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ARTICLE

Late-Neoproterozoic ferroan granitoids of the Transversal subprovince, Borborema Province, NE Brazil: petrogenesis and geodynamic implications

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ABSTRACT

Ferroan granites (585–530 Ma) have been described in the Transversal subprovince of the Borborema Province (BP) and in Pan-African counterparts. They comprise two groups: Group 1 – slightly peraluminous to metaluminous, alkali-calcic rocks, with low Fe# mica and crystallized under intermediate fO_2 (Aroeiras Complex and Serra Branca – Coxixola dike swarms); Group 2 metaluminous to slightly peraluminous, alkalic to alkali-calcic rocks, with high Fe# mica and crystallized under low fO_2 (Queimadas and Prata intrusions). Group 1 marks transition from collision to transcurrence (ca. 585 Ma), or from transcurrence to uplift and transtension (ca. 545 Ma). Group 2 – represents granitoids intruded during extensional tectonics in transcurrent setting (ca. 550 Ma), or coeval with deposition of transtensional intracratonic basins (ca. 530 Ma). Hf and Nd model ages are older than 2.0 Ga, suggesting that the ferroan granitoids involved partial melting of Paleoproterozoic rocks. The data presented in this paper show that the ferroan magmatism was widespread in the BP and its counterparts in Africa in pre-drift reconstructions.

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Granite; ferroan; geochemistry; geochronology; extensional tectonics; Borborema province

1. Introduction

The Borborema Province (Almeida *et al.* 1981) has a long tectonic history that culminated with assembly of western Gondwana, as result of collision between major cratonic landmasses (São Francisco/Congo and São Luís/West Africa Cratons) along the Cryogenian/Ediacaran period, otherwise known as the Brasiliano/Pan-African event (Van Schmus *et al.* 2008; and references therein)

Succeeding the collisional events, the BP was influenced by strike-slip and extensional tectonics, which led to the intrusion of several post-collisional plutons, 'A-type' granites and dike swarms, followed by development of sag-basins, collapse of orogenic chains and rupture of continental crust (Fetter 1999; Santos *et al.* 2008a). The endurance of those events is best controlled through the ages of their magmatic expressions.

Almeida *et al.* (1967) recognized four granitoid types, on a petrographic basis: 1) Conceição-type comprises medium to fine grained tonalites and granodiorites; 2) Itaporanga-type, granodiorites with large K-feldspar crystals; 3) Itapetim-type, fine grained biotite granites related to the Itaporanga-type; 4) Catingueira-type peralkaline granites, syenites and quartz syenites.

Sial (1986), using geochemical data, characterized the granitoids from the Cachoeirinha-Salgueiro Belt, and correlated them with the petrographic types of Almeida *et al.* (1967): 1) Calc-alkalic (Conceição-type); 2) High-K Calc-alkalic (Itaporanga-type); 3) Peralkalic, ultrapotassic and shoshonitic (Catingueira-type); 4) Trondhjemitic (Serrita-type). The BP granitoid types were further divided into magmatic epidote-bearing or epidote-free associations (Sial *et al.* 1997; Ferreira *et al.* 1998; Sial and Ferreira, 2015).

Using geochronological data from several plutons from the eastern part of the Transversal subprovince, Guimarães *et al.* (2004) identified four granitoid groups: 1) 640–600 Ma medium to high-K calc-alkaline granitoids intruded throughout the peak of high T, low-P metamorphism and development of the flat-lying foliation during the convergence of major cratonic landmasses (São Francisco-Congo Craton and São Luís-West Africa Craton); 2) 590–581 Ma high-K calc-alkaline and shoshonitic granitoids marking the transition between the flat-lying event and

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Supplemental data for this article can be accessed here.

the transcurrent event; 3) ca. 570 Ma alkaline post-collision granites marking the final stage of the Brasiliano – Pan-African orogeny and the beginning of the uplift, synchronous with the ultrapotassic intrusions in the western sector of the Transversal subprovince; 4) ca. 540–510 Ma A-type post-orogenic extension-related associated with subvolcanic bimodal magmatism, coeval with the deposition of small basins from the North and Transversal subprovince.

The classification schemes proposed for the Borborema Province Ediacaran granitoids, neither mentioned nor characterized ferroan suites as a cohesive group of rocks. Nonetheless, some authors have referred to ferroan occurrences as A-type, ferro-potassic and extensional granitoids in Brasiliano and Pan-African belts (e.g. Ferré *et al.* 1998; Guimarães *et al.* 2005; Santos *et al.* 2014; Lima *et al.* 2017). The ferroan granitoids have geochemical signatures similar to those described as Group 3 and 4 of Guimarães *et al.* (2004).

This study reports new ferroan intrusions along the Coxixola Shear Zone and compares with already known ferroan (A-type and ferro-potassic) intrusions in the Transversal subprovince of the Borborema Province. We present new geochronological (U-Pb by LA-ICP-MS and SHRIMP), isotope (Lu-Hf and Sm-Nd) and geochemical data to discuss reasonable sources, tectonic setting and compare our data with coeval geological records on regional scale. The aim of this paper is to show that ferroan granitoids can occur in distinct tectonic regimes and are widespread in the Borborema Province and its counterparts in Africa, in pre-drift reconstructions.

2. Geology of the Borborema Province

The Borborema Province, in pre-drift reconstructions, lies adjacent to the Pan-African fold Belts (Figure 1) (De Wit *et al.* 1988; Brito Neves *et al.* 2000; Toteu *et al.* 2001). It comprises three subprovinces (Figure 2(a)) which are subdivided into domains (Van Schmus *et al.* 1995, 2008, 2011): 1) the Northern subprovince lies north of the Patos shear zone and comprises the Médio Coreaú, Ceará Central and Rio Grande do Norte domains; 2) the Transversal subprovince occurs between the Pernambuco and Patos shear zone, comprising the Rio Capibaribe, Alto Moxotó, Alto Pajeú and Cachoeirinha-Salgueiro domains; 3) the Southern subprovince stands between the Pernambuco shear zone and the São Francisco craton, and contains the Riacho do Pontal, Sergipano and Pernambuco-Alagoas domains. The studied plutons are located in the Transversal subprovince.

Basement rocks of the BP consist dominantly of Paleoproterozoic orthogneisses with TTG affinities and ages within 2.5–2.0 Ga (Santos 1995; Van Schmus *et al.* 1995, 2011, Martins *et al.* 1998, 2009, Fetter 1999; Brito Neves *et al.* 2001; Cavalcante *et al.* 2003; Neves *et al.* 2006a, 2015, Souza *et al.* 2007; Sial *et al.* 2008; Santos *et al.* 2015). Archean nuclei (3.4–2.7 Ga) have been reported in the North and South subprovinces (Dantas *et al.* 1998, 2004, 2013; Fetter 1999; Fetter *et al.* 2000; Oliveira *et al.* 2010; Hollanda *et al.* 2015).

Small volume of granite (orthogneisses), meta-anorthosites and rare supracrustal sequences with Statherian – Calymmian ages (1.8–1.52 Ga) have been reported in the North (Sá *et al.* 1995; Santos *et al.* 2008b; Hollanda *et al.* 2011) and in the Transversal (Van Schmus *et al.* 1995; Accioly *et al.* 2000; Sa *et al.* 2002; Santos *et al.* 2015) subprovinces.

The Tonian evolution of the BP was marked by intrusion of granites and bimodal volcanic suites including pyroclastic, intercalated with metapelites, marbles and banded iron formations (Brito Neves *et al.* 2001; Kozuch 2003; Guimaraes *et al.* 2012, Guimarães *et al.* 2016). So far, no consensus has been reached regarding the tectonic setting of the Tonian granitoids and sequences. Some authors refer to a magmatic arc with possible back-arc association (Brito Neves *et al.* 2000; Kozuch 2003; Oliveira *et al.* 2010; Santos *et al.* 2010; Van Schmus *et al.* 2011; Caxito *et al.* 2014a), other authors refer to rift related setting, with generation of A-type granites and bimodal volcanism (Guimaraes *et al.* 2012, Cruz and Acciolly 2013; Guimarães *et al.* 2016). Tonian magmatism has been reported in the Transversal and South subprovince.

The Brasiliano/Pan-African event (650– ca 550 Ma) is represented by supracrustal sequences with maximum deposition age between the Cryogenian-Ediacaran interval. The peak of regional metamorphism took place under amphibolite conditions (high T, medium to low P), and occurs between 630–610 Ma (Neves *et al.* 2006a), along with the development of flat-lying foliation and intrusion of several pre- to syn-orogenic plutons (Neves *et al.* 2006b; Sial *et al.* 2008; Ferreira *et al.* 2011; Guimarães *et al.* 2011, Silva Filho *et al.* 2016, Silva *et al.* 2016). Despite the numerous studies, there is no consensus on concerning the tectonic evolution of the Brasiliano event. Models refer to collage of tectonostratigraphic terranes (Santos 1995; Brito Neves *et al.* 2000), closure of large oceans between the Borborema and cratonic landmasses or subduction model (Oliveira *et al.* 2010; Araújo *et al.* 2014; Caxito *et al.* 2014b), and convergence of small continental blocks after extension of a pre-existing continent, with minor consumption of oceanic lithosphere or intracontinental model (Neves 2003, 2011, 2015).

