drill cores, showing three groups of geochemically correlated samples.

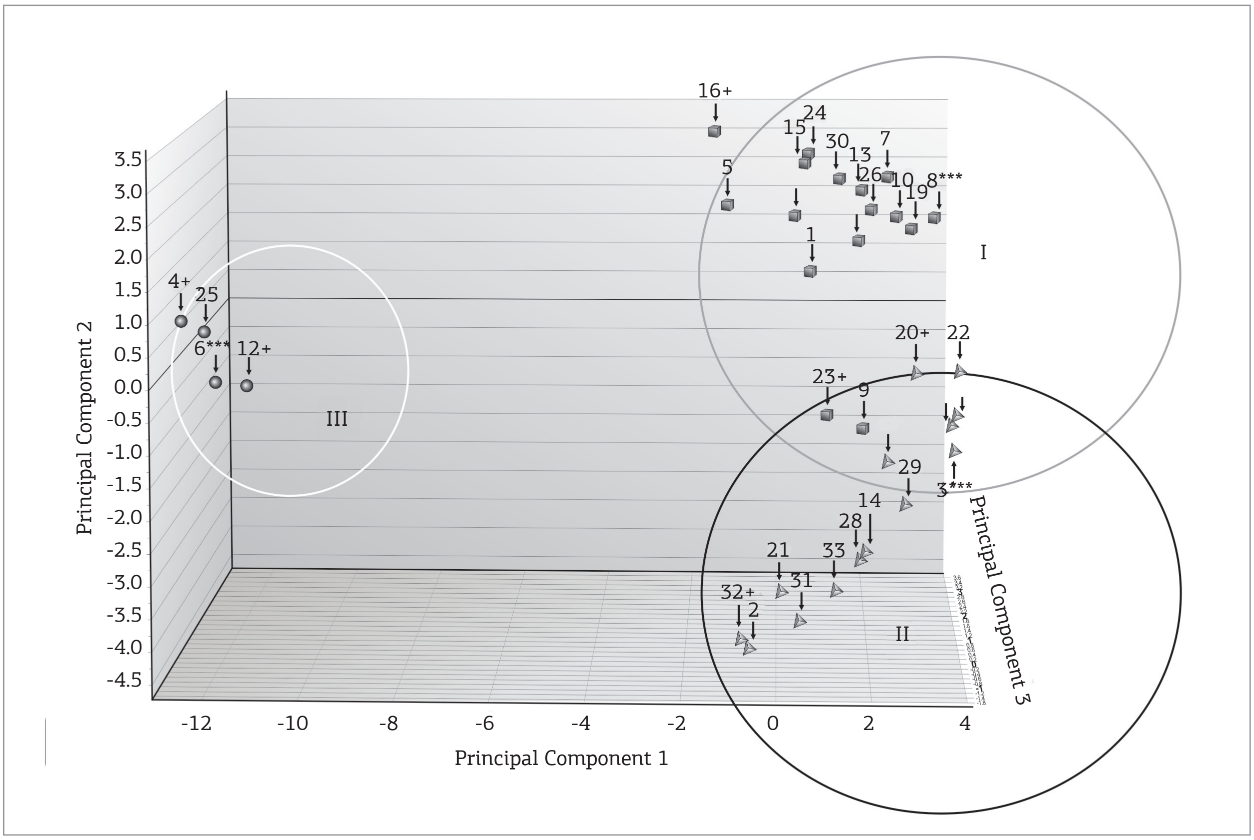

Figure 5. Main clusters of variables (numbers) explained by multivariable calculation (Main Components), showing three groups of samples that record early sodic-calcic (I), late sodic (II) and potassic (III) alteration. Explanations in the text.

Figure 6. Host rocks and hydrothermal alteration zones of the Riacho do Pontal prospect. (A) banded amphibole-biotite gneiss of the Sobradinho Remanso Complex; (B) detail of Photo 6A, showing amphibole-rich zone (sodic-calcic alteration zone); (C) zone of sodic-calcic alteration, in which amphibole and plagioclase are intermixed with chlorite and apatite according to the incipient foliation; (D) zone of silicification (hematite, albite and carbonate) parallel to the mylonitic foliation; (E) quartz-albite-hematite breccia; (F) biotite-rich rock with malachite in strongly deformed domain; (G) hematite-fuchsite mylonite; (H) pyrite and chalcopyrite filling fractures in the brecciated gneiss within the potassic and sodic-calcic alteration zone.

