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^{40}Ar-^{39}Ar age of the copper mineralization at Riacho do Pontal IOCG District and detrital zircon U–Pb ages of paragneiss host rocks

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ABSTRACT

Geological, structural and metallogenetic characteristics related to the Proterozoic Riacho do Pontal iron-oxide copper gold (IOCG) mineral systems in northeast Brazil have been reinterpreted recently and there is an ongoing discussion regarding their genetic model and associated tectonic setting. The mineralization in the Riacho do Pontal district is represented by small copper deposits strongly controlled by the structural features of the basement rocks. Hydrothermal biotite associated to the copper mineralization has a ^{40}Ar-^{39}Ar of ca. 691 Ma, indicating a probable late Neoproterozoic age for the main mineralization event. Detrital zircon grains from the host rock show that the sedimentary protolith is younger than ca. 2035 Ma and was probably deposited in a convergent setting, representing a favorable environment for the formation of Cu-rich porphyry. Our results thus help to link the tectonic setting of the Riacho do Pontal Belt to its copper-gold ore deposits.

Keywords: Riacho do Pontal District, IOCG, ^{40}Ar-^{39}Ar ages, Detrital zircon.

1. INTRODUCTION

The São Francisco Craton, located in southeast Brazil, represents one of the main cratonic area in South America (Fig. 1A)(Alkmim and Marshak, 1998; Cordani et al., 2016; Lana et al., 2013; Romano et al., 2013; Teixeira and Figueiredo, 1991). The São

Francisco Craton comprises three main continental blocks that stabilized by the end of the Archean, referred to as the Gavião, Jequié and Serrinha blocks, and magmatic arcs of the Itabuna-Salvador-Curaça Belt (Fig. 1B) (Barbosa and Barbosa, 2017). These blocks and continental arcs were amalgamated together during the early Paleoproterozoic as a result of the Transamazonian Orogeny (Almeida et al., 2000; Baldim and Oliveira, 2021; Barbosa and Barbosa, 2017; Barbosa and Sabaté, 2004; Hurley et al., 1967; Teixeira and Figueiredo, 1991; Zincone et al., 2021). Remnants of the Transamazonian Orogen located at the border of the São Francisco Craton were later reworked and overprinted by the Brasiliano/Panafrican Orogeny, which resulted in the formation of numerous orogenic belts surrounding the São Francisco Craton, among which the Riacho do Pontal Belt represents an important, although yet poorly documented segment of this orogenic system. Brasiliano/Panafrican belts resulted from the formation of the supercontinent Gondwana at the end of the Neoproterozoic and beginning of the Paleozoic (Aguilar et al., 2017; Bertrand and Jardim de Sa, 1990; Caxito et al., 2016; Cutts et al., 2019, 2018; Heilbron et al., 2010; Moreira et al., 2018; Narduzzi et al., 2017; Schannor et al., 2019).

The Riacho do Pontal Belt, located in to the north of the of the Gavião Block is a part of the giant strike-slip system of the Borborema Province (Fig. 1) (Barbosa and Barbosa, 2017; Caxito et al., 2014a; Heilbron et al., 2017). Like other Archean and Precambrian terranes within and bordering the São Francisco Craton, such as the Quadrilátero Ferrífero (Farina et al., 2016), the Riacho do Pontal Belt comprises zones with significant mineral resources forming ore deposits referred to as the Riacho do Pontal Mineral District. The latter is situated in the southern portion of Borborema Province (Fig. 1) and consists of a cupriferous province subdivided in two districts: the Vale do Curaçá and the Riacho do Pontal copper districts (Garcia, 2017). The province also comprises mineralization in Au, Fe and Cr and other metals (Teixeira et al. 2010, 2019; Juliani et al. 2016). The relationships between copper ore deposits and the geodynamic evolution of the region are debated. This is partly due to the complex, yet incompletely understood geodynamic evolution of this area, which experienced at least two orogenic cycles which could have both contributed to ore mineralization. Garcia (2017) emphasized that ore deposits mainly formed during the Neoproterozoic Brasiliano/Panafrican orogenic cycle. In detail, Garcia (2017) suggested that Neoarchean (ultra)mafic magmatic rocks constitute the main copper source that was later remobilized by hydrothermal processes during the Brasiliano/Panafrican Orogeny. On the contrary, gold mineralization is suggested to have occurred during the Transamanzonian Orogeny, with some remobilization and mineralization events during the Brasiliano/Panafrican Orogeny (Teixeira et al., 2019). Alternatively, Hühn et al. (2020) pointed out that the Vale do Curaçá and the Riacho do Pontal copper districts are located within the northern part of the São Francisco Craton and represent two pulses of mineralization (Fig. 2). An older magmatic event associated with the Caraíba Cu deposit, which is located within the Vale do Curaçá District, is related to Paleoproterozoic (ca. 2.0 to 2.2 Ga) hydrothermal processes. A younger Neoproterozoic (ca. 630 Ma to 530 Ma) episode of volcanism and associated plutonism is also documented in the Riacho do Pontal Belt (Caxito et al., 2017).

