Ediacaran Águas Belas pluton, Northeastern Brazil: Evidence on age, emplacement and magma sources during Gondwana amalgamation

Adejardo F. da Silva Filho a,⁎, Ignrez P. Guimarães a, Valderez P. Ferreira a, Richard Armstrong b, Alcides N. Sial a

⁎ Corresponding author. Tel.: +55 81 21268240; fax: +55 81 21262834. E-mail address: afs@ufpe.br (A.F. da Silva Filho).

a Departamento de Geologia—CTG, Universidade Federal de Pernambuco, Rua Acadêmico Helio Ramos S/N Cidade Universitária, Recife, Pernambuco, 50740-530, Brazil
b Research School of Earth Sciences, the Australian National University, Canberra, Australia

1. Introduction

The Brasiliano orogeny (650–550 Ma) in the Borborema Province, northeastern Brazil, is marked by a large number of granitoid intrusions associated with either low- or high-angle large scale shear zones (e.g. McReath et al., 2002; Guimarães et al., 2005; Bueno et al., 2009). Geochronological data of these granitoids can constitute an important tool in dating these tectonic events.

The post-collisional tectonic setting is characterized by large intrusion of high-K calc-alkaline magmas. This tectonic setting usually ends with minor amounts of highly evolved high-K calc-alkaline or alkaline magmatism, which mark the end of the orogeny. Highly evolved high-K calc-alkaline magmatism generally shows some similarities with A-type granites (Liegéois et al., 1998). As pointed out by Pearce (1996), the post-collisional granites are the most difficult to classify, since some of them have subduction-like mantle sources with many characteristics of volcanic-arc granites while others show within plate character. According to Eby (1992), A-type granitoids can be divided into A1- and A2-types. The A1-type occurs in a true anorogenic setting and it has OIB signatures, while the A2-type occurs in post-collisional or post-tectonic setting, usually shortly (10–20 million years) after compressional tectonics, is rarely, or not associated with silica-undersaturated alkaline rocks, have trace element signatures similar to sub-continental lithosphere and crust, and never have OIB signature.

Oxygen isotope ratios of magmas reflect their source and contaminants. According to Eiler (2001) the mantle is a homogeneous reservoir. Igneous zircons in high temperature equilibrium with mantle magmas have an average of δ18O = 5.5 ± 0.3‰ (Valley et al., 1998). This value remains approximately constant during fractionation processes, and change can only be achieved by adding a material of a distinct oxygen isotope composition to the magma (Valley, 2003).
Significant deviations from the mantle value are the result of magma interactions with low temperature rocks (supracrustal rocks) and rocks from near the surface associated with large oxygen isotopic fractionation.

Granites are classically considered by various authors to probe the crust, giving important clues to the understanding of the crustal evolution. The Pernambuco–Alagoas domain, which is among the major crustal domains of the Borborema Province, was shown by Silva Filho et al. (2002) to be comprised by various crustal sections of very different Nd model ages. The Águas Belas pluton shows Paleoproterozoic Nd model ages (Silva Filho et al., 2002) but is surrounded by supracrustals and volcanics of Mesoproterozoic Nd model age (Van Schmus et al., 2008), and then has been considered among the main metaluminous granitic intrusion from the Pernambuco–Alagoas domain, with some A-type petrographic and geochemical signature (Silva Filho et al., 1996). The aim of this paper is to present geochemical, U–Pb SHRIMP zircon and oxygen isotopic data for discussing the age, the sources and the tectonic setting of a large granite intrusion, the Águas Belas pluton, located in the Pernambuco–Alagoas domain of the Borborema Province, which altogether could shed light on the last stages of the Gondwana amalgamation.

2. Regional geology

The Borborema Province (Almeida et al., 1977) is located in northeastern Brazil, north of the São Francisco craton (Fig. 1a). Although the region was highly deformed and metamorphosed during the Brasiliano orogeny, many features of pre-Brasiliano geology can still be recognized from the rocks, including isotopic signatures. In a pre-drift reconstruction (De Wit et al., 1988), the Borborema Province lies adjacent to coeval Pan-African and cratonic terranes from western Africa (Toteu et al., 2001).

The Pernambuco–Alagoas crustal domain (PEAL) is one among the six crustal domains identified by Van Schmus et al. (2008) in the Borborema Province. It is limited to the north with the Transverse Zone domain, to the south with the Sergipano domain, and its eastern part is cut by large granitic batholiths (Fig. 1b).

