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# Hydrothermal alteration related to a deep mantle source controlled by a Cambrian intracontinental strike-slip fault: Evidence for the Meruoca felsic intrusion associated with the Transbraziliano Lineament, Northeastern Brazil

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A B S T R A C T

One of the most prominent geological structures in Borborema Province, northeast Brazil, is the Transbraziliano Lineament that crosscuts most of the South American Platform and was active at least until the Devonian. This continental structure is responsible for the formation of rift and pull-apart basins in Northeastern Brazil, most of which filled with volcanic and continental sedimentary rocks (Parente et al., 2004). In the region of Sobral, Ceará State, this same continental structure controlled the intrusion of the Meruoca pluton and the formation of the Jaibaras Basin, which is bounded by strike-slip shear zones. Hydrothermal alterations seem to have been pervasive in Meruoca, as indicated by disturbances in both the Rb–Sr and U–Pb systems (Sial et al., 1981; Fetter, 1999) and by the large dispersion of anisotropic magnetic susceptibility (AMS) (Archanjo et al., 2009).

In this paper, we address the origin of the hydrothermal fluids that affected the borders of the Meruoca batholith and their relationship with the activity of the Transbraziliano Lineament. These fluids were responsible for carbonate veins and Fe–Cu mineral concentrations that are commonly found associated with hydrothermally altered breccias. The carbon and oxygen isotope composition of these carbonate veins suggest that they may be related to $CO_2$-bearing mantle-derived fluids that were channelized by the Transbraziliano Lineament. Based on oxygen isotopes, we argue that Fe–Cu concentrations may have formed in isotope equilibrium with the rhyolitic rocks at temperatures between 500 and 560 °C. This scenario points to magmatism as the main process in the formation of these rocks.

We also report a K–Ar age of 530 ± 12 Ma for muscovite associated with the last ductile event that affected the Sobral-Pedro II Shear Zone and a U–Pb age of 540.8 ± 5.1 Ma for the Meruoca pluton. We further suggest that this granite is a late-kinematic intrusion that is most likely associated with the Parapuí volcanic rocks of the Jaibaras basin (535.6 ± 8.5 Ma, Garcia et al., 2010).



## 1. Introduction

Strike-slip faults (also known as wrench faults) occur either as linear to curvilinear structures in plain view that may comprise several fault segments in an irregular braided pattern or as fault segments that split and rejoin, forming a series of slices (Sylvester, 1988; Pirajno, 2010). Many strike-slip structures are discontinuous or split into several branches. Structural patterns controlled by strike-slip movements are very complex because these structures form during continuous tectonic movements and over long time intervals (Storti et al., 2003). Movement between blocks along these structures is usually slightly oblique; such movement is thus commonly observed in alternating zones of divergent (trans-tensile) components on releasing bends and in convergent (transpressive) components on restraining bends (McClay and Bonora, 2001).

Strike-slip shear zones that are up to several hundred kilometers long and tens of kilometers wide, such as the Transbraziliano

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structure in South America that extends more than 4000 km, are common in many continental regions (Almeida et al., 1981; Brito Neves and Cordani, 1991; Araújo et al., 2001; Oliveira and Mohriak, 2003). These structures define continental deformation zones and lithospheric blocks, which tend to be re-activated during tectonic and accretionary events. They may reach the crust level and are, therefore, able to act as conduits for mantle material to reach the SCLM (sub-continental lithospheric mantle) and/or to provide enough heat to induce melting in the lithospheric material (Vauchez and Tommasi, 2003; Groves et al., 2010; Pirajno, 2010). They generally act as the primary channelways for the circulation of hydrothermal fluids of meteoric and magmatic origin. The thermal energy driving this circulation may be derived from different heat sources, including mafic underplating and/or syn-kinematic to post-kinematic A-type granitic intrusions (Pirajno, 2007; Schaltegger and Brack, 2007; Pirajno et al., 2008). Kimberlites, carbonatite and lamprophyres may also be part of the magmatic systems associated with strike-slip fault settings. A varied range of mineral deposits are associated with this magmatism, from magmatic to hydrothermal polymetallic, including Ni–Cu–PGE, Fe–Ti–V, Fe–Cu–Au–(ETR-U), low-sulphidation epithermal Au–Ag, granitoid-related greisen and rare earth pegmatites (Tornos et al., 2004, 2005; Till et al., 2007; Bryan and Ernst, 2008; Groves et al., 2010).

The Borborema province of Northeastern Brazil is a mosaic of crustal terrains of different ages and thermal–tectonic histories that are bordered by major tectonic structures (Fig. 1). The geometry of these terrains is also related to the Brazilian/Pan-African Orogeny that was active between the end of the Neoproterozoic and the beginning of the Paleozoic (Almeida et al., 1981). One of the most prominent structures in the region is the Transbraziliano Lineament that crosscuts most of the South American Platform and was active at least until the Devonian. This continental structure is