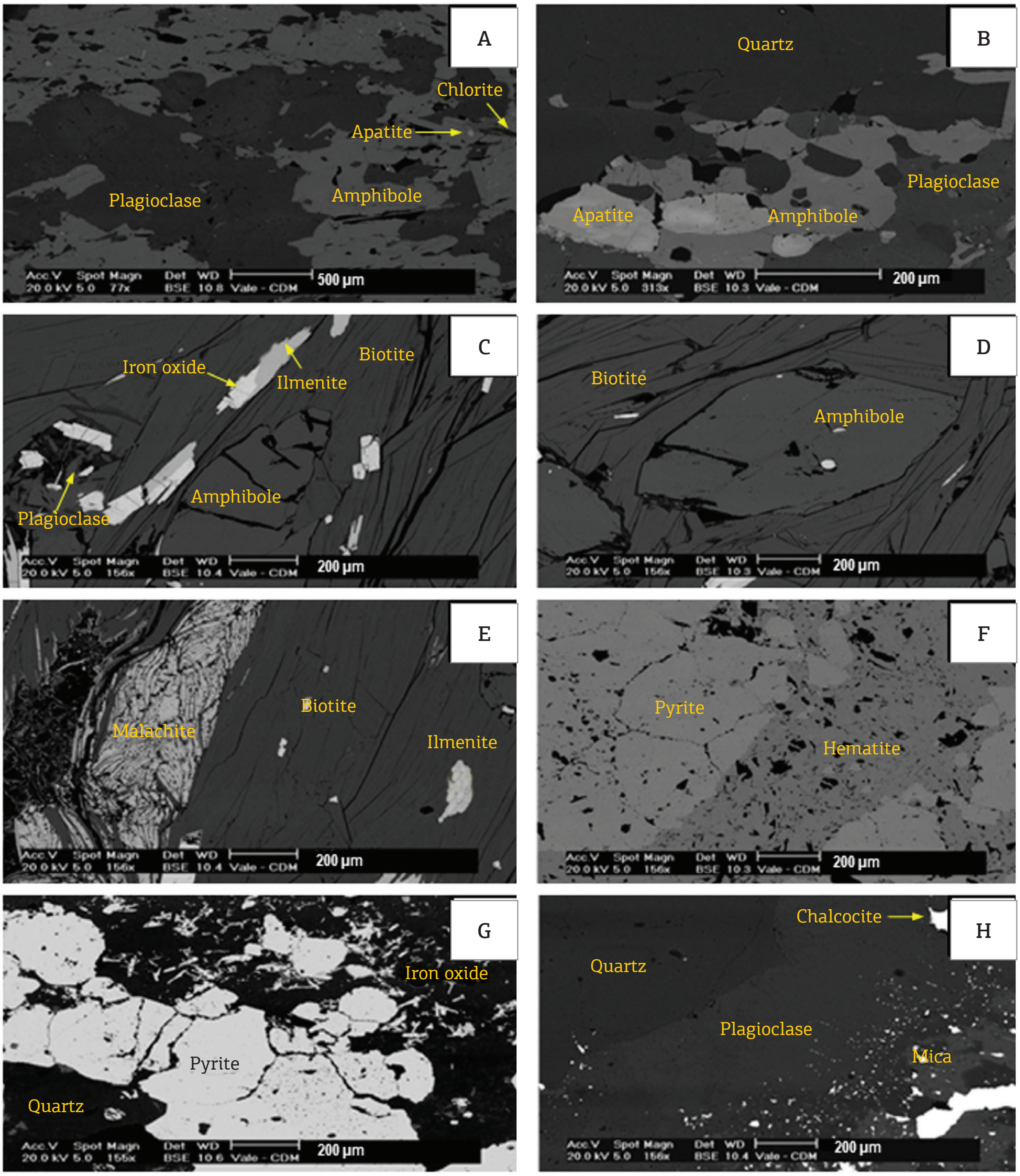

Figure 7. Scanning Electron Microscope images of the hydrothermal alteration zones. (A) zone of sodic-calcic alteration with hydrothermal amphibole and plagioclase (oligoclase) intermixed with chlorite and apatite according to the incipient mylonitic foliation; (B) zone of sodic alteration characterized by hydrothermal amphibole, quartz, and apatite controlled by the mylonitic foliation; (C) hematite and ilmenite associated with biotite, amphibole and albite; (D) zone of potassic alteration in which amphibole porphyroclast is surrounded by hydrothermal biotite, and minor iron oxide and ilmenite; (E) zone with intense potassic alteration (hydrothermal biotite) interspersed with malachite; (F and G) quartz vein with pyrite and crosscutting hematite; (H) chalcocite veinlets associated with quartz-albite-biotite.

stages of hydrothermal alteration; (d) silicification and potassic alteration in the strongly hydrothermally altered zones (Fig. 8).

Considering these data, it is possible to identify the spatial distribution of the main hydrothermal alteration zones associated with the Riacho do Pontal prospect (Figs. 9 to 11).

The geological mapping of the region tested by exploratory drilling (Fig. 9) showed hydrothermal zoning associated with deformation and highlighted the main zones of hydrothermal alteration.

Figure 10 shows a geological section illustrating the distribution of hydrothermal alteration zones identified in the drill holes performed in the region of the Riacho do Pontal prospect. The mineralized zone is spatially related to areas richer in biotite.