The main objective of this study is to document the ages of mineralizing events of copper deposits in the Riacho do Pontal Mineral District and their link with the geodynamic evolution of the Riacho do Pontal Belt. To this purpose, we provide new geochronological ^{40}Ar-^{39}Ar age obtained on hydrothermal biotite and U-Pb ages obtained on zircon from the host rocks. Based on these data, we propose a model for the Cu mineralization of the Riacho do Pontal Mineral District.

2. GEOLOGICAL SETTING

2.1. Regional setting

The northern part of the São Francisco Craton is bordered, from west to east, by the Rio Preto, the Riacho do Pontal and the Segipano belts (Fig. 1B). These belts corresponds to segments of the Brasiliano/Panafrican collisional zone that resulted from the convergence between Borborema Province and the São Francisco Craton between ca. 640 Ma to ca. 500 Ma (Alkmim and Martins-Neto, 2012; Caxito et al., 2017; Heilbron et al., 2017).

Within the Riacho do Pontal Belts, a suture zone is marked by a negative-positive pair of strong gravimetric anomalies. The positive anomaly corresponds to the lower crust of the Borborema Province, and the negative signal corresponds to nappes pushed towards the craton (Oliveira, 2008). The supracrustal rocks of the Riacho do Pontal and Sergipano belts crop out as allochthon, with displacements of the order of 30 to 60 km over the São Francisco Craton (Jardim de Sá et al. 1992; Oliveira, 2008).

The Borborema Province records deformation and magmatism related to the Brasiliano Orogeny and comprises domains of distinct evolution juxtaposed by shear zones (Jardim de Sá et al., 1992; Jardim de Sá, 1994; (Caxito et al., 2016, 2014a). The main lithostratigraphic terranes of the Borborema Province were formed or metamorphosed during the early Neoproterozoic Cariris Velhos Orogeny (ca. 1000 Ma to 960 Ma; (Caxito et al., 2014b) and the Late Neoproterozoic Brasiliano/Panafican Orogeny (ca. 630 Ma to 530 Ma; Santos, 1996; (Caxito et al., 2016, 2014a). The Borborema Province is classically subdivided into five major tectonic blocks: 1) Médio Coreaú; 2) Ceará (or Cearense); 3) Rio Grande do Norte; 4) Transversal Zone or Central: and 5) South or External (e.g., Santos et al. 1997; Brito-Neves et al., 2000; Oliveira and Medeiros, 2000; Oliveira, 2008). The contact of the Borborema Province with the northern portion of the São Francisco Craton is represented by the fronts of the Brasiliano Nappes. This area corresponds to the Brasiliano collisional zone that resulted from 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 anomalies.

2.2. Local geology of Riacho do Pontal Belt

The Riacho do Pontal Belt is located in the southern portion of the Borborema Province (Brito-Neves 1975, 1983; Almeida et al. 1976; (Almeida et al., 2000) (Figs. 1 and 3). From south to north, the Riacho do Pontal Belt is subdivided into the External, Central and Internal zones which are characterized by distinct sedimentary, metamorphic and structural features (Caxito et al., 2016). The External Zone comprises south-verging nappes overriding the São Francisco Craton basement. The Central Zone is made up of metavolcaniclastic rocks deformed by south-verging thrusts and E–W strike -slip faults.

The Central zone also comprises rock units interpreted as Neoproterozoic ophiolites (Caxito et al., 2016, 2014a). The Internal Zone comprises metavolcaniclastic, gneiss and migmatites (Caxito et al., 2016).