Medeiros and Santos (1998) recognized some metamorphic sequences in the Pernambuco–Alagoas domain: (i) The Cabrobó complex is a dominantly supracrustal unit comprised of biotite garnet gneisses, locally migmatized, intercalated with quartzite, schist, calc-silicate and amphibolite, orthogneisses and migmatite; (ii) The Belém do São Francisco complex is an infra-crustal segment composed of migmatites, biotite-gneisses, tonalitic orthogneisses, and leucogranite São Francisco complex is an infra-crustal segment composed of gneisses, locally migmatized, intercalated with quartzite, schist, calc-silicate and amphibolite, orthogneisses and migmatite; (iii) The Garanhuns Complex is a high-grade metamorphic unit exposed in the southern part of the Borborema Province.

Silva Filho et al. (1996, 1997, 2002) have identified various late-tectonic granitic intrusions and suites in the eastern part of the PEAL domain, with compositions ranging from high-K to calc-alkaline, shoshonitic, mildly alkaline or peraluminous (+ garnet-bearing) granites. These intrusions were grouped into four granitic batholiths: Buíque–Paulo Afonso, Águas Belas–Canindé, Marimbondo–Correntes, and Ipojuca–Atalaia. The Águas Belas granitoids are part of the Águas Belas–Canindé batholith.

The Águas Belas–Canindé batholith is limited to the south by the Sergipano domain, to the north and to the east by migmatites from the Belem do São Francisco complex, and to the west by the supracrustal Inhapi sequence (Fig. 2). It comprises biotite, amphibole syenogranites and amphibole–pyroxene bearing syenogranites cutting metatexites and diatexites of tonalitic composition. The metatexites grade to diatexites from the margin to the centre of the western part of the batholith.

The ages of the PEAL domain units are still poorly constrained. It is probable that grouping units based primarily on rock-type has lumped together units having primary depositional or plutonic ages ranging from Paleoproterozoic (or older) to Brasiliano (Neoproterozoic). Brito Neves et al. (1995) presented Rb–Sr isochron ages ranging between 1.13 Ga (diatexites) and 0.96 Ga for rocks assigned to the Cabrobó and Belém do São Francisco complexes (Santos, 1995) in western PEAL domain. The TDM model ages for rocks of these complexes range between 1.50 Ga to 1.30 Ga (Santos, 1995).

Very few U–Pb (zircon) ages are available for the PEAL domain. Van Schmus et al. (1995) reported a zircon upper-intercept apparent age of 1577 ± 73 Ma for garnet-bearing migmatite, west of Palmeira dos Indios town. A single U–Pb zircon in zircon obtained by LA-ICPMS from migmatitic tonalitic orthogneisses in the Jupi area, NE of Garanhuns, yields an age of 2000 Ma (Neves et al., 2005a,b). The early interpretations of a Paleoproterozoic to Archean age for most of the PEAL domain have not been confirmed by the few new zircon ages.

U–Pb zircon ages in granitoids of the PEAL domain show an interval from 570 Ma to 625 Ma (Silva Filho et al., 1997, 2008; Silva Filho and Guimarães, 2000) and Nd model ages range from 1200 to 2000 Ma (Silva Filho et al., 2006). A larger data set reported by Silva Filho et al. (2002, 2006) expanded the range of TDM ages from 900 to 2800 Ma and the data show a bimodal distribution, indicating that most of the Nd formation ages are either Neoproterozoic or Paleoproterozoic. The low frequency of samples with TDM model ages from 1500 to 1800 Ma may indicate that Cariris Velhos (980–920 Ma) igneous rocks, which commonly have TDM ages in this range (Van Schmus et al., 1995; Brito Neves et al., 2001), are scarce or not found in the PEAL domain. Silva Filho et al. (2002) evaluated the evolution of the PEAL domain based on Sm–Nd isotopic data from the Neoproterozoic granitoids, and defined two crustal sub-domains: Garanhuns and Água Branca sub-domain.