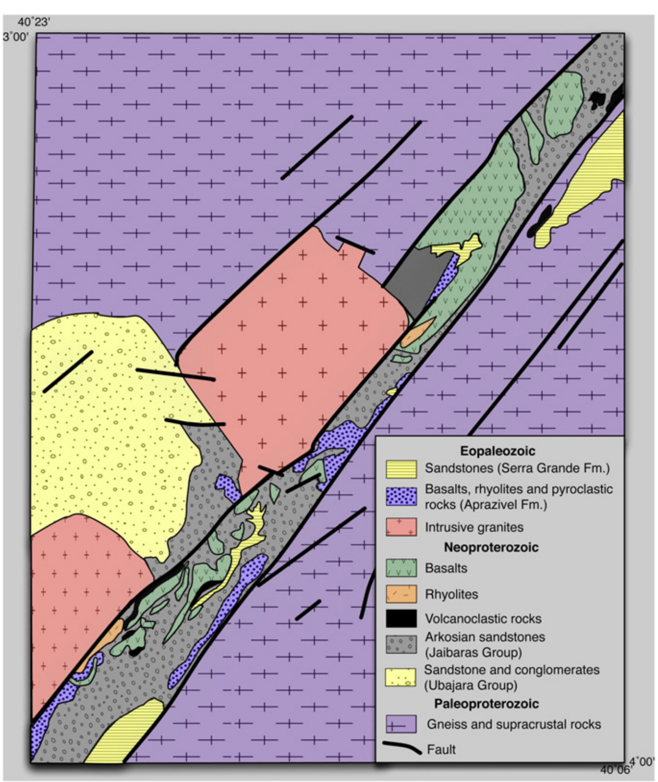


**Fig. 1.** Schematic geological mapping showing the location of the Meruoca pluton and Jaibaras rocks. Modified from Nascimento and Gorayeb, 2004.

responsible for the formation of rift and pull-apart basins in Northeastern Brazil, most of which filled with volcanic and continental sedimentary rocks (Parente et al., 2004). In the region of Sobral, Ceará State, this same continental structure controlled the formation of the Jaibaras Basin, which is bounded by the Sobral-Pedro II, Café-Ipueiras, and Massapê strike-slip shears. The Transbraziliano Lineament also controlled the emplacement of the Meruoca intrusive pluton — a granitic intrusion consisting of coarse syenogranites, quartz syenites, and alkali–feldspar granites (Sial et al., 1981) — and its associated hydrothermal features (Gorayeb et al., 1988). Hydrothermal alterations appear to have been pervasive in Meruoca, as indicated by disturbances in both the Rb–Sr and U–Pb systems (Sial et al., 1981; Fetter, 1999) and by the large dispersion of anisotropic magnetic susceptibility (AMS) (Archanjo et al., 2009).

In this paper, we address the origin of the hydrothermal fluids that affected the borders of the Meruoca batholith and their relationship with the activity of the Transbraziliano Lineament. These fluids were responsible for the brick red color of feldspar commonly found on the southeastern part of the pluton and for the Fe–Cu mineral concentrations that are commonly found associated with hydrothermally altered breccias. We also present a new zircon U–Pb dating showing that the Meruoca pluton and the Jaibaras basin were formed at the same time.

## 2. Geology

The Meruoca granitic pluton is a post-orogenic granitic body related to the magmatic activity that took place at the end of the Precambrian. It intrudes into the volcanic rocks and sediments of the Jaibaras basin and has imprinted those rocks with strong thermal effects (Fig. 1). The pluton has an area of 400 $km^2$ and a rectangular-to-square shape due to its tectonic contact with the Jaibaras Group in the east–southeast and the Ubajara Group in the north–northwest. The main petrographic types are alkali–feldspar granites in the eastern and southeastern borders, syenogranites in the central portion of the pluton, and leucocratic fayalite–hornblende–biotite granites in the northern portion of the intrusion (Sial et al., 1981). The contacts among these facies are not clear and there is no evidence of multiple intrusions. Novais et al. (1979) and Sial and Long (1987) reported Rb–Sr ages of 540 $\pm$ 7 Ma and 485 $\pm$ 14 Ma, respectively, while Archanjo et al. (2009) reported a U–Pb Shrimp age of 523 $\pm$ 9 Ma.

Rocks from the central portions of the pluton do not show signs of deformation because they are generally isotropic. In contrast, rocks from the margin of the intrusion are usually highly fractured and brecciated, with strong hydrothermal alteration, indicating that they were affected by tectonic processes responsible for the migration of fluids. These features are even more evident near the Café-Ipueiras Shear Zone that bounds the pluton and the Jaibaras Group. This area, which is a focus of this study, is home to several dimension-stones quarries, such as the Dragon Red and Marcelo Moulão quarries. At these sites, the granitic rock presents a reddish-brick color due to hydrothermal alteration that occurred along the interconnected fractures that are filled with epidote, carbonate, chlorite, and iron oxide (Fig. 2). The origin of these fluids is not clear but is believed to be related to deep crustal or mantle processes connected to the shear zone.

The southern boundary of the Meruoca pluton is also characterized by important Fe–Cu concentrations that occur discontinuously along more than 40 km of the Café-Ipueiras Shear Zone, where the Meruoca Granite and the felsic volcanic and mafic breccias of the Jaibaras basin are in contact. Parente et al. (2011) described five different Fe–Cu (iron oxide–Cu occurrences) occurrences, most of which are hosted both in the Meruoca granites