The Riacho do Pontal Mineral District was the focus of intense exploration from the seventies to the nineties, during the mineral exploration boom. Efforts were mainly focused on the characterization Volcanic-Hosted Massive Sulfide mineralization in greenstone belts (VHMS; Franklin et al., 1981; Barrie and Hannington, 1999) and copper mineralization in mafic-ultramafic layered complexes. Several copper occurrences have been recognized during this period (Delgado and Sousa, 1975) and have been considered as VMS type (CBPM 2001). The possibility that copper deposits could be associated with iron oxides, similar to Iron Oxide Copper-Gold deposits know elsewhere (IOCG deposits; Hitzman et al. 1992; Hitzman 2000), was emphasized only in more recent studies (Maas et al., 2003; Hühn et al., 2011). Early investigations conducted by the Companhia Baiana de Pesquisa Mineral (CBPM) near the Riacho Seco town (Fig. 3) showed that these deposits are located along a WNW shear zone and hosted in biotite-garnet mylonites, revealing important structural control. Mineral assessment conducted by CBPM indicates a reserve of 5 Mt @ 0.8% Cu for this deposit.

Since then, more than twenty copper occurrences have been described in the Riacho do Pontal Mineral District, among which the Ria4 and the Riacho Seco deposits are the main Cu occurrences (Fig. 2; Teixeira et al., 2010). Geologically, these occurrences are mostly located in the contact zone between the Borborema Province and the São Francisco Craton. Copper occurrences are structurally controlled by shear zones similar to those reported in other areas of the Borborema Province (Parente et al., 2004, Caxito et al., 2014a, Hühn et al., 2011; 2018, Garcia 2017). In addition to tectonic structures, hydrothermal processes have been shown to control ore mineralization and several alteration types related to hydrothermal processes have been identified in the Riacho do Pontal District (Hühn et al. 2014).

3. METHODOLOGY

3.1. Sampling, samples and characterization of hydrothermal overprint

Sampling has been conducted in three cored wells (RIA4-DH00001-001, RIA4-DH00001-003 and RIA4-DH00002) drilled where the RIA4 malachite occurrence hosted in folded biotite-rich rocks has been documented (Fig. 3). Drill core location and sampling depth are provided in the Appendix A. The samples consist of paragneisses and migmatites which have been overprinted by hydrothermal alteration. To further document hydrothermal alteration, we conducted petrographic studies using Energy-Dispersive X-ray spectroscopy (EDX), which allows characterizing hydrothermal mineral signatures (Hühn et al., 2014; Hühn et al., 2018). To complement EDX analyses, Electron Microprobe Analyses (EMA) have been conducted for precise determination of the composition of biotite minerals related to hydrothermal processes.

3.2. Whole rocks elemental geochemical analyses

All samples were digested by Agua Regia and analyzed by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) for major and trace element analyses (33 analyzed elements). The elemental geochemical data were then used to select samples for further geochronological analyses.

3.3. ^{40}Ar-^{39}Ar geochronology

One biotite sample has been dated and was loaded into a 21-pits aluminum disk along with the neutron fluence monitor Fish Canyon Sanidine (age 28.201 ± 0.046 Ma), following the geometry illustrated in Vasconcelos et al. (2002). The irradiation disks were closed with aluminum covers, wrapped in aluminum foil and vacuum heat sealed into quartz vials. All samples were irradiated for 14 hours over the period from 8 June 2016 to 10 June 2016 in the Cadmium-lined B-1 CLICIT facility, a TRIGA-type reactor, Oregon State University, USA.

After irradiation, noble gas mass spectrometry was performed in a fully automated MAP-215–50 mass spectrometer equipped with a Balzers 217 electron multiplier. The heating time for all analyses was ~45 seconds, not including the laser ramp-up time. The error in the J factor is not included in the tabulated error in the age in Appendix B, but is included in all plateau ages throughout the text. The mass spectrometer gain was calculated based on the analysis of an air pipette (1.634×10^{-13} moles ^{40}Ar) on the Faraday detector (4.257 mV) equipped with a 1×10^{11} Ohms resistor, yielding a Faraday sensitivity of 3.84×10^{-9} moles/nA. The current multiplier sensitivity measured on a Balzers 217 Electron Multiplier, operated with a gain of ~145,000 is ~4.5×10^{-14} moles/nA. The historical irradiation correction factors for the CLICIT facility, TRIGA reactor, Oregon State University, USA are: $(2.64 \pm 0.02) \times 10^{-4}$ for ($^{36}Ar/^{37}Ar$) Ca, $(7.04 \pm 0.06) \times 10^{-4}$ for ($^{39}Ar/^{37}Ar$) Ca, and $(8 \pm 3) \times 10^{-4}$ for ($^{40}Ar/^{39}Ar$) K (values determined at the Berkeley Geochronology Center; Appendix B). Age plateaus were defined as at least three consecutive steps yielding apparent ages within 2σ error from the variance-weighted mean, comprising 50% or more of total ^{39}Ar released (Fleck et al., 1977). Plateau age errors are reported at the 95% confidence level (2σ) and include the errors in the irradiation correction factors and the error in J, but do not include the uncertainty in the potassium decay constants.