Silva Filho et al. (2006) based on new Nd isotopic data from granitoids, orthogneisses and supracrustal rocks proposed three crustal sub-domains for the PEAL domain: (i) Garanhuns with TDM model ages in the interval 1600 to 2600 Ma, (ii) Águas Branca with TDM model ages ranging from 900 to 1590 Ma and (iii) Palmases–TDM model ages around 1110 Ma. The Águas Belas pluton is intruded into rocks from the Agua Branca sub-domain (Fig. 1b). This sub-domain is comprised by the Águas Belas–Canindé batholith (Silva Filho et al., 2002) and by the Inhapi Sequence (Van Schmus et al., 2008). It has been shown that the Agua Branca sub-domain is comprised mainly by rocks of TDM model ages from 900 Ma and 1590 Ma, and various granitic plutons and orthogneisses of TDM ca. 2000 Ma, among them the Águas Belas pluton. These data point to a setting where tectonic blocks of different ages have been put in contact during a collisional process. Collisional process has been constrained at 628 ± 12 Ma in the adjoining Sergipano Terrane (Oliveira et al., 2006). Previous geological and geochemical reconnaissance of the Águas Belas pluton (Silva Filho et al., 1996) showed that it is comprised by late-tectonic metaluminous and high-K calc-alkaline rocks. Metaluminous and amphibole ± pyroxene suites are classically extracted from the lower crust or from the upper mantle. This pluton was selected to study because it would bear inheritance from lower crust or upper mantle, and, as it shows high and restricted SiO₂ contents, which is typical of crustal-derived granites, it would bear as well an inheritance from the middle to the upper crust. So, the whole set of data could shed light into the Brasiliano collisional process. This paper tries to approach some complexities of the crustal evolution of this crustal domain of the Borborema Province, using SHRIMP U–Pb zircon, oxygen isotopes and trace elements geochemistry from the Águas Belas pluton. A brief evaluation on the emplacement of this pluton has been done in order to position it in relation to the chronology of the adjoining shear zones and to the flat-lying foliation from the adjoining supracrustal sequences.
Fig. 1. a) Sketch geological map of the Borborema Province. The main tectonic domains are from Van Schmus et al. (1995) and Van Schmus et al. (2008). PESZ = Pernambuco shear zone; PSZ = Patos shear zone. 1—Palaeozoic sedimentary basin. b) Schematic map for the crustal sub-domains of the PEAL domain.
3. Geology and petrography

The Águas Belas pluton constitutes an elongated intrusion with an 18 km long E–W-trending major axis (Fig. 2b). It is intruded along the contact between the Inhapi supracrustal sequence and the Águas Belas–Canindé batholith, being part of the Água Branca crustal sub-domain (Silva Filho et al., 2006). Northwards and very close to the pluton the Venturosa Sequence crops out. This sequence is comprised of metasedimentary rocks and orthogneisses. Structural analysis of this sequence shows a main Sp low-angle foliation with SE–NW stretching lineations (Silva Filho et al., 2007). Another main feature of this sequence is a high-angle foliation related to NE–SW shear zones, which are younger than the Sp low-angle foliation and spatially related to various high-K calc-alkaline granitoids. The country rocks to the north are sillimanite–garnet–biotite-gneisses, to the west biotite-muscovite–garnet gneisses both from the Inhapi Sequence, and to the south are other Neoproterozoic granitic plutons from the Águas Belas–Canindé Batholith. The contacts of the pluton are sharp with both gneisses and granitoids. An E–W-trending mylonitic foliation has been identified in the northern contact. Xenoliths of migmatized gneisses are observed along the northern outer contact. The Águas Belas pluton truncates the Maravilha ductile low-angle shear zone which runs NE–SW (Fig. 2b). The NE–SW Limitão–Caetés ductile shear zone cuts the Venturosa Sequence and terminates at the NE tip of the Águas Belas pluton. This shear zone shows low-angle foliation (Osako, 2005) dipping eastward. The Águas Belas pluton cuts the Inhapi Sequence foliation at a high angle. Within the pluton an E–W weak lineation, parallel to its main axis has been recognized. Remote
sensing imagery (Osako, 2005) shows internal E–W and NE–SW brittle foliations as well.

A geophysical discontinuity has been identified a few kilometres to the north of the Águas Belas pluton (Silva Filho et al., 2007). It runs from the E–W Pernambuco shear zone, the northern limit of the Pernambuco–Alagoas domain, with trends ranging from NE–SW to E–W, suggesting that the Águas Belas pluton is intruded close to an important E–W-trending crustal discontinuity. Syn- to late-tectonic granitoid intrusions, with ages ranging from 580 to 590 Ma have been mapped along NE–SW shear zones (Neves et al., 2006; Silva Filho et al., 2007).