COPPER MINERALIZATION

In the regional context, dozens of copper occurrences are situated between the RSSZ and the MSZ shear zones. Locally, mineralized zones are anastomosed along a mylonitized corridor with approximately 50 km in length and width between 5 – 10 km, which corresponds to a thrust front with a horizontal component.

These copper occurrences are predominantly hosted in sheared paragneisses and are spatially related to thrust zones associated with the Basal Thrust of the Sergipano Belt (Fig. 2). Such rocks were significantly modified by hydrothermal alteration processes, which resulted in zones that may vary in size, with thickness from a few meters up to 100-meters thick, and may extend according to the foliation for more than 5 km, being strongly transposed.

The local structural controls are related to the area of intersection between the NNW-trending thrust shear zones and secondary NE-trending thrust faults. Mylonite to ultramylonites predominate, with associated L-S tectonites. The orebodies comprise ore shoots related to the stretching lineation. Copper mineralization is predominantly composed of chalcopyrite, chalcocite, and pyrite, which are disseminated and associated with breccia bodies.

A 3-D geological model showing the major shear zone and related hydrothermal alteration zones are summarized in Fig. 11. Potassic and silicified zones follow the secondary thrust faults.

DISCUSSIONS AND CONCLUSIONS

The hydrothermal system of the Riacho do Pontal Belt is closely related to a set of sub-parallel ductile shear zones and associated mylonites. Hydrothermal alteration