3.4. U-Pb zircon geochronology

3.4.1. Analytical methods

Zircon U–Pb ages were obtained using the Sensitive High-Resolution Ion Microprobe - Reverse Geometry (SHRIMP-RG) at the Research School of Earth Sciences (RSES), The Australian National University (ANU). following the procedures described by Williams (1998) and Ireland et al. (2008). Briefly, a 2–4 nA mass filtered O_2^- primary ion beam was focused to a spot ca. 25 μm diameter, positive secondary ions were extracted at 10 kV. The magnet was stepped through peaks of $^{90}Zr_2{}^{16}O$, ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, $^{232}Th^{16}O$, and $^{238}U^{16}O$. FC1 zircon standard (Paces and Miller Jr., 1993; 1099 ± 0.5 Ma) was used for $^{206}Pb/^{238}U$ calibration, whereas the OGC zircon (Stern et al., 2009; 3465.4 ± 0.6 Ma) was used for $^{207}Pb/^{206}Pb$ calibration and to monitor instrument-induced mass fractionation he common Pb correction was based on the measured $^{204}Pb/^{206}Pb$ (Compston et al., 1984). Data reduction and plotting were processed with SQUID 2 (Ludwig, 2009) and IsoplotR (Vermeesch, 2018), respectively.

3.4.2. Data filtering and age calculations

As zircon grains were collected in high-grade metasedimentary rocks, a special attention was paid to zircon microstructures identified by cathodoluminescence (CL) imaging. Maximum depositional ages (MDA) were calculated from analyses performed in the cores of zircon grains, avoiding rims and overgrowths that could have crystalized during high-grade metamorphism and rims that could have suffered Pb loss. After selecting analyses performed in zircon cores, a two-step procedure has been applied to calculate MDAs. The first step consisted of filtering the data based on their probability of concordance calculated using IsoplotR (Vermeesch, 2018), including decay constant errors. The cut-off level applied to filter the data was 10% (Rossignol et al., 2016). As slight Pb loss could still result in apparently concordant dates, resolving whether the data represent truly concordant ages or apparently concordant dates requires a close inspection of each dataset (Corfu, 2013). In cases where the data do not show evidence of Pb loss, with no skewed age distribution toward younger ages (Spencer et al., 2016), MDAs were calculated for each sample from the youngest cluster of at least three grains overlapping at 2σ (standard deviation) (Coutts et al., 2019; Dickinson and Gehrels, 2009) as the concordia age of these youngest clusters (Ludwig, 1998). In cases where data show skewed distribution toward younger ages, the selection of data to calculate a weighted mean concordia date from multiple analyses is discussed in detail in the text, because such spreading could result from variable amounts of Pb loss, hence producing apparently concordant dates with no geological significance.

The age of metamorphic events was calculated as the lower intercept of the unforced discordia passing through analyses that align along a Pb loss trend in the Wetherill diagram. To regress the data for intercept date calculations, the points were weighted proportionally to the inverse square of their errors (“model 1” regression in IsoplotR; Vermeesch, 2018). All uncertainties are provided with 95% confidence limits.

3.4.3. Analyses of age distributions

To assess the tectonic setting of deposition of the studied sedimentary unit, we used the 10th-50th percentile age difference in age distribution combined with a modified χ^2 statistic distribution of the zircon population (Barham et al., 2022). The latter parameter was calculated by binning detrital zircon ages from the youngest grain age to 4 Ga. This approach is independent of the age of deposition and allow to discriminate convergent from divergent settings (Barham et al., 2022).