The data available suggest that intrusion of the Águas Belas occurred after the peak of the Brasiliano metamorphism, which was probably associated with the flat-lying foliation in both Venturosa (Limitão–Caetés shear zone) and Inhapi Sequences (Maravilha shear zone). The E–W-trending lineation recorded within the Águas Belas pluton and lack of large mylonitic zone within it suggest that the intrusion took place at the beginning of the operation of a discrete ductile E–W shear zone. The pluton was later cut by brittle faults, which were the channels for the ascent of bimodal volcanic rocks that include pyroclastic rhyolites and basalts. These brittle faults are associated with the initial stage evolution of the interior sedimentary basins of Gondwana break-up.

The Limitão–Caetés high-angle shear zone is a splay of the Pernambuco shear zone, and it terminates at the east contact of the Águas Belas pluton. A two-mica granite, the Serrato dos Macacos pluton, intruded a few kilometres north of the Águas Belas pluton, within the Limitão–Caetés shear zone (Fig. 2), yielded U–Pb monazite age of 580 ± 3 Ma (Osako, 2005).

Two main petrographic facies were recorded in the Águas Belas pluton (Fig. 2b): amphibole ± biotite syenogranite to quartz syenite and pyroxene ± amphibole syenogranite. They are coarse to medium grained rocks with low concentration of modal mafic minerals (less than 6%). Evidence of deformation under low temperature was recorded in the northern and southern border of the Águas Belas pluton. The low temperature deformation is characterized by recrystallized quartz as micro grains and elongated quartz grain showing undulose extinction.

Amphibole-rich clots are frequently recorded. In the pyroxene ± amphibole syenogranite, the amphibole is green, bluish, and Fe-rich, formed by the reaction of light green pyroxene and the magma. Na-rich amphibole (afverdsonite) is recorded as a later crystallized phase in the amphibole ± biotite syenogranite to quartz syenite. Anti-rapakivi texture was recorded in both petrographic units reflecting later crystallization of K-feldspar. Biotite occurs in very small modal amounts (<1%) always as inclusions in amphiboles or, as a later phase, replacing amphiboles. Sphene is the main accessory phase. It occurs as subidiomorphic to idiomorphic orange crystals reflecting high LREE concentrations (Guimarães et al., 1993). Zircon, opaque minerals, allanite and apatite are the other accessory minerals recorded in the Águas Belas granitoids.

4. Geochemistry and Sm–Nd data

Representative samples from the Águas Belas pluton were analyzed for major elements by ICP-AES and for trace elements by ICPMS at ACME Laboratories in Canada. The results are shown in Table 1.

The Águas Belas granitoids range from metaluminous to slightly peraluminous, straddling the boundary with the peralkaline field (Fig. 3a). They plot in the fields of alkaline to highly fractionated calc-alkaline granites (Fig. 3c) in the scheme proposed by Sylvester (1989). The plutonic TAS diagram (Fig. 3b), with fields after Middlemost (1997), emphasizes the trans-alkaline character of the Águas Belas granitoids. They have high SiO₂ (69.1–73.1 wt.%) and total alkalis, with Na₂O + K₂O ranging from 8.3 to 10.5 wt.% and K₂O/Na₂O ratios ranging from 1.2 to 1.9. One sample analyzed from the southern border of the batholith shows higher K₂O/Na₂O ratio (2.2). They have high Fe₉₃[FeO₉₋₁(FeO₉₋₁+MgO)] values (0.8 to 0.92, Fig. 3d), which classify them as belonging to the ferroan series granitoids (Frost et al., 2001). All the analyzed samples fall within the shoshonitic field in the K₂O vs. SiO₂ diagram (Fig. 3e).

The Águas Belas granitoids show high Ba contents (1300–2650 ppm), medium Sr contents (430–690 ppm) and low to medium Rb contents (203–258 ppm). The contents of the high field-strength elements (HFSE) are relatively low (Nb = 8–14 ppm; Ta = 0.2–2.0 ppm; Zr = 81–189 ppm). One sample from the southern border of the batholith shows high Ba (6155 ppm) and Sr contents (1660 ppm) and have high K₂O/Na₂O ratio (2.2).

