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Age of magmatic events in the Eopaleozoic Jaibaras Basin, NE Brazil: Constraints from U-Pb zircon geochronology

Maria da Glória Motta Garcia [a, c, *], Clóvis Vaz Parente [b, c], Wellington Ferreira da Silva Filho [b, c], Afonso Rodrigues de Almeida [b, c]

[a] Institute of Geosciences, University of São Paulo, Rua do Lago, 562, CEP: 05508-080, São Paulo-SP, Brazil
[b] Department of Geology, Centre of Sciences, Federal University of Ceará, Campus do Pici - Bloco 912, CEP: 60440-554, Fortaleza-CE, Brazil
[c] Graduate Programme in Geology, Federal University of Ceará, Brazil

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ABSTRACT

The Late Neoproterozoic to Early Paleozoic Jaibaras Basin is located between the southeastern margin of the Médio Coreaú Domain (MCD) and northwestern edge of the Ceará Central Domain (CCD) of the Borborema Province, Northeastern Brazil, which is also the location of the main axis of the Transbrasiliano Lineament. The lower volcano-sedimentary rocks in the Jaibaras Basin are composed of two lower Vendian-Cambrian sedimentary units, Massapê paraconglomerates and Pacujá reddish sandstones, and one volcanic unit, the Parapuí Formation. The whole set is partially crosscut by two post-tectonic granite suites, the Mucambo and Meruoca plutonic bodies. The upper Cambrian-Ordovician sequence in the basin is represented by the polymitic conglomerates of the Aprazível Formation. In order to gain information on the relationship between magmatic and sedimentary events, in this paper we present new U-Pb zircon and K-Ar geochronological analyses that have been carried out on both volcanic and plutonic magmatic lithotypes. According to our data, emplacement of the Meruoca Pluton took place over a large time interval (539 Ma to 523 Ma), and was synchronous with the emplacement of the Mucambo Pluton (532 Ma) and at lower part of the Parapuí Suite (535 Ma). The last ductile event related to the movement of the Sobral-Pedro II Shear Zone is dated at 530 Ma, and the subsequent emplacement of the Aroeira Suíte dikes occurred between 524 and 500 Ma (Middle Cambrian). Finally, at 492-484 Ma is the age of cooling of the magmatic system related to the Aroeiras Suite.

1. Introduction

The final stages of the Brasiliano Cycle (Almeida, 1969; Almeida et al., 1981) is marked by the occurrence of a series of basins that have been interpreted as molasses formed at the end of the Neoproterozoic III as a result of final continental collision – e.g. Camaquã, Itajaí, Camarinha, and Castro basins, in the south of Brazil, Pouso Alegre and Eleutério, basins, among others, in the southeast, and Iara, Cococi, Catolé, and Jaibaras basins, in the northeast (Teixeira et al., 2004). Although the use of the term molasse is controversial, the essentially extensional character of the majority of these basins is normally accepted, as well as the close relationship with the end of an orogenic cycle (Brasiliano), notable crustal discontinuities, and the proximity to the main Phanerozoic intracratonic basins. Also the presence of extensive felsic-to mafic bimodal volcanism and granitic bodies are common features.

One of the largest basins related to this orogenic phase is the Jaibaras Basin in the northwestern part of Ceará State, Brazil. Its formation is associated to recurrent, dextral deep-seated regional shear zones formed as a result of the NWN-ESE convergence of West African, São Francisco and Congo cratons in the Neoproterozoic. These shear zones are part of the Transbrasiliano Lineament and superpose both ductile and brittle structures (mylonites, cataclasites, and pseudotachylites). Except for the Camaquã Basin, in which important both disseminated and vein Cu (Au) mineralisation occur, no significant ore deposits have been reported in the other aforementioned basins, despite the fact that they have been explored for many years. In the Jaibaras Basin, the tectonic contact of the granitic bodies with the volcano-

* Corresponding author. Institute of Geosciences, University of São Paulo, Rua do Lago, 562, CEP: 05508-080, São Paulo-SP, Brazil.
E-mail addresses: mgmgarcia@usp.br (M.G.M. Garcia), clovis@ufc.br (C.V. Parente), welfer@ufc.br (W.F. Silva Filho), almeida@ufc.br (A.R. Almeida).

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sedimentary sequences is marked by occurrences of iron as hematite-to magnetite veins and cataclastic breccias associated to hydrothermal alterations in the granite which may have some disseminated and vein copper mineralisations (Parente et al., 2005a; b; Garcia et al., 2006). Recent field research has shown that these features are similar to those found in Fe-Cu-(Au) world-class ore deposits (Hitzman, 2000), which makes the region a potential target for future mineral exploration.

In this paper we present new LA ICP-MS U-Pb and K-Ar ages from magmatic rocks and shear-zone muscovite from the Transbrasiliano Lineament, and discuss how this information enhances our understanding of the chronological relationship between these late-Brasiliano magmatic and tectonic events, and the associated sedimentary sequences.

2. Geological context

The Borborema Province (BP) is a complex mosaic of crustal blocks, represented by Archean and Proterozoic terranes that were generated and/or reworked in several tectono-thermal events (3.4–3.2 Ga - Guriense Cycle, 2.7 Ga- Jequié Cycle, 2.1–1.8 Ga - Transamazonic Cycle, 1.0–0.95 Ga - Cariris Velho Orogenesis) (e.g. Brito Neves et al., 1995; Fetter, 1999; Fetter et al., 2003; Van Schmus et al., 1995; Van Schmus et al., 1998). At the end of the Neoproterozoic and beginning of the Phanerozoic, these older terranes were strongly affected by the Brasiliano/Pan-African Orogeny (0.7–0.55 Ga), which configured the current geometric pattern marked by: i) Several mobile belts around Archean and Paleoproterozoic terranes; ii) Complex systems of branched, mostly NE-SW-oriented regional ductile shear zones that were active between 580 and 500 Ma (40Ar/39Ar method, Féraud et al., 1993) and; iii) Important 650 to 520 Ma crustal and/or hybrid granite magmatism characterised by pre-collisional to post-orogenic granitic bodies (e.g. Brito Neves et al., 2003). Later, the mega strike-slip shear zones, including the Transbrasiliano Lineament, show signs of brittle, discontinuous movements during the end of the Cambrian/early Ordovician and even into the early Devonian (Soares et al., 1998; Oliveira and Mohriak, 2003; Arthaud et al., 2008).

At the end of the Brasiliano/Pan-African Cycle, late activity of these transcurrent structures, related to the collapse of the Brasiliano Orogen, controlled the formation these basins, such as Jaibaras Basin, which is the focus of this work (Jardim de Sá et al., 1979; Matos, 1992; Santos et al., 2002; Parente et al., 2004).

3. Structural and lithostratigraphic framework

The Jaibaras Basin (Fig. 1) is structured as a NE-SW-elongated, approximately 120×11–20-km depression included in the Médio Coreaú Domain (MCD) and bounded by three NE-SW-oriented shear zones: Café-Ipueiras, Massapê, and Sobral-Pedro II, the last one representing a major crustal discontinuity that separates the MCD from the Central Ceará Domain (CCD) – the Transbrasiliano Lineament. This regional fault system corresponds to essentially ductile dextral shear zones, normally superposed by later ductile-brittle and brittle reactivations, probably related to oblique rifting that resulted in the opening of these basins. Some fault and joint systems occur as subsidiary structures to these shear zones, especially close to the southeastern border of the granitic bodies. All these shear zones show a recurrent behaviour, characterised by superposition of either ductile (folds, mylonites), and brittle structures (fault breccias, cataclasites, and pseudotachylites).

The volcano-sedimentary record is represented by Jaibaras Group, an over 3000 m-thick sequence that crops out along the rift from the base of the Serra da Ibiapaba, to the SW, to its contact with sedimentary rocks of the coastal plain, to the NW (Costa et al., 1979). As described in Parente et al. (2004) and Costa et al. (1979), it can be divided in two volcano-sedimentary sequences separated by an erosive discomformity and crosscut by a volcanic unit, the Parapuí Formation (continental, bimodal extrusive rocks). The Lower sequence (Vendian-Cambrian) is composed of two sedimentary units, the Massapê (normally clast-suported polymitic conglomerates with basement fragments) and the Pacujá (reddish, fine-to coarse-grained mostly fluvial sandstones and pelites) formations. The Upper sequence (Cambrian-Ordovician) is represented by Aprazível Formation (polymitic conglomerates with plutonic and/or volcanic fragments). This basal volcano-sedimentary set is partially crosscut by two post-tectonic granite suites, the Mucambo and Meruoca plutonic bodies, which were emplaced in the northern border of the basin, along Café-Ipueiras Shear Zone. Both intrusive (Mucambo and Meruoca granitic plutons) and extrusive (Parapuí bimodal suite) magmatic rocks occur broadly inside and in the vicinity of the basin. The tectonic, partially intrusive contact, of both granitic bodies with the volcano-sedimentary sequences is marked by occurrences of iron as hematite and magnetite veins, cataclastic breccias associated to hydrothermal alterations in the granite, and Cu and Fe sulfides, as well as Cu carbonates (Parente et al., 2005a; b; Garcia et al., 2006; Parente et al., 2011).