4. RESULTS

4.1. Petrography and geochemistry

Rocks of the Riacho do Pontal prospect have a strong NW-SE lineation and were overprinted by two main shearing events: a) D1-top to the north thrusting, forming a series of northwest-trending parallel structures related to hydrothermal alteration and mineralization; and b) D2-dextral strike-slip shear zones showing evidence of multiple reactivations that are responsible for strong shearing. Both events were related to transpressive structural regimes. Locally, strongly mylonitized rocks along shear zones define an L-S tectonic fabric. Ore zones are strongly controlled by shear zones and breccia zones along the bends of shear zones. The drill core RIA4-DH00001-001 (Fig. 2) intersects paragneiss comprising malachite occurrences down to 32m, and pyrite-chalcopyrite-bornite down to 157m. biotite-quartz leucogneiss with quartz veins parallel to the foliation and chalcopyrite as accessory mineral The drill core RIA4-DH00002 also intersects malachite occurrences and foliated leucogneiss with silicified zones and several biotite-rich or amphibole-rich intervals, some having trace chalcopyrite and pyrite. Magnetite, albite and biotite are derived from the hydrothermal alteration related to shear zones.

Geochemical results from mineralized samples collected in the three drill-cores have Cu contents up to> 10 000 ppm. The Cu content shows a moderate correlation with Au content. Gold and copper correlate well with Fe, K, Na, Al, Ba, Co, Cr, Mg, Ni and Ti contents.

Based on the Fe, Mg, K and Ti contents from electron microprobe analyses, biotite minerals are classified as iron-rich biotite type (Figs. 4A and 4B; Nachit et al., 1985; Foster, 1960; Ardalan et al., 2014). The formation of such biotite is related to hydrothermal alteration process.

4.2. ^{40}Ar-^{39}Ar geochronological results

The sample (PCB-R002) corresponds to biotite grains extracted from a biotite- and amphibole-rich mylonite. This sample yielded a plateau age of 691.0 ± 3.7 Ma (MSWD = 0.49; Fig. 5).

4.3. U-Pb geochronological results

Cathodoluminescence images of representative grains and geochronological results are presented in Fig. 6. Analytical results are available in the Appendix C.

Sample DH001-003. Most of the grains appear rounded to sub-rounded (Fig. 6A) and exhibit various sizes ranging from ca. 50 μm to ca. 200 μm, and a few grains are sub-angular and elongated. Most of the grains have no apparent internal structure in CL, but some grains display a core-rim texture, with the core displaying a typical oscillatory zoning and the rim lacking particular structure. A total of 63 spots on 63 zircon grains were measured, among which 55 are concordant.

In a Wetherill diagram, concordant analyses spread along the concordia line between ca. 1985 Ma and ca. 2060 Ma (Fig. 7A). The age distribution of this sample is unimodal, with most of the grains being centered around ca. 2040 Ma, and skewed toward younger ages, suggesting that the youngest concordant grains suffered Pb loss

(Fig. 7B). Discarding the 12 youngest grains that could have been affected by Pb loss, a concordia date of 2034.6 ± 5.0 Ma based on 27 grains (MSWD of concordance and equivalence = 1.4, probability of concordance and equivalence = 0.04; Fig. 7A) is interpreted as the MDA for this sample.

Sample DH002-009. Zircon grains from this sample are mostly rounded to sub-rounded. In CL, the grains show various structures. Some grains displaying a typical oscillatory zoning, other have a core-rim texture or a patchy zonation, and some grains do not show any particular structure (Fig. 6B). Several grains show metamitic zones.

A total of 35 analyses on 32 grains were measured, among which only three analyses are concordant (Fig. 7C). The two youngest concordant analyses give a concordia age of 2938.0 ± 26.4 Ma grains (MSWD = 2.7, probability = 0.04), but the statistical requirements are not met to confidently consider this date as MDA. The other concordant analysis gives a slightly older Mesoarchean date of 2993.1 ± 4.1 Ma. All the other spot measurements suggest that the grains had undergone either significant post or pre-depositional modification. Most analyses align a in a Wetheril diagram, allowing to calculate an upper intercept date of 2945.0 ± 15.1 Ma and a lower intercept date of 584.7 ± 21.3 Ma (MSWD = 4.5; n = 25; Fig. 7C). The upper intercept is identical, within uncertainties, to the concordia age calculated from the two youngest concordant grains and might correspond to the age of the main detrital zircon population comprised in this sample. The lower intercept could correspond to a metamorphic overgrowth or Pb-loss event.