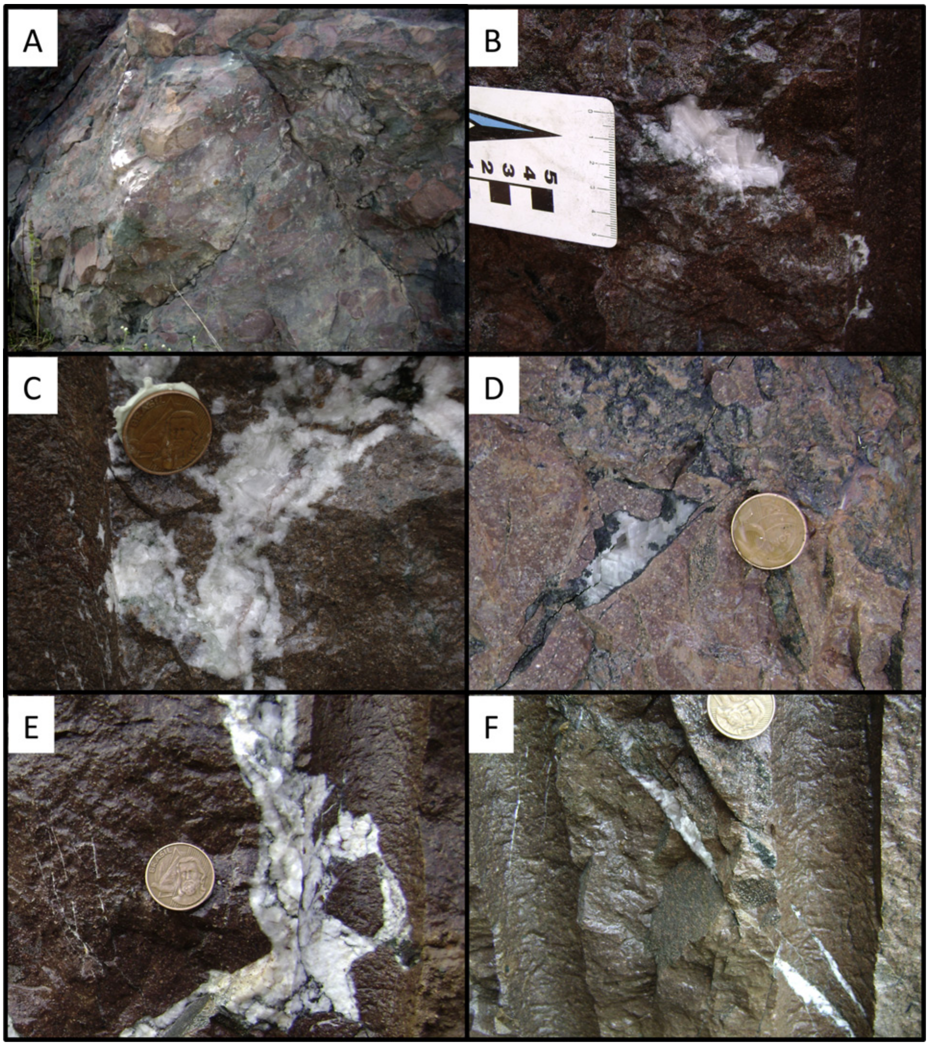


**Fig. 2.** (A) Volcanic breccia near the Marcelo Moulão quarry; (B–F) Carbonate veins from the Marcelo Moulão quarry showing their ruptile nature.

and in the volcanic and sedimentary rocks of the Jaibaras Basin. In general, the iron concentrations occur as dispersed blocks that measure up to a few meters long and commonly display irregular voids; these concentrations are made of oxidized magnetite with low silica content. The iron concentrations also occur as tabular and lenticular structures that are up to 8 m long and characterized by a homogeneous mixture of magnetite and hematite. Both types of occurrences usually present intergranular pyrite being transformed into limonite and ilmenite crystals in which inclusions of exsolved hematite and pyrrotite, pyrite, and chalcopyrite are found. A few silica-hematite-rich blocks also display malachite crystals along fracture plans, indicating the presence of copper-bearing minerals. The origin of the fluids that affected the Meruoca Pluton as well as their relationship to the intrusion is the primary focus of this study.

## 3. Methodology and sampling

In the Marcelo Moulão quarry, near the contact between the Meruoca pluton and the Jaibaras basin (Fig. 1), we sampled carbonates for C and O isotopes. These are mostly calcite, and they often fill connected fractures within the partially altered rhyodacite (Fig. 2). Field evidence, including venulation and brecciation, indicates that these carbonates are associated with a brittle deformation event, likely involving fluids under high pressure (hydrothermal or hydraulic breccias). In addition to calcite, these veins also contain chlorite and epidote on their margins. Approximately 300 μg of carbonate was extracted from each sample using a hand-micro drill, and these carbonate samples were analyzed for carbon and oxygen isotopes by IRMS (Delta Plus Advantage) at the Geochronos Lab of the University of Brasília. Analyses of NBS 18 during the period of this study yield an average value of $-5.1‰$ for $\delta^{13}C_{VPDB}$ and $23.1‰$ for $\delta^{18}O_{VSMOW}$.

Samples for O and H isotopes were collected from different parts of the Meruoca pluton with the goal of evaluating the origin of the hydrothermal fluids and iron concentrations and to compare the behavior of less- and more-altered specimens. Of the 18 samples analyzed, 3 are syenogranites from the center of the pluton, 5 are alkali–feldspar granites from the outside portion of the pluton, 2 are rhyolites, 4 are hydrothermalized rhyolites, and 5 are iron ores. All O and H analyses were performed at the Scottish Universities Environmental and Research Centre (SUERC), Scotland, following Sharp (1990). Oxygen was extracted by reacting 1–2 mg of sample with purified chlorine trifluoride in a laser fluorination system based. The oxygen was converted to $CO_2$ by reaction with a hot graphite rod and its isotopic composition analyzed on a VG PRISM III mass-spectrometer. All oxygen ratios are given in the standard permil-notation relative to SMOW (Standard Mean Ocean Water) as defined by Craig (1957). A laboratory internal quartz standard (SES) was regularly tested during the course of analyses and furnished a precision of 0.2‰ (1 sigma). Analyses for hydrogen isotopes were performed on whole-rock samples. An aliquot of each sample was heated at 1800 °C and the released $H_2O$ was trapped cryogenically. After purification, the $H_2O$ reacted within a Cr furnace in order to produce hydrogen gas, which was used the measure the D/H ratios.

We collected syn-kinematic muscovite crystals from mylonitic planes found in the Sobral-Pedro II Shear Zone, and K–Ar analyses were performed on these at the Center of Geochronological Research (CPGeo/USP). The geochronological age dates constrain the main movement of the Transbraziliano Lineament in the area.