Many comprehensive studies have been carried out regarding the tectono-magmatic and stratigraphic evolution of the basin. These studies are detailed in articles by Torquato (1995), Oliveira (2000, 2001), Oliveira and Mohriak (2003), and Parente et al. (2004).

3.1. Crystalline basement and shear zones

The continental-expression, deep-seated Sobral Pedro II Shear Zone (SPIISZ), which marks the southern boundary of the basin, represents the local denomination of the Transbrasiliano Lineament (Schobbenhaus, 1975; Parente et al., 2009; Santos et al., 2014), a huge lithospheric discontinuity that extends from Africa (the Hoggar-Kandi lineament) through northeast Brazil and into Paraguay and Argentina. It has a prevailing ductile character, being represented by a mylonitic belt that is kilometer-scale in width. In the area studied, this shear zone affect rocks of the Canindé Unit, which is part of the Central Ceará Domain nappe system and comprises mainly partly migmatised granitic to quartz-dioritic gneissic rocks, as well as calc-silicate rocks. Along the shear zone the dominantly NE-SW-oriented high-angle mylonitic foliation is preferentially associated with a sub-horizontal, quartz and muscovite-defined stretching lineation (Fig. 2a). Ductile kinematic indicators are compatible with dextral shear movement. Features of transposition are common, as isoclinal folds with axis parallel to the shear. Late mobilised granite occurs commonly along the mylonitic foliation and some mylonites show evidence of cataclasis, indicating reactivation under shallow crustal conditions.

The Café-Ipueiras Shear Zone (CISZ), which bounds the granitoid bodies (Meruoca and Mucambo Plutons), is parallel to the SPIISZ, constituting the northern boundary of the basin. It shows evidence of ductile behaviour, as mylonitic foliation displayed in leucosome in basement rocks, in the north-central sector of the basin, but brittle deformation probably associated with reactivation is shown by fault breccias and/or cataclasites that affect both basement and volcanic rocks, as well as fault striae and en echelon joints (Fig. 2b). This brittle deformation facilitated the distribution and the concentration of hydrothermal, metal-enriched fluids, which is evidenced by the extensive fractured, stockwork-type iron-ore and sulfide occurrences found along the contacts of both the volcano-sedimentary sequence and granitic plutons. According to Parente et al. (2009, 2011) most of the volcanism, particularly felsic,

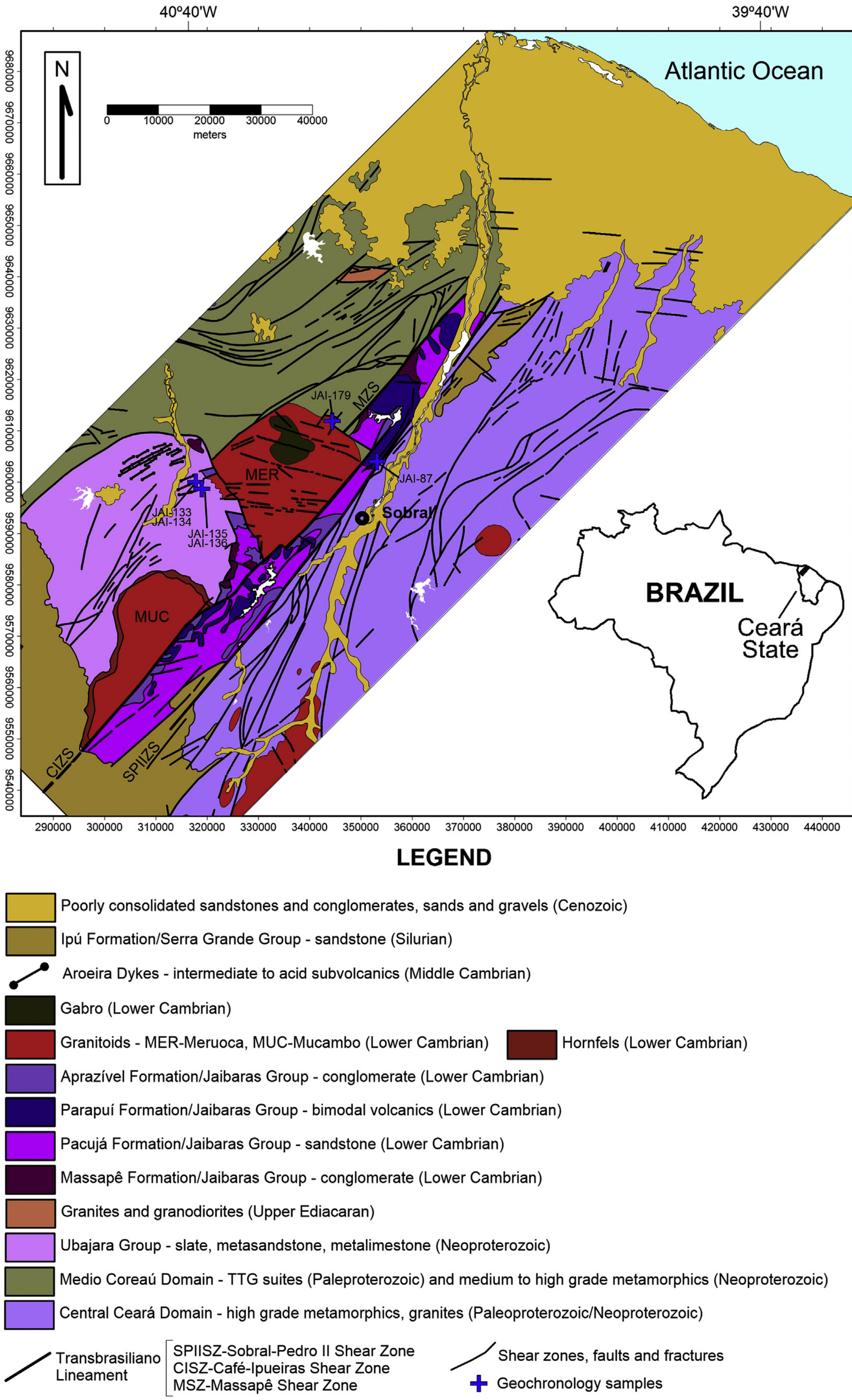

Fig. 1. Schematic geological map of the Jaibaras Basin showing the location of the dated samples. Modified from Cavalcante et al. (2003) and Pedrosa Jr. et al. (2017).