Sample DH001-0010. This sample yielded only a few, rather large grains (ca. 200 μm) (Fig. 6C). In CL, a few grains display oscillatory zoning but most of the grains are characterized by a patchy zonation typical of metamorphic zircon (Corfu et al., 2003).

Eleven analyses were performed on 11 grains, all yielding highly discordant results (Fig. 7D). Regression of all points gives an upper intercept age of 2039.9 ± 26.5 Ma and a lower intercept at 491.3 ± 29.6 Ma (MSWD = 0.54). The upper intercept is identical, within uncertainties, to the MDA of sample DH001-003 and might correspond to the age of the main detrital zircon population comprised in this sample. The lower intercept could correspond to a metamorphic overgrowth or Pb-loss event.

5. DISCUSSION

5.1. Age of copper mineralization in the Riacho do Pontal District

The biotite minerals comprised in the samples investigated in this study are of hydrothermal origin (Fig. 4; Nachit et al., 1985; Foster 1960; Ardalan et. al., 2014). The ^{40}Ar-^{39}Ar plateau age of 691.0 ± 3.7 Ma given by a biotite sample (Fig. 5) is thus interpreted as the age of the main hydrothermal event. Consequently, the Cu deposit investigated here has a Neoproterozoic age. This age is older than the main collisional event that formed the Riacho do Pontal Belt (Caxito et al., 2016, 2014a). The age of copper mineralization could thus correspond to the initial stage of convergence of the Riacho do Pontal orogenic cycle.

5.2. Ages of deposition of host-rocks and metamorphic events

Copper mineralization occurred in metasedimentry rocks, of which the MDA of the sample DH001-003 indicates that this sedimentary unit is younger than 2034.6 ± 5.0 Ma. This shows that the deposition occurred during or after the late Rhyacian. The lower intercepts given by samples DH002-009 and DH001-0010 suggest that the sedimentary protolith underwent one or several metamorphic event(s) at 584.7 ± 21.3 Ma and 491.3 ± 29.6 Ma, i.e., during the latest Neoproterozoic to Cambrian. The MDA and lower intercept ages thus give a large time-window, ranging from the late Rhyacian to the early Cambrian, during which this sedimentary unit could have been deposited.

The latest Neoproterozoic to Cambrian metamorphic event(s) recorded by samples DH002-009 and DH001-0010 might correspond to the building of the Riacho do Pontal Orogen, that occurred between the Ediacarian (ca. 620 Ma) and the Cambrian (ca. 530 Ma) as a result of the collision between the São Francisco Craton and the Borborema Block (present-day coordinates; (Caxito et al., 2017, 2016). The oldest metamorphic event, at 584.7 ± 21.3 Ma could record syn-collision high grade metamorphism, while the younger metamorphic event at 491.3 ± 29.6 is more likely related to the late orogenic evolution, characterized by of large shear zones and he emplacement of late-orogenic plutonic rocks (Caxito et al., 2016).

5.3. Potential provenances and tectonic setting of deposition

Zircon age distribution of the sedimentary units investigated in this study shows a main peak around 2035 Ma and a smaller peak at ca. 2950 Ma (Fig. 8A). Zircon grains from the ca. 2035 Ma population likely derive from magmatic rocks that formed during the Transamazonian Orogeny that resulted from the collision between the Serrinha and Gavião blocks (Fig. 1B) (Baldim and Oliveira, 2021; Barbosa and Barbosa, 2017; Barbosa and Sabaté, 2004; Teixeira and Figueiredo, 1991; Zincone et al., 2021). The minor Mesoarchean population likely originate from magmatic rocks forming the basement of the São Francisco Craton (Farina et al., 2015; Lana et al., 2013) or from the erosion of sedimentary rocks containing such Mesoarchean zircon population (Rossignol et al., 2020). Zircon grains found in the studied sedimentary unit thus all originate from the São Francisco Craton. Although based on a limited number of zircon grains, the sedimentary unit investigated in this work exhibit marked differences in zircon provenance with the Formosa Fm., a ca. 1.96 Ga unit of the Rio Preto Belt, located ca. 200 km to the southwest of the Riacho do Pontal Belt (Fig. 8B) (Caxito et al., 2014a). This difference in age distribution also indicates contrasted tectonic settings during the deposition of both sedimentary units (Fig. 8C). While the Formosa Fm plot in the field of divergent settings, the sedimentary unit studied in this work show a marked affinity for convergent settings. This suggests that the sedimentary unit investigated in this study could have been deposited in a Paleoproterozoic foreland basin associated with the Transamazonian orogeny (Baldim and Oliveira, 2021; Barbosa and Barbosa, 2017; Barbosa and Sabaté, 2004; Teixeira and Figueiredo, 1991; Zincone et al., 2021). Alternatively, the sedimentary unit studied in this work could also have been deposited in a convergent setting related to the building of the Riacho do Pontal Orogen during the Neoproterozoic (Caxito et al., 2017, 2016).