For an in situ U–Pb analysis, zircon concentrates were extracted from 20 kg fayalite–hornblende–biotite granite rocks that were collected from the northern portion of the Meruoca Pluton (Fig. 1). The zircon crystals were placed on epoxy mounts, where they were polished and cleaned with 3% nitric acid before they were analyzed. The U–Pb isotopic analysis was performed on the zircon grains from sample Jai-179 using a Thermo-Fisher Neptune MC-ICP-MS coupled with a Nd:YAG UP213 New Wave laser ablation system at the Geochronos Lab of the University of Brasilia–UnB. The U–Pb analyses on the zircon grains were carried out following Bühn et al. (2009), using the standard-sample bracketing method (Albarede et al., 2004). During the analytical session, zircon standard Temora-2 was analyzed as an unknown sample.

## 4. Results

Table 1 presents the carbon and oxygen isotopic results from the analyses of carbonates from the Marcelo Moulão quarry. Most of the $\delta^{13}C$ values of the carbonates are quite homogeneous and range between −4.07 and −2.45‰. In contrast, the $\delta^{18}O$ values present a wider range, varying between +9.39‰ and +14.32‰. Fig. 3 shows the isotopic variation of this quarry and also those of copper-bearing IOCG mineral deposits. Based on this diagram, the Meruoca carbonates fall on the edge between the field of carbonatites and Olympic Dan-like carbonates.

The $\delta^{18}O$ and δD values of the Meruoca granite are presented in Table 2 and in Fig. 4, which also shows the expected range values for meteoric, hydrothermal and magmatic waters. As for the oxygen isotopic composition, the analyzed samples fall within the following two main ranges: i. Samples of iron oxide that fall between 0.61‰ and 2.00‰, and ii. Other samples that present oxygen isotopic values ranging between 8.47‰ and 11.41‰. In comparison to the oxygen isotopic composition, the hydrogen isotopic composition of the samples is much more variable (Fig. 4). The alkali feldspar granites of the pluton border have δD values that range from −79‰ to 106‰, while the syenites at the center of the complex range between −108‰ and −181‰. Rhyolites present δD values that range between −81‰ and −181‰, while hydrothermally altered rhyolite breccias present values that vary between −122‰ and −185‰. The iron oxide ores have δD values ranging between −113‰ and −144‰.

Muscovite from the surface of mylonitic foliations of the Sobral-Pedro II Shear Zone yielded a K–Ar age of 530 ± 12 Ma. This structure marks the southern limit of the Jaibaras Basin and of contact with the metavolcano–sedimentary sequences of the Ceará Central Domain; it is generally understood to be the main branch of the Transbraziliano Lineament in the region.

As for U–Pb zircon dating, twelve grains of sample JAI-179 yielded a 2 sigma Concordia U–Pb age of 540.8 ± 5.1 Ma (Fig. 5A); this is thought to be the crystallization age of the Meruoca pluton. The zircons are euhedral homogeneous grains that do not show strong zoning patterns (Fig. 5B) and display a few inclusions and fractures.

**Table 1**
Carbon and oxygen isotopic data of carbonate veins from the Marcelo Moulão quarry.

| Sample | $\delta^{13}C_{PDB}$ | $\delta^{18}O_{SMOW}$ |
|---|---|---|
| P10ML01 | −3.29 | 11.61 |
| P10ML02 | −3.07 | 12.02 |
| P10ML03 | −3.13 | 11.89 |
| P10ML04 | −3.01 | 14.97 |
| P10ML05 | −3.21 | 15.08 |
| P10ML06 | −3.98 | 11.24 |
| P10ML07 | −3.30 | 11.37 |
| P10ML07A | −2.45 | 10.30 |
| P10ML07B | −4.07 | 12.02 |
| P10ML08 | −3.16 | 11.18 |
| P10ML09A | −3.55 | 10.85 |
| P10ML09B | −3.40 | 11.17 |
| P10ML10 | −3.33 | 12.83 |
| P10ML11 | −3.00 | 12.71 |
| P10ML12 | −3.26 | 11.85 |
| P10ML13 | −3.19 | 11.39 |
| P10ML14 | −3.13 | 12.32 |
| P10ML15 | −3.09 | 12.83 |
| P10ML16 | −3.35 | 11.07 |
| P10ML17 | −3.20 | 15.22 |

## 5. Discussion

### *5.1. Carbon and oxygen isotopes of carbonates veins from Marcelo Moulão quarry*

Calcitic veins from the Marcelo Moulão quarry represent a rare manifestation of carbonate hydrothermalism in the area. Although they are rare, these carbonate veins are most likely connected to fluid flow related to the Transbraziliano Lineament and may indicate how deeply this structure could have channelized fluids into the crust. With the exception of three samples, the remaining veins present carbon isotopic values ranging from −2.9‰ to −3.6‰, indicating that these carbonates were deposited from a fluid with very homogeneous carbon isotopic ratios. In contrast, the oxygen isotopic compositions of these veins are in a wider range of variation (9.5–14.5‰), suggesting that temperature fluctuation may have played an important role during these carbonate precipitation. For instance, the oxygen isotopic fractionation factor between calcite and water is strongly dependent on temperature, as it varies between 5‰ and 16‰ in the temperature range of 300 °C–100 °C (O'Neil et al., 1969). In contrast, the carbon isotopic fractionation factor between calcite and $CO_2$ ranges between −2.9‰ and 3.8‰ in the same temperature interval (Deines et al., 1974).