According to Guimarães *et al.* (2004) and Silva Filho *et al.* (2010), the high-K calk-alkaline and shoshonitic

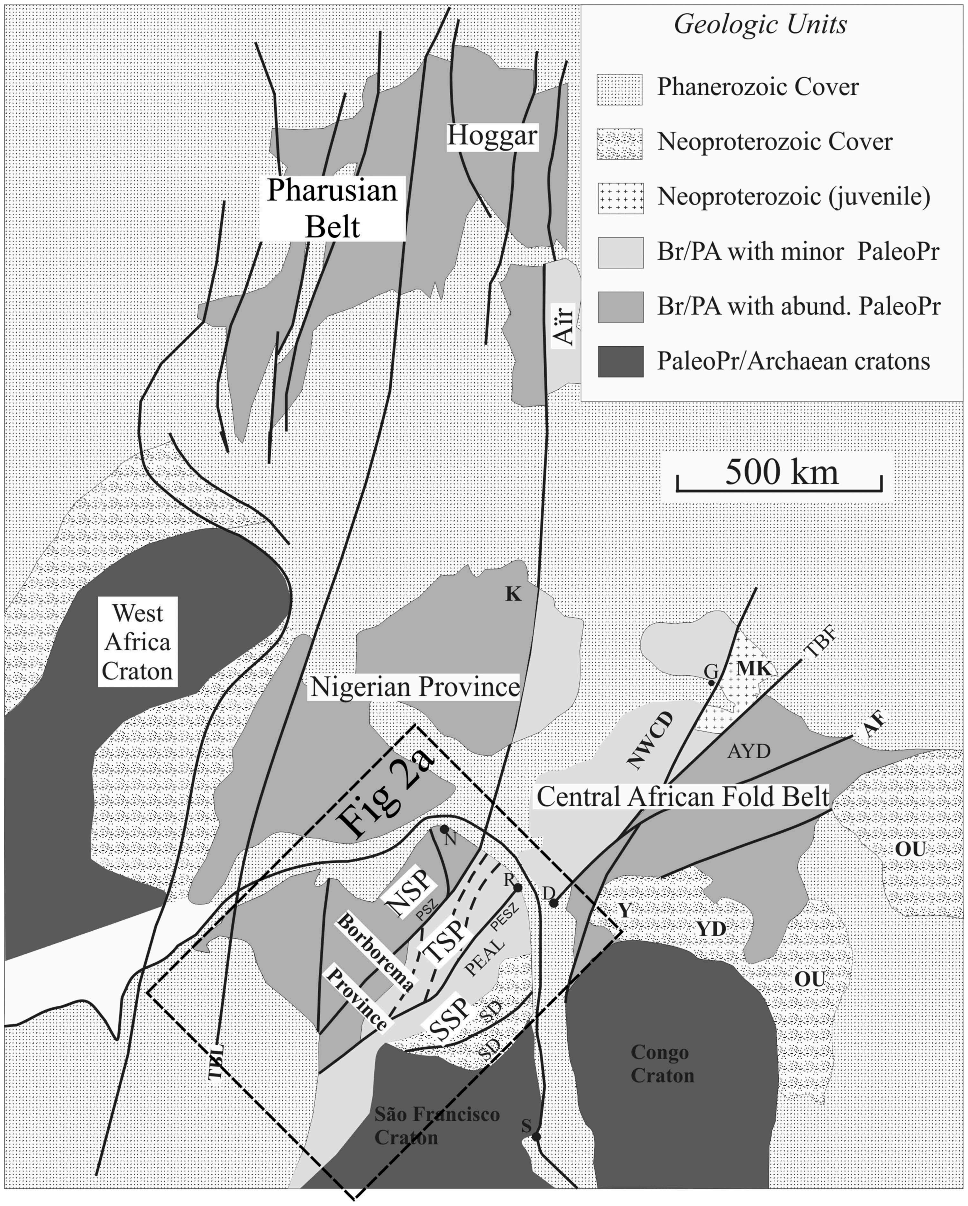

Figure 1. Sketch map of a part of west Gondwana in pre-drift reconstructions modified from Van Schmus *et al*. (2008) (Legend: BR/PA, Brasiliano/Pan-African belts; PaleoPr, Paleoproterozoic crust. Subprovinces and domains: NSP, North subprovince; TSP, Transversal subprovince; SSP, South subprovince; PEAL, Pernambuco-Alagoas domain; SD, Sergipano domain; MK, Mayo Kebi terrane; NWCD, NW Cameroon domain; AYD, Adamawa-Yadé domain; YD, Yaoundé domain; OU, Oubanguides fold belt. Shear zones andfaults: PaSZ, Patos shear zone; PeSZ, Pernambuco shear zone; TBL, Transbrasiliano Lineament; TBF, Tchollirė-Banyo fault; AF, Adamawa Fault. Cities: N, Natal; R, Recife; S, Salvador; D, Douala; G, Garoua; K, Kaduna area of Nigeria).

granitoids with zircon ages between 590–581 Ma mark the transition between the flat-lying regime and the transcurrent event. The authors also propose that these plutons post-date an interval of migmatization related to the metamorphic peak. Vauchez *et al*. (1995) and Neves *et al*. (1996), (2000a)) propose that such intrusions could nucleate the shear zones, since incompletely solidified plutons represent rheological heterogeneities and induce strain localization.

Post-collisional plutons ca. 570 Ma are reported in the North and Transversal subprovinces. They are high-K calc-alkaline to alkaline granitoids syn- to late-transcurrence (Guimarães *et al*. 2004, Guimaraes *et al*. 2009). Emplacement was assisted by synchronous movements of strike-slip shear zones setting up extensional spots (Guimaraes *et al*. 2009; Santos *et al*. 2014; Lages *et al*. 2016; Lima *et al*. 2017). Coeval ultrapotassic intrusions occur in the west sector of the Transversal subprovince (Ferreira *et al*. 1997, 1998, Sial and Ferreira 2015).

The final stages of the Brasiliano orogeny (ca. 550–510 Ma) are marked by the intrusion of extension- or uplift-related A-type granites and sub-volcanic bimodal

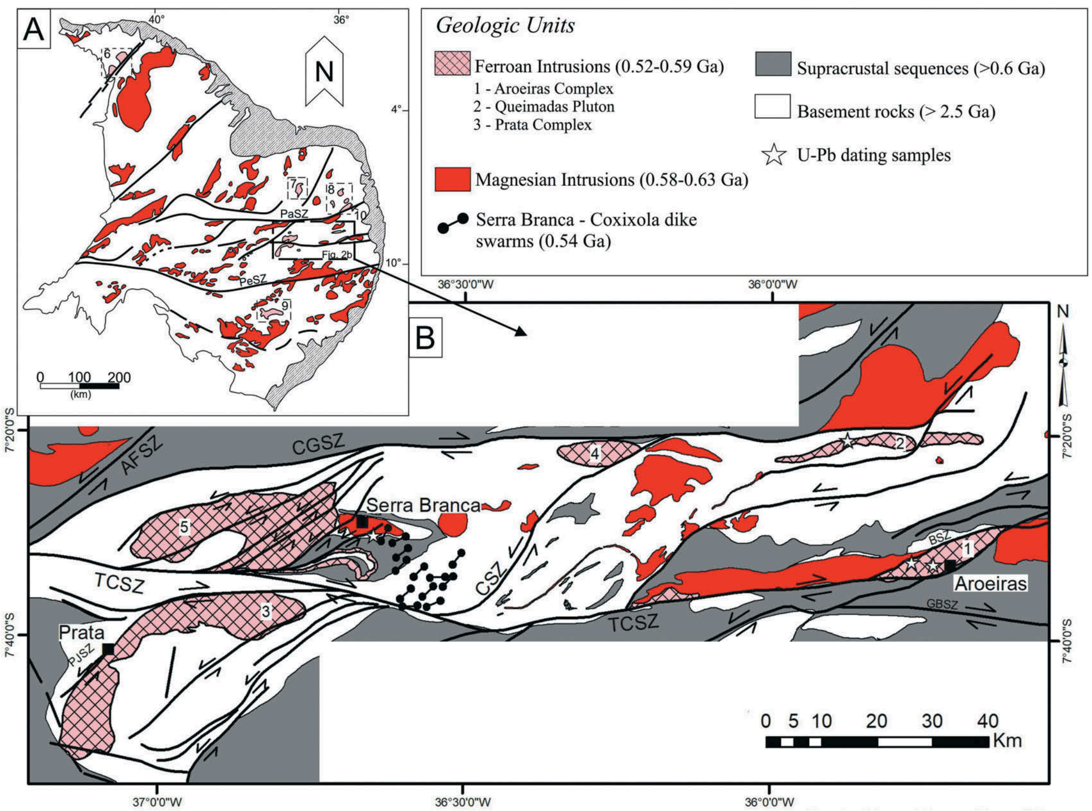

Figure 2. (a) Sketch map of the Brasiliano intrusions in the Borborema Province. Abbreviations: PaSZ – Patos Shear Zone, PeSZ – Pernambuco Shear Zone; Ferroan intrusions: 6- Mucambo and Meruoca Plutons (Santos et al., 2008a; Archanjo *et al*. 2009), 7- Acari Pluton (Archanjo *et al*. 2013; Nascimento *et al*. 2015), 8- Solânea and Dona Inês Plutons (Guimaraes *et al*. 2009), and Riachão Mafic rocks (Guimarães *et al*. 2017), 9-Águas belas Pluton (Silva Filho *et al*. 2010), 10- Pilõezinhos Pluton (Lima *et al*. 2017); (b) Simplified geological map with the studied Intrusions, country rocks and associated shear zones of the Transversal subprovince. Abbreviations: AFSZ – Afogados da Ingazeira Shear Zone, TCSZ – Coxixola Shear Zone, CGSZ – Campina Grande Shear Zone, CSZ – Cabaceiras Shear Zone, PJSZ – Prata Shear Zone, BSZ – Batista Shear Zone, GBSZ – Gado Bravo Shear Zone. Ferroan intrusions: 1- Aroeiras Complex (this paper); 2- Queimadas Pluton (Almeida *et al*. 2002, this paper); 3- Prata Complex (Melo, 1997; Guimarães *et al*. 2005; Hollanda *et al*. 2010; this paper), 4- Bravo Pluton (Lages *et al*. 2016); 5- Serra Branca Pluton (Santos *et al*. 2014).

magmatism, in the Transversal subprovince (Guimarães *et al*. 2004, 2005). Monié *et al*. (1997), in the Northern subprovince, demonstrated the swift uplift of the 2.7 Ga granulites of Granja Massif with $^{40}Ar/^{39}Ar$ biotite plateau ages of 558 ± 3 Ma, confirmed by Fetter (1999) with a precise Sm-Nd isochron (plagioclase-whole rock-garnet) of 557 ± 1 Ma. Fetter (1999) and Guimarães *et al*. (2005) suggest that the late-Ediacaran and early-Cambrian magmatic records are coeval with the deposition of pull-apart basins in the Northern and Transversal subprovinces.

3. Geological setting of ferroan intrusions

3.1. Aroeiras Complex

The Aroeiras Complex (Figures 1 and 2(b)) intruded into a Neoproterozoic Pluton (Serra do Inácio Pereira), metapelites and marbles of the Surubim Complex, and Rhyacian orthogneisses and migmatites. It comprises several dikes, sheets, small dioritic bodies and an ENE-WSW trending main pluton, emplaced during synchronous activities of E-W trending dextral sense Coxixola shear zone and NE-SW trending sinistral sense Batista shear zone. Such structural context is propitious to the development of extensional sites and emplacement of granitic rocks (Guimaraes *et al*. 2009; Santos *et al*. 2014; Lages *et al*. 2016; Lima *et al*. 2017).