5.4. A model for IOCG mineralization in the Riacho do Pontal Mineral District

Pioneering studies on the Caraíba Cu deposit within the Vale do Curaçá Mining District emphasized orthomagmatic processes as responsible for the genesis of Cu mineralization (Lindenmayer 1981; D´el Rey Silva et al., 1996). Maier and Barnes (1999) noted some unusual aspects the Caraíba deposit shared with other Cu deposits of magmatic origin including: a) the presence of primary sulfides including bornite and chalcopyrite; b) the presence of large amounts (> 50 wt %) of magnetite; 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 the Caraíba deposit was initially suggested by Rocha (1999) and more recently confirmed by Teixeira et al. (2009), who proposed that the type of mineralization in the Vale do Curaçá Copper District is analogous to other IOCG deposits documented worldwide. Since then, a number of studies (Teixeira et al. 2010; Hühn et al. 2014; Juliani et al. 2016; Hühn and Silva, 2018; Garcia et al. 2018; Teixeira et al. 2010) confirmed the IOCG nature of the Riacho do Pontal copper occurrences based on: a) their association with potassic and albite alteration, b) the hydrothermal and epigenetic origin of copper ore, which is closely associated with shear zones; c) the presence of hydrothermal iron oxides spatially and temporally related to copper orebodies, d) the fact the copper mineralization is not spatially related to granites, and e) isotopic and whole-rock geochemical analyses related to IOCG deposits.

Hydrothermal alteration has led to a pervasive calcic-potassic and calcic-ferric overprint of the host gneisses and migmatites (Hühn et al. 2014). Early-stage sodic hydrothermal alteration is distal in relation to areas with calcic-potassic and potassic-ferric alterations, which are present where rocks exhibit higher strain deformation. Hydrothermal alteration processes led to a replacement of metamorphic minerals within foliated gneiss to a suite of minerals including albite, biotite, hematite and amphibole. The replacement minerals are spatially connected to penetrative shear deformation and ore plunge along stretching lineation (Hühn and Silva, 2018). Pyrite, hematite, chalcopyrite and chalcocite are related to the ore zones. Magnetite typically occurs in association with the Cu-ore minerals and constitutes less than 1% of the paragenesis (Garcia et al., 2018).

Magnetic and gravity anomaly signatures related to magnetite and hematite-rich Cu ore zones have led researchers to use these data as an effective exploration tool to find new IOCG deposits (Smith, 2002; Clark et al., 2013; Hayward et al., 2013; Hayward et al., 2016). The occurrences of copper at Riacho do Pontal Deposit are positioned at magnetic-field lows. This observation is explained by the fact that the mineralized zone is related to hematite zones in which the content of iron oxide is low (< 2%).

World-class IOCG deposits express their metallogenic footprint in different tectonic settings with variable volumes and metal endowments (Hitzman et al., 1992; Pollard et al., 2018; Barton, 2014; Groves et al., 2010). Convergent settings represent propitious tectonic environments for the development of Cu ores (Pirajno, 2016). The Riacho do Pontal Cu deposits are hosted in a sedimentary formation that have been deposited in a convergent setting (Fig. 8C). This suggests that the Cu forming the IOCG deposits of the Riacho do Pontal Mineral District was sourced by subduction related Cu-rich porphyry and was later remobilized by hydrothermal processes.

The general hydrothermal zoning pattern for IOCG deposits is usually vertical, from magnetite-dominant at 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 should be performed by searching for deeper (or more eroded) areas of the IOCG system related to more magnetic and denser areas, such as those identified to the north of the Riacho Seco area. Finally, the potential for discoveries of IOCG deposits related to the collision zone between the São Francisco Craton and the Borborema Province has a high potential and exploratory work needs to be carried out systematically.