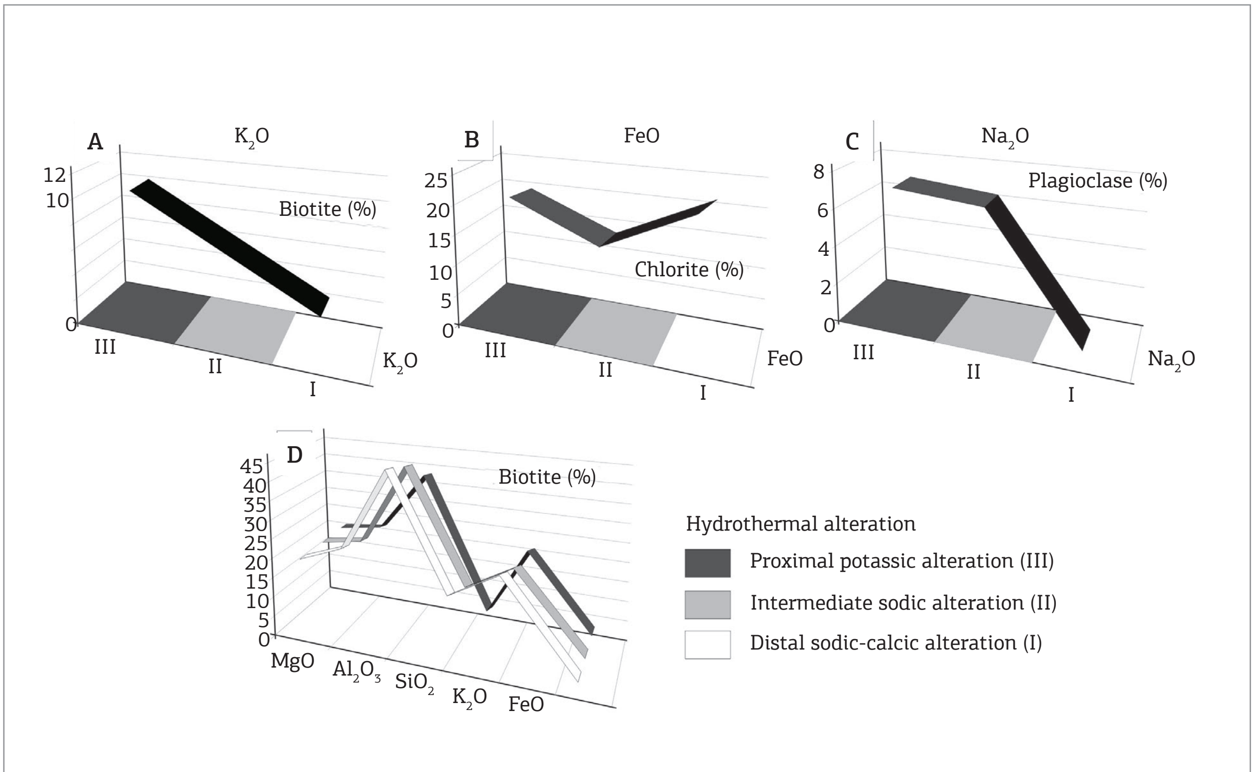

Figure 8. Changes in the abundance of the hydrothermal minerals identified by Energy Dispersive X-ray Spectrometry in the hydrothermal alteration I (distal), II (intermediate) and III (proximal) zones in bore hole records. (A) biotite; (B) chlorite; (C) plagioclase; (D) variation in the chemical composition of the biotite from different alteration zones.

in mylonitized gneissic rocks of the Sobradinho Remanso Complex (Sobradinho Block of the São Francisco Craton), close to the contact with the southern Sergipano Belt of the Borborema Province, is controlled by these deformation zones, mainly represented by the Riacho Seco and Macururé shear zones.

Hierarchical cluster analysis permitted the identification of the main hydrothermal alteration mineral associations recorded in these gneissic rocks. The hydrothermal alteration zoning (Fig. 11) recognized in the Riacho do Pontal prospect is represented by distal sodic-calcic areas (amphibole-plagioclase-chlorite-ilmenite) and more proximal areas that are mainly enriched in potassium and iron (biotite-hematite-albite-ilmenite-quartz-apatite). These biotite-rich rocks are recognized along major deformation corridors and possibly were formed from coupling of shearing and metasomatism from gneissic and migmatitic rocks from the Sobradinho Remanso Complex.

In addition, silicification and late hematitization are represented by veins and veinlets with quartz-hematite ± fuchsite. These veins sustain the topography and represent scars of seismogenic events in the center of reactivated shear/faulting zones. The mineralized zone is