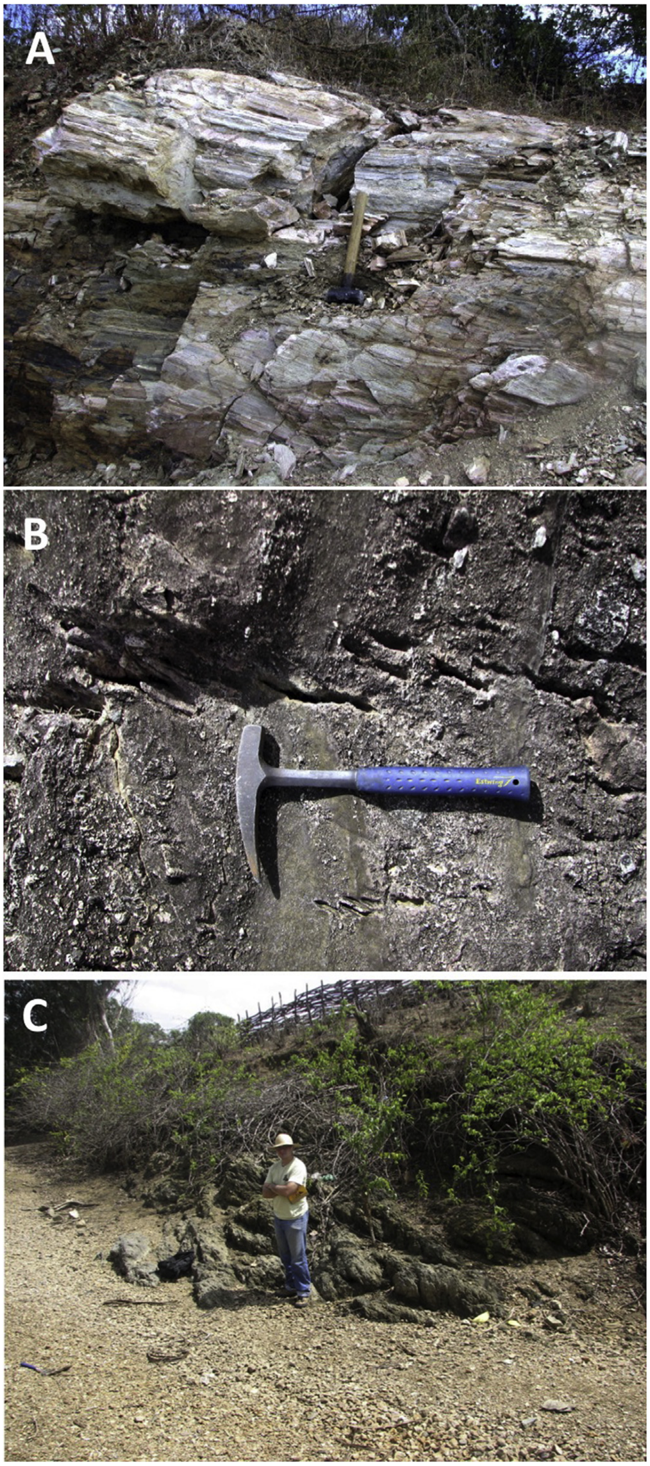

Fig. 2. Aspects of main shear zones affecting both crystalline basement rocks and volcano-sedimentary sequence from Jaibaras Basin. A) Mylonitic, fine-grained granitic leucosome of partially migmatitic gneiss from Canindé Unit. Sobral-Pedro II Shear Zone; B) Conglomerates of Aprazível Formation showing en echelon jointing resulting from brittle reactivation of Café-Ipueiras Shear Zone; C) Mylonitic quartzite from Covão Formation, Neoproterozoic, showing high-angle foliation related to the Massapê Shear Zone.

occurs along this shear zone, indicating that this structure has been a major area of weakness for the emplacement of the magma and constitutes the main source of volcanoclastic deposits of the basin. This shear zone and related structures, such as faults and fractures, are the main structural controls of mineral occurrences of the basin, especially in places with a greater density of fractures. It is along contact between the Meruoca Granite and the volcano-sedimentary sequence that strong brecciation occurs, followed by potassification, propylitisation, metasomatic hematisation and sulphidation (pyrite and chalcopyrite). In addition, it is also in the vicinity that the major hematitic bodies were observed.

The Massapê Shear Zone constitutes the upper northeastern branch of the shear zone system that marks the northwestern boundary of the northeast part of the Jaibaras Basin. Its contact with the Neoproterozoic Martinópole Group is characterised by ductile, strong mylonitic foliation that affects both metasedimentary lithotypes and orthogneisses, superposed by brittle, oblique-slip and normal faulting oriented in the same direction (Fig. 2c). Cataclastic features such as brecciation and pseudotachylites are also observed and seem to be associated with the previous ductile structures.

3.2. Sedimentary rocks

3.2.1. Massapê formation

This unit corresponds to the most basal sedimentary sequence in the Jaibaras Basin (base of the Jaibaras Group, Costa et al., 1979). It is composed mainly of polymictic, framework-supported conglomerates and breccias with clasts that vary both in size, from pebbles to boulders, and in composition, depending on the source area. At the central northern portion of the basin, the main source is the crystalline basement and clasts consisting of gneiss, quartz, amphibolite and calc-silicate rocks in a medium-to fine-grained brownish sandstone matrix (Fig. 3a). To the central southern part of the basin, the main source is the Ubajara Group, which contains clasts mostly composed of meta-sandstones distributed in a sandstone blue-greyish matrix, partly cemented by calcite (Fig. 3b). Near the limits of the basin these rocks show poor internal organisation, but in the distal portions, they present normal-graded centimetre-sized layers in which the percentage of matrix increases from bottom to top, characterizing a lateral/upper gradational/interdigitated contact with the Pacujá Formation (Parente et al., 2004).

3.2.2. Pacujá formation

This unit occupies most of the basin, especially its central and southern portions (Costa et al., 1979). It comprises fine-to medium-grained micaceous sandstones that vary from greenish-grey to purplish-brown and occur as decimetre-sized, well-stratified layers interlayered with shales and/or siltstones and conglomerates. It represents a distal facies of the basal Massapê Formation, which together comprise a deltaic fan-lacustrine system (Parente et al., 2004). These sedimentary rocks were locally affected by anchimetamorphism represented by occurrence of sericite and chlorite, but no secondary penetrative foliation was observed.

Sedimentary layering dips towards the SSE at low angles (Fig. 3d), but locally they may be deformed as southeast-verging, asymmetric open folds whose axes plunge to the southwest and evolve to local, northwest-dipping reversal faults parallel to the axial planes (Fig. 3e). Orthogonal and shear joint families are common and reflect brittle tectonic stresses in the basin that may evolve to cataclasis, especially along the Café-Ipueiras Shear Zone.

3.2.3. Aprazível formation

This unit is characterised by immature, framework-supported conglomerates (Costa et al., 1979) in discordant contact with the lower units (Parente et al., 2004). The clasts consist mainly of volcanic rocks (rhyolites, dacites, basalts), as well as granites, sedimentary rocks from the underlying formations or even basement rocks in a medium-to coarse-grained lithic sandstone matrix

