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Tonian granitic magmatism of the Borborema Province, NE Brazil: A review

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ABSTRACT

Tonian granitoids, today augen-gneisses and migmatites, showing crystallization ages ranging from 870 Ma to 1000 Ma occur in the Borborema Province, NE Brazil. The majority of them have ages within the 925–970 Ma interval. Few intrusions with ages of ~1.0 Ga and <900 Ma occur in the Transversal and South subprovinces. The Tonian granitoids constitute the most expressive magmatic rocks of the Cariris Velhos event. The studied granitoids (herein CVG -Cariris Velhos granitoids) intrude slightly older bimodal (but mostly felsic) volcanic successions and metasedimentary sequences in the Transversal and South subprovinces. Tonian granitoids are unknown in the North subprovince. The CVG comprise mainly coarse-grained augen-gneisses of granite to granodiorite composition. Fe-rich biotite (annite) is the main mafic mineral phase, constituting up to 15% of the modal composition. Garnet, muscovite and tourmaline occur as accessory phases in many plutons.

The CVG augen–gneisses have high SiO_2 (>71%) and alkali contents, they vary from slightly peraluminous to slightly metaluminous, and from slightly magnesian to typical ferrroan rocks. In the migmatized orthogneisses the SiO_2 contents are usually <70%. Trace element variations in the CVG are extensive, reflecting the migmatization recorded in some plutons and/or distinct sources. They are Ca-, Sr- and Nb-poor, showing variable Ba (100–1260 ppm), Rb (164–400 ppm) and Zr (144–408 ppm) contents, and high abundances of Y (>40 ppm). The chondrite normalized REE patterns are characterized by strong to moderate negative Eu anomalies ($Eu/Eu^* = 0.23–0.70$). In general, the spidergram patterns show deep troughs at Ti, P, Ba and Sr and less pronounced Nb–Ta troughs. These patterns are similar to those reported for anorogenic granites evolved from mixtures of magmas from both crustal and mantle sources. The CVG exhibit T_{DM} model ages ranging from 1.9 to 1.1Ga, with slightly negative to slightly positive $\varepsilon Nd(t)$ values, suggesting the involvement of distinct proportions of mantle and crustal components in the source of their protoliths.

There is no consensus in the literature about the tectonic setting of the CVG ie they have been related to either continental margin magmatic arc, with possible back–arc association, or extention-related setting, with generation of A-type granites. However, all the available geochemical data suggest that the CVG represent extension related magmatism. The geochemical signature associated to bimodal volcanism, including pyroclastic rocks, with similar ages, and absence, up to now, of evidence for metamorphism of Tonian age, support the hypothesis of extension - related magmatism.

1. Introduction

The Borborema Province (Almeida et al., 1981) constitutes a region located in the northeast part of the South American continent, between the West Africa-São Luis craton to the north, and to the west by late Neoproterozoic (Brasiliano/Pan African) terranes that extend northward from central Brazil (Pimentel and Fuck, 1992; Pimentel et al., 1997, 2000) mostly covered by Phanerozoic sediments. According to Van Schmus et al. (2008), the Borborema Province resulted from the breakup of a Palaeoproterozoic

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supercontinent (Columbia: Rogers and Santosh, 2002, 2003; 2004) during the late Mesoproterozoic to early Neoproterozoic.

Van Schmus et al. (1995) proposed that the E–W trending Patos and Pernambuco shear zones divided the Borborema Province into three tectonic domains, later denominated subprovinces (Van Schmus et al., 2011): North, Transversal and South.

The North subprovince, located north of the Patos shear zone, comprises Paleoproterozoic basement, including some Archean nuclei, overlapped by Neoproterozoic metasedimentary sequences, and Ediacaran plutonic rocks. The South subprovince comprehends the region between the Pernambuco shear zone and the São Francisco craton, resulted from a tectonic collage of various blocks, terranes or domains with ages ranging from Archean to Neoproterozoic (Van Schmus et al., 2008).

The South subprovince comprises three domains (Fig. 1): (a) Sergipano, north of the São Francisco Craton; (b) Pernambuco–Alagoas (PEAL), north of the Sergipano domain, and (d) Riacho do Pontal. The Rio Preto belt is considered part of the South subprovince, but is not referred to as a domain by Van Schmus et al. (2011). The Sergipano domain or belt (Oliveira et al., 2010) is subdivided into five lithotectonic domains: Canindé, Poço Redondo-Marancó, Macururé, Vaza Barris, and Estância. The PEAL domain constitutes a region of high-grade gneisses, migmatites, and the largest Brasiliano granitic intrusions in the Borborema Province, which lies to the north of the Sergipano domain. The Riacho do Pontal domain consists of metasedimentary and metavolcanic supracrustal sequences with late Neoproterozoic (Brasiliano) granites and some older gneisses.

The Transversal subprovince lies between the Patos and Pernambuco shear zones, within a major shear couple formed by dextral displacement of these two shear zones. This shear couple formed many faults, that caused fragmentation and clockwise block rotation, during the Pan African/Brasiliano Orogeny, which makes complex the reconstruction of the pre-Brasiliano geotectonic history of this domain. The Transversal subprovince was subdivided into two belts by Brito Neves (1983) and in four terranes by Santos (1995) and Santos et al. (1999). The terranes model has been contested by several works, and the Van Schmus et al. (2011) designation, will be used in this work.

Previous work (Brito Neves, 1983) did not consider the east branch of the Pernambuco shear zone as the limit of distinct domains, ie, the north part of the Pernambuco Alagoas domain continues in the Transversal subprovince of Van Schmus et al. (1995, 2008, 2011). Some recent works, carried out in the north part of the Pernambuco Alagoas domain and in the southeast part of the Transversal subprovince, have shown that the east branch of the Pernambuco shear zone is not a limit of distinct domains (Neves et al., 2012; Silva Filho et al., 2014a, b).

The Tonian (Cariris Velhos) suite comprises bimodal metavolcanic (mostly felsic) with small occurrence of pyroclastic, metasedimentary and metaplutonic rocks, yielding U–Pb zircon ages ranging from 870 Ma to 1000 Ma. This suite, mostly identified in the Transversal subprovince, is coeval with rocks from other parts of the South subprovince, notably in the Poço Redondo-Marancó subdomain of the Sergipano domain, in the Pernambuco Alagoas, Riacho do Pontal and Rio Preto domains.

At present, there is no integration for the Tonian orthogneisses dataset from distinct domains of the Borborema Province. The aim of this paper is to present a review of the Tonian orthogneisses from the Borborema Province, including geochronological, geochemical and Sm–Nd isotopic data from the literature and new geochemical and geochronological data. It is an attempt to constrain the Tonian orthogneisses geotectonic meaning in an integrated way, and doing so, to contribute to the understanding of the Cariris Velhos event in the Borborema Province.

2. Geological aspects of the Borborema Province

The Borborema Province consists of gneissic and migmatitic basement complexes, mostly formed during the Paleoproterozoic (1.98 Ga to 2.2 Ga), including minor Archean blocks, partially covered by Neoproterozoic metasedimentary and metavolcanic rocks (Van Schmus et al., 1995, 2008; Dantas et al., 1998; Fetter, 1999; Brito Neves et al., 2001; Kozuch, 2003; Guimarães et al., 2012).

Two contrasting tectonic models have been proposed to the late Neoproterozoic evolution of the Borborema Province: The accretionary model (Brito Neves and Cordani, 1991; Santos, 1995; Jardim de Sá, 1994 among others) in which the main shear zones represent boundaries of continental fragments or terranes amalgamated during the Pan-African – Brasiliano Orogeny. In opposition to the accretionary model, Neves (2003) and Neves et al. (2006) argued that the Borborema Province constitutes a consolidated block since 2.0 Ga ago (the single-block model).