The Aroeiras Complex encompasses porphyritic to equigranular biotite-hornblende monzogranite and biotite syenogranite (Figures 3 and 4(b)), the main accessory phases are prismatic crystals of allanite and zircon, acicular apatite and ilmenite crystals mantled by sphene. Microgranular mafic enclaves (MME), composed of hornblende-biotite-diorite and quartz-diorite are common (Figure 4(a)). Droplets of ovoid MME with crenulated borders, double enclave relations, granitic

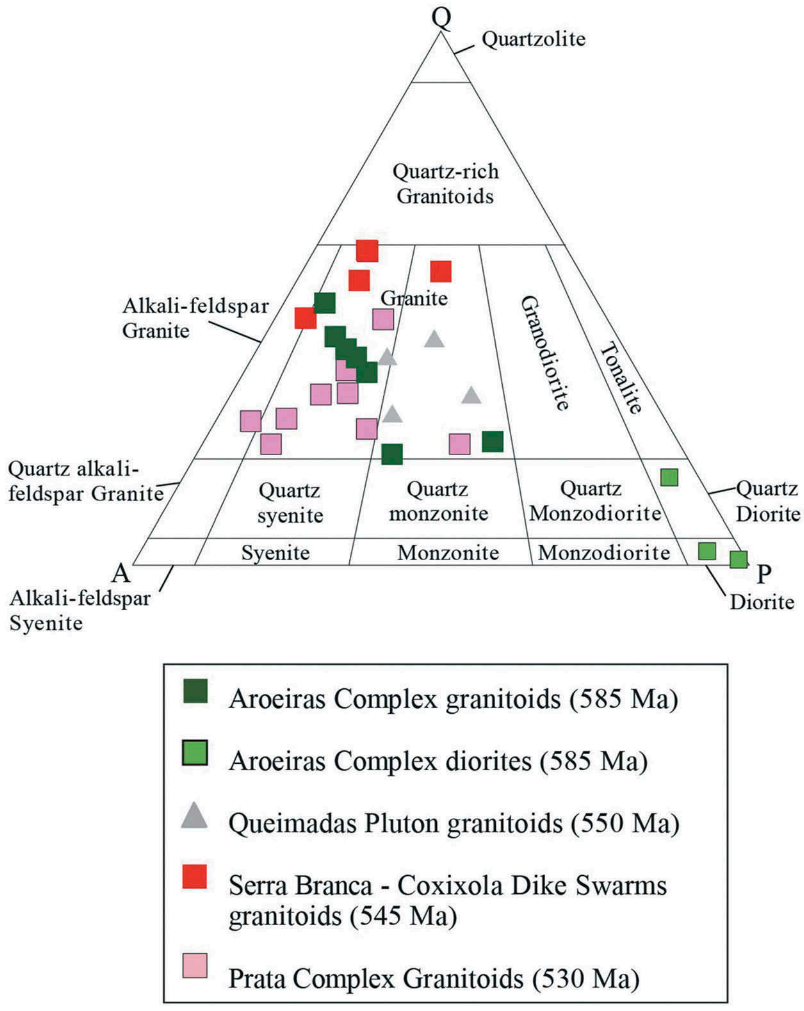

Figure 3. Modal classification of the studied ferroan suites in the Transversal subprovince.

venules, and hybrid rocks with rapakivi-like texture are indicative of mingling and mixing processes that acted throughout the evolution of the Aroeiras granitoids.

3.2. Queimadas Pluton

The Queimadas Pluton (Figure 2(b)) intruded Rhyacian gneisses of tonalitic to granitic composition and comprises an E-W elongated 50 km^2 body, showing S-C dextral foliation with C foliation plan parallel to the E-W trending branch of the Campina Grande Shear Zone. A 60Az trending late transcurrent dextral sense shear zone disrupts the body in a mega-boudin-like shape (Almeida *et al*. 2002).

Petrographically, it consists of porphyritic biotite ± amphibole monzogranites to syenogranites (Figure 3) and the main accessory phases are large euhedral crystals of allanite, apatite, prismatic or rounded crystals of zircon, subhedral crystals of ilmenite hosted by biotite or amphibole, and rare monazite crystals. Mafic phases (amphibole ± biotite) represent less than 10%. Quartz-monzonites and quartz-diorites occur close to the contact with the country rocks, and MME are locally observed in the porphyritic monzogranites and syenogranites (Almeida *et al*. 2002).

Almeida *et al*. (2002) suggest that the pluton was deformed under brittle-ductile conditions of the transcurrent event during the Brasiliano (=Pan-African) orogeny. Textural aspects of ductile deformation are represented by quartz ribbons and mosaic texture, kinks of biotite, disrupted sigmoidal porphyroclasts of plagioclase with patchy extinction, while necking, disruption and boudin-like shape of the Queimadas Pluton are result of the brittle system.

3.3. Serra Branca – Coxixola dike swarms

The Serra Branca – Coxixola dike swarms (Figure 2(c)) intruded Paleoproterozoic orthogneisses, Neoproterozoic

Figure 4. Field aspects of the studied ferroan intrusions. (a) Mingling of hbl-bt diorite with bt syenogranite in the Aroeiras Complex; (b) Petrographic granitic varieties, coexisting porphyritic and equigranular granites from the Aroeiras Complex; (c) Leucocratic dike from the Serra Branca – Coxixola region cross-cutting flat-lying foliation of supracrustal sequences; (d) Dikes from the Serra Branca – Coxixola swarms associated with subvolcanic mafic rocks.

supracrustal sequences and magnesian alkali-calcic Ediacaran plutons of the Transversal subprovince. The main dike population trends NE-SW and cross-cuts the flat-lying foliation of supracrustal sequences (Figure 4(c)) and basement rocks. Close to the dextral sense E-W trending Coxixola Shear Zone, dike swarms intruded concordant with the steeply-dipping mylonitic foliation, but evidence of deformational processes were nearly absent. The dike sets comprise porphyritic hornblende-biotite granite and equigranular biotite granites associated with subvolcanic mafic dikes (Figure 4(d)).

3.4. Prata Complex

The Prata Complex (Figures 2(b) and 3) intruded Siderian to Rhyacian orthogneisses and migmatites from the Transversal subprovince. It contains several granitic intrusions, as dikes and elongated stocks (Guimarães *et al.* 2005; Hollanda *et al.* 2010). Swarms of MME occur near the eastern boundary of the Complex and follow the NNE and E-W trend of syn-plutonic dolerite dikes. Solid state deformation is rare and restricted to the western boundary of the Prata Complex, where it adjacent to the Prata – Jabitacá Shear Zone (Figure 2(b)).

Petrographically, biotite syenogranites and hornblende-biotite monzogranites (Figure 3) are the main facies. The mafic petrographic facies comprise monzodiorite, quartz monzonite, diorite and norite. Enclave swarms of norite, showing evidence of magma mixing with felsic granites, divide the Prata Complex into north and south intrusions (Guimarães *et al.* 2005). The southern body, the Santa Catarina Pluton comprises biotite syenogranites, while the Sumé Pluton, to the north, comprises hornblende-biotite monzogranites (Hollanda *et al.* 2010). The main accessory phases are allanite rimmed by epidote, titanite, apatite and zircon. Several MME and syn-plutonic dolerite dikes are observed in the SE limit of the Sumé Pluton, displaying crenulated contacts and ovoid feldspar crystals mantled by plagioclase (rapakivi-like texture). Such characteristics are indicative of mingling and mixing processes between granitic and dioritic magmas (Guimarães *et al.* 2005).

4. Analytical procedures

4.1. Mineral chemistry

Mineral compositions described in this paper include those from this work (Aroeiras and Serra Branca – Coxixola dike swarms) and from the literature ie. Queimadas Pluton (Almeida *et al.* 2002) and Prata Complex (Guimarães *et al.* 2005). Representative analyses of biotite are shown in Supplementary Table 1, while representative analyses of amphibole are in Supplementary Table 2.

New major element compositions for individual mineral phases (amphibole and biotite) were obtained by electron microprobe analyses and performed on C-coated thin sections using a JEOL JXA-8600S microprobe (University of São Paulo, Laboratório de Microssonda Eletrônica), under 15kv accelerating voltage and 20nA beam current, and a JEOL JXA-8230 microprobe from the University of Brasília, under 15kv accelerating voltage and 10nA beam current.

4.2. Whole-rock geochemistry

Major elements analyses of samples from the Aroeiras Pluton and the Serra Branca – Coxixola dike swarms were obtained by $LiBO_2$ fusion ICP-AES (Inductively Coupled Plasma Emission Spectrometry) and trace elements concentrations by $LiBO_2$ fusion ICP-MA (Inductively Coupled Plasma Mass Spectrometry) at Acme Laboratories Canada. Representative analyses and standards are shown in Supplementary Table 3, detection limits are available online in the Acme Laboratories brochure.

Whole-rock compositions of the Queimadas Pluton and Prata Complex included in this work were collected from the literature, and trace element data were recalculated to reasonable comparison (Almeida *et al*. 2002; Guimarães *et al*. 2005).

4.3. Sm-Nd isotopes

Bulk rock Sm-Nd Isotopic analyses were carried out at the University of Brasília Geochronology Laboratory (Supplementary Table 4). First, REEs were separated as a group, using cation-exchange columns, then Sm and Nd were isolated using columns loaded with HDEHP (di-2-ethylhexyl phosphoric acid) supported on Teflon powder (Richard *et al*. 1976). Sm and Nd samples were loaded onto Re filaments and the isotopic analyses were carried out in a Finnigan MAT-262 mass spectrometer. Uncertainties on Sm/Nd and $^{143}Nd/^{144}Nd$ ratios were based on repeated analyses of international rock standards BCR-1 and BHVO-1. Supplementary data on procedures can be found in Gioia and Pimentel (2000).

Isotopic data from the Queimadas pluton and Prata Complex were compiled from literature (Almeida *et al*. 2002; Guimarães *et al*. 2005).

4.4. U-Pb isotopes

Zircon grains were separated using conventional techniques. Morphology of zircons was studied using BSE (back-scattered electron) and CL (cathodoluminescence) images.

In situ dating of the porphyritic hornblende-biotite granite (MA-50) from the Serra Branca – Coxixola dike swarms was performed using a Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) from the Federal University of Ouro Preto (UFOP), and a deformed granite from the Aroeiras Comples (ARO-103) was analysed at the LA-ICP-MS from the Brasilia University (Supplementary Table 5).

SHRIMP analyses were carried out at the University of São Paulo (biotite-syenogranite from the Aroeiras Pluton, sample ARO-01) and the Australian National University (monzogranite from the Queimadas Pluton, sample NA-97). SHRIMP analyses are available on Supplementary Table 6.