Fig. 3 compares the isotopic composition of these carbonates with different carbon reservoirs and shows that most of the samples fall within the "carbonatite box" of Taylor et al. (1967). Circulation of $CO_2$-bearing fluids derived from the mantle is commonly associated with deep crustal structures and may be responsible for regional carbonation events, such as that described in South India (Newton, 1989; Whickham et al., 1994; Wickham, 1987). The absence of marble and limestone in the Meruoca area reinforces the proposition that these carbonates are related to deep $CO_2$ fluids channelized by the Transbraziliano Lineament. This regional structure extends for more than 4000 km and, based on airborne magnetometric geophysics, separates two of the most important tectonic compartments in Ceará State (Santos et al., 2008). It was also responsible for the formation of the Jaibaras Graben and the basaltic, rhyolitic and vulcanoclastic rocks of the Parapuí Formation (Nascimento and Gorayeb, 2004). The presence of albite and sanidine together with explosive volcanism suggests an alkaline affinity

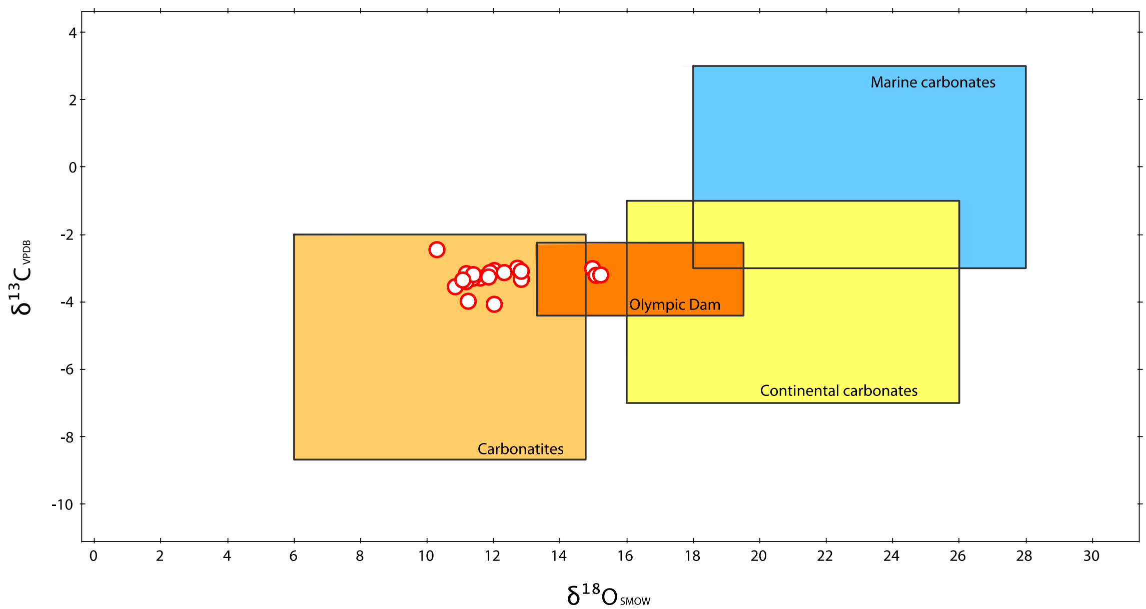


**Fig. 3.** Carbon versus oxygen isotope diagram for the carbonate veins from the Marcelo Moulão quarry. The diagram also shows fields for expected values of the following carbonates formed in different geological environments: limestone (Craig, 1953; Keith and Webber, 1964); carbonatites (Taylor et al., 1967; Deines and Gold, 1973; Pineau et al. 1973); carbonate-bearing ore deposits (Olympic Dam – Oreskes and Einaudi, 1992).

for these rocks and further supports the hypothesis that these carbonate veins are related to magmatic fluids. Thus, we argue that these fluids may have derived from a deep part of the crust and/or even from the mantle, indicating that the Transbraziliano Lineament may have been an important pathway for mantle-derived rocks, such as carbonatites.

### *5.2. Oxygen and hydrogen isotopes of the Meruoca Granite*

The oxygen and hydrogen isotopic composition of granitic rocks, as well as the most common processes that affect the composition

**Table 2**
Oxygen and hydrogen isotopes of granitic, volcanic and magnetite-bearing samples from the Merouca pluton and Jaibaras sequence.

| Sample | Description | $\delta^{18}O_{SMOW}$ | $\delta D_{SMOW}$ |
|---|---|---|---|
| CLGW-6N | Hydrothermally altered rhyolitic breccia | 9.38 | −122 |
| CLGW-2B | Iron ore | 0.47 | −114 |
| CLGW-6O | Hydrothermally altered rhyolitic breccia | 9.49 | −142 |
| CE-13A | Hydrothermally altered rhyolitic breccia | 8.47 | −185 |
| CVP-02 | Rhyolite | 11.41 | −81 |
| AF-30B | Rhyodacite | 10.32 | −107 |
| RD-01 | Partially altered granite | 9.44 | −91 |
| RD-03 | Partially altered granite | 9.78 | −92 |
| RD-06 | Partially altered granite | 9.28 | −79 |
| RD-07 | Partially altered granite | 9.58 | −106 |
| AF-08 | Alkaline granite | 8.97 | −100 |
| CVPA-18 | Syenogranite | 9.20 | −137 |
| CVPA-20 | Syenogranite | 9.11 | −181 |
| CVPA-21 | Fayalite–hornblend–biotite granite | 8.62 | −108 |
| IO-01 | Iron ore | 2.35 | −123 |
| IO-02 | Iron ore | 1.48 | −117 |
| IO-04 | Iron ore | −0.61 | −124 |
| IO-05 | Iron ore | 2.01 | −113 |
| PR-1C | Iron ore | 1.92 | −144 |
| JAI-14D | Granite | 0.53 | −138 |