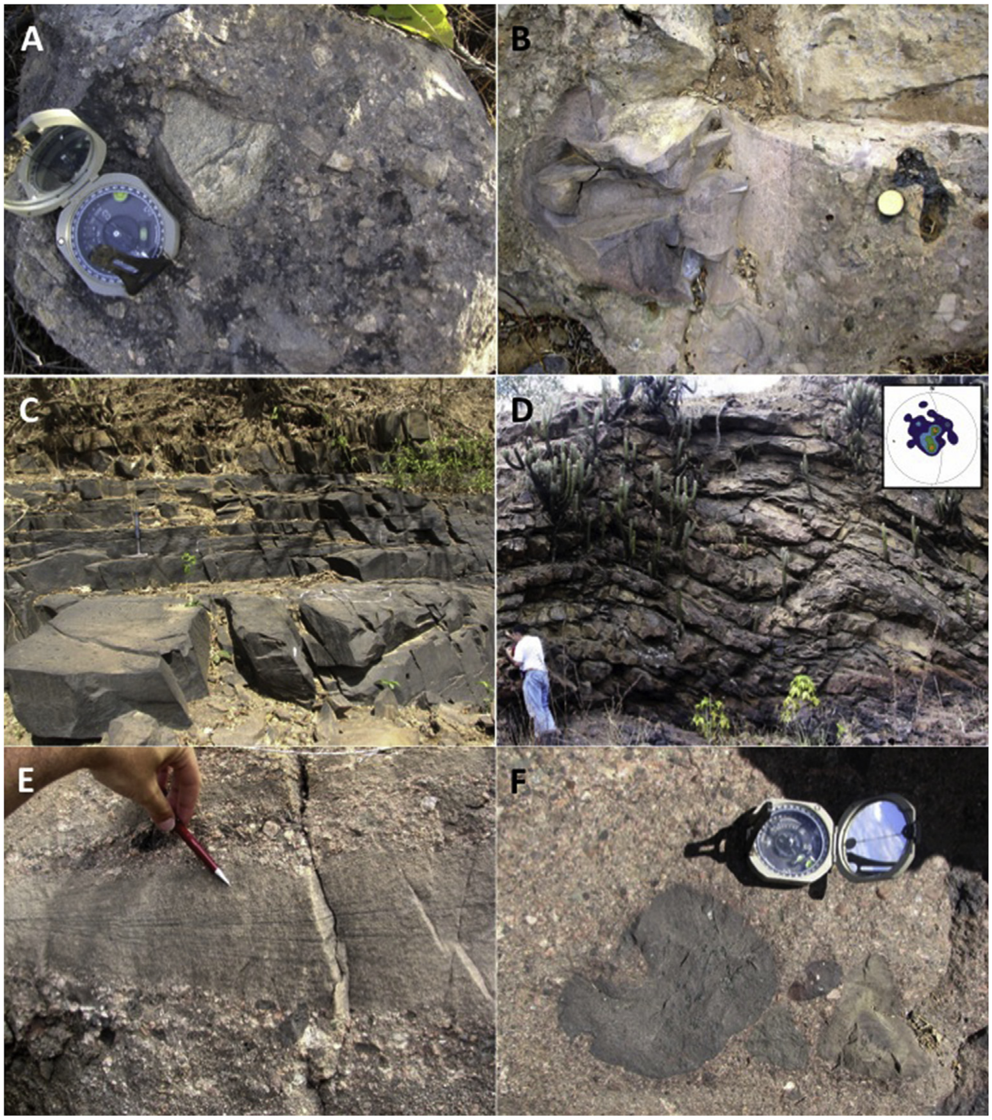

Fig. 3. A) and B) Massapê Formation, basal portion of the Jaibaras Basin. A) Poorly-sorted polymictic breccia showing clasts of gneisses and calc-silicate rocks from the basement and B) Layered conglomerates showing clasts of metasandstones and calc-silicate rocks, mainly from Ubajara Group; C) and D) Pacujá Formation, the most extensive sedimentary unit of Jaibaras Basin. C) Well-stratified arkosic sandstones showing conspicuous fracture families; D) Open folds with N260/15 axis, which is consistent with a ~ N-S compression and axial-plane cleavage turning to E-W-oriented faults. See the foliation and fold axis stereogram. This is observed, above all, in the riverbed of Aires de Sousa Dam. In this place, the sedimentary layers are continuous, sometimes tilted and folded, and showing a ductile-brittle deformation; E) and F) Aprazível Formation, representing the Upper Sedimentary Sequence. E) Polymictic conglomerates with cross-bedding layering showing clasts of volcanic rocks and granite; F) Clast of volcanic rock showing border invaded by matrix, forming gulfs indicating high-plasticity during its incorporation to sediment.

(Fig. 3e). The sequence is marked by several facies that reflect changes of energy in the depositional environment. In proximal zones, conglomerates are dominated by centimetric to decimetric volcanic clasts, sometimes showing irregular borders forming gulfs invaded by the clastic matrix, indicative of plasticity at the time of their incorporation into the sediment (Fig. 3f). In more distal zones conglomerates grade to thinner, more organised types, sometimes arranged in matrix-dominant, cross-bedded stratified arkosic sandstones. These features (consistent with lahars) indicate gravitational flows at low temperatures and a close proximity to high-relief volcanic sources (Parente et al., 2004).

3.3. Magmatic rocks

Magmatic rocks associated with the Jaibaras Basin are represented by several intrusive and extrusive post-Brasiliano magmatic rocks that occur within and adjacent to the limits of the basin. They comprise: i) the Meruoca and Mucambo Suites, which includes the homonym granitic plutons; .ii) the Parapuí Suite, corresponding to both basaltic and rhyolitic flows, as well as their plutonic equivalents of the interior of the Basin and; iii) the Aroeira Suite, occurring adjacent to the Basin.

Distribution and mode of occurrence of magmatic rocks within the basin is irregular or even asymmetric, reflecting probably distinct stages in the evolution within the Jaibaras Trough.

3.3.1. Meruoca and Mucambo Plutonic suites

These intrusive suites are represented by two granitic plutons that crosscut the volcano-sedimentary set in the northwestern part of the basin, controlled mainly by the Café-Ipueiras Shear Zone.

The 180 km^2-wide 400 m-high, ellipsoidal-shaped Mucambo Pluton has its major axis oriented NE, and its relief is discontinuous and jagged (Fig. 4a). It is composed of equigranular to porphyritic granitic types, showing little facies variation. Among granite sensu lato, it is predominated by quartz syenites, quartz monzonites, and granodiorites (Sial et al., 1981; Gorayeb et al., 1988, 1993; Parente et al., 2004) – that occur mainly as large, flat outcrops (Fig. 4b). Elongated enclaves of schist and/or biotite gneiss are common (Fig. 4c). The granitic body crosscuts rocks of Ubajara and Jaibaras groups, creating an aureole of thermal metamorphism.

The post-orogenic Meruoca Pluton occupies an area of around 400 km^2, and is composed of alkaline to peralkaline, greyish to reddish granitic rocks, the latter is associated with pervasive late hydrothermal alteration (Sial et al., 1981). It is bounded, to the southeast, by the Café-Ipueiras Shear Zone, along which many quarries of dimension stones occur. The Meruoca Pluton has a roughly rectangular or square shape reaching 1000 m in height, constituting an inselberg in the middle of the Sertaneja Depression geomorphological domain (Fig. 4d). This suite is composed of several lithological or faciological types of varied composition, texture and colour. Among the petrographic types, alkali-feldspar granites dominate at the eastern and southeastern portion (Fig. 4e), while syenogranites and fayalite-hornblende-biotite granites occur mainly in the central portion of the suite. The syenogranites are grey, coarse-grained, equigranular and isotropic, being mainly composed of K-feldspar and quartz, with plagioclase and ferromagnesian minerals (Fig. 4f). In general, most of the granitic rocks, particularly those along the Café-Ipueiras Shear Zone, in contact with the rocks of the Jaibaras Group, are hydrothermally altered.

3.3.2. *Parapuí suite*

This suite is dominated by extrusive, bimodal, continental volcanic to sub-volcanic rocks associated with different stratigraphic portions of the sedimentary sequences, which denotes its recurrent character (Almeida, 1998). These rocks are represented by i) basalts and basalt-andesitic subvolcanic and/or plutonic rocks, such as diabase, microgabbro and gabbros, which dominate in the NE portion of the basin (Fig. 5a). They represent the main topographic highs in the interior of the basin, such as Madeiro, Morro and

Fig. 4. Magmatic rocks. A to C) Mucambo Suite. A) Panoramic view of Mucambo Pluton; B) Flat, large typical Mucambo Granite outcrop; C) Mucambo Granite showing elongated xenolith of biotite gneiss from basement. D to F) Meruoca Suite. D) Panoramic view of the Meruoca Pluton; E) Reddish facies of the Meruoca Granite showing brittle features associated to the hydrothermal interactions along the Café-Ipueiras Shear Zone; F) Grey facies of Meruoca Granite showing centimetric dike of fine, hololeucocratic granite.