Trompette (1997) suggested the continuation of the Transversal subprovince to the African side of West Gondwana, between the Adamaoua and Garoua shear zones in Cameroon (Median Shear Corridor). Some recent works (Silva Filho et al., 2014a; Neves et al., 2015) showed the at least in the east side of the Borborema Province, the Pernambuco lineament does not separate distinct blocks. However, there is a major contrast in Sm–Nd T_{DM} ages on either sides of the Patos shear zone: Archean model ages to the north and Mesoproterozoic model ages to the south. The distribution of the Sm–Nd T_{DM} model ages favors the hypothesis that the Patos shear zone represents a major terrane boundary (Brito Neves et al., 2001; Kozuch, 2003; Van Schmus et al., 2008). Geochemical and geochronological similarities between the Paleoproterozoic orthogneisses from the north and south of the Patos shear zone (Souza et al., 2007; Neves et al., 2006) suggest that they represent the basement of the supracrustal rocks with Mesoproterozoic T_{DM} model ages, recorded in the south of the Patos shear zone. They are now in the same level due to later vertical movement of the Patos shear zone. Dias et al. (2015), using seismic data, concluded that the Patos shear zone is likely to be a supracrustal structure, rather than a limit of lithospheric terranes, as suggested in the single-block model discussed above.

The Paleoproterozoic basement of the Borborema Province was affected by three major events, which took place at 2.35 Ga; 2.15 Ga and 2.0 Ga (Dantas, 1997; Neves et al., 2006, 2015; Souza et al., 2007). These events are interpreted as part of a Paleoproterozoic collage which led to the assembly of the Columbia Supercontinent of Rogers and Santosh (2002).

Sá et al. (2002); Accioly (2003) reported A-type metagranitoids and meta-anorthosites emplaced at 1.6 Ga and 1.77 Ga respectively, within the Transversal subprovince of the Borborema Province. In addition to the Paleoproterozoic orogenic cycle, the Borborema Province was affected by a Tonian event, the so-called Cariris Velhos event with magmatic ages within 870 Ma – 1000 Ma interval, and the Brasiliano (650–580 Ma) event.

The Cariris Velhos event in the Transversal subprovince is represented mainly by bimodal metavolcanic rocks, including pyroclastic varieties and granitic plutons, now orthogneisses (Santos, 1995; Brito Neves et al., 2001; Kozuch, 2003; Guimarães et al., 2012) and, restricted occurrence of metasediments (muscovite-biotite gneisses, garnet-biotite schists, marbles and BIF) intercalated with metavolcanic rocks. Jardim de Sá et al. (1988), reported the first Tonian age in the Borborema Province. Using Rb–Sr whole rock, they defined an isochronic age of 968 ± 35 Ma, for the orthogneisses of the Afeição suite in the South subprovince (Riacho do Pontal domain) of the Borborema Province, which has been interpreted as representing mixed ages. Later, Van Schmus et al.

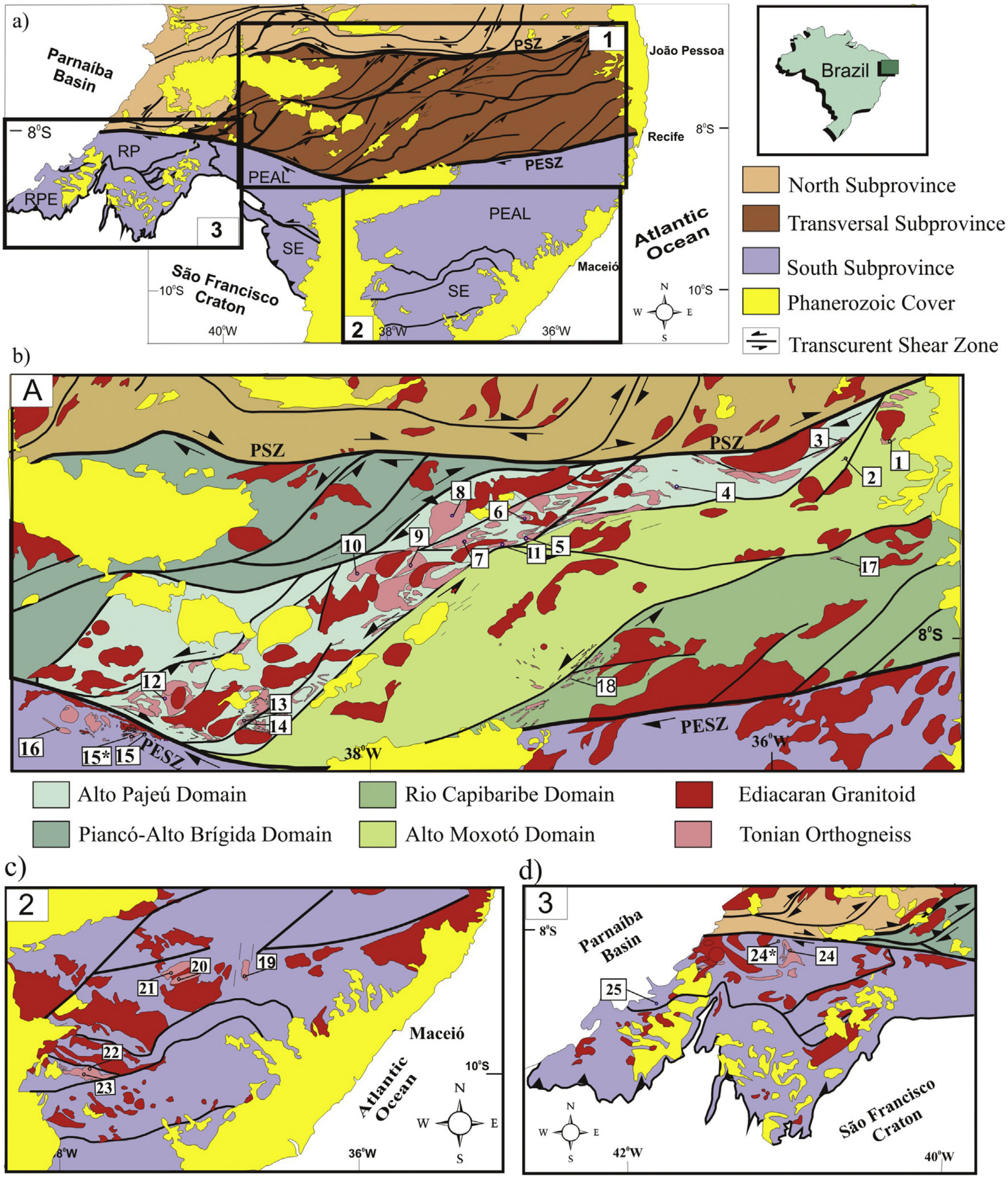

Fig. 1. a) The subprovinces of the Borborema Province, according to Van Schmus et al. (2011), showing the areas detailed in figures b, c and d. Sketch geological maps of: b) the Transversal and part of the South subprovinces (part of the Pernambuco – Alagoas domain), c) the Pernambuco–Alagoas and Sergipano domains, and d) Riacho do Pontal and Rio Preto domains showing the location of plutons with available U–Pb zircon geochronological data. 1- (925 ± 10 Ma – Jardim), 2- (952 ± 7 Ma) and 3 - (942 ± 22 Ma – Fazenda Agra) are from Brito Neves et al. (2001). 4 – Sítio do Icó (1005 ± 5 Ma – this work). 5 – (960 ± 4 Ma Morro do Cruzeiro Pluton) from Guimarães et al. (2012). 6 – (958 ± 9 Ma, Ambó pluton), 7 – (926 ± 12 Ma), 8 – (941 ± 17Ma – Imaculada pluton), 9-(959 ± 5 Ma – Queimadas orthogneisses), 10 – (963 ± 14 Ma.- Serra Talhada orthogneisses) all from Kozuch (2003). 11- (Tabira pluton – 972 ± 5 Ma) from Leite et al. (2000). 12 – (999 ± 50 Ma -Canoas gneiss) from Van Schmus et al., 1995). 13 – (Recanto – 1037 ± 30 Ma) from Santos (1995). 14 – Riacho do Forno (993 ± 5 Ma – this work), 15 – (Lobo - 974 ± 6 Ma) from Cruz et al. (2014), 15* - (994 ± 25Ma – Lobo pluton) from Brito and Freitas (2011). 16- (956 ± 2Ma – Rocinha pluton) from Cruz et al. (2014), 17 – (870 ± 8 Ma – Pinhões pluton) from Neves et al. (2012), 18 – (960 ± 11- Riacho do Tigre metavolcanics) of Accioly et al. (2010). c) 19 – (947 ± 6Ma – Flores) from Brito et al. (2008), 20 – (972 ± 30 Ma – sample SI-100) from Silva Filho et al. (2014a, b), 21 – (SI-125 – 983 ± 9Ma – this Work), 22– (979 ± 3 Ma – Poço Redondo migmatites) and 23 – (952 ± 2Ma - Serra Negra pluton) are from Carvalho (2005). d) 24 – (966 ± 5 Ma – Afeição augen gneisses) and 24* – (1001 ± 4 Ma – granite sill) are from Caxito et al. (2014) and 24 – (969 ± 11 Ma – Serra da Pintada) from Aquino and Batista (2011). The Sketch geological maps are modified from Medeiros (2004).