of these rocks, were presented in the literature by Taylor (1968, 1978) and Criss and Taylor (1986). Based on this research, the average oxygen isotopic composition of ortho-derived acid igneous rocks, such as granites, granodiorites, and tonalites, falls between 8‰ and 10‰, which is also the same variation found in most of this study's samples. Oxygen isotopes have also been used to evaluate the origin of granitic rocks. For instance, the isotopic composition of Mesoproterozoic anorogenic granites from the Baltics and Laurentia varies according to their mineralogy; ilmenite series granites have $\delta^{18}O$ varying between +5.7 and +7.7‰, magnetite series granites between +7.6‰ and +10.8‰, and peraluminous granites have $\delta^{18}O$ values ranging between 8.8‰ and 12.0‰ (Anderson and Morrison, 2005). Using these intervals, the Meruoca granite ($\delta^{18}O$ varying from 8.62 to 9.78‰) may be classified as magnetite series granite.

Oxygen isotopic data of the Meruoca granitic rocks were previously reported by Sial and Long (1978, 1987, 1996). Except for the samples from the northern part of the pluton, the isotopic data presented by Sial and Long (1978) are quite similar to the data reported here, as shown in Fig. 6, which compares their data to our data. According to Sial et al. (1996), these brick red granites from the northern part of the pluton have high whole-rock $\delta^{18}O$ values and display isotopic disequilibrium between quartz and feldspar. The authors argued that these rocks were affected by low-temperature hydrothermal alteration driven by late mafic dikes intrusions.

The volcanic rocks of the Jaibaras basin have oxygen isotopic values that fall within the upper range of the granitic rocks. In contrast, most samples of massive iron oxide found near the border of the Meruoca granite present much lower oxygen isotopic composition (Fig. 4). Except for one sample with a $\delta^{18}O$ value of −0.61‰, the remaining samples all have isotopic values that fall between 1.48 and 2.35‰. The origin of these iron concentrations has been attributed either to hydrothermal processes related to meteoric fluids or to magmatic differentiation processes connected to the Meruoca granite (Parente et al., 2011).

Evidence of meteoric fluids is commonly found in hydrothermal alteration zones of intrusive granites (Criss and Taylor, 1986). The

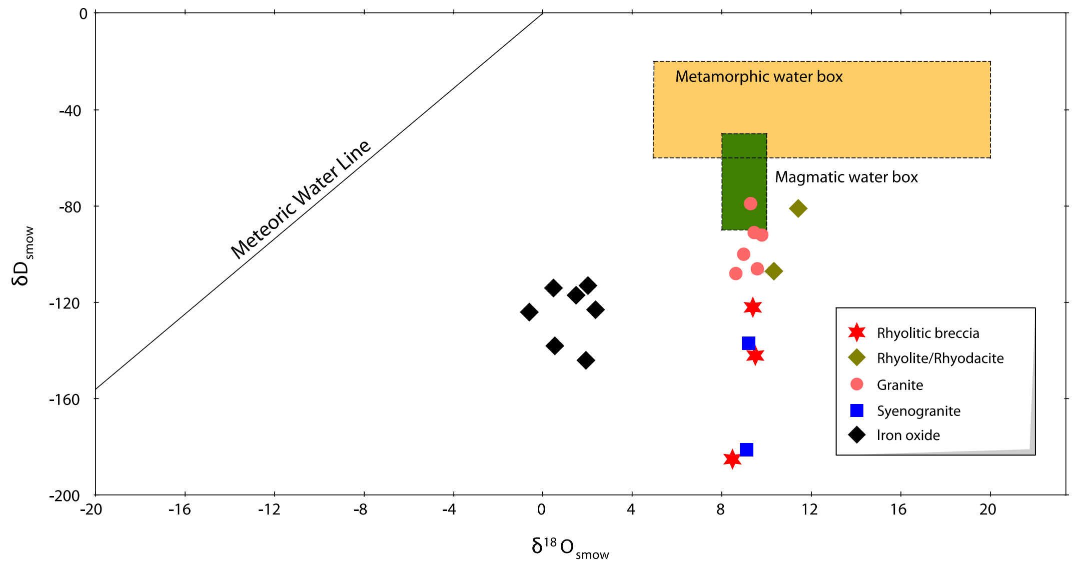


**Fig. 4.** A diagram showing δD vs $\delta^{18}O$ for the samples of this study and boxes of meteoric and metamorphic waters (Taylor, 1974). The diagram also plots the meteoric water line.