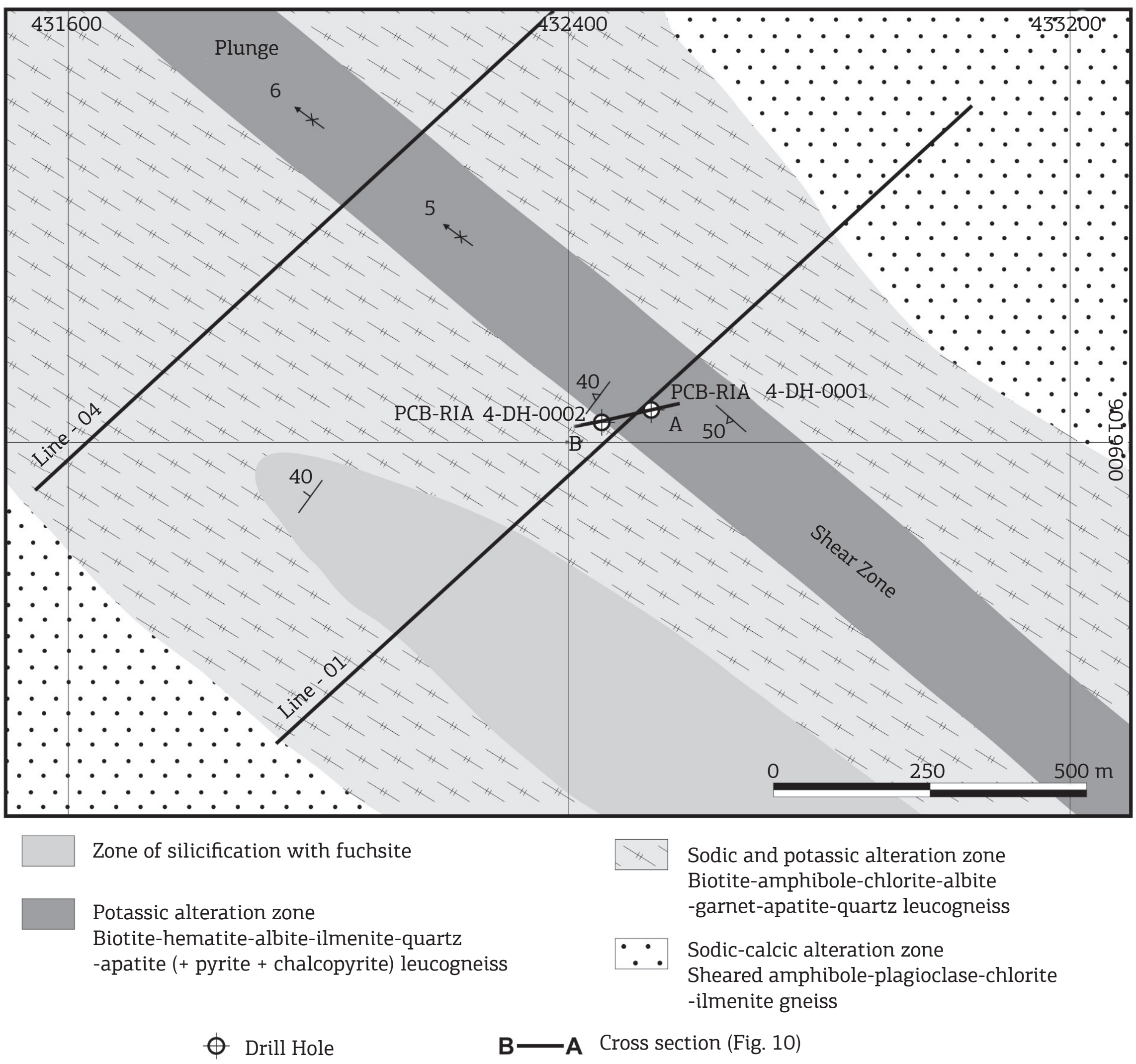

Figure 9. Map of spatial distribution of the hydrothermal alteration zones located in the central portion of the Riacho do Pontal prospect. Note the association between the hydrothermal potassic alteration zone and the main shear zone.