The REE patterns (Fig. 4) normalized to chondrite values of Nakamura (1974) are characterized by gentle fractionated pattern, with Ce₄/Yb₄ ranging from 8.7 to 3.3, with only one sample showing higher value (19.5), without substantial negative Eu anomalies (0.98 to 0.86).

Bivariate plots between elements that readily enter rock-forming minerals may be used to test the fractional crystallization hypothesis by comparing model mineral fractionation vectors with observed data arrays. Ba versus Sr correlations can provide information particularly on the feldspars and biotite fractionation. The Ba versus Sr data for the Águas Belas granitoids define a trend compatible with K-feldspar and biotite fractionation (Fig. 5a), which agrees with the negative Eu anomalies recorded in the REE patterns. The lack of correlation between Ba and Sr with Eu/Eu* (Fig. 5b, c) does not support plagioclase fractionation during the evolution of the Águas Belas granitoids. On the other hand, the positive correlation between Na₂O and SiO₂ reflects the later crystallization of Na-rich amphiboles, as observed in the petrographic studies.

Nd isotopic analysis for one sample was carried out at the Isotope Geochemistry Laboratories–Kansas University. It shows negative εNd (600 Ma) values (−12.4) with Paleoproterozoic 187Os (2130 Ma) model age.

5. Geochemical signature

In spite of their high Ba contents, the studied granitoids do not meet the criteria established by Tarney and Jones (1994) for high Ba–Sr (HIBaSr) granitoids, due to their medium Sr contents and low HREE and high HREE contents. The REE patterns of the studied granitoids are distinct from either HIBaSr granites, which have highly fractionated patterns and from A-type granites, which have gentle fractionated patterns but with substantial negative Eu anomalies.

Multi-element diagrams normalized to the values suggested by Thompson (1982) for the studied granitoids and the average element concentration of I-type S-type and HIBaSr granites (Fowler et al., 2008) are shown in Fig. 6a and b. The studied granite patterns are characterized by troughs at Nb, Ti, P and either peak or troughs at Sr. Compared to the average of I-type and HIBaSr granites (Tarney and Jones, 1994) the studied granitoids have lower Sr, P and Ti concentrations.

Morrison (1980) pointed out the main characteristics of the shoshonitic association: high total alkalis (K₂O + Na₂O > 5), low TiO₂ (< 1.3 wt.%), no Fe enrichment in the AFM diagram and high contents of LILE (Ba, Sr, Rb), low Nb, and steep REE patterns. The Águas Belas granitoids show some distinctions when compared to granitoids of the shoshonitic association because they have low Sr contents and have REE patterns characterized by lower (Ce/Yb)₄ ratios.

The Águas Belas granitoids exhibit a trans-alkaline and ferro-potassic character. These features are common to most alkaline granite suites. However, the studied granitoids show high Ba and low Nb and Y contents, whereas the alkaline granites have low Ba and high Nb and Y contents. According to Liegeois et al. (1998), alkaline granites, not peralkaline granites, show K-feldspar always dominating over plagioclase, i.e. they are alkali-feldspar granite and syenogranite in composition. The alkaline granites show petrography very similar
to evolved calc-alkaline granitoids, and the distinction can be obtained on geochemical grounds.

The Águas Belas granitoids are mainly syenogranite in composition and, plot (Fig. 7) within the post-collisional field in the Rb versus (Y + Nb) diagram (Pearce, 1996). They have high values of Fe# (>0.8), Fe-rich and Na-rich amphiboles, REE patterns characterized by low (Ce/Yb)N values and high total alkalis, with Al2O3/(Na2O+K2O) molecular ratios ~1.0. In the Yb/Ta versus Y/Nb diagram (Fig. 8) the Águas Belas granitoids plot along a trend between the OIB and IAB average fields, showing trace element signature distinct from OIB-like signature (Fig. 9). In spite of the many similarities with A2-type granites, the studied granitoids have much lower contents of Y and Zr, and higher Sr concentrations, when compared to those for alkaline granites, the studied granitoids have much lower contents of Y and Zr, and higher Sr concentrations, when compared to those for alkaline granites.

The geochemical signature of the Águas Belas granitoids favours their classification as a transitional high-K calc-alkaline to alkaline post-collisional magmatism.