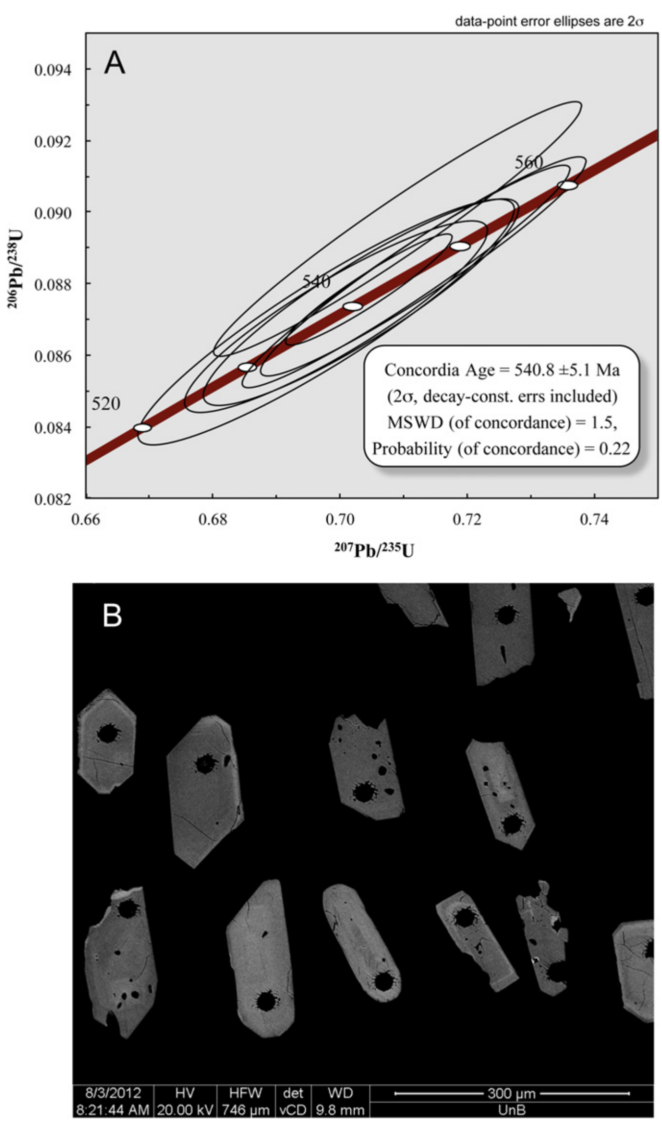


**Fig. 5.** (A) Diagram $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ for zircon grains from the Meruoca pluton displaying a U–Pb age of 540.8 ± 5.1 Ga. (B) SEM images of the dated zircon grains showing that they are euhedral homogeneous and do not show strong zoning patterns.

resulting altered rock may shift its primordial oxygen isotopic values to lower or higher values, depending on the temperature, the initial isotopic composition of fluids and the fluid–rock ratio. In evaluating the role of meteoric fluids in the oxygen isotopic composition of these magnetites, it is important to know that the isotopic fractionation magnetite-$H_2O$ varies between −8.8‰ and −7.1‰ at temperatures between 300 °C and 600 °C (Cole et al., 2004). Assuming these conditions, these magnetites would have been formed in isotopic equilibrium with a fluid with a $\delta^{18}O$ value near 10‰, which is quite high for a meteoric fluid, suggesting that the oxygen isotopic composition of this magnetite cannot be reconciled with a hydrothermal origin related to meteoric fluids.

Another possibility that should be considered is that the magnetite may result from the magmatic evolution of the granitic magma. Fig. 7 models the isotopic composition of magnetite in isotopic equilibrium with a rhyolitic magma at temperatures between 300 °C and 600 °C, assuming that the magma has an infinite amount of oxygen compared to that of magnetite. The estimated isotopic composition of the rhyolite (+9‰) is close to the average value of the Meruoca samples. Based on this modeling, these magnetites were formed at temperatures between 500 and 560 °C,

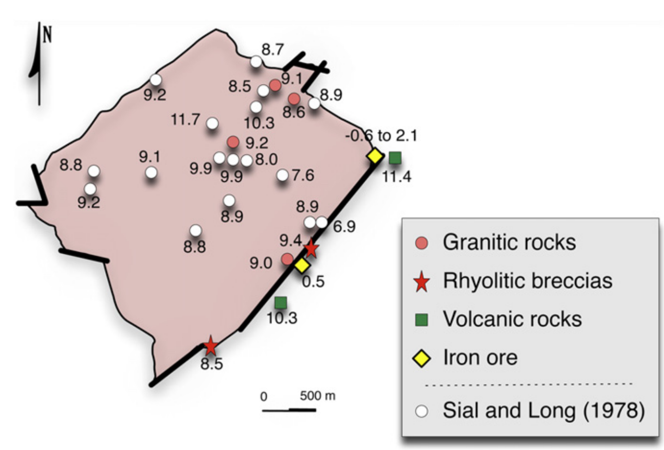


**Fig. 6.** Comparison of $\delta^{18}O$ data of the study with previously published data of Sial and Long (1978).

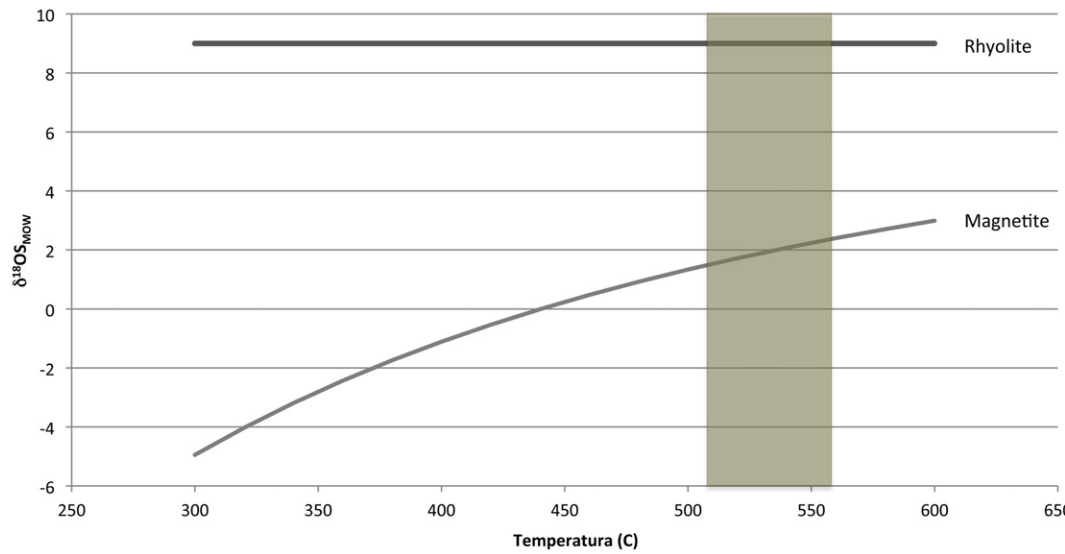


**Fig. 7.** Modeling of the isotopic composition of magnetite in equilibrium with a rhyolitic magma at different temperatures. The model assumes an infinite amount of oxygen in the magma when compared to the magnetite. The shadowed area depicts the oxygen isotopic range of magnetites from Jaibaras, thus suggesting that these rocks were formed at temperatures between 510 and 560 °C. The model was performed using fractionation curves from Cole et al. (2004).

as shown by the grey area in Fig. 7. This scenario seems much more realistic than the previously investigated possibilities and suggests that magmatism is the primary process related to the formation of these rocks.