(1995), using U–Pb zircon TIMS data in a sample from the same suite, obtained similar age (966 ± 10 Ma), and interpreted it as the crystallization age of the orthogneisses protolith.

There is no consensus in the literature concerning the tectonic setting of the Tonian granitoids. They are related to either continental margin magmatic arc, with possible back–arc association (Brito Neves et al., 2000; Santos et al., 2010; Oliveira et al., 2010; Kozuch, 2003; Caxito et al., 2014, Van Schmus et al., 2011), or extension-related setting, with generation of A-type granites (Oliveira et al., 2010; Guimarães et al., 2012; Cruz et al., 2014; Aquino and Batista, 2011).

The Pan African/Brasiliano event (650 Ma – 550 Ma) affected the entire Borborema Province and was responsible for low-to high-temperature and low-pressure metamorphism, a great abundance of granitic intrusions, and the development of continental-scale transcurrent shear zones. The Brasiliano event was also responsible by the actual structural framework of the Borborema Province.

3. Geology and petrographic aspects of the Cariris Velhos granitoids

3.1. Transversal subprovince

The Cariris Velhos orthogneisses encompass a 50–100 km wide belt that extends for more than 700 km west–southwestwards from the Atlantic coastline. The orthogneisses, representing granitic plutons, intrude a metavolcano - metasedimentary sequence, which crops out on both sides of the gneissic core. The metasediments with Tonian deposition ages appear to have a restrict distribution (Guimarães et al., 2012), being recognized only at east of the Serra do Caboclo shear zone, the so-called metavolcano–metasedimentary Riacho Gravatá Complex (Bittar, 1998). However, late Neoproterozoic sediments have received contribution from the Cariris Velhos suite and were deposited within the same belt.

According to Bittar (1998) the Riacho Gravatá Complex comprises three stratigraphic units: Serra do Mocambo (NNE), Macacos-Piaus (center) and Serra da Pinheira (SW). U–Pb zircon TIMS (Kozuch, 2003) and SHRIMP (Guimarães et al., 2012) data show that the metavolcanic rocks from the three stratigraphic units proposed by Bittar (1998) yield ages ranging from 970 ± 15 Ma to 986 ± 19 Ma.

The Serra do Caboclo shear zone is the boundary between the Riacho Gravatá Complex and the Pianco-Alto Brigida domain. The Riacho Gravata Complex is bounded to the east by the Texeira-Terra Nova high. Bittar (1998) described the Riacho Gravatá Complex as a metavolcano-metasedimentary sequence metamorphosed under low to medium metamorphic grade; it includes muscovite ± graphite biotite schists, metagreywackes, marble, metatuffs, metaultramafic rocks, metasiltite, bimodal (but mostly felsic) metavolcanic rocks, and local occurrences of banded iron formation. The metavolcanic mafic rocks are greenschist and amphibolite grade.

The studied orthogneisses represent a set of individual small plutons (<80 km^2) comprising mainly coarse-grained augen-gneisses of granite to granodiorite composition. Fe-rich biotite (annite) is the main mafic mineral phase constituting up to 15% of the modal composition. Garnet, muscovite and tourmaline occur in many plutons. Zircon, apatite and allanite are the main accessory phases. Some plutons comprise strongly migmatized gneisses and some others are composed of banded orthogneisses. However, most consist of augen-gneisses, and some of them (Ambó and Morro do Cruzeiro plutons among others) show enclaves preserved from the Brasiliano deformation.

Fine grained migmatitic orthogneisses have been described in the east part (Lages et al., 2014) and in the south part of the Cariris Velhos belt. The migmatites from east part comprise amphibole-rich layers intercalated with felsic layers, folded and migmatized. In the south, the migmatites are also fine grained and have biotite but smaller modal amount of amphiboles. The other Tonian orthogneisses of the Borborema Province have only biotite as the main mineral mafic phase.

3.2. South subprovince

3.2.1. Sergipano domain

The Sergipano domain has a triangular shape, with a NW–SE structural strike (Fig. 1). It represents the southern segment of a Brasiliano continental collision zone which continues into Central Africa as the North Equatorial fold belt and may have resulted from the closure of a large intracontinental basin, along the northern margin of the São Francisco-Congo Craton (Davison and Souza, 1989). According to Trompette (1997, 2000) the Sergipano domain comprises the western segment of the Oubanguide orogen, which extends into NW Africa in pre-drift reconstructions.

Davison and Souza (1989) recognized five lithotectonic domains in the Sergipano domain, namely from N to S: Canindé, Poço Redondo-Marancó, Macururé, Vaza Barris and Estância, which are mutually separated by Neoproterozoic shear zones. The Poço Redondo-Marancó domain is composed of two units: Poço Redondo, which constitutes the basement, and the Marancó supracrustal rocks (Oliveira et al., 2010).

Carvalho (2005) and Oliveira et al. (2010) described occurrences of late Mesoproterozoic to early Neoproterozoic migmatites (Poço Redondo) and augen gneisses (Serra Negra), which constitute the basement of the Marancó – Poço Redondo domain. The Serra Negra augen – gneisses occur as an elongated WNW ––ESE oriented pluton, in the south part of the Poço Redondo subdomain. The gneisses show tectonic contacts, made mainly through transcurrent shear zones, with the Poço Redondo migmatites (Carvalho, 2005). Metasedimentary xenoliths are common within the Serra Negra orthogneisses.

The Poço Redondo migmatites constitute a belt that extends in the WNW–ESE direction, for more than 30 km long and 8 km wide. Silva Filho et al. (1997) firstly described these rocks as homogeneous and heterogeneous migmatites. They suggest that part of these migmatites has a metasedimentary source.

The timing of deformation was constrained by Oliveira et al. (2010), using $^{40}Ar–^{39}Ar$ dating of amphiboles, at 625 ± 3 Ma and muscovite plates from supracrustal rocks at 612 ± 7 Ma. The data support that the deformation has a late Neoproterozoic (Pan African/Brasiliano) age.

3.2.2. Riacho do Pontal domain

The Riacho do Pontal domain is located just south of the westernmost branch of the Pernambuco shear zone (Fig. 1a). According to Van Schmus et al. (2011) the Riacho do Pontal domain may represent the SW continuation of some of the terranes in the Transversal subprovince, including the Cariris Velhos belt.

Oliveira (1998) and Caxito et al. (2014) subdivided the Riacho do Pontal domain into three tectono-stratigraphic zones or domains: external, central and internal zones.

The external zone comprehends a south-verging nappe system in the southernmost part of the domain. It comprises a supracrustal sequence (Casa Nova Group) composed mainly of clastic metasedimentary rocks such as quartzite, garnet-mica schist containing staurolite and kyanite, greywacke and marble intercalations. According to Caxito et al. (2012), this supracrustal sequence is related to a syn-orogenic basin.