6. Conclusions

The combined petrographic and ^{40}Ar-^{39}Ar geochronological analyses presented in this study suggest that the age of Cu mineralization in the Riacho do Pontal Mineral District occurred during the Neoproterozoic, around 691 Ma. Zircon grains from the host rock indicate that the protolith has a maximum depositional age of ca. 2035 Ma and was later affected by a late Neoproterozoic to Cambrian metamorphic event potentially related to the building of the Riacho do Pontal Orogen as a result of the collision between the São Francisco Craton and the Borborema Block. The detrital zircon grains also suggest that the deposition of the protolith occurred in a convergent setting which could have favored the formation of Cu-rich porphyry that provided a source for the Neoarchean Cu mineralization. Together with literature data, our results depict the Cu ore deposits of the Riacho do Pontal Mineral Province as a typical iron oxide-copper gold (IOCG) deposits. This further suggests that other Brasiliano/Panafrican belts could host this important type of mineralization.

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DATA AVAILABILITY

Datasets related to this article can be found in the Appendices.

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FIGURES CAPTION

Figure 1. Tectonic subdivisions of the São Francisco Craton.
A. Schematic West Gondwana reconstruction of the main tectonic elements of South America and Africa. Modified after (Cordani et al., 2016). A: Amazonian Craton; C: Congo Craton; SF: São Francisco Craton; WA: West African Craton. BP: Borborema Province. **B**. Main structural units of the São Francisco Craton and location of the Minas Basin. ISCA: Itabuna-Salvador-Curaça. Modified after (Alkmim and Marshak, 1998; Barbosa and Barbosa, 2017; Barbosa and Sabaté, 2004).

Figure 2. Main geological features of the study area.
A. Riacho do Pontal copper district. **B.** Vale do Curaçá copper district. Major copper mines, structures and occurrences are shown on the map.

Figure 3. Geological map of Riacho do Pontal IOCG District.
Riacho do Pontal SW-NE showing drill holes RIA4-DH001 and RIA4-DH002. Samples collected along drill holes are highlighted.

Figure 4. Geochemical characterization of biotite grains.
A. Biotite types. **B.** Source of biotite. Plots after Nachit et al. (1985) and Foster (1960).

Figure 5. Spectrum of apparent ^{40}Ar-^{39}Ar ages for sample PCB-SBH-02 (biotite hydrothermal ore zone).

Figure 6. Cathodoluminescence images of representative zircon grains.
Red circles indicate the location of analyses. Ages correspond to concordia dates (A, B) and ^{207}Pb/^{206}Pb dates (C), with uncertainties given at the 2σ level. **A**. Sample DH001-003. **B**. Sample DH002-009. **C**. Sample DH001-0010.

Figure 7. Geochronological diagrams.
Wetherill diagrams were generated using IsoplotR (Vermeesch, 2018). Error ellipses are depicted at the 2σ level. Analyses used to calculate the Maximum Depositional Age (MDA) are depicted in dark blue. Other concordant analyses are depicted by pale blue. The weighted mean error ellipse (concordia date) of the youngest cluster of concordant grains is depicted in pink. Analyses used to regress the data for intercept date calculations are depicted in green. N_a: number of analyses performed for each sample; N_{zrc}: number of analyzed grains. MSWD: Mean Square Weighted Deviate (given for both concordance and equivalence when referring to a concordia date); Prob.: probability for concordance and equivalence. **A.** Wetherill diagram for sample DH001-003. **B.** Age distribution for sample DH001-003, generated with Density plotter (Vermeesch, 2012). Bin width: 10 Ma, bandwidth: 8 Ma. Open circles indicate individual analyses. **C.** Wetherill diagram for sample DH002-009. **D.** Wetherill diagram for sample DH001-0010.

Figure 8. Age probability distribution and tectonic discrimination diagrams.
The histograms were generated with a bin width of 10 Ma. The kernel densities were estimated using a bandwidth of 12 from concordant ages. The open circles below each diagram denote the individual analyses used to generate the diagrams (using Density

Plotter; Vermeesch, 2012). N: number of analyses. **A.** Dataset from this study. **B.** Formosa Formation (Caxito et al., 2014a). **C.** Tectonic discrimination diagram (Barham et al., 2022).

APPENDICES

Appendix A. Drill-core location and sampling depth.
Appendix B. 40Ar-39Ar analytical results.
Appendix C. U-Pb zircon analytical results.