6. SHRIMP U–Pb and oxygen isotope zircon data

6.1. Analytical methods

SHRIMP U–Pb dating was used to determine the age of zircons from the studied granitoids. Zircon grains were separated from the total rock sample (AB-08) using standard crushing, washing and heavy liquid. Hand-picked selected zircons were placed onto double-sided tape and mounted together with chips of the reference zircons (FC1 and SL13) in epoxy resin, ground to half thickness, and polished with 3 µm and 1 µm diamond paste. A conductive gold-coating was applied just prior to analysis. The grains were photographed in reflected and transmitted lights, and cathodoluminescence (CL) images were produced in a scanning electron microscope in order to investigate the internal structures of the zircon crystals, to characterize different populations, and to ensure that the spot was wholly within a single age component within the sectioned grains.

The U–Th–Pb analyses were made using the SHRIMP II of the Research School of Earth Sciences, The Australian National University, Canberra, Australia. Each analysis consisted of 6 scans through the mass range. SHRIMP analytical procedures followed the methods described in Williams (1998, and references therein). The standard zircon SL13 (Claue-Long et al., 1995) was used to determine U concentration and the Pb/U ratios were normalized relative to a value equivalent to an age of 1099 for the FC1 reference zircon (Paces and Miller, 1993). Raw isotopic data were reduced using the Squid program (Ludwig, 2001), and age calculations and Concordia plots were done using both Squid and Isoplot/Ex software (Ludwig, 2003). The results are listed in Table 2.
6.2. Zircon description and results

The analyzed zircon crystals are pale yellow, with rare inclusions. They are usually elongate, prismatic, length/width ratio ranging from 4:1 to 4:2 (Fig. 10), with length ranging from 100 µm up to 270 µm. All of them, except the core of crystal 4 (Fig. 10), show oscillatory zoning and many show a clear overgrowth. The contact core-overgrowth is irregular and sharp, and the core usually shows elongate shape. The analyzed zircons show Th/U ratios ranging from 0.2 to 0.7, which is typical of magmatic zircons (Williams and Claesson, 1987).

Twenty three zircon grains were analyzed, totalling 26 analyzed spots. A cluster of 14 concordant analyses yields a $^{206}\text{Pb}^{238}\text{U}$ age of 588±4 Ma (Fig. 11). The euhedral shape and the high Th/U ratio of the grains suggest that this age must correspond to a best estimation for the emplacement age of the Águas Belas pluton.

The analyzed sample also shows inherited zircon cores that yield slightly discordant $^{207}\text{Pb}^{206}\text{Pb}$ ages (Table 2). The zircon cores yield ages of 1594±13 Ma, 1895±14 Ma, and 2060±23 Ma. The core of the crystal 4 (Fig. 10) yielded an age of 1594±13 Ma while the rim shows an age of 613±6 Ma. The core shows no oscillatory zoning, but the rim...
does show. Both of them show high Th/U ratios, suggesting that at least the zircon rim has igneous origin.

6.3. Oxygen isotopes

The oxygen isotope analyses were conducted using the SHRIMP II in 23 spots in the same zircon spots analyzed previously for U–Pb (Fig. 11), and results are reported in the SMOW scale. The δ¹⁸O values lie between 6.35‰ and 10.30‰. Only spot 23.2 (Table 2), with ²⁰⁷Pb/²⁰⁶Pb age = 1315 ± 300 Ma, shows a significantly lower δ¹⁸O value = 5.79‰. Due to being highly discordant (66%) and large age error, this analyzed spot is not going to be taken under further consideration.

Grain 4 shows the lowest δ¹⁸O values, 6.69‰ and 6.35‰, for core and rim respectively. Grain 11 shows ¹⁸O/¹⁶O values of 8.19‰ and 10.01‰ for the rim and core respectively. The core of zircons, spots 11.2 and 22.1, show rounded shape and high values of ¹⁸O/¹⁶O. The δ¹⁸O values for rims of Neoproterozoic age range from 6.69 to 10.30‰, with average value of 8.26 ± 0.71‰. This >2‰ variation is large and not compatible with cogenetic rocks crystallized in a closed system. Average δ¹⁸O (zircon) value is lower (8.23 ± 0.46‰) when the highest (10.30‰) and the lowest (6.69‰) values are not considered. In this case, considering whole rock silica contents, calculated average whole rock δ¹⁸O values, following Valley et al. (1994), vary from 10.06 ± 0.46‰ to 10.30 ± 0.46‰, for SiO₂ contents of 69.14% and 73.12%, respectively, the silica range observed for the Águas Belas rocks. These average values are consistent and compatible with high δ¹⁸O crustal-derived magmas crystallized in a closed system. The highest δ¹⁸O (zircon) values (10.01 and 11.01‰) from the Paleoproterozoic cores are 2–3‰ higher than the δ¹⁸O (zircon) values observed for zircons of this age studied by Valley et al. (2005), who reported that during the Proterozoic the range of δ¹⁸O (zircon) gradually increases in a secular change that documents maturation of the crust. The high δ¹⁸O values of Proterozoic zircon cores of this study are compatible with high δ¹⁸O values of (meta) sedimentary rocks.