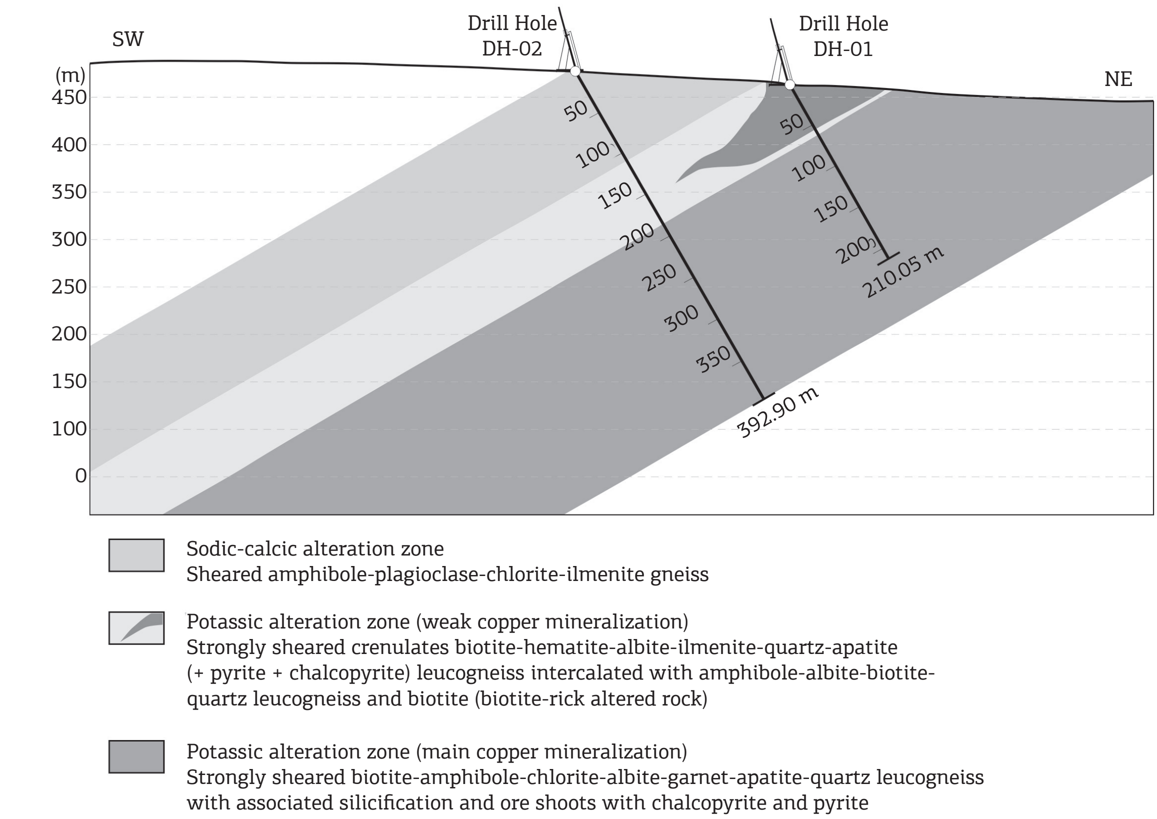

Figure 10. Geological cross section illustrating the drill holes (PCB-RIA4-DH-01 and 02) performed in the mineralized zone of the Riacho do Pontal prospect. Note the hydrothermal zoning represented by distal sodic-calcic alteration (amphibole-plagioclase-chlorite-ilmenite) and more proximal potassic alteration (biotite-amphibole-chlorite-quartz) zones.