In contrast to the $\delta^{18}O$ values, hydrogen isotopes are much more variable and are strongly dependent on the nature of igneous rocks. While oxygen behaves as a major component, being present in both the fluid and the solid phases, most hydrogen is concentrated in the fluid phase (Taylor, 1978; Valley, 1986). As shown in Fig. 4, this means that interaction between the rock and a small amount of fluid may significantly change the isotopic composition of hydrogen-bearing minerals without affecting their oxygen isotopic composition. The most hydrothermally altered samples thus present the lowest δD values, further indicating that hydrogen is much more sensitive to alteration processes than oxygen. Our data contrast with whole-rock and biotite samples presented by Sial et al. (1996), since the syenogranites and rhyolitic breccias of this study are more hydrothermally altered and present much lower δD values.

### 5.3. Age of the main activity of the Transbraziliano Lineament

In the Jaibaras Basin area, the Transbraziliano Lineament is represented by a strike-slip linked fault system made up of at least three main shear zones/faults that bound the basin and dictates its elongate, northeast-oriented shape. Movement along the main structure was responsible for the opening of the basin, for the emplacement of both the Meruoca and the Mucambo granites, for the infusion of deep fluids whose distribution is largely controlled by fracture nets, and for the oblique extension fractures in the rocks of the Ubajara Group, the Aroeiras Suite dykes (Almeida and Andrade Filho, 1999). These shear zones worked both under deep crustal regimes, as evidenced by the mylonitic deformation affecting rocks from the adjacent basement, and under lower crustal levels, as indicated by brittle and brittle/ductile events registered in striated fault planes and by extensive brecciation.

We interpret the 530 ± 12 Ma K–Ar muscovite age obtained in this work as the age of the last ductile event affecting the Sobral-Pedro II Shear Zone. This event postdated the formation of the Meruoca granite, which was dated in this study by U–Pb at 540.8 ± 5.1 Ma, thus suggesting that it is a late-kinematic intrusion that is the same age as the Parapuí volcanic rocks of the Jaibaras basin (535.6 ± 8.5 Ma, Garcia et al., 2010) and of the Mucambo Pluton (532 ± 7 Ma; Santos et al., 2008).

The age of 523 ± 9 Ma previously reported by Archanjo et al. (2009) differs significantly from the age presented here. We argue that the post-magmatic process most likely affected the isotopic composition of the previously dated sample. Based on their data, the zircons they have analyzed present a low concentration of total Pb (<10 ppm) and a high concentration of common Pb, which may explain both the non-alignment of the data and the large 1 sigma age error (20 Ma). The age reported by Archanjo et al. (2009) may be reconciled, however, with available K–Ar and Ar–Ar aging of 520 Ma for the cooling of the Meruoca granite, which has been interpreted as a post-magmatic process that affected the isotopic system.

## 6. Conclusions

The Transbraziliano Lineament is a regional structure that extends for more than 500 km and, based on airborne magnetometric geophysics, separates two of the most important tectonic compartments in Ceará State, the Northwestern and Ceará Central Domains. In the Meruoca Granite, the absence of marble and limestone reinforces the hypothesis that carbonate veins from the Marcelo Moulão quarry are related to deep $CO_2$ fluids channelized by this deep structure. With the exception of three samples, the carbonate veins from the Marcelo Moulão quarry present carbon isotopic values that range from −2.9‰ to −3.6‰, suggesting that these carbonates were deposited from a fluid with very homogeneous carbon isotopic ratios. In contrast to their carbon composition, the oxygen isotopic composition of these veins presents a wide-ranging variation (9.5–14.5‰), indicating that they were formed over a wide range of temperatures.

The oxygen isotopic composition of granitic rocks from the Meruoca pluton fall within the range of ortho-derived igneous rocks, and volcanic rocks from the Jaibaras Basin present oxygen isotopic values that fall within the upper range of these granitic rocks. Finally, the oxygen isotopes of massive magnetite occurrences point to magmatism as the primary process related to the formation of these rocks.

The following three magmatic suites are associated with the activity of the Transbraziliano Lineament and the formation of the Jaibaras Basin: the Aroeiras (dyke swarms in its western border), the Parapuí (within-basin magmatism), and the Meruoca (540.8 ± 5.1 Ma)/and the Mucambo (532 ± 7 Ma) suites (anorogenic granitic bodies). The Parapuí magmatism is represented by bimodal continental volcanic rocks that are synchronic with the main sedimentation at an age of 535.6 ± 8.5 Ma, which is interpreted as its initial phase of magmatism and the age of the deposition of the Pacujá arenites (Garcia et al., 2010). This event likely continued until the deposition of the Aprazível conglomerates, when correlated rhyolitic domes and basaltic flows took place. Crosscut relationships indicate that felsic and basic magmatism were coeval, and, according to our data, the formation of the magnetite from iron ores is coherent with rhyolitic magma at 500–560 °C, making it possible that ore generation is associated with the Parapuí magmatism.

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