The central zone comprises metamafic rocks with MORB signature (Moraes, 1992), intercalated within a metasedimentary sequences of metacherts, metagreywackes and garnet mica schist (Monte Orebe Complex). Angelim (1988) based in field relationships suggested a Tonian age for the Monte Orebe Complex. According to Caxito et al. (2014), the central zone marks an ancient suture zone between two distinct lithospheric blocks: the São Francisco Craton to the south, without Tonian-related intrusions, and the internal zone block, which contains the Afeição suite. However, few U–Pb zircon SHRIMP data, presented by Brito Neves et al. (2015), suggest a Neoproterozoic deposition age, between 650 Ma and 850 Ma, for part of the Monte Orebe sediments.

The internal zone comprehends granitic plutonism, today augen

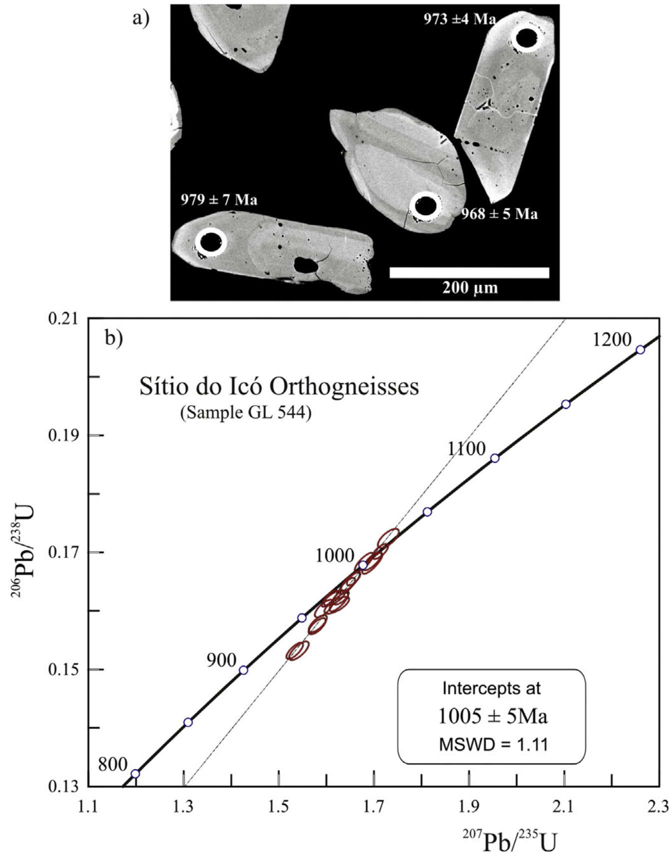

Fig. 2. a) Zircon SEM – CL pictures for sample GL-544 (Sitio do Icó). b) Concordia diagram for sample GL-544 (location 4 in Fig. 1b).

gneisses of the Afeição suite, reworked migmatitic basement and predominantly metasedimentary sequences, with minor volcanic contribution (Gomes and Vasconcelos, 1991; Angelim and Kosin, 2001).

The supracrustal sequences of the Riacho do Pontal domain are intruded by plutons with crystallization ages, mostly Rb – Sr data, within the 668 – 550 Ma interval (Jardim de Sá et al., 1988, 1992; Jardim de Sá, 1996; Caxito et al., 2014).

3.2.3. Rio Preto domain

The Rio Preto domain borders the northwestern São Francisco Craton, southwest of the Riacho do Pontal domain (Fig. 1a). According to Caxito et al. (2014), it represents the geological link between the Borborema and the Northern Tocantins orogenic provinces of Brazil. The Rio Preto domain comprises a Paleoproterozoic basement, extensively reworked during the Brasiliano Orogeny (Egydio-Silva et al., 1989) and two metasedimentary units: 1) Canabravinha Formation to the south, which is composed of a para-derived sequence constituted by conglomerates and sediments similar to turbidites (Egydio-Silva et al., 1989) with Neoproterozoic (~900–600 Ma) deposition ages (Caxito et al., 2014). 2) The Formosa Formation to the north, comprises fine-grained sediments, associated with cherts and probably submarine volcanic activity, now represented by greenschists (Caxito et al., 2012). The deposition of the Formosa Formation sediments appear to have occurred during the Orosirian Period (~1.9 Ga – Caxito et al., 2014).

The Serra da Pintada pluton comprises leucocratic coarse – grained augen–gneisses of syenogranite composition (Aquino and Batista, 2011). The pluton forms an elongated body, showing maximum axis with E–W direction, intruded into Paleoproterozoic orthogneisses. Three more plutons (Algodões granitoids) with Tonian ages are described in the Rio Preto domain (Aquino, 2014), less than 15 km southwest of the Serra da Pintada pluton. The plutons comprise coarse – to medium - grained augen gneiss, locally mylonitic, with composition ranging from alkali-feldspar granite to syenogranite.

4. Geochronological data

4.1. Transversal subprovince

This subprovince has the majority of the geochronological data available for Tonian orthogneisses. A large number of U–Pb zircon ages, for Tonian orthogneisses from the Cariris Velhos belt of the Transversal subprovince, was obtained by Van Schmus et al. (1995) and Kozuch (2003), using standard isotope-dilution, thermal-ionization mass spectrometry (ID-TIMS) methods. This dataset was important to constraint the crystallization ages of the orthogneisses protolith. The U–Pb zircon TIMS ages came out very similar to that defined by Brito Neves et al. (2000, 2001) using whole rock Rb–Sr methodology. Guimarães et al. (2012) provided U–Pb zircon SHRIMP age of 960 ± 4 Ma for one orthogneisse sample of the Cariris Velhos belt (Morro do Cruzeiro pluton - Fig. 1b). This pluton is constituted by coarse - grained augen - gneisses having granitic compositions, similar to that of the granitoids from the Ambó pluton which has U–Pb zircon TIMS crystallization age of 958 ± 9 Ma (Kozuch, 2003). Twenty-five zircon grains were analyzed and all analyses are concordant and no significantly older inherited cores were recorded. Guimarães et al. (2012) also reported very narrow zircon overgrowths, and in attempt to define their ages, seven overgrowths were analyzed. However, the obtained $^{206}Pb/^{238}U$ ages (678 Ma to 881 Ma) were not able to define the metamorphic age.

Besides the Ambó pluton, Kozuch (2003) analyzed four more plutons from the same belt (Fig. 1b), by U–Pb zircon TIMS, and obtained the following ages: Imaculada gneisses - 941 ± 17Ma; Fazenda Arroz orthogneisses – 926 ± 12 Ma; Queimadas gneisses – 959 ± 5Ma and Serra Talhada gneisses 963 ± 28Ma. In the Serra Talhada gneisses, Kozuch (2003) recorded a younger zircon population that gave an age of 626 ± 28Ma, which was interpreted as the Brasiliano metamorphic age. This age is similar to Ar–Ar ages in amphiboles obtained by Oliveira et al. (2010) in the Sergipano domain. Leite et al. (2000) reported U–Pb zircon TIMS age of 969 ± 4Ma for an augen - gneiss sample (Fig. 1b), which they called Tabira pluton. In the same sample, Leite et al. (2000) also analyzed one fraction of titanite, which gave a concordant age of 612 ± 9Ma, interpreted as a metamorphic age. Guimarães et al., 2012 reported granitoids, denominated as Tabira pluton, intruded into the orthogneisses described by Leite et al. (2000) and has U–Pb zircon SHRIMP crystallization age of 593 ± 7 Ma (Guimarães et al., 2012), which is similar to the U–Pb titanite age recorded by Leite et al. (2000).

Felsic metavolcanic rocks from the Cariris Velhos belt, within the so-called Riacho Gravatá Complex, have U–Pb TIMS age ranging from 913 ± 25 Ma to 980 ± 10 Ma (Kozuch, 2003) and U–Pb zircon SHRIMP ages of 996 ± 13 Ma and 986 ± 10 Ma (Guimarães et al., 2012). Brito Neves et al. (2001) reported U–Pb zircon TIMS age of 925 ± 10 Ma and 952 ± 7 Ma (Jardim pluton) in granitoids from the east part of the Cariris Velhos belt (Fig. 1b). Brito Neves et al. (2001) also suggest that the metasediments in this specific area have Tonian ages. However, U–Pb zircon SHRIMP data presented by Guimarães et al. (2012) show that the deposition of these sediments occurred during the Pan African/Brasiliano orogeny.