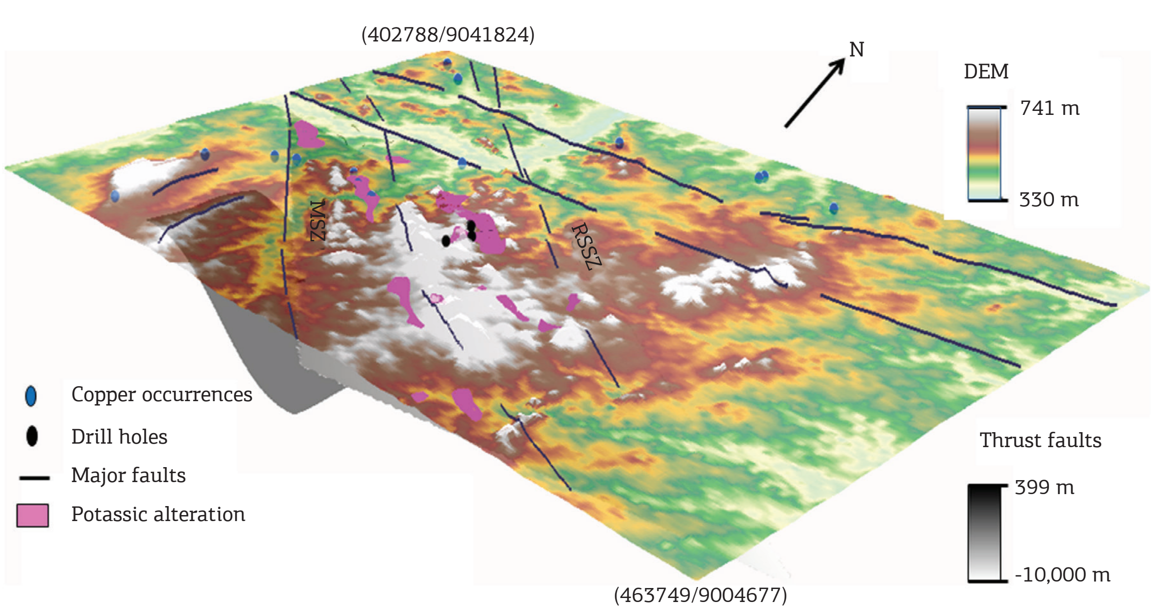

Figure 11. Geological 3-D model of the Riacho do Pontal prospect, showing Digital Elevation Model, faults, copper occurrences, and associated hydrothermal alteration zones.

intrinsically related to biotite-rich areas, where mylonites to ultramylonites predominate. The ore shoots are related to the stretching lineation and consist of chalcopyrite, chalcocite and pyrite, which occur disseminated in LS tectonites and in breccia bodies.

Based on the spatial association with zones of hydrothermal potassic alteration, as well as with the local presence of hematite in zones of thrust zones, it is postulated that the Riacho do Pontal prospect represents a Brasiliano analogue of an IOCG system, as defined by Hitzman *et al.* (1992). The criteria used to suggest this prospect as an IOCG system are:

- it is strongly associated with alkaline alteration (potassic and albite alteration);
- copper ore is hydrothermal and epigenetic, closely associated with shear zones;
- presence of hydrothermal iron oxides spatially and temporally related to copper orebodies;
- mineralization that is not spatially related to proximal granites;
- deposits that in general are approximately 20 to 50 Mt, as characteristic in the majority of this deposit class in the world.

The IOCG deposits occur in a variety of crustal levels. According to the model proposed by Pollard (2006), in deep crustal levels, CO_2-rich fluids are separated from magma at high pressure with respect to systems depleted in CO_2. This favors the partitioning of metals for the fluid phase, which would concentrate the metals of magmatic origin. At these deep crustal levels, ductile shear zones predominate and deposits are hosted in structural traps. In shallower crustal levels, deposits would be hosted in hydrothermal systems dominated by hydrothermal brecciation, caused by overpressure with major contribution of externally-derived fluids (Hitzman 2000).

The typical hydrothermal alteration zoning in an IOCG system is characterized by sodic-(calcic) hydrothermal alteration in deeper and distal zones, evolving to potassic and carbonate-rich zones at shallow crustal levels, in which hematite predominates with respect to deeper zones with magnetite. Such zoning is similar to that observed in the Riacho do Pontal prospect, which has distal amphibole formation and proximal potassic alteration zones with biotite and hematite-quartz veins and breccias. This would suggested that the hydrothermal system of the Riacho do Pontal prospect was developed in an evolving system at intermediate crustal levels at ductile to brittle-ductile conditions.

With respect to the origin of the cupriferous mineralization of the Riacho do Pontal prospect, the participation of components derived from magmatic fluids associated with the emplacement of Brasiliano or late-Brasiliano granitic batholiths can be suggested. However, as in other IOCG deposits in major metallogenetic provinces, such as those from the Carajás Province, there is not a direct connection between the positioning of these batholiths and the mineralization investigated here. In contrast, the strong structural control seems to play a key role in the genesis of the IOCG deposits and is ubiquitous in these deposits worldwide.