4.5. Lu-Hf isotopes

Lu-Hf isotope analyses were carried out in the Isotope Geology Laboratory of the Federal University of Ouro Preto (Supplementary Table 7), following the procedures of Matteini *et al*. (2010). Hafnium model ages were calculated using a double staged evolution. Hf isotope data were obtained in zircon grain spots with well-defined magmatic crystallization age, since different age components will have different Hf isotope compositions (Vervoort and Kemp 2016). The $\varepsilon Hf_{(t)}$ and the depleted model age were calculated using the (λ) decay constant of 1.867×10^{-11} (Soderlund *et al*. 2004). Chondritic values of $^{176}Hf/^{177}Hf = 0.0336$ and $^{176}Lu/^{177}Lu = 0.282785$ (Bouvier *et al*. 2008). Model depleted mantle with present day $^{176}Hf/^{177}Hf = 0.28325$ and $^{176}Lu/^{177}Hf = 0.0388$ (Griffin *et al*. 2000; Andersen *et al*. 2009), mafic and felsic crust $^{176}Lu/^{177}Hf$ ratios from Pietranik *et al*. (2008) were used.

5. Mafic mineral chemistry

5.1. Biotite

Biotite compositions of the studied granitoids show Fe# [$Fe_{tot}/(Fe_{tot} + Mg)$] values ranging from 0.60 to 0.9 (Figure 5(a)).

The biotite compositions from the granitoids Aroeiras Complex and Serra Branca – Coxixola dike swarms show Fe# varying from 0.6 to 0.77. In contrast, the biotite compositions of the Queimadas Pluton and Prata Complex exhibit Fe# > 0.8 (Almeida *et al*. 2002; Guimarães *et al*. 2005).

In the FeO*-MgO-Al_2O_3 biotite discriminant diagram (Figure 5(b)) (Abdel-Rahman 1994), biotite from the Aroeiras Complex and Serra Branca – Coxixola dike

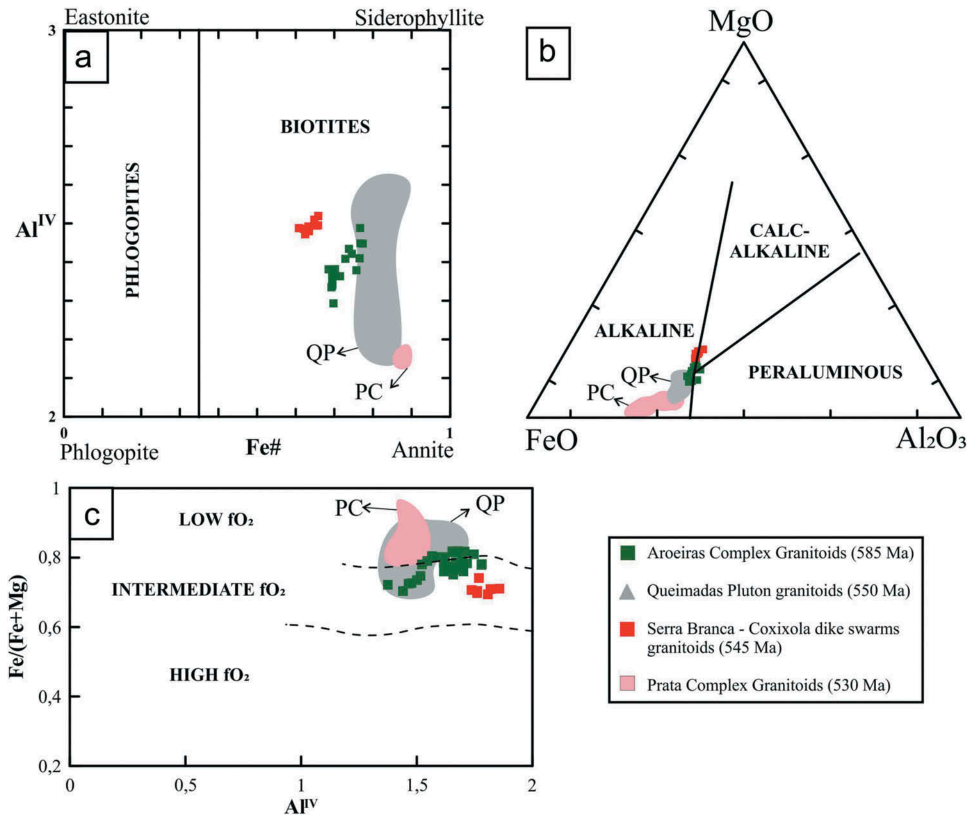

Figure 5. (a) Biotite compositions of Aroeiras Complex and Serra Branca – Coxixola dike swarms compared to mineral compositions of the Queimadas Pluton and Prata Complex, QP – field of the Queimadas biotites, PC – field of the Prata biotites; (b) Biotite compositions of Aroeiras Complex and Serra Branca – Coxixola dike swarms compared to the Queimadas Pluton and Prata Complex samples, on the FeO-MgO-Al2O3 diagram with fields after Abdel-Rahman (1994), Abbreviations QP – field of the Queimadas biotites, PC – field of the Prata biotites; (c) Composition of amphiboles from the Aroeiras Complex and Serra Branca Coxixola dike swarms granitoids in terms of Fe/(Fe + Mg) versus AlIV. Fields of fO2 (Anderson and Smith 1995) and composition of hornblende from Ediacaran and Cambrian ferroan granitoids of the Queimadas Pluton (Almeida *et al.* 2002) and Prata Complex (Guimarães *et al.* 2005) from the Transversal Subprovince, QP – field of the Queimadas amphiboles, PC – field of the Prata amphiboles.

swarms plots in the boundary of the calc alkaline and alkaline (Serra Branca – Coxixola dike swarms), and peraluminous and alkaline fields (Aroeiras). Biotite of the Prata Complex and Queimadas Pluton (Almeida *et al.* 2002; Guimarães *et al.* 2005) shows a distinctly iron-richer character for these rocks, plotting within the alkaline field.

5.2. Amphibole

Amphiboles from the Aroeiras Complex and Serra Branca – Coxixola dike swarms have been classified in accordance with the scheme proposed by Leake *et al.* (1997). Fe^{2+} and Fe^{3+} were calculated according to Holland and Blundy (1994), with Fe^{2+}/Fe^{3+} estimation assuming Σ13 cations.

Amphibole compositions in the studied granitoids correspond to Hastingsite, Fe-Edenite and Fe-Tschermakite.

Oxygen fugacity is believed to have a strong role on the chemistry of calcic amphiboles. With increasing oxygen fugacity amphiboles crystallizing from a magma become Mg-richer. Thus, amphiboles with high Fe-number [$Fe_{tot}/(Fe_{tot} + Mg)$] are considered to have formed under low oxygen fugacities (Wones 1981; Anderson and Smith 1995). In the Aroeiras Complex and Serra Branca – Coxixola dike swarms, the amphiboles have $Fe_{tot}/(Fe_{tot} + Mg)$ ratios ranging from 0.69 to 0.82, suggesting intermediate to low oxygen fugacities, and in the Prata Complex and Queimadas Pluton the $Fe_{tot}/(Fe_{tot} + Mg)$ ratios range between 0.82 and 0.93, suggesting low fO_2 conditions (Figure 5(c)).

6. Geochemistry

Most granitoids have SiO_2 contents higher than 70%, high K_2O contents (>4%), and K_2O/Na_2O ratios >1. According to the geochemical classification of Frost *et al.* (2001), these granitoids are ferroan (Figure 6), with $FeO_t/(FeO_t + MgO)$ ratios >0.81. The studied granitoids are metaluminous to slightly peraluminous, showing

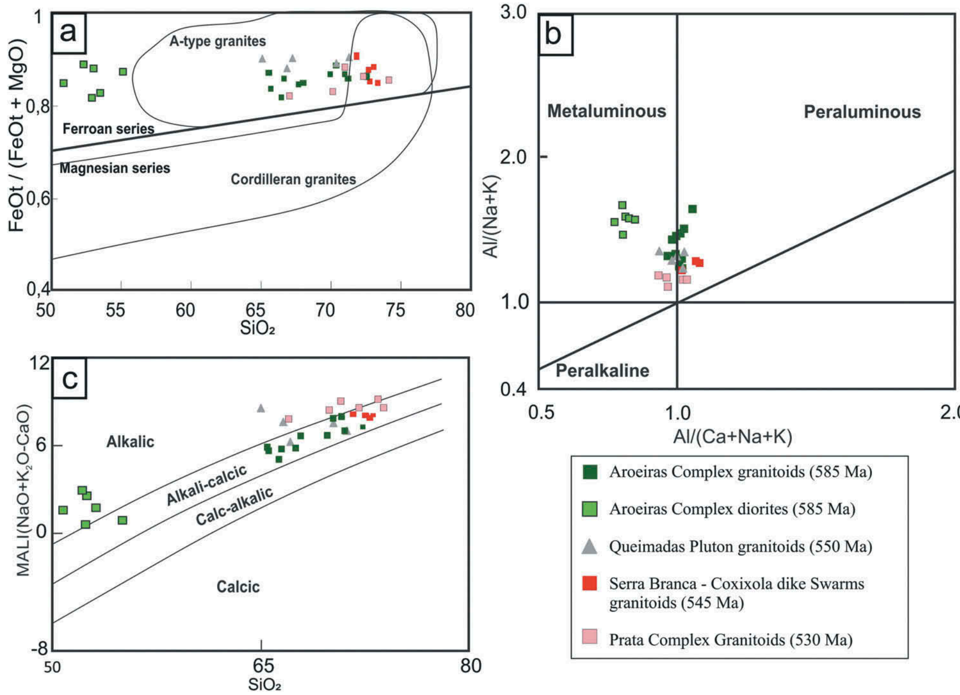

Figure 6. Granitoids chemical classification after Frost *et al.* (2001). (a) Studied suites in the FeOtot/(FeOtot + MgO) versus silica diagram; (b) Studied suites in the Alumina Saturation index diagram; (c) Plot of the studied suites on the modified alkali-lime index versus SiO2 diagram.

alumina saturation index (ASI) ranging from 0.93 to 1.06. They display alkali-calcic to slightly alkalic character, modified alkali-lime index (MALI) between 4.86 and 8.8. Dioritic rocks of the Aroeiras Complex are metaluminous (ASI between 0.79 and 0.87), alkalic (MALI from 1.08 to 2.94) and have $FeO_t/(FeO_t + MgO)$ ratios >0.81.