Thirty six zircon grains were extracted from a fine-grained, amphibole rich layer of a migmatized orthogneisse sample from the east part of the Cariris Velhos belt (Sítio do Icó – Fig. 1b). U–Pb

Table 1
Summary of U/Pb SHRIMP data for sample GL-544 – Sítio do Icó.

Samples	%	ppm	ppm		Ratios							ρ	Apparent ages						Conc.(%)
Spots	Comm 206	U	Th	Th/U	206 Pb/204 Pb	207 Pb/206 Pb	±1σ	207 Pb/235U	±1σ	206 Pb/238U	±1σ		207 Pb/206 Pb	(Ma)	207 Pb/235U	(Ma)	206 Pb/238U	(Ma)	
016-Z9				0.68	59225	0.072616	0.46	1.534	0.75	0.153176	0.60	0.75	1003	9	944	5	919	5.14	92
045-Z27				0.81	82962	0.073030	0.57	1.542	0.89	0.153183	0.68	0.73	1015	12	947	5	919	5.84	91
015-Z8				0.48	251120	0.072850	0.48	1.581	0.75	0.157374	0.58	0.71	1010	10	963	5	942	5.04	93
046-Z28				0.87	127713	0.072716	0.51	1.582	0.80	0.157797	0.62	0.72	1006	10	963	5	945	5.41	94
041-Z25				0.87	174645	0.072122	0.50	1.595	0.80	0.160402	0.62	0.73	989	10	968	5	959	5.50	97
005-Z2				0.53	84051	0.071346	0.83	1.601	1.30	0.162749	1.00	0.75	967	17	971	8	972	9.05	100
048-Z30				0.91	109495	0.073855	1.26	1.602	1.41	0.157320	0.63	0.64	1038	25	971	9	942	5.55	91
040-Z24				0.44	186668	0.071880	0.34	1.607	0.67	0.162136	0.58	0.82	983	7	973	4	969	5.21	99
024-Z15				0.82	87259	0.072298	0.74	1.617	0.91	0.162221	0.53	0.71	994	15	977	6	969	4.79	97
042-Z26				0.51	138735	0.073084	0.88	1.622	1.06	0.160962	0.59	0.71	1016	18	979	7	962	5.26	95
047-Z29				0.51	315027	0.073021	0.45	1.626	0.80	0.161531	0.66	0.79	1015	9	980	5	965	5.89	95
027-Z16				0.86	188356	0.072836	0.47	1.630	0.69	0.162311	0.50	0.63	1009	10	982	4	970	4.49	96
039-Z23				0.93	191008	0.072572	0.39	1.644	0.67	0.164270	0.54	0.75	1002	8	987	4	980	4.96	98
034-Z20				0.77	90941	0.072554	0.44	1.651	0.80	0.165021	0.67	0.80	1002	9	990	5	985	6.13	98
021-Z12				0.94	68449	0.072644	0.33	1.657	0.56	0.165459	0.45	0.69	1004	7	992	4	987	4.09	98
036-Z22				0.73	73451	0.074654	1.18	1.665	1.37	0.161798	0.70	0.71	1059	24	995	9	967	6.25	91
018-Z11				0.40	114661	0.074410	0.95	1.674	1.07	0.163191	0.50	0.60	1053	19	999	7	974	4.51	93
033-Z19				0.79	175713	0.072370	0.42	1.679	0.76	0.168282	0.64	0.80	996	9	1001	5	1003	5.90	101
022-Z13				0.55	89653	0.073025	0.44	1.697	0.76	0.168513	0.62	0.78	1015	9	1007	5	1004	5.78	99
035-Z21				0.29	69472	0.073201	0.43	1.697	0.82	0.168113	0.70	0.83	1020	9	1007	5	1002	6.52	98
009-Z4				0.63	56826	0.074494	0.57	1.711	0.77	0.166569	0.53	0.60	1055	11	1013	5	993	4.87	94
029-Z18				0.51	145602	0.073026	0.40	1.713	0.64	0.170149	0.50	0.70	1015	8	1013	4	1013	4.70	100
017-Z10				0.54	71993	0.076295	0.61	1.721	0.86	0.163564	0.61	0.65	1103	12	1016	6	977	5.53	89
004-Z1				0.71	117145	0.072804	0.57	1.730	0.84	0.172386	0.63	0.69	1009	11	1020	5	1025	5.94	102
006-Z3				0.92	56317	0.074142	0.74	1.740	0.91	0.170201	0.54	0.71	1045	15	1023	6	1013	5.07	97
023-Z14				0.90	41067	0.075086	0.59	1.763	0.85	0.170280	0.61	0.66	1071	12	1032	5	1014	5.72	95
010-Z5				0.67	20429	0.075809	0.55	1.768	0.83	0.169193	0.62	0.69	1090	11	1034	5	1008	5.76	92
011-Z6				0.53	4034	0.081642	0.54	1.781	0.81	0.158219	0.60	0.68	1237	11	1039	5	947	5.26	77
012-Z7				0.43	22041	0.079917	1.09	1.791	1.37	0.162508	0.84	0.78	1195	21	1042	9	971	7.61	81
028-Z17				0.80	5609	0.077710	0.54	1.803	0.79	0.168254	0.58	0.66	1139	11	1046	5	1002	5.34	88

zircon analysis were carried out with a Thermo-Finnigan multi-collector LA-ICP-MS at the Geochronology Laboratory of Brasilia University. An apparent age of 1005 ± 5 Ma (Fig. 2a, b; Table 1) was obtained in the upper intercept. This age is interpreted as the crystallization age of the gneiss protolith. The zircon grains are euhedral to sub-euhedral and zoned; overgrowths are rare and, when they occur, they are very narrow (Fig. 2a). Xenocrystic cores analyzed from 3 grains; yielded $^{206}Pb/^{238}U$ ages ranging from 1013 ± 5Ma to 1025 ± 6 Ma. The $^{232}Th/^{238}U$ ratios range from 0.40 to 0.93, which are compatible with magmatic source. No substantially older cores were found. The zircon grain shapes (Fig. 2b) are similar to those recorded by Guimarães et al. (2012) in a metavolcanic rock from the Riacho Gravatá Complex.

A sample from a migmatized orthogneisse (Sample AM-536), of muscovite monzogranite composition, was collected from the Riacho do Forno type locality (Fig. 1b). Thirteen spots were analyzed from 12 zircon grains. U–Pb analysis were done by SHRIMP at the Geochronological Research Center (CPGeo) of the Geosciences Institute of the São Paulo University, Brazil. Details of the analytical procedures and calibration of the device are described by Stern (1997), Williams (1998) and Sato et al. (2008).

Zircon grains are prismatic with length/width ratios up to 1 to 4 (Fig. 3a), however, rounded shape grains were also recorded. Oscilatory zoning is ubiquitous. Overgrowths are not apparent, but many outer zones have embayment (Fig. 3a). Six substantially older cores were found (Table 2), showing $^{206}Pb/^{238}U$ ages ranging from 1777 ± 45 Ma to 2333 ± 60 Ma. A Concordia age was defined at 993 ± 9 Ma (Fig. 3b). This age is interpreted as the crystallization age of the orthogneiss protolith. This age helps to improve the U–Pb zircon TIMS age of 1037 ± 30 Ma obtained by Santos (1995) for the Recanto – Riacho do Forno orthogneisses.

The ages of Serra do Icó and Recanto -Riacho do Forno orthogneisses are slightly older than those of the other orthogneisses from the Cariris Velhos belt, but they are similar to those recorded in felsic metavolcanic rocks of the Riacho Gravatá Complex (Guimarães et al., 2012). One sample, analyzed from the Canoa orthogneiss, from the south part of the Cariris Velhos belt (Fig. 1b), shows age of 999 ± 50 Ma (Van Schmus et al., 1995). The error is too large and more data is necessary to better constraint the crystallization age of the gneiss protolith.