The δ¹⁸O (zircon) values of Mesoproterozoic cores are lower (6.35‰ and 6.89‰) and can be interpreted as resulting from the exchange of protoliths with surface waters at low temperature followed by melting or contamination, as suggested by Valley et al. (2005) for Archaen zircons that show δ¹⁸O values in the range 6.5–7.5‰.

7. The granitoid source and tectonic setting

Values of δ¹⁸O (zircon) lower than 7‰ recorded in the 592 ± 7 Ma zircon grain from the studied granitoids reflect interactions between crustal rocks and lithospheric mantle magmas. The involvement of a crustal component in the Águas Belas granitoids protolith is supported by the presence of zircon grains with Paleoproterozoic and Mesoproterozoic age and their Nd isotopic data. However, this crustal component could be incorporated to the magma, during its ascent through the crust.

Mesoproterozoic zircon grains with low δ¹⁸O values were probably inherited from igneous rock originated from a protolith involving mantle and minor crustal components. Mesoproterozoic igneous

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Fig. 4. Chondrite-normalized REE patterns (Nakamura, 1974) of the Águas Belas granitoids.

Fig. 5. Bivariate trace element diagrams monitoring feldspar involvement in the evolution of the Águas Belas granitoids. The fractionated vectors were built using the partition coefficients from Villemant et al. (1981).
rocks have not been identified so far within the PEAL Domain. Neves et al. (2008) have determined U–Pb zircon age of 1560 ± 16 Ma for the Cabanas pluton in the Garanhuns sub-domain, but with no clear indication of an igneous origin for it. Van Schmus et al. (1995) had found migmatitic garnet-gneiss with similar age near Palmeira dos Indios, yielding an upper intercept of 1577 ± 73 Ma and lower intercept of 538 ± 34 Ma. The presence of zircons of Mesoproterozoic age within the Pernambuco–Alagoas Domain suggests that part of its crust should contain rocks with this age. The only well documented Mesoproterozoic igneous suite within the Borborema Province is the Taquaritinga orthogneisses (Sá et al., 2002), which occur within the Transverse Domain. They show a clear A-type granite character and yielded U–Pb zircon age of 1521 ± 6 Ma. The presence of zircon with 1560 Ma and mantle oxygen isotope value within the Águas Belas granitoids favours the presence of juvenile Mesoproterozoic rocks in the PEAL Domain. This hypothesis should be further investigated because there is no oscillatory zoning in this zircon.

The Paleoproterozoic Nd TDM model age recorded in the studied granitoids cannot support the presence of juvenile lithospheric mantle in the Águas Belas granitoids protolith. The involved lithosphere should have a Paleoproterozoic age otherwise. If a juvenile Neoproterozoic lithosphere had been involved, the εNd (0.60 Ga) value showed by the Águas Belas pluton would be much less positive than −12.4.
Errors are 1-sigma; Pb and Pb⁎ indicate the common and radiogenic portions, respectively. Error in standard calibration was 0.24% (not included in above errors but required when comparing data from different mounts). (1) Common Pb corrected using measured 204Pb. % Dis = % discordant.