The Aroeiras Complex granites REE patterns, normalized to the chondrite values of Nakamura (1974) are fractionated (Figure 7), with $(Ce/Yb)_N$ ratios ranging from 8.15 to 21.15, and show negative Eu anomalies (Eu/Eu* = 0.45 to 0.68), while the diorites are less fractionated, with $(Ce/Yb)_N$ ratios between 6.9 and 8.56 and show smaller negative Eu anomalies (Eu/Eu* = 0.81–0.84). The granitoids of the Queimadas Pluton display negative Eu anomalies and $(Ce/Yb)_N$ ratios from 10.14 to 17.47. The Serra Branca – Coxixola samples exhibit significant negative Eu anomalies (Eu/Eu* = 0.23 to 0.34) and $(Ce/Yb)_N$ ratios ranging from 30.58 to 104.39. The REE patterns of the Prata Complex granitoids are fractionated, with $(Ce/Yb)_N$ ratios ranging between 6.8 and 19.76 and are characterized by negative Eu anomalies (Eu/Eu* = 0.21–0.65).

The trace element patterns (Figure 8) normalized to the values of Sun and McDonough (1989) display many affinities: variable troughs at Nb and Ta; deep troughs at Sr, P and Ti; and Ba troughs, except for the Aroeiras Complex granitoids. Diorites of the Aroeiras Complex exhibit troughs in Th, Sr and Ti and peaks in Ba, K and P.

The studied granitoids (Figure 9(a)) have high HSFE contents (Zr + Nb + Ce + Y > 350 ppm), and plot on the A-Type granites field of Whalen *et al.* (1987). In the trace-element discrimination diagrams (Pearce *et al.* 1984; Pearce 1996), most of the studied samples plot on the within-plate field and post-orogenic granites (Y + Nb > 50ppm) (Figure 9(b)). However, the most fractionated analysed samples of the Serra Branca – Coxixola dike swarms plot within the VAG and Syn-COLG fields of the Pearce *et al.* (1984) diagram (Figure 9(b)). Samples plotted on the A-Type (Whalen *et al.* 1987) and Within-Plate (Pearce *et al.* 1984) fields exhibit Y/Nb ratios >1.2, equivalent to the A_2-subtype (Eby 1992).

Zircon saturation temperatures of the ferroan studied granites were calculated according to Watson and Harrison (1983) and range from 795.2°C to 895.4°C.

7. U-Pb geochronology

7.1. Aroeiras complex

Two samples of the Aroeiras Complex were dated: 1) deformed monzogranite sample (ARO-103) close to

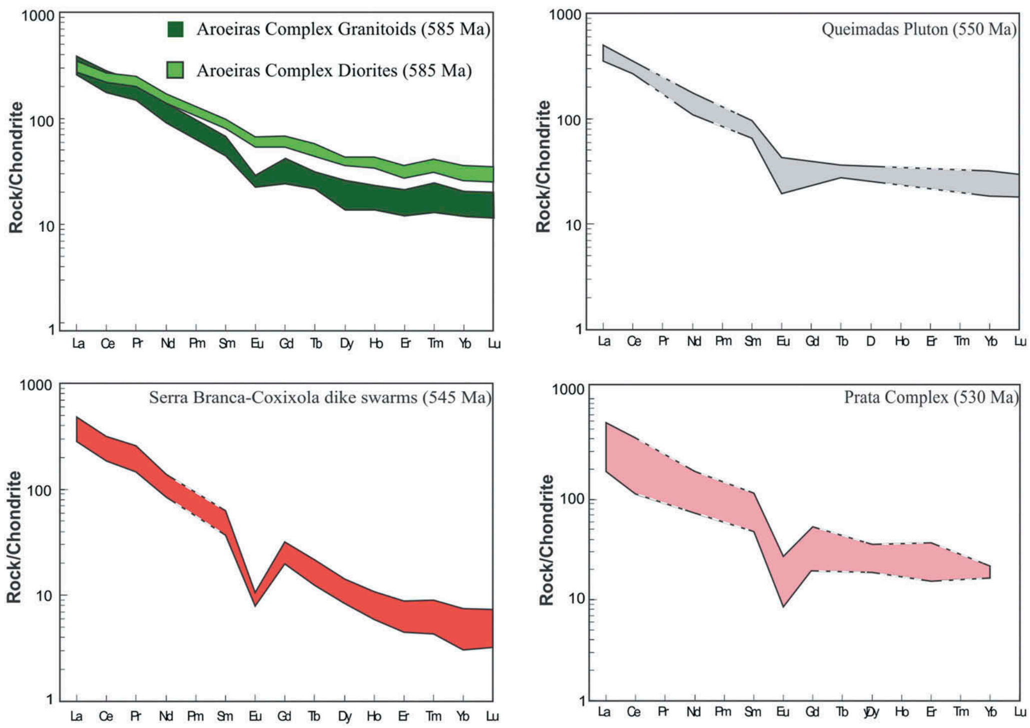

Figure 7. Chondrite-normalized REE patterns (Nakamura 1974) of the ferroan suites.

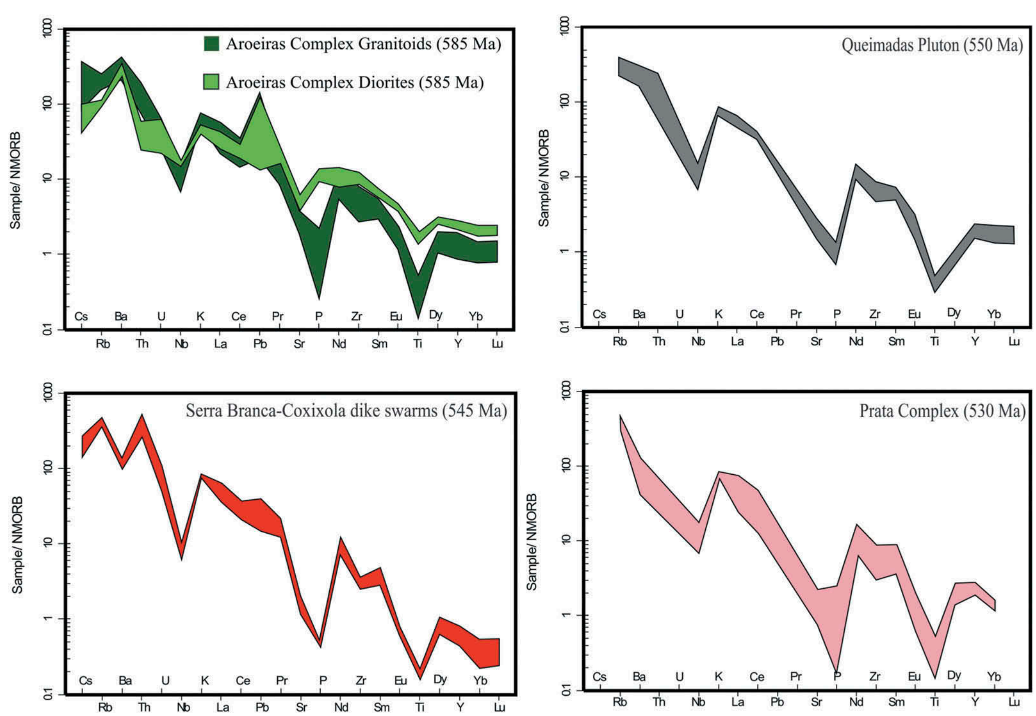

Figure 8. Trace elements abundance diagrams normalized to the values proposed by Sun and McDonough (1989).

the contact with the granitic country rocks of the Serra do Inácio Pereira Pluton (Coordinates of this sample: 7°32′23″S and 35°46′11″W); and 2) a sample from a dike of leucocratic biotite-syenogranite composition (ARO-1A) (Coordinates of this sample: 7° 32′37″S and 35°44′03″W).

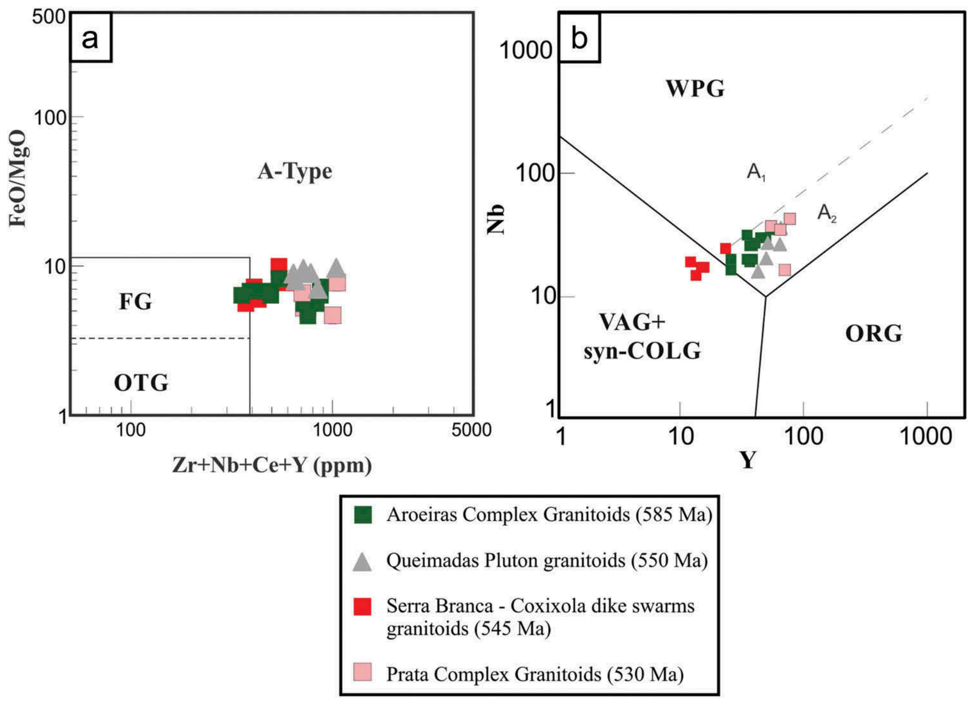

Figure 9. Studied granitoids plot in tectonic discriminant diagrams. (a) FeO/MgO versus Zr + Nb + Ce + Y, fields after Whalen *et al.* (1987); (b) Nb versus Y, fields after Pearce *et al.* (1984). Abbreviations: WPG – Within Plate Granites; VAG – Volcanic Arc Granites; ORG – Ocean Ridge Granites; COLG – Collisional Granites.

7.1.1. ARO-103

A total of 27 grains were analysed comprising 40 spots. The majority of the zircon grains are rounded. Narrow overgrowths were recorded in some grains. The analysed spots show Th/U ratios ranging mainly from 0.208 to 0.663, with few spots, including rim and core, showing Th/U ratios <0.2. Most of the analysed zircon grains exhibit Paleoproterozoic ages (1.7–2.1 Ga). The Neoproterozoic zircons defined two clusters of concordant ages in the concordia diagram: 603 ± 5 Ma (MSWD = 0.16; Probability of concordance = 0.69), and 585 ± 5.6 Ma (MSWD = 1.4; Probability of concordance = 0.24). The age of 585 Ma was obtained from two spots in the core of two distinct grains, and are interpreted as the crystallization age, due to coherence with the geochemical nature of this magmatic complex. Plutons older than 600 Ma in the Transversal subprovince are tonalitic to granodioritic, calc-alkaline and related to the Brasiliano compressional event of the Borborema Province.