The important structural control and the hydrothermal alteration types of the Riacho do Pontal prospect are similar to those of the giant Salobo iron oxide-copper-gold deposit (1.112 Mt @ 0.69 wt% Cu and 0,43 g/t Au; Vale 2012). The Salobo deposit is located within the regional WNW-ESE-trending Cinzento Transcurrent Shear Zone (DOCEGEO 1988; Lindenmayer 1990; Machado *et al*. 1991) and hosted by banded gneissic rocks attributed to the Mesoarchean Xingu Complex (Melo 2014) and possibly by meta volcano-sedimentary units (Lindenmayer 2003). The mylonitized gneissic rocks underwent very strong hydrothermal alteration, under conditions of high fluid/rock ratio, which obliterates the textures of the protoliths. At Salobo, the hydrothermal system evolved from early and distal sodic-calcic (hastingsite-actinolite) alteration to an important stage of proximal iron- and potassic (grunerite-almandine-biotite-tourmaline) alteration (Lindenmayer 1990, 2003; Réquia *et al*. 2003; Melo 2014). The copper-gold ore comprises mainly bornite, chalcocite and gold and is related to magnetite-rich zones. Thus, the nature of host rocks (e.g. reactive feldspar-rich gneissic rocks), intense fluid-rock interaction and spatial hydrothermal alteration zoning (e.g. distal sodic-calcic and proximal potassic alteration zones) are also common characteristics between the Riacho do Pontal prospect and major IOCG deposits.

Additionally, the Caraíba deposit, which is also located in the northern portion of the São Francisco Craton, in the Bahia state, has been compared with the IOCG deposits (Teixeira *et al*. 2010; Garcia 2013). This deposit stands out among the copper deposits hosted in mafic-ultramafic complexes in this region. Its genesis was considered magmatic in nature according to a substantial part of the pioneering studies in the region of the Curaçá Valley (Delgado & Sousa 1975; Lindenmayer 1981; Oliveira & Tarney 1995). However, Maier & Barnes (1999) highlighted unusual aspects of this deposit compared to those of typical magmatic origin, such as:

a) the association of sulfides mainly represented by bornite and chalcopyrite; b) large amount of magnetite, which represents 50% wt. of the ore; c) high Cu/Ni ratio (~ 40); d) orthopyroxenites with abundant phlogopite and, locally, significant amounts of zircon and apatite.

The studies conducted by Del'Rey Silva *et al.* (1996) were of fundamental importance to show the effects of deformation events superimposed on the Caraíba deposit. According to these authors, the mineralization was interpreted as confined and restricted to a hinge zone of a main fold. However, new geological data confirmed by prospecting executed in the Caraíba mine are not consistent with the proposed structural control for ore. Drill holes intercepted the mineralized zone, which is associated with a fault that cuts the hinge zone. Based on this new evidence, the epigenetic model related to hydrothermalism within shear zones has gained greater prominence to explain most of the cupriferous mineralization at the Curaçá Valley. This paradigm shift has led to an increase in resources of 15 Mt @ 2.56% copper for the underground mining at the Caraíba mine in 1995 (Fraguas 2012).

Expressive hydrothermal alteration was identified in the Caraíba deposit, including potassic (microcline and phlogopite), sodic (andesine), chlorite, epidote, sericite, and barite alteration, as well as silicification and hematite formation (Garcia 2013). An orthomagmatic origin overprinted by an iron oxide-copper-gold system has been proposed for the Caraíba deposit in recent studies (Teixeira *et al.* 2010; Garcia 2013).

The existence of epigenetic copper mineralization in the Caraíba deposit has important consequences as it broadens the search for other epigenetic hydrothermal copper deposits associated with significant amounts of magnetite and/or hematite in the Borborema Province. It is worth noting that, despite the distinct nature of the host rocks, the hydrothermal processes identified in the Caraíba deposit, including potassic and sodic alteration, are similar to those identified in the Riacho do Pontal area.

The similarity between the attributes of the Riacho do Pontal prospect and those recognized in IOCG deposits, as well as at Caraíba, improves the metallogenic potential for copper in the Borborema Province, mainly along large regional crustal discontinuities. Such discontinuities may have favored the circulation of large volumes of hydrothermal fluids with important implications for copper metallogenesis in the Borborema Province, chiefly during the Neoproterozoic, though the age of the hydrothermal overprint at Caraíba is yet uncertain.

Given the magnitude of the hydrothermal processes associated with shear zones in the Riacho do Pontal Belt, it is reasonable to assume the possibility that the contact zone between the Borborema Province and the São Francisco Craton may host world-class copper deposits.

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