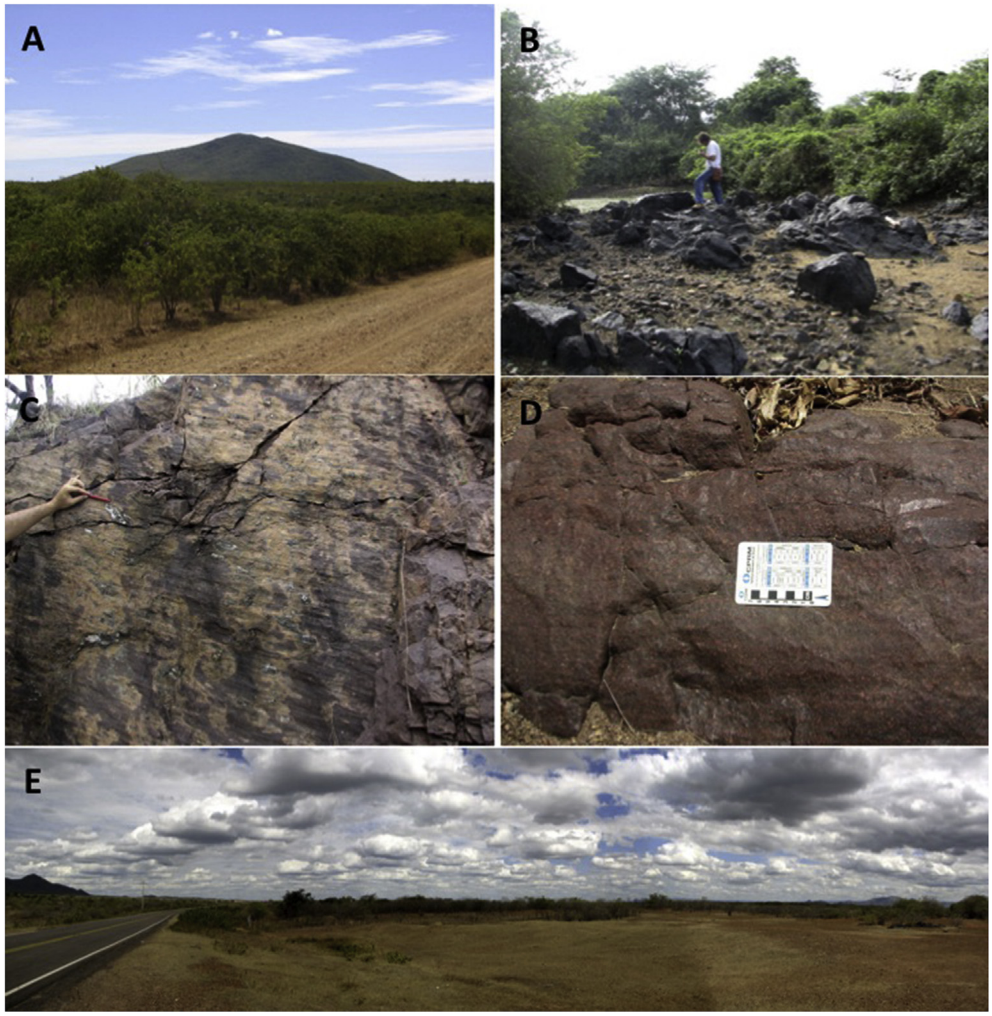

Fig. 5. Magmatic Rocks. A) and B) Parapuí Suite basalts. A) Parapuí Hill, type-section of this suite, one of the topographic highs in the basin, which is supported by these rocks; B) Example of a typical outcrop of basalt; C) and E) Parapuí Suite rhyolites. C) Outcrop of rhyolite affected by brittle reactivation of the Café-Ipueiras Shear Zone. Note the sub-horizontal striae at the fault plane; D) Pyroclastic stratified rock associated with rhyolitic lava flow; E) Aspects of occurrence of intermediate-to felsic dikes associated to the Aroeira Suite. Notice the decimetric blocks at the right.

Parapuí hills (Fig. 5b); ii) Dacites, rhyolites, including lavas and pyroclastic (tuffs, lapili-tuffs), breccias and peperites, which occur in the form of domes, sills and/or dikes (Fig. 4d). Flow structures and layering as well as volcanic breccias also occur (Fig. 5c).

3.3.3. Aroeira suite

The Aroeiras Magmatic Suite (Almeida and Andrade Filho, 1999b) is composed of intermediate to felsic subvolcanic rocks that occur as N80E-oriented dikes intrusive in the metasediments of the Neoproterozoic Ubajara Group. The dikes are composed of basalts, quartz-diorites, dacites, rhyodacites and porphyry rhyolites that are exposed in the NW portion of the basin, mainly along the Aprazível-Coreaú highway (Fig. 5d). According to these authors, this suite represents the oldest magmatic suite related to the basin development.

4. U-Pb and K-Ar geochronology

4.1. Methodology

LA-ICP-MS U-Pb analyses were carried out at the Geochronology Laboratory of the University of Brasília (UnB), following the analytical procedure described by Buhn et al. (2009). Zircon concentrates were obtained at the Centre of Geochronological Studies (CPGeo/USP) of the University of São Paulo. K-Ar ages were obtained at the Centre of Geochronological Research of the University of São Paulo (CPGeo/USP), using the method described in Sonoki and Onoe (2009).

U-Pb and K-Ar geochronological data were obtained for the magmatic rocks related to the Eopaleozoic Jaibaras Basin, where volcanic and plutonic associations were grouped by Almeida and Andrade Filho (1999a, b) in three suites: Aroeiras - dike swarms in its western edge, Parapuí - within-basin magmatism, and Meruoca and Mucambo – post-orogenic granitic bodies.

4.2. Results

Zircons from the grey facies of the Meruoca granite collected in the O.C.S. Quarry (sample JAI-179) along the road to Massapê municipality were analysed by LA-ICP-MS and yielded an age of 538.6 ± 3.6 Ma (Fig. 6). The zircon grains are normally elongated and well-formed, euedric to subedric and show well-defined zoning.

Two samples of microgranite dikes from Aroeira Suite were

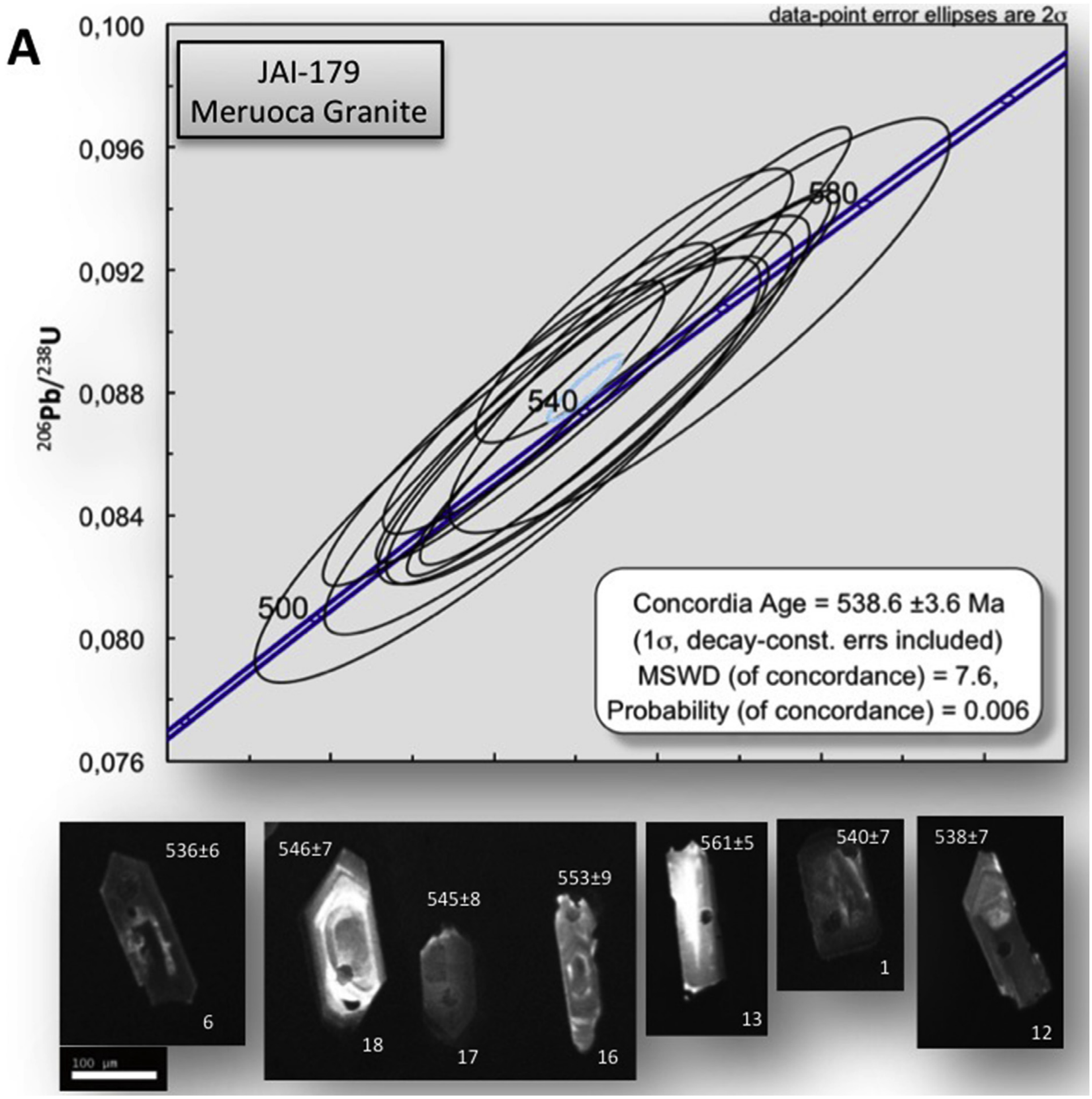

Fig. 6. A) U-Pb Concordia diagram for the Meruoca Pluton (Sample JAI-179); B) CL images of selected zircon grains with location of ablated spots and ages on the analysed zircons. UTM: 24M 344493/9611448.

collected for U-Pb analyses and gave ages of 512.5 ± 2.7 Ma (JAI-133) and 521.6 ± 5.9 Ma (JAI-136) – Fig. 7a and b. Two other samples of trachyandesitic dikes from the same suite were analysed for K-Ar dating. Sample JAI-134 yielded an age of 484 ± 9 Ma (whole rock). Sample JAI-135 was analysed for both whole rock and feldspar and gave an age of 488 ± 10 Ma and 492 ± 9 Ma, respectively (Table 2). Both samples show quite elongated grains with well preserved magmatic zoning. Detailed zircon data for the samples analysed are shown in Table 1.