7.1.2. ARO-01

A total of 20 spots in the core of 20 grains were analysed. Most of the spots show Th/U ratios >0.2. Zircon grains display variable contents of U, up to 2000ppm. Some crystals exhibit high contents of common Pb, increasing the analytical error, hence making difficult to obtain a precise age. Zircon grains (Figure 10(b)) are euhedral to subhedral (length/width ratios from 5:1 to 5:3), show oscillatory zoning, and some crystals have xenocrystic cores inherited from Mesoproterozoic sources (~1.58 Ga). Eighteen spots an age of 567 ± 12 Ma in the upper intercept when forced to zero (MSWD = 0.5). However, 11 spots show a concordia age of 545 ± 3 Ma (MSWD = 9.6), which we interpreted as the crystallization age.

7.2. Queimadas Pluton

Zircons from the Queimadas Pluton were collected from the same sample that Almeida *et al.* (2002) dated using ID-TIMS (570 ± 24 Ma), a monzogranite located at 7°20′30″S and 35°52′30″W.

7.2.1. NA-97

Zircon grains (Figure 11(a)) are euhedral to subhedral (length/width ratios from 5:1 to 2:1), prismatic and exhibit oscillatory zoning. A sum of 15 grains were analysed and a cluster of 16 spots show a concordia age of 550 ± 5 Ma (MSWD = 0.81; Probability of concordance = 0.848). Although the crystallization age obtained is 20 Ma younger than the data presented by Almeida *et al.* (2002), it still lies within the calculated error.

7.3. Serra Branca – Coxixola dike swarms

A northeast trending porphyritic hornblende-biotite syenogranite dike with dioritic enclaves and mafic

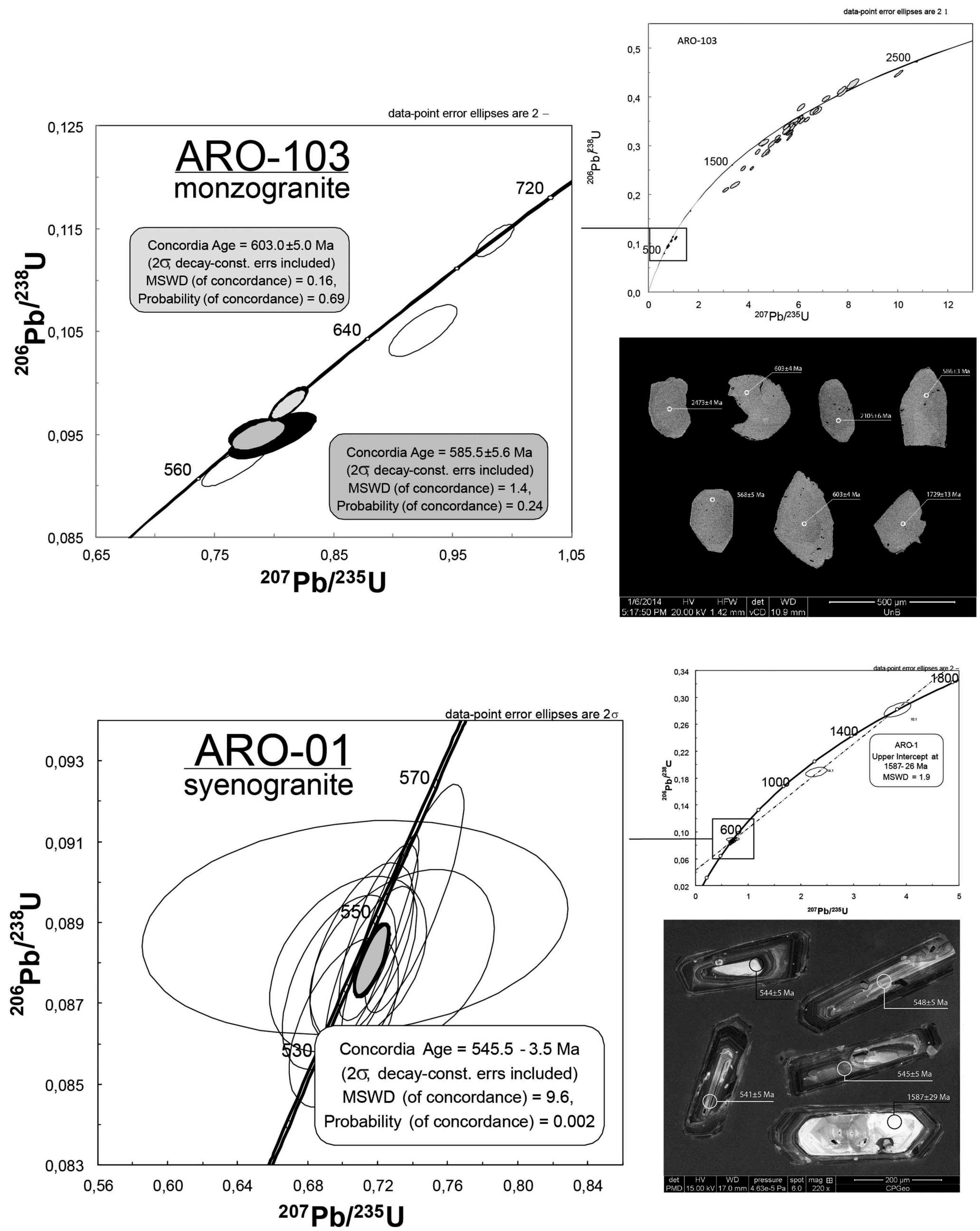

Figure 10. (a) Left: Concordia Diagram of sample ARO-103; Right: full concordia diagram with emphasis on showing inherited Paleoproterozoic zircons and cathodoluminescence images of zircons. Sample localities and details are provided in the text; (b) Left: Concordia Diagram of sample ARO-01; Right: full concordia diagram with emphasis on showing inherited Mesoproterozoic zircons and BSE images of zircons. Sample localities and details are provided in the text.

clots was used to date this sample located at 7°30′42″S and 36°38′51″W.

7.3.1. MA-50

Zircon grains (Figure 11(b)) are prismatic and exhibit oscillatory zoning. Most of the zircon crystals show evidence that they were magmatically resorbed according to the textures described by Corfu *et al.* (2003). An aggregate of 58 zircon spots were analysed in this sample, but 19 spots give a nice cluster of data, defining a concordia age of 545 ± 3 Ma (MSWD = 1.01; Probability of concordance = 0.44). This is interpreted as the crystallization age.

8. Isotope geochemistry (Sm-Nd and Lu-Hf)

8.1. Lu-Hf in zircon

A total of 18 of the 19 spots from the sample MA-50 were used to define the Lu-Hf compositions, the results

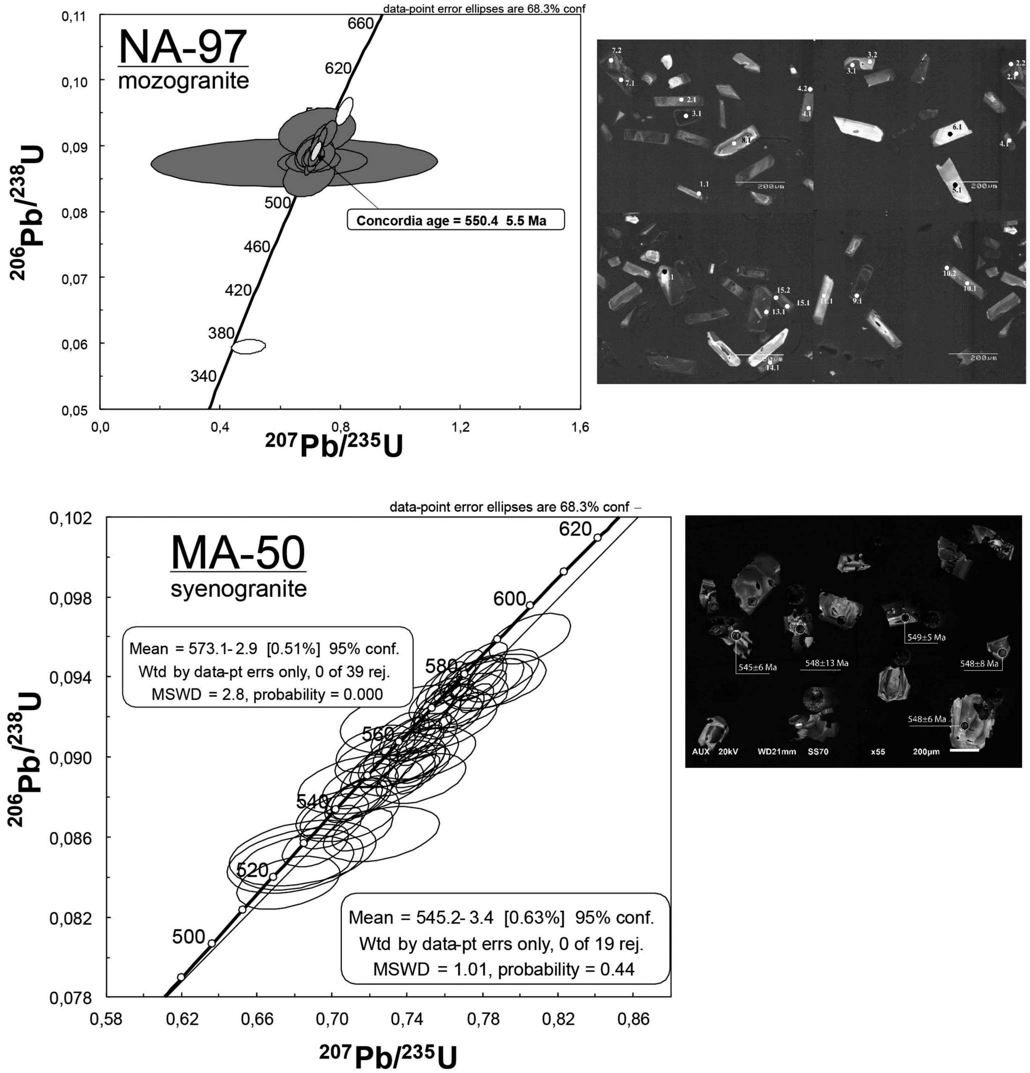

Figure 11. (a) Left: Concordia Diagram of sample NA-97; Right: BSE images of zircons. Sample localities and details are provided in the text; (b) Left: Concordia Diagram of sample MA-50; Right: CL images of zircon crystals. Sample localities and details are provided in the text.

are presented in Figure 12(a). Relatively uniform initial $^{176}Hf/^{177}Hf$ ratios have been observed, ranging from 0.281730 to 0.281789. Samples exhibit very negative $\varepsilon Hf_{(t)}$ values, between −21.6 and −24.8, and Hf T_{DM} model ages are exclusively Paleoproterozoic, varying between 1.97 Ga and 2.12 Ga.