Flat-lying foliation is dominant in the area, including metasedimentary (Inhapi) and metagneous (Venturosa) sequences. This flat-lying foliation is always cross-cut by subvertical sinistral shear zones. Granulitic orthogneisses from the Venturosa Sequence have U–Pb zircon (TIMS) age of 642 ± 15 Ma (Osako et al., 2006). An elongated E–W-trending granitic intrusion mapped in the north part of the PEAL Domain, shows flat-lying foliation and a 206Pb/238U weighted apparent mean age of 606 ± 8 Ma (Neves et al., 2008). This age is interpreted as the age of the high-grade Brasiliano metamorphism and consequently the age of the flat-lying foliation. The age obtained for the Águas Belas pluton is similar to the 40Ar/39Ar ages (581 ± 2 Ma and 591 ± 3 Ma) recorded by Araújo et al. (2004) for the E–W-trending Belo Monte–Jeremoabo shear zone, within the Sergipano Domain, and to the U–Pb zircon age (587 ± 8 Ma) for the beginning of the transcurrent regime that produced the dextral E–W-trending East Pernambuco shear zone (Neves et al., 2008). Ages ranging from 630 Ma to 608 Ma determined in orthogneisses and granitoids have been used to constrain the flat-lying foliation in the Pernambuco–Alagoas domain and in the Transversal Zone Domain (Guimarães et al., 2004; Neves et al., 2005a, b; Neves et al., 2008).

The lack of penetrative ductile deformation within the Águas Belas Pluton, and the E–W-trending of its main axis, suggests that it was not intensively affected by NNE strike–slip–related deformation. It also suggests that the emplacement occurred during the early stage of the transcurrent tectonic regime. A similar model has been proposed by Neves et al. (2008) for the intrusion of the NE–SW-trending Cachoeirinha Pluton, which shows similar age to the Águas Belas pluton (587 ± 8 Ma). However, the Águas Belas pluton shows an E–W-trending main axis, and, as pointed out by Guimarães et al. (2004, 2009) and Neves et al. (2008), plutons intruded along E–W transcurrent shear zones in the Transversal Zone domain, in the North Tectonic domain and in the northern part of the Pernambuco–Alagoas domain show younger ages (~570 Ma). The presence of E–W-trending flat-lying foliation within the Pernambuco–Alagoas domain, in the Jupi orthogneisses and in quartzites from Venturosa Sequence, which occur along the Garanhuns low-angle shear zone, suggest that the Águas Belas pluton emplacement involved activation of E–W pre-existing crustal structure by the NNE-trending Limitão–Caetés sinistral shear zones. The E–W-trending structure acted as a continental transform fault, and was reactivated during a high-angle tectonic regime, creating the necessary space for the intrusion of the Águas Belas Pluton. A similar model has been proposed for the Donegal Batholith (Stevenson et al., 2008). These arguments are consistent with the post-collisional geochemical signature of the Águas Belas granitoids, if it is taken into account that a high-angle tectonic regime occurred after the collisional process.

8. Conclusions

All the chemical features suggest that the Águas Belas granitoids correspond to a transitional high-K calc-alkaline to alkaline magmatism, emplaced during the late stage of the Brasiliano orogeny, under the control of a set of shear zone, in between the Inhapi Sequence to the north and Neoproterozoic granitoids to the south. The structural and geochronological data suggest that NNE–SSW-trending sinistral shear zones were initiated at ca 590 Ma, and activated E–W pre-existing structures at the current crustal level. The synchronicity of these shear zones allowed the dilatation needed to facilitate the space required to the emplacement of the Águas Belas Pluton.

The magma evolved through K-feldspar and biotite fractionation, but lack of plagioclase fractionation, which increased the Na₂O contents in the magma promoting the later crystallization of Na-rich amphiboles.

The U–Pb SHRIMP age associated with oxygen isotopes in zircon, geochemical and Nd isotopic data suggest that four intervening components: Paleoproterozoic lithospheric mantle, Paleoproterozoic crustal rocks, Neoproterozoic supracrustal sequences, and Mesoproterozoic igneous rocks were involved in the studied granitoids magmas. The necessary heating for promoting fusion was probably the Paleoproterozoic lithospheric mantle magnets, which invaded the crust through the deep-seated shear zones during the transition
between compression and extension, during the final stage of the Brasiliano orogeny. During its emplacement, the magma may have interacted with Paleoproterozoic and/or Neoproterozoic supracrustal rocks and, Mesoproterozoic igneous rocks.

Acknowledgments
AFSF thanks CAPES for a post-doctoral scholarship (BEX 3534/07-3). A grant from the PRONEX/FACEPE program (APQ-0479-1.07/06) made possible SHRIMP analyses at the ANU-Research School of Earth Sciences at Canberra, Australia. We are thankful to Sam Mertens and Shane Paxton for their assistance with the sample preparation. This manuscript has been improved by the constructive review of William R. Van Schmus and one anonymous reviewer from Gondwana Research.

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