A U-Pb age 535.6 ± 8.5 Ma was also obtained in rhyolite associated to peperites from the Parapuí Suite in zircons collected near the Pacujá Formation sandstones (Garcia et al., 1988) (Fig. 8).

Table 2 synthesises the main geochronological data obtained for these magmatic events. As an attempt to place the last ductile shear event that affected the major Sobral-Pedro II Shear Zone we analysed muscovite from a mylonitic facies.

In order to investigate the time of last ductile deformation related to the Sobral-Pedro II Shear Zone, muscovite from mylonitic foliation in fine-grained leucossome of basement gneisses lying within this lineament were also analysed for K-Ar, giving an age of 531 ± 12 Ma (Table 3). The muscovite is dynamically recrystallized and is taken as formed at the time of mylonitisation.

5. Discussion

Models of crustal extension related to the formation of sedimentary basins typically require detailed information about the age and duration of magmatic events often associated with sedimentation and tectonics. Many models have been proposed for the tectono-magmatic evolution of the Jaibaras Basin (Oliveira, 2001) and according to the most accepted models, the Early Cambrian may have been the main period for both within-basin and plutonic

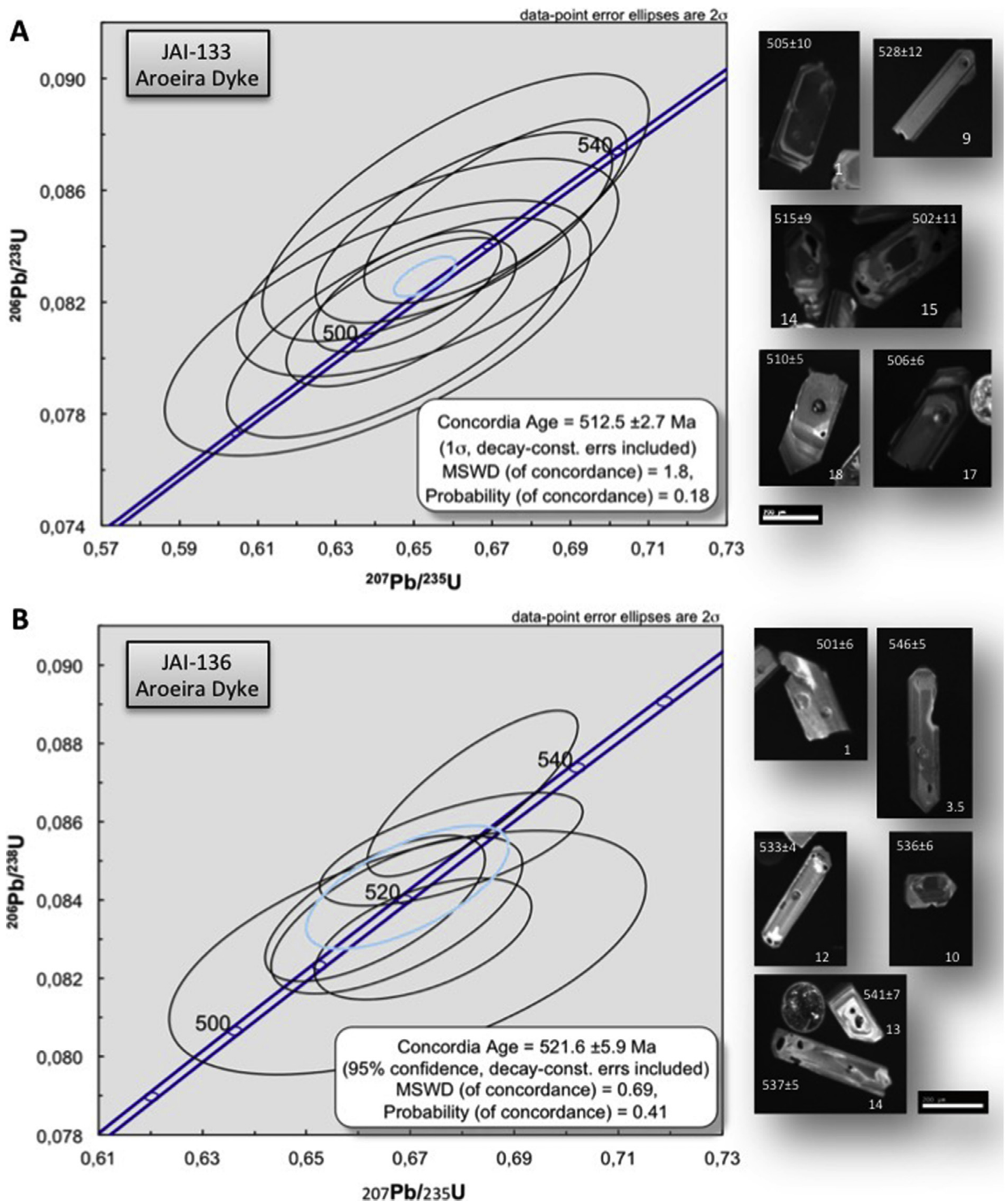

Fig. 7. U-Pb Concordia diagram for dikes from the Aroeiras Suite. A) Sample JAI-133. Concordia diagram for Aroeira Dike and CL images of selected zircon grains with location of ablated spots on the analysed zircons. UTM: 24M 318649 9600310; B) Sample JAI-136. Concordia diagram for Aroeira Dike and CL images of selected zircon grains with location of ablated spots and ages on the analysed zircons. UTM: 24M 319445 9599285.

magmatism, as well as the deposition of the Pacujá Formation.

Barroso et al. (2014), in a study that reports the first occurrence of Ediacaran fauna in northeastern Brazil, suggest the existence of a new geological event that would be placed between Pacujá and Aprazível formations, in a depositional environment associated to a fluviomarine system. According to the authors, the inferred ages of the deposits are at least 560 Ma. In an attempt to test this hypothesis, Santos et al. (2016) obtained LA-ICP-MS U-Pb zircon ages in two samples of sandstones: one containing Ediacaran fossils and other from the type-section of Pacujá Formation. Both samples exhibit roughly the same ranges - Ceará Central (2.0–2.2 Ga), Orós (1.7–1.8 Ga), Santa Quitéria Magmatic Arc (around 590–600 Ma) and a larger family in the interval (580-560 Ma). These data would indicate a maximum age for deposition and suggest that these

Table 1
LA-ICP-MS U-Pb zircon isotopic data for the analysed samples.

Spot n.	Isotopic ratios						Ages (Ma)						Rho
	$^{207}Pb/^{206}Pb$	error (%)	$^{207}Pb/^{235}U$	error (%)	$^{206}Pb/^{238}U$	error (%)	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	
JAI-179													
Z1 1-37	0,05829	1,22	0,7033	2,97	0,0875	2,68	541	7	541	7	541	7	0,90
Z7 1–15 e 29-40	0,05820	1,51	0,6978	3,49	0,0869	3,20	537	8	537	9	537	8	0,92
Z12 1-40	0,05823	1,45	0,6993	2,79	0,0871	2,50	538	7	538	8	538	7	0,90
Z16 1-38	0,05743	0,87	0,7092	3,35	0,0896	3,23	554	9	554	7	554	9	0,97
Z17 1-30	0,05841	0,83	0,7104	2,98	0,0882	2,86	545	8	545	7	545	8	0,96
Z 18 1-20	0,05845	1,11	0,7132	2,94	0,0885	2,81	547	8	547	7	547	8	0,96
JAI-133													
03 Z1	0,057780	1,94	0,645977	2,77	0,081084	1,98	503	10	506	11	521	43	0,70
09 Z5	0,056771	1,67	0,662751	2,34	0,084669	1,64	524	8	516	9	483	37	0,69
15 Z9	0,056114	2,03	0,660639	3,06	0,085387	2,29	528	12	515	12	457	45	0,72
23 Z14	0,056936	2,37	0,653477	3,05	0,083242	1,91	515	9	511	12	489	52	0,61
24 Z15	0,057316	2,60	0,640726	3,47	0,081077	2,30	503	11	503	14	504	57	0,64
27 Z16	0,057073	1,31	0,670826	2,05	0,085247	1,57	527	8	521	8	494	29	0,73
28 Z17	0,057446	1,30	0,646741	1,86	0,081652	1,33	506	6	506	7	509	29	0,66
29 Z18	0,057060	1,08	0,648243	1,52	0,082396	1,07	510	5	507	6	494	24	0,65
JAI-136													
31 Z20	0,057347	2,42	0,612768	2,08	0,077496	1,23	481	6	485	8	505	52	0,57
25 Z16	0,057410	1,59	0,663205	1,30	0,083784	0,91	519	5	517	5	507	35	0,68
15 Z9	0,057889	1,11	0,667381	1,48	0,083613	0,98	518	5	519	6	526	24	0,65
28 Z19	0,058742	2,34	0,669436	2,80	0,082653	1,54	512	8	520	11	558	51	0,54
26 Z17	0,058756	1,48	0,672433	1,27	0,083003	0,76	514	4	522	5	558	32	0,53
06 Z4	0,058198	1,43	0,682267	1,89	0,085025	1,24	526	6	528	8	537	31	0,64
10 Z6	0,057231	0,82	0,685768	1,19	0,086905	0,87	537	4	530	5	500	18	0,72
21 Z 12	0,057836	0,95	0,687408	1,21	0,086202	0,75	533	4	531	5	524	21	0,57
22 Z13	0,057528	0,65	0,695452	1,38	0,087676	1,22	542	6	536	6	512	14	0,90
23 Z14	0,058084	1,13	0,695724	1,50	0,086872	0,99	537	5	536	6	533	25	0,64
05 Z3	0,058190	1,26	0,709234	1,56	0,088398	0,92	546	5	544	7	537	28	0,56
16 Z10	0,058459	0,86	0,710997	1,17	0,088209	0,79	545	4	545	5	547	19	0,66

Table 2
Geochronological data for the magmatic suites in the Jaibaras Basin region. [1]Novais et al. (1979); [2]Sial et al. (1981); [3]Sial and Long (1987); [4]Tavares et al. (1990); [5]Fetter (1999), [6]Brito Neves et al. (2003), [7]Archanjo et al. (2009), [8]Garcia et al. (1988), [9]This paper.

Rock Suite/Method	*Rb-Sr (RT)*	*U-Pb*	*K-Ar*	*OBS*
Aroeiras	580 ± 30 Ma[1] 562 ± 19 Ma[3] 562 ± 10 Ma[4]	499 ± 28 Ma[9] 524 ± 14 Ma[9]	484 ± 09 Ma[9] 488 ± 10 Ma[9] 492 ± 09 Ma[9]	N80°E-oriented felsic to intermediate dikes that crosscut the Ubajara Group at the NW border of the basin
Parapuí		535 ± 9 Ma[8]	478 ± 6 Ma[1] 502 ± 8 Ma[1]	Dikes and sills of bimodal volcanic rocks (basalts and rhyolites) among sediments of the Pacujá Formation
Meruoca & Mucambo plutons				
Meruoca Granite	540 ± 07 Ma[1] 507 ± 36 Ma[2] 485 ± 14 Ma[3]	523 ± 09 Ma[6] 538 ± 04 Ma[9]		Anorogenic bodies with contact halos Meruoca – alkaline to peralkaline granites Mucambo – granodiorite to qtz-monzonites, qtz-syenites and hb-bt-granites
Mucambo Granite	548 ± 24 Ma[2] 548 ± 12 Ma[3]	532 ± 06 Ma[5]		

sandstones are related to the early sedimentation of Jaibaras Basin. Additionally, Neoproterozoic zircons from the Pacujá sandstone were dated by Ganade de Araújo et al. (2012) and mainly Ediacaran-ages were defined, between 550 and 630 Ma. These ages indicate the Tamboril Santa Quitéria granitic–migmatitic Complex as the main source area.

The Parapuí Suite is predominantly represented continental, bimodal-character volcanic rocks (Fig. 9a). The relationship of this magmatism with the sedimentary rocks at different stratigraphic levels indicates that the sedimentation and volcanism occurred synchronously, probably starting during the deposition of Pacujá Formation, and are composed of fine to medium sandstone associated with pelitic layers that constitute the lateral and vertical gradations represented by the Massapê basal conglomerates. Interactions between sedimentary and magmatic units may be exemplified by the existence of peperites, a particular type of hybrid rock that was recently defined within Jaibaras Basin. According to White et al. (2000), these rocks result from interaction between magmas and unconsolidated or slightly consolidated and humidified sediments (Fig. 9b). Additionally, rhyolite dikes that crosscut sandstones from Pacujá Formation were also found along the basin (Fig. 9c).

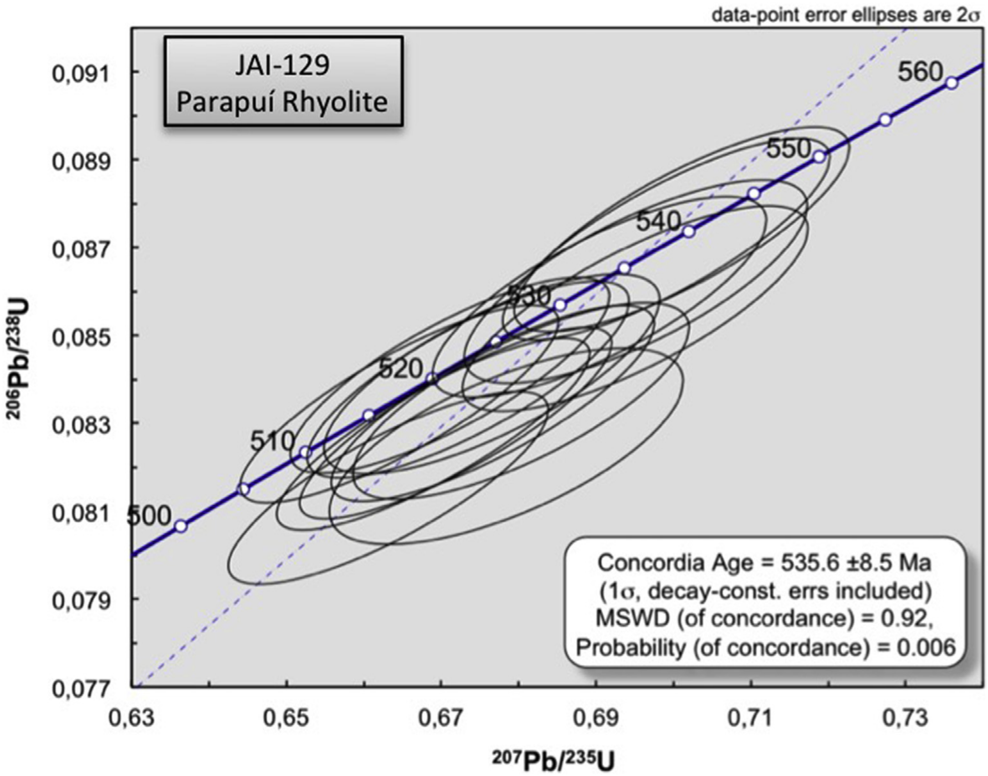

Fig. 8. U-Pb Concordia diagram for rhyolites from the Parapuí Suite, sample JAI-129. UTM: 24M 349929/9602082.

Table 3
Analytical data of new K-Ar determinations from Jaibaras Basin region.

Sample	UTM (24M)	Analysis	Age (Ma)	%K	40Ar Rad ccSTP/g (*10-6)	40Ar Atm (%)
JAI-134	318662 9600016	Whole-rock	484 ± 9	3.8173	82.24	1.60
JAI-135	319436 9599628	Whole-rock	488 ± 10	4.0795	88.83	1.90
		Feldspar	492 ± 9	6.4438	141.61	2.97
JAI-87	347020 9595387	Muscovite	531 ± 12	7.5263	180.31	5.67

Parapuí volcanism is concomitant with the sedimentation of Pacujá sandstones. Therefore, the 536 ± 8 Ma-U-Pb age (Garcia et al., 1988) may indicate that the lower sedimentation of the Jaibaras Group was developed during the Cambro-Ordovician, probably representing the initial phase of within-basin magmatism, synchronous with the deposition of the Pacujá Formation. This initial phase lasted until the deposition of the Aprazível Formation and is characterised by the formation of both rhyolitic domes and basaltic flows (Parente et al., 2011).

Interlayering between the Parapuí rhyolites and upper Aprazível conglomerates were also described by Parente et al. (2004), and reinforce the synchronous character of magmatism with clastic sedimentation.