8.2. Sm-Nd

Sm-Nd data were obtained from three samples of the Aroeiras Complex. Data of the Queimadas Pluton and Prata Complex were compiled from Almeida *et al.* (2002) and Guimarães *et al.* (2005), results are shown in Figure 12(b). The Aroeiras Complex samples have T_{DM} model ages in the 2.04–2.15 Ga range, and display very negative $\varepsilon Nd_{(585\ Ma)}$ values ranging from −11.68 to −14.15. The Queimadas Pluton granitoids have T_{DM} model ages similar to those recorded in the Aroeiras Complex (2.07 to 2.2 Ga), but lower $\varepsilon Nd_{(550\ Ma)}$ values, from −16.37 to −17.13. The Prata Complex samples show the oldest T_{DM} model ages, ranging from 2.06 to 2.44 Ga, and remarkably negative $\varepsilon Nd_{(530\ Ma)}$ values (−17.67 and −19.85).

9. Discussion

9.1. Sources of the ferroan intrusions

Ferroan granitic rocks are those with $FeO_t/(FeO_t + MgO)$ ratios higher than subduction-related Cordilleran granitoids. Those are correspondingly more reduced (Frost *et al.* 2001). Most of the ferroan granitoids are referred to as 'A-type' granites, but the term has become confusing due to the wide spectrum of chemical

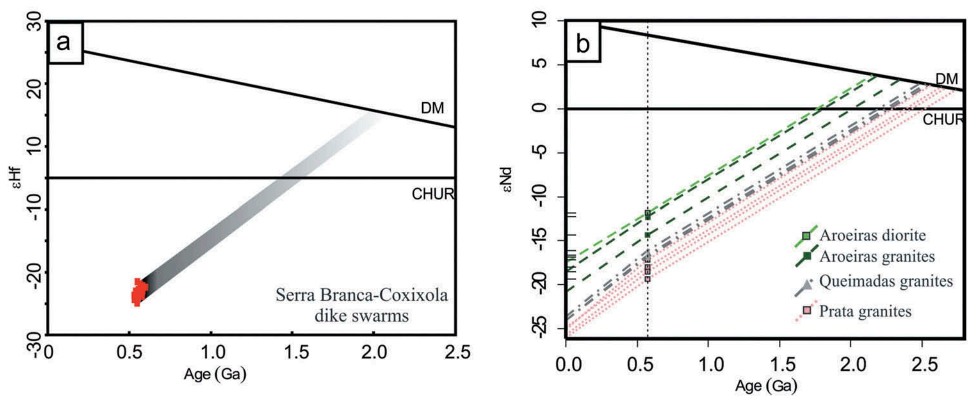

Figure 12. (a) ?Hf plot for zircon grains of the Serra Branca-Coxixola granites; (b) Nd isotopic composition of the studied ferroan suites.

compositions with diverse petrogenesis (Bonin 2007; Frost and Frost 2011).

The Transversal subprovince ferroan granites define two groups: Group 1 – slightly peraluminous to slightly metaluminous, alkali-calcic rocks, with low Fe# mica and crystallized under intermediate oxygen fugacity (Aroeiras Complex and Serra Branca – Coxixola dike swarms); Group 2 – metaluminous to slightly peraluminous, alkalic to alkali-calcic rocks, with high Fe# mica and crystallized under low oxygen fugacity conditions (Queimadas Pluton and Prata Complex).

Frost and Frost (2011) summarized three main models to produce ferroan granitic compositions: 1) Partial melting of quartzfeldspathic crust; 2) differentiation of basaltic magma; 3) partial melting of quartzfeldspathic crust or assimilation and fractional crystallization of basaltic magma.

Experimental studies show that partial melting of quartzfeldspathic crust produce ferroan granitoid compositions by: 1) dehydration melting of magnesian tonalite gneiss containing 20% biotite and 2% hornblende at 10 and 6 kbar (Skjerlie and Johnston 1993); 2) dehydration melting of magnesian tonalites at 950°C, from 4 to 8 kbar (Patiño Douce 1997); 3) vapour-excess melting of ferroan granodiorites performed at 4 kbar (Bogaerts *et al*. 2006).

Except for the Queimadas Pluton, the other studied granitoids exhibit expressive relationships between felsic and mafic rocks. Their genesis could be either related to fractionation from mafic melts, or incomplete mixing between crustal and mantle melts. Field evidences of mingling and mixing between diorites, norites and dolerites with granitic rocks favour interactions between crustal and mantle melts.

9.1.1. Sources of the Queimadas pluton

The T_{DM} model ages (2.07–2.2 Ga; Almeida *et al*. 2002) are similar to those described by Neves *et al*. (2015) for the calc-alkalic TTG suites in the east part of the Transversal subprovince and also in the Northern subprovince (Souza *et al*. 2007). The lack of significant volume of mafic rocks (MME) and geochemical and isotopic signature suggest that the best candidate for the source of the Queimadas granitoids is the lower crust.

The low water contents recorded in the Queimadas granitoids could suggest derivation from dehydrated source, such as granulites (Collins et al., 1982). However, under vapour-absent conditions the required temperatures to promote fusion is higher (>900°C) than those obtained by Almeida *et al*. (2002) using zircon saturation (<835°C).

According to Skjerlie and Johnston (1993), high degrees of partial melting in magnesian tonalite gneiss containing ~20% biotite and ~2% hornblende, under low-pressure, produce high-silica, alkali-calcic, metaluminous to slightly peraluminous ferroan melts, similar to those recorded in the Queimadas.

9.1.2. Sources of the Aroeiras and Prata Complexes

Both complexes show many evidence of the strong interaction between mafic and felsic rocks, favouring partial melting of lower crust (granites) coupled with incomplete mixing with mantle derived melts (diorites, norites and dolerites).

Diorites of both complexes are LILE enriched, show Paleoproterozoic T_{DM} model ages (2.04–2.1 Ga) and strong negative εNd values. These characteristics have been recognized in many plutons of the Borborema Province, several authors attribute these aspects to a lithospheric mantle previously metasomatized by orogenic events (Silva Filho *et al*. 1993; Ferreira *et al*. 1997; Neves and Mariano 1997, 2004; Neves *et al*. 2000b; Mariano *et al*. 2001; Hollanda *et al*. 2003; Guimarães *et al*. 2005). The 2.04 Ga T_{DM} model ages are consistent with the peak of a metamorphic event dated at ca. 2.06–2.04 Ga in the Aroeiras Complex country rocks (Neves *et al*. 2015).

On the other hand, noritic rocks from the Prata Complex show positive εNd values and are LILE poorer. We suggest, in this case, crustal extension build up to the rise of astenospheric mantle. Since norites display the same interactions with felsic melts of the Prata Complex as diorites, the Nd signature of these rocks cannot reflect homogenization with enclosing granites (Guimarães *et al*. 2005). Furthermore, interaction between mafic and felsic melts favours heat, fluids and LILE diffusion from mafic to felsic members, resulting in chemical quenching of the mafic members (Pistone *et al*. 2016). Therefore, the isotopic signature of MME in the Aroeiras and Prata Complexes, should express the lithosphere composition beneath the Borborema Province.

The Aroeiras granitoids exhibit ca. 2.15 Ga T_{DM} Nd model ages and show Meso- to Paleoproterozoic inherited zircons. We suggest that generation of these rocks involved partial melting of Paleoproterozoic TTG rocks, as those described by Neves *et al*. (2015). Mesoproterozoic inherited zircon grains may represent assimilation during the ascent of the Aroeiras granitoids through the crust.

The Aroeiras granitoids could not be generated by simple fractionation processes from dioritic melts. Fractionation from alkalic diorites would lead to strongly alkalic granitic compositions. Since alkali-calcic character is hardly achieved by partial melting of quartzfelspathic rocks, it is likely that besides partial melting from TTG rocks, interactions between intermediate and felsic melts favoured diffusion of LILE from diorites to granites.

A similar source model for the Prata granitoids was proposed by Guimarães *et al*. (2005). However, the older T_{DM} Nd model ages recorded in the Prata granitoids (2.06–2.44 Ga) suggest that the crustal component involved in their source is older than those recorded in the Aroeiras source. This older crustal component could be similar to the granitic to granodioritic orthogneisses with crystallization ages of ca. 2.44 Ga, reported in the area by Santos *et al*. (2015).

9.1.3. Sources of the Serra Branca – Coxixola dikes

The granitoids of the Serra Branca – Coxixola dikes are silica-rich SiO_2 >70%, alkali-calcic and peraluminous. Rocks with analogous compositions were described in collisional settings (Pichavant *et al*. 1988; Visona and Lombardo 2002), and anorogenic settings (Kleeman and Twist 1989; Hildreth *et al*. 1991; Hill *et al*. 1996). Frost *et al*. (2016), compiled petrogenetic models, suggest that in collisional settings such compositions can be reached by either partial melting of pelitic rocks, or in anorogenic settings through partial melting and/or differentiation of tholeiite.

However, the studied granitoids neither display typical peraluminous assemblages with tourmaline and two-mica granites, nor metaluminous granites associated. Thus, the processes involved in their generation should differ from other silica-rich, alkali-calcic, peraluminous granites.

Hafnium model ages point to Paleoproterozoic sources to these rocks (1.9–2.12 Ga). Lithospheric stretching leads to crustal thinning and increases the geothermal gradient (McKenzie 1978), providing the necessary heat to promote limited melting of Rhyacian tonalitic to granodioritic rocks with assimilation of metasedimentary components during their ascent. Small percentages of melts could explain the alkali-calcic nature and assimilation of pelitic sedimentary rocks would contribute to achieve peraluminous compositions.

9.2. Geodynamic implications of the Ferroan granites

Ferroan (A-Type) igneous suites have been reported in continents, oceans and even other terrestrial planets associated with several tectonic contexts and orogenic stages (Bonin 2007), therefore often attributed to extensional tectonics.

9.2.1. Ferroan granites with 590–580 Ma crystallization ages

The Aroeiras Complex (ca. 585 Ma) is coeval with the magnesian high-K calc-alkaline and shoshonitic plutons that mark the transition between the flat-lying foliation and transcurrent event in the Transversal subprovince. It represents the development of early extensional sites related to the transcurrent event or lateral scape of the Brasiliano collision. Conjugate sinistral (NE-SW) and dextral (E-W) shear zones set up extensional sites opportune to emplacement of this type of magmatism.