Outside the main belt, Tonian LA-ICP-MS zircon ages are reported in metavolcanic acid rock from the Riacho do Tigre Complex (Fig. 1b), with crystallization age of 960 ± 11 Ma (Accioly et al., 2010). Metaplutonic rocks of younger Tonian ages, the Pinhões orthogneisses (870 ± 8Ma – Fig. 1b) are recognized in the east part of the Transversal subprovince (Rio Capibaribe domain) by Neves et al. (2012), and may represent the end of the Tonian event in the Borborema Province.

4.2. The south subprovince

4.2.1. Pernambuco Alagoas (PEAL) domain

Geochronological data are available for the west part of the PEAL domain, in three granitic plutons intruded just south of the Pernambuco shear zone (Fig. 1c). The granitoids have ages of 994 ± 25Ma (Lobo 1 pluton – Brito and Marinho, 2014; Brito and Freitas, 2011); 974 ± 8 Ma (Lobo 2- pluton – Cruz et al., 2014) and 956 ± 2Ma (Cruz and Accioly, 2013).

Within the east part of the PEAL domain, Brito et al. (2008) reported age of 947 ± 6 Ma for the Flores pluton (Fig. 1c) which has a maximum N–S oriented axis. U–Pb zircon SHRIMP data from a metatexite (sample SI-100, Fig. 1c), west of the Flores orthogneisses gave an age of 972 ± 30 Ma (Silva Filho et al., 2014b). Both ages are interpreted as the protoliths crystallization ages.

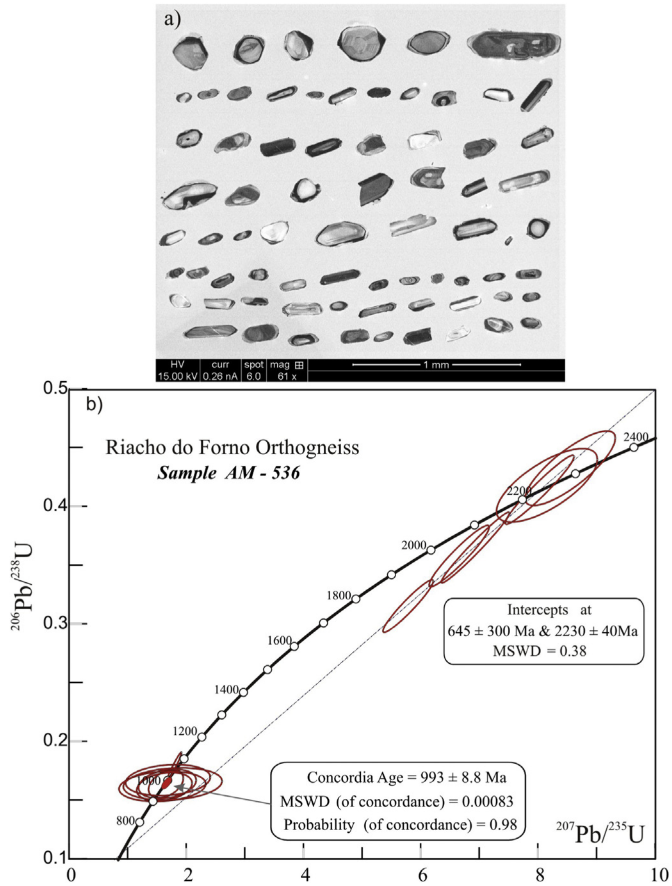

Fig. 3. a) Zircon SEM – CL pictures for sample AM-536 (Riacho do Forno – location 14 in Fig. 1b). b) Concordia diagram for sample AM-536.

Zircon grains were extracted from sample SI-125, collected from a migmatite close to the sample SI-100 (Fig. 1c). Twenty zircons grains were analyzed at SHRIMP RG (Sensitive High Resolution Ion Microprobe) from the Research School of Earth Sciences of the Australia National University. Analytical methods and data reduction followed those detailed by Williams (1998) and Stern (1997) using the FC1 standard (1099 Ma; Paces and Miller, 1993).

The majority of the zircon grains are euhedral to subhedral and show igneous zoning. Narrow overgrowths occur in many grains. (Fig. 4a). Some grains exhibit corroded rims. No substantially older cores were found.

In a Concordia diagram (Fig. 4b) a mean $^{207}Pb/^{206}Pb$ age of 983 ± 9Ma (MSWD = 0.78, probability of fit = 0.62) was defined for nine cores of the zircon grains (Fig. 4, Table 3), and interpreted as the crystallization age of the migmatite protoliths. A mean $^{207}Pb/^{206}Pb$ age of 664 ± 8Ma (MSWD = 0.88, probability of fit = 0.50) was defined for seven zircon rims and interpreted as a metamorphic age.

Oxygen zircon data (Silva Filho et al., 2014a, b) from sample SI-100 show $\delta^{18}O$ values ranging from +3.45‰ to +5.53‰, consistent with mantle derived magmas, crystallized in a closed system. In spite of few Tonian granitoids recognized in the Pernambuco Alagoas domain up to now, many detrital zircon grains with Tonian ages are reported in metassediments of the PEAL domain (Neves et al., 2015; Silva Filho et al., 2014a, b).

4.2.2. *Sergipano domain*

The occurrences of granitoids with Tonian ages within the Sergipano domain are restricted to the Poço Redondo - Marancó subdomain (Fig. 1c). The available dataset comprises ages of the Serra Negra augen - gneisses and Poço Redondo migmatite. Carvalho (2005) reported two U–Pb SHRIMP ages of 980 ± 4Ma and 961 ± 32Ma for two samples of the Poço Redondo paleosome migmatites and an age of 951 ± 2Ma to the Serra Negra augen-gneisses. The ages are interpreted as the crystallization ages of the migmatite and augen-gneisses protoliths. A zircon population with Concordia age of 967 ± 2Ma, recorded in the Serra Negra augen-gneisses, is interpreted as inherited from the Poço Redondo migmatite country rock (Carvalho, 2005).

The Marancó metasediments have a large population of zircon grains with ages within the 980–1000 Ma interval, few Paleoproterozoic and Archean ages and some ages within the 960–970

Table 2
- Summary of U–Pb SHRIMP zircon data for sample SI-125, from the PEAL domain.

Grain/Spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	±%	(1) ppm $^{206}Pb^*$	(1) $^{206}Pb/^{238}U$ Age		(1) $^{207}Pb/^{206}Pb$ Age		% Disc.	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^*/^{235}U$	±%	(1) $^{206}Pb^*/^{238}U$	±%	err corr
1	0.07	187	117	0.65	0.26	25	952	±12	972	±15	+2	0.0715	0.74	1.569	1.5	0.1591	1.3	0.87
2.1	0.49	1603	155	0.10	7.26	137	611	±8	669	±21	+9	0.0618	0.96	0.848	1.6	0.0995	1.3	0.80
3.1	0.01	273	195	0.74	0.53	39	988	±17	989	±10	+0	0.0721	0.50	1.647	1.9	0.1656	1.9	0.97
4.1	0.20	526	3	0.01	1.07	45	617	±16	677	±16	+9	0.0621	0.73	0.861	2.8	0.1005	2.7	0.96
5.1	0.17	168	100	0.61	0.29	22	933	±11	967	±18	+4	0.0713	0.88	1.532	1.5	0.1558	1.3	0.82
6.1	0.02	141	58	0.42	0.32	20	973	±14	982	±16	+1	0.0719	0.78	1.615	1.8	0.1630	1.6	0.90
7.1	–	655	5	0.01	0.80	58	636	±6	679	±10	+7	0.0621	0.46	0.889	1.2	0.1038	1.1	0.92
8.1	0.17	197	70	0.37	2.43	24	852	±10	898	±17	+6	0.0690	0.83	1.344	1.5	0.1413	1.2	0.83
9.1	0.08	903	7	0.01	0.71	79	621	±6	666	±10	+7	0.0618	0.48	0.862	1.2	0.1012	1.1	0.91
10.1	0.04	200	91	0.47	6.46	24	836	±22	914	±15	+9	0.0695	0.71	1.326	2.9	0.1384	2.8	0.97
11.1	–	236	181	0.79	1.19	32	950	±17	974	±12	+3	0.0716	0.58	1.568	2.0	0.1588	1.9	0.96
12.1	0.01	752	5	0.01	0.92	68	648	±9	660	±9	+2	0.0616	0.43	0.899	1.6	0.1058	1.5	0.96
13.1	0.26	548	129	0.24	4.36	55	713	±15	775	±28	+8	0.0650	1.33	1.048	2.6	0.1170	2.2	0.86
14.1	0.06	197	115	0.60	0.45	27	965	±17	983	±15	+2	0.0719	0.72	1.601	2.1	0.1615	1.9	0.94
15.1	0.08	195	120	0.64	0.25	27	972	±19	1009	±15	+4	0.0728	0.73	1.634	2.2	0.1627	2.1	0.95
16.1	0.05	90	59	0.68	1.23	12	952	±10	998	±20	+5	0.0724	1.00	1.589	1.5	0.1591	1.2	0.76
17.1	0.41	215	85	0.41	1.63	21	682	±7	961	±24	+31	0.0711	1.20	1.095	1.6	0.1116	1.1	0.68
18.1	0.18	258	181	0.73	0.26	33	891	±16	975	±16	+9	0.0716	0.77	1.463	2.0	0.1482	1.9	0.93
22.1	0.04	869	8	0.01	0.69	78	640	±8	660	±10	+3	0.0616	0.44	0.887	1.4	0.1045	1.4	0.95
21.1	0.03	717	4	0.01	0.95	64	642	±9	650	±11	+1	0.0613	0.49	0.885	1.6	0.1048	1.5	0.95

Errors are 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively. Error in Standard calibration was 0.25% (not included in above errors but required when comparing data from different mounts)0.1 –Common Pb corrected using measured ^{204}Pb. 2-Common Pb corrected by assuming $^{206}Pb/^{238}U–^{207}Pb/^{235}U$ age-concordance.

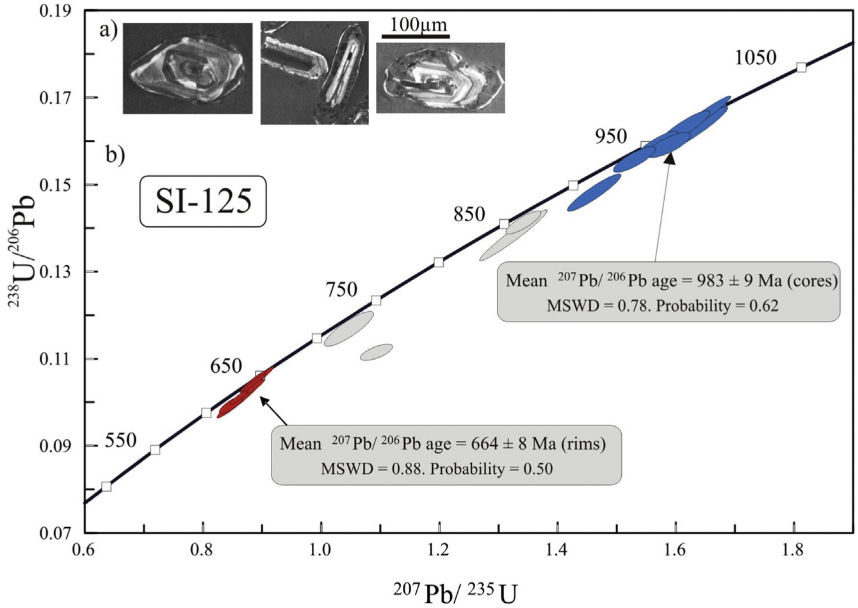

Fig. 4. a) Cathodoluminescence images showing the internal and external characteristics of zircon grains extracted from sample SI-125 and b) U–Pb Concordia diagram of SHRIMP analyses of zircon from sample SI-125.

Table 3
Summary of U/Pb SHRIMP data for sample SI-125.

Grain/Spot	% $^{206}Pb_c$	ppm U	ppm Th	$^{232}Th/^{238}U$	±%	(1) ppm $^{206}Pb^*$	(1) $^{206}Pb/^{238}U$ Age		(1) $^{207}Pb/^{206}Pb$ Age		% Disc.	(1) $^{207}Pb^*/^{206}Pb^*$	±%	(1) $^{207}Pb^{*235}U$	±%	(1) $^{206}Pb^{*238}U$	±%	err Cor
1	0.07	187	117	0.65	0.26	25	952	±12	972	±15	+2	0.0715	0.74	1.569	1.5	0.1591	1.3	0.87
2.1	0.49	1603	155	0.10	7.26	137	611	±8	669	±21	+9	0.0618	0.96	0.848	1.6	0.0995	1.3	0.80
3.1	0.01	273	195	0.74	0.53	39	988	±17	989	±10	+0	0.0721	0.50	1.647	1.9	0.1656	1.9	0.97
4.1	0.20	526	3	0.01	1.07	45	617	±16	677	±16	+9	0.0621	0.73	0.861	2.8	0.1005	2.7	0.96
5.1	0.17	168	100	0.61	0.29	22	933	±11	967	±18	+4	0.0713	0.88	1.532	1.5	0.1558	1.3	0.82
6.1	0.02	141	58	0.42	0.32	20	973	±14	982	±16	+1	0.0719	0.78	1.615	1.8	0.1630	1.6	0.90
7.1	–	655	5	0.01	0.80	58	636	±6	679	±10	+7	0.0621	0.46	0.889	1.2	0.1038	1.1	0.92
8.1	0.17	197	70	0.37	2.43	24	852	±10	898	±17	+6	0.0690	0.83	1.344	1.5	0.1413	1.2	0.83
9.1	0.08	903	7	0.01	0.71	79	621	±6	666	±10	+7	0.0618	0.48	0.862	1.2	0.1012	1.1	0.91
10.1	0.04	200	91	0.47	6.46	24	836	±22	914	±15	+9	0.0695	0.71	1.326	2.9	0.1384	2.8	0.97
11.1	–	236	181	0.79	1.19	32	950	±17	974	±12	+3	0.0716	0.58	1.568	2.0	0.1588	1.9	0.96
12.1	0.01	752	5	0.01	0.92	68	648	±9	660	±9	+2	0.0616	0.43	0.899	1.6	0.1058	1.5	0.96
13.1	0.26	548	129	0.24	4.36	55	713	±15	775	±28	+8	0.0650	1.33	1.048	2.6	0.1170	2.2	0.86
14.1	0.06	197	115	0.60	0.45	27	965	±17	983	±15	+2	0.0719	0.72	1.601	2.1	0.1615	1.9	0.94
15.1	0.08	195	120	0.64	0.25	27	972	±19	1009	±15	+4	0.0728	0.73	1.634	2.2	0.1627	2.1	0.95
16.1	0.05	90	59	0.68	1.23	12	952	±10	998	±20	+5	0.0724	1.00	1.589	1.5	0.1591	1.2	0.76
17.1	0.41	215	85	0.41	1.63	21	682	±7	961	±24	+31	0.0711	1.20	1.095	1.6	0.1116	1.1	0.68
18.1	0.18	258	181	0.73	0.26	33	891	±16	975	±16	+9	0.0716	0.77	1.463	2.0	0.1482	1.9	0.93
22.1	0.04	869	8	0.01	0.69	78	640	±8	660	±10	+3	0.0616	0.44	0.887	1.4	0.1045	1.4	0.95
21.1	0.03	717	4	0.01	0.95	64	642	±9	650	±11	+1	0.0613	0.49	0.885	1.6	0.1048	1.5	0.95

Errors are 1-sigma; Pb_c and Pb^* indicate the common and radiogenic portions, respectively. Error in Standard calibration was 0.25% (not included in above errors but required when comparing data from different mounts)0.1 – Common Pb corrected using measured ^{204}Pb. 2-Common Pb corrected by assuming $^{206}Pb/^{238}U–^{207}Pb^{235}U$ age-concordance.

Ma interval. Oliveira et al. (2015) interpreted the ages of 960–970 Ma as the maximum deposition age of the Marancó sedimentary protolith. These ages are similar to those described by Guimarães et al. (2012) in metavolcanic rocks intercalated in metasediments of the Riacho Gravatá Complex.

4.2.3. Riacho do Pontal domain

Two geochronological data are available for this domain (Fig. 1d). 1) U–Pb zircon LA-ICP-MS age of 1001 ± 4 Ma, obtained by Caxito et al. (2014) in a metric granite sill concordantly intruded within pelitic metarhythmite. 2) U–Pb zircon LA-ICP-MS age of 966 ± 5 Ma in the augen-gneisses of the Afeição suite (Caxito et al., 2014), which are similar to those previously defined by Jardim de Sá (1994, 1988) using U–Pb zircon TIMS and Rb–Sr isochron age. The Afeição augen-gneisses are described (Caxito et al., 2012) as an NW–SE elongated body showing a conspicuous foliation, parallel to the main regional foliations. The central part of the intrusion is underformed and the analyzed sample was collected from this area. Caxito et al. (2012) suggest that the augen-gneisses of the Afeição suite are intrusive or thrust upon metasedimentary rocks, orthogneisses and migmatites of the basement and show tectonic contact with Brasiliano syn-collisional granitoids. These field relationships are similar to those described in the Cariris Velhos belt by Guimarães et al. (2012).

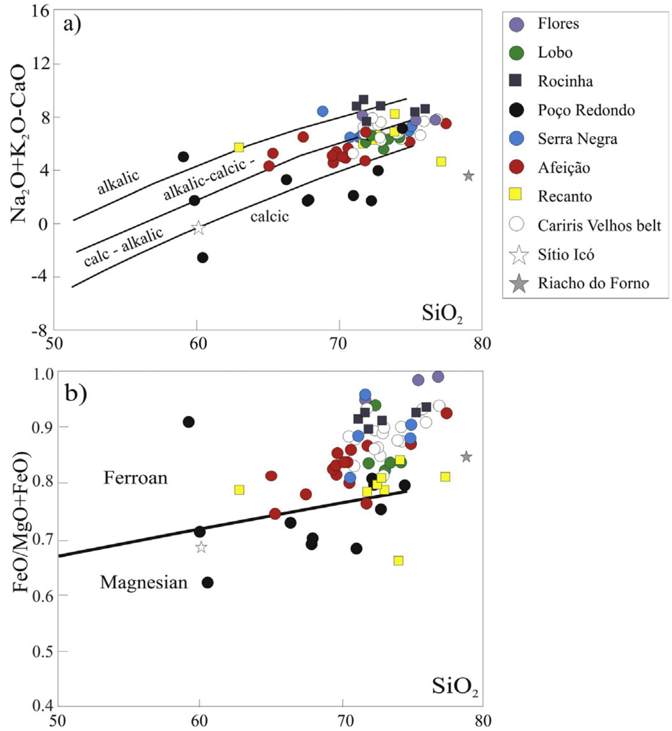

Fig. 5. a) Plot of $Na_2O + K_2O + CaO$ (MALI) versus SiO_2 (%wt) showing the distribution of the Tonian orthogneisses from the Borborema Province. Fields after Frost and Frost (2008) b) The composition range of the Tonian orthogneisses in the $FeO_{tot}/(FeO_{tot} + MgO)$ vs. weight percent of SiO_2 diagram. Fields of ferroan and magnesian granitoids are from Frost et al. (2001).

4.2.4. Rio Preto domain

Some small plutons with Tonian ages occur in this domain. However, only one of them, the Serra da Pintada pluton (Aquino and Batista, 2011) has available geochronological data. Two other plutons have been described in regional map (Aquino, 2014), as of Tonian age, but geochronological data are not provided. The Serra da Pintada pluton comprises leucocratic, coarse - grained augen - gneisses similar to those of the Afeição suite in the Riacho do Pontal domain. Eleven zircon grains analyzed from one sample of the Serra da Pintada pluton (Aquino and Batista, 2011) gave a nice cluster of U–Pb zircon SHRIMP data, defining a concordia age of 969 ± 11 Ma (MSWD = 0.72), interpreted as the crystallization age of the orthogneiss protolith. Only two, of the thirteen analyzed zircon grains, have $^{208}Pb/^{238}U$ ages of 1.9 Ga and 2.1 Ga, suggesting some contribution of the Paleoproterozoic country rock orthogneisses in their source (Aquino and Batista, 2011).

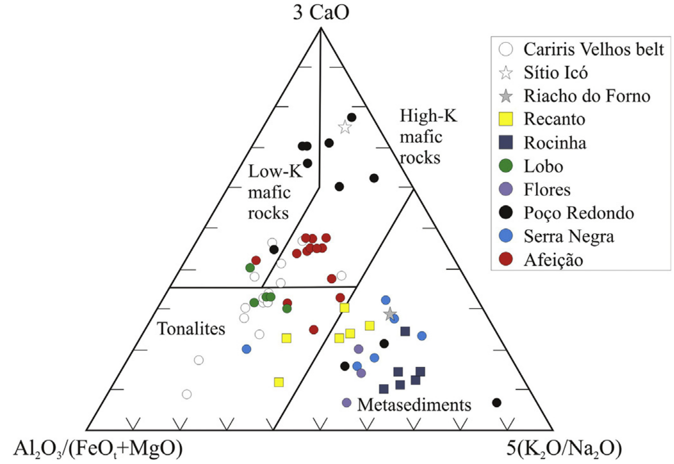

Fig. 7. The Tonian orthogneisses in the ternary diagram $Al_2O_3/(FeOt + MgO)$; 3*CaO; 5*(K_2O/Na_2O), with fields representing composition of melts derived from a range of potential sources, after Laurent et al. (2014).

5. Geochemistry

The Cariris Velhos granitoids described in this section include those from this work and those from the literature ie. the Cariris

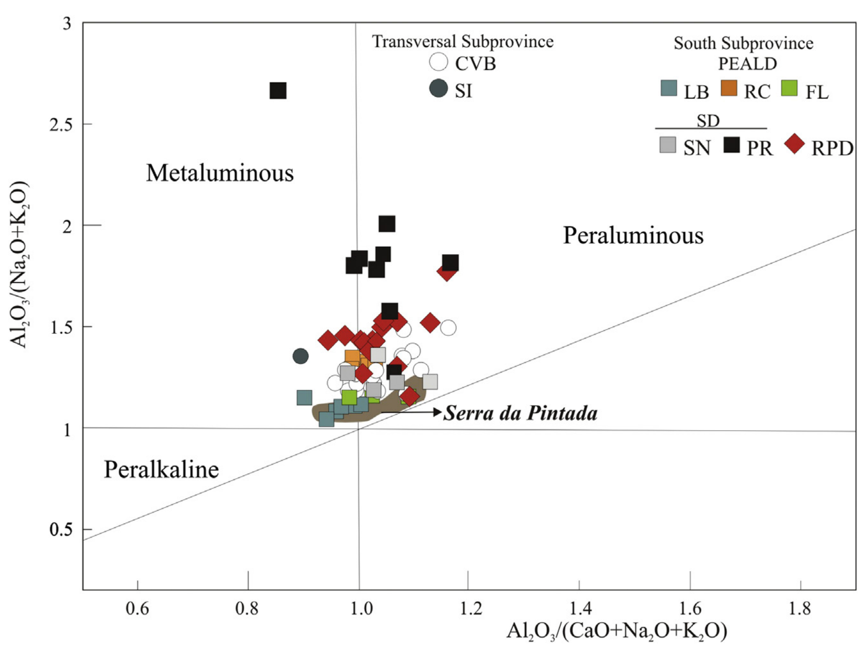

Fig. 6. Shand's Index for the granitoids of the Tonian orthogneisses of the Borborema Province. Fields after Maniar and Piccolli (1989). CVB – Cariris Velhos belt; SI – Sitio do Icó; PEALD – Pernambuco Alagoas domain; LB – Lobo pluton; RC – Rocinha pluton; FL – Flores pluton; SD – Sergipano domain; SN- Serra Negra; PR – Poço Redondo migmatites; RPD = Riacho do Pontal domain.