The age of the tectonic intrusion of the Mucambo and Meruoca plutonic suites is still debatable. According to Costa et al., (1973), based on field relations, both plutons would be the same age and would be intrusive in the Jaibaras Group, being overlain by the Aprazível Formation. For Oliveira (1999) and Oliveira and Mohriak (2003), the Mucambo Suite would be older, being developed after the dike swarm attributed to the Aroeira Suite and previously to the Massapê Group. Granites of the Meruoca Suite would be younger than the sedimentary sequence of Jaibaras Group (Massapê and Pacujá formations) and are possible sources of debris flow of Aprazível Formation. Fetter (1999) and Santos et al. (2008) obtained for Mucambo Suite U-Pb ages of 532 ± 6 Ma and 530 Ma, respectively. According to Sial et al. (1981), the Meruoca Suite experienced prolonged low temperature interaction processes with hydrothermal fluids, which disturbed the Rb-Sr system, compromising the interpretation of analyses. For the Meruoca Suite, dating made by Archanjo et al. (2009) showed SHRIMP U-Pb zircon ages of 523 ± 9 Ma, attributed to magmatic crystallization. The difference between these ages may indicate the polyintrusive character of the Meruoca Pluton and the oldest age should correspond to older, less differentiated rocks, whilst Archanjo et al. (2009) age would be more differentiated. Alternatively, it may represent a granitic body formed by crustal melting induced by mantle heat, with succession of discontinuous magma inputs, spaced in time and each having its own mineralogical, geochemical and isotopic signatures (e.g., Vigneresse, 2007). The presence of massive mafic rocks within the Meruoca granite body may be an indication of the influence of the mantle rocks, which support the idea of multiple magma inputs. (Fig. 1).

In general, the central portions of the magmatic bodies are isotropic, while the edges are deformed along the shear zones that delimit both the Meruoca and Mucambo suites. Good examples can be best observed near the Café-Ipueiras shear zone, where the granitic lithotypes occur in well-exposed outcrops (mainly in ornamental stones quarries in the region) showing numerous

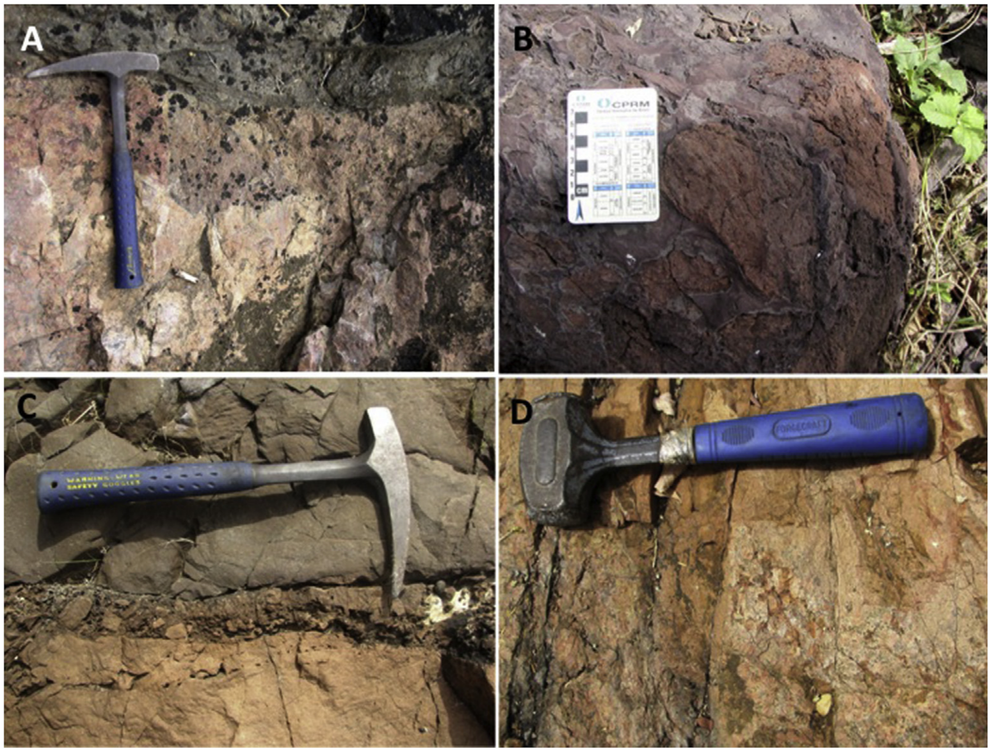

Fig. 9. Interactions between lithotypes from Jaibaras Basin. A) Interaction between rhyolite (pinkish colour, at the centre) and basalt (dark) showing the bimodal character of Parapuí magmatism; B) Peperites, resulting from interaction between magma and non-consolidated sediments from Pacujá Formation; C) Rhyolite dike related to the Parapuí magmatism in sandstone of the Pacujá Formation. Notice the formation of breccia along the contact; D) Contact between rhyolite and granite at the Meruoca Pluton. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

interconnected systems and irregular fractures filled with iron oxide, sulfides, chlorite, and epidote. These occurrences indicate that both the Meruoca and Mucambo suites were affected by later reactivation of this shear zone, which took place under a strike-slip regime.

Volcanic rocks composed mainly of felsic pyroclastic rocks and lava occur associated and in direct contact with the Meruoca granitic body. Their relationship with the granite is not clear, but although no description of volcanic rocks associated with the Meruoca Pluton is known, this may confirm the epizonal, recurrent character of this magmatism (Fig. 9d). Rhyolites occur mostly along the Café-Ipueiras Shear Zone, in diffuse and/or irregular contact with the Meruoca and Mucambo putonic suites.

The emplacement of the Meruoca Pluton has thus taken place over a large time interval (539 Ma to 523 Ma), and was synchronous with the emplacement of the Mucambo Pluton (532 Ma) and at least part of the Parapuí Suite (535 Ma). This may have been also synchronous with the sedimentation of the Pacujá and Aprazível formations, since crosscutting evidence were found in both sedimentary units. According to Pedrosa Jr. (2015), Pedrosa Jr et al. (2014) and Pedrosa Jr et al. (2017) strong magnetic anomalies in the Meruoca and Mucambo granites may suggest their association with mafic rocks, which would emphasise the long-term character of the magmatism in the region. These authors also note the absence of volcanism associated with SPIISZ, in contrast with the CISZ, which would imply that the main source of volcanic-rock fragments found in the Aprazível Formation is on the northwestern side of the basin, not related to the development of ZCSPII. Archanjo et al. (2009) report strong dispersion on the anisotropy of magnetic susceptibility axes possibly associated to later growth of fine oxides.

Another important feature is the scarcity of mineral occurrences, as well as significant hydrothermal alteration, associated with ZCSPII. This may result, in part, from its mostly ductile behaviour (low porosity and low permeability) that hinders the percolation of solutions (Parente et al., 2011).

A transtensional regime still existed during the emplacement of Aroeira Suite (527-500 Ma), thus highlighting the end of magmatic activity related to the Jaibaras Basin development.

A basin inversion took place, possibly after cooling of the Aroeira rocks (484–492 Ma), with deformation under a nearly NW-SE compressional axis, causing the folding in Aires de Sousa dam rocks. The effects of later crustal movements subsequently created the current basin configuration observed today.

6. Conclusions

According to our and other new geological and geochronological data, the geodynamic evolution of the Jaibaras Basin occurred in different stages, being summarised into the following events:

- 560-550 Ma - a shallow basin, with little or no magmatic activity. As wrench processes evolved, magmatic activity occurred concurrently or not with sedimentation;
- 542–514 Ma – emplacement of the Meruoca Pluton (U-Pb ages, Archanjo et al., 2009; Santos et al., 2013) in a transtensional gap formed by dextral shear along the Transbrasiliano Lineament. The emplacement of the Mucambo Pluton occurred within this interval – 539-525 Ma (Fetter, 1999);
- 535.6 ± 8.5 Ma – Parapuí rhyolite age and beginning of the sedimentation of the Pacujá Formation (Garcia et al., 1988);
- ~530 Ma – age of movement of the Sobral-Pedro II Shear Zone – K-Ar muscovite ages;

- 527–509 Ma (Middle Cambrian) – emplacement of the Aroeira Suíte (dikes) – crystallization ages. This age range may also represent the age of thin, local rhyolite dykes that crosscut the Aprazível Formation.
- ~484–492 Ma – age of cooling of the magmatic system related to the Aroeiras Suite

After cooling of Aroeira rocks, a basin inversion, possibly associated to a nearly NW-SE compressional axis deformation, took place, which caused folding in Aires de Sousa Dam rocks. The effects of later crustal movements subsequently created the current basin configuration observed today.

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