Lages *et al*. (2016) described 581 Ma ferroan syenogranites associated with diorites, with similar geochemical and isotopic characteristics, further west in the Transversal subprovince. Guimarães *et al*. (2017) reported gabbros and leucogranites intruded into an extensional setting in the Rio Grande do Norte Domain, Northern Subprovince in the same time span (588–-582 Ma). Silva Filho *et al*. (2010) also identified coeval (ca. 588 Ma) extensional magmatism related to the development of strike-slip shear zones in the Pernambuco-Alagoas Domain, from the Southern Subprovince. In the Ribeira Belt, southeastern Brazil, post-collisional (590–580 Ma) A-type granite plutons, derived from enriched subcontinental lithosphere, have been described by Janasi *et al*. (2009).

Extension related magmatism has also been described in several belts of the Pan-African counterpart. Attoh *et al*. (2007) dated carbonatite and alkaline rocks from the Dahomeyide suture zone related to transtensional tectonics with ages between 590 and 580 Ma. Goodenough *et al*. (2014) recorded ca. 588 Ma extension related ferroan granites associated with LILE-enriched diorites and rare metal pegmatites in western Nigeria. Toteu *et al*. (2001) suggested that the transition between the flat-lying foliation event and development strike-slip shear zones occurred ca. 580 Ma, in the Central African Orogenic Belt. Tagne-Kamga (2003) reported extensional ferro-potassic trans-alkaline granites emplaced during the shift from collision to the strike-slip event, in the same orogenic belt.

This 590–580 Ma age interval is represented by granitic magmatism with strong mantle connection, characterized by either magnesian granitoids with fO_2 ranging from high to intermediate conditions, marking the end of the collisional setting, or ferroan granitoids with fO_2 ranging from intermediate to low marking the onset of extensional sites related to strike-slip tectonics (Figure 13).

9.2.2. *Ferroan granites with 570–550 Ma crystallization ages*

In the Transversal subprovince, this age interval represents heterogeneous thinning and partial melting of previously thickened crust, related to post-collisional syn-transcurrent setting, with intrusion of ferro-potassic plutons with little to no mafic input (Figure 13).

Similar intrusions have been described in the ca. 570Ma in the North Subprovince (Guimaraes *et al*. 2009; Archanjo *et al*. 2013; Nascimento *et al*. 2015), and Transversal subprovince ca. 560 Ma (Santos *et al*. 2014; Lima *et al*. 2017). The Queimadas Pluton represents the youngest intrusion of this group ca. 550 Ma. Rocks with similar ages and compositions, emplaced in the same tectonic context have been reported in Pan-African belts, such as syn-transcurrent ferroan alkali-calcic magmatism in the Tuareg Shield (Liégeois and Black 1984) and eastern Nigeria (Ferré *et al*. 1998).

9.2.3. *Ferroan granites with 545–520 Ma crystallization ages*

The granitoids with crystallization ages within this interval comprise the Serra Branca – Coxixola and Aroeiras Complex late dikes (ca. 545 Ma) and Prata Complex (ca. 530 Ma, Hollanda *et al*. 2010). These granitoids record the decrease in strike-slip activity progressing to uplift and transtension (Figure 13), marking the final stages of the Brasiliano – Pan-African event during the Ediacaran – Cambrian transition, with development of intracratonic transtensional basins (Fetter 1999; Oliveira and Mohriak 2003; Pedrosa Jr. *et al*. 2015).

The intrusion of these granitic rocks is often associated with gabbros and intermediate rocks. Juvenile signature of norites associated with the Prata Complex must be related to progressive extension and ascent of asthenospheric mantle.

Hollanda *et al*. (2010) reported coeval intermediate subvolcanic dikes (ca. 548 Ma) and the Uruçu gabbro (ca. 541 Ma) in the Tranversal Subprovince. In the North Subprovince, ferroan Mucambo and Meruoca granites, related to the Jaibaras Basin, were dated at 530–520 Ma (Santos *et al*. 2008a; Archanjo *et al*. 2009).

The 545–520 Ma interval marks major shifts in Gondwana. Extensional magmatism seems to be widespread, and have been reported in some Pan-African belts. Uplift and crustal thinning with intrusion of ferroan granites between 550–520 Ma is reported in the Saldania belt in South Africa (Kisters *et al*. 2002). Azzouni-Sekkal *et al*. (2003) described c. 530 Ma transtensional and uplift related granites marking the final stages of the Pan-African Orogeny in the Tuareg Shield.

10. Conclusions

Ferroan granites in the Transversal subprovince distinguish two geochemical groups in different stages of the Brasiliano Orogeny:

(1) slightly peraluminous to slightly metaluminous, alkali-calcic rocks, with low Fe# mica and amphiboles crystallized under intermediate oxygen fugacity. This group marks shifts in geotectonic settings. For instance, the Aroeiras Complex marks the transition from collisional to strike-slip tectonics (ca. 585 Ma); and the Serra Branca – Coxixola and late leucocratic dikes of the Aroeiras Complex, marks the transition from strike-slip to uplift and transtensional tectonics with development of intracratonic basins (ca. 545 Ma);

(2) metaluminous to slightly peraluminous, alkalic to alkali-calcic rocks, with high Fe# mica and low oxygen fugacity crystallization of amphibole (Queimadas Pluton and Prata Complex). This group is related with fully developed extensional environments. The Queimadas Pluton granitoids are related to heterogenous thinning of previously thickened lithosphere, in post-collisional environments associated with strike-slip shear zones between 570–550 Ma; and the Prata

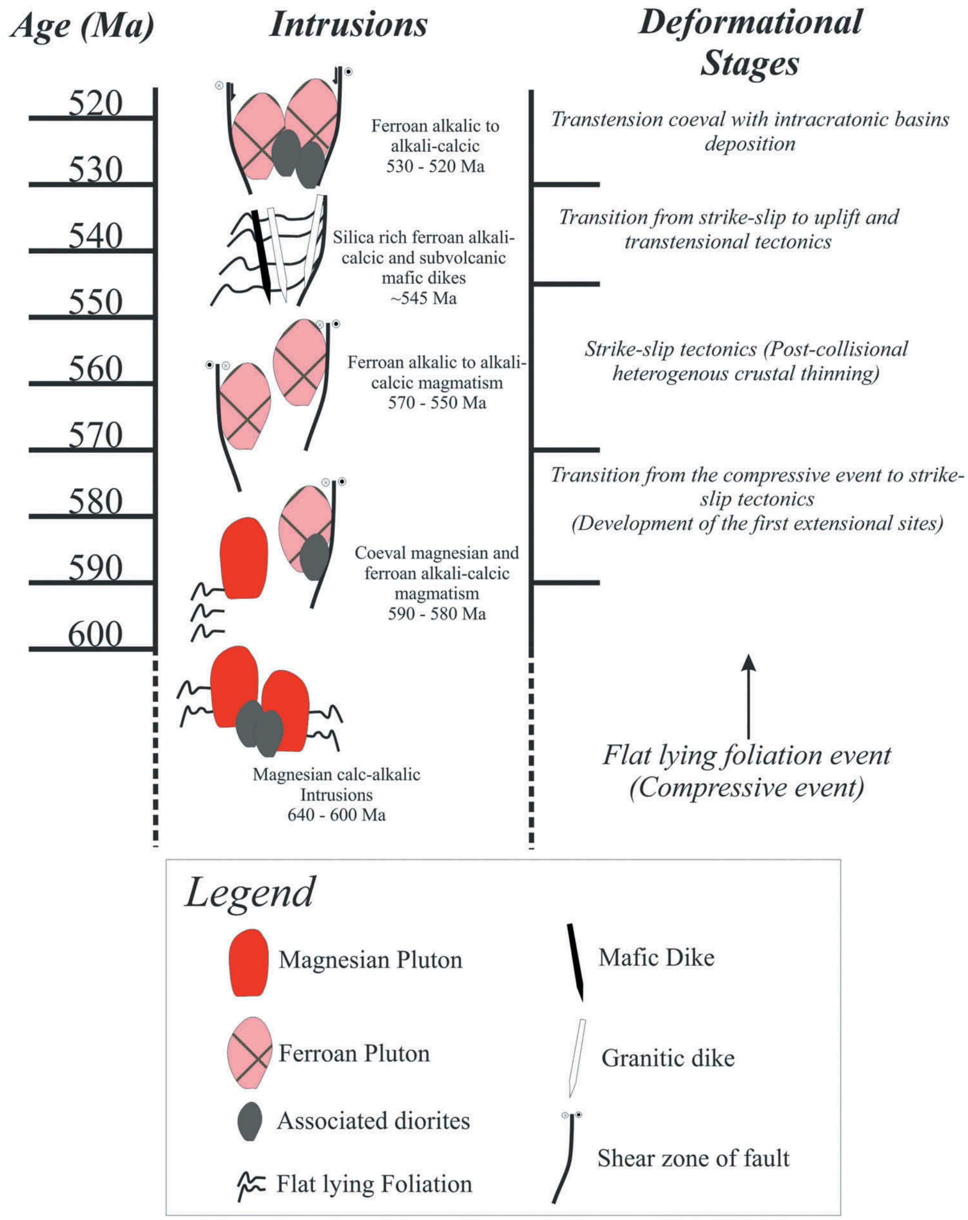

Figure 13. Summary diagram of the tectonomagmatic evolution of the Transversal Subprovince, Borborema Province as discussed in this study. The focus in on the post-collisional phases and their relatioships with ferroan intrusions, ages of Magnesian calc-alkalic and alkali-calcic granitoids are those described in Guimarães *et al*. (2004), as age intervals of Ferroan intrusions are the ones described in this paper. 590–580 Ma marks the transition from collision to strike-slip tectonics, and early extensional sites; 570–550 Ma marks extensional events and heterogenous crustal thinning related to the transcurrent event; 545–520 Ma marks the uplift and onset of transtensional tectonics in the Transversal subprovince.

Complex granitoids are associated with transtension contemporary with deposition in the intracratonic basins and the latest ferroan intrusions the Borborema Province.

Generation of ferroan granites in the Transversal subprovince involve largely partial melting of the TTG rocks of Paleoproterozoic age in the basement of the Borborema Province, and variable volume of mafic melts from a metasomatized lithosphere modified during the Rhyacian orogeny and also small volume of the astenosphere. Country rocks assimilation was a minor process. The mafic rocks presence reflects heat transfer and also geochemical diffusion in granite compositions.

Ferroan granitoids can occur at any of the deformational stages of the Brasiliano-Pan-African orogenic cycle, since extensional sites can develop in any tectonic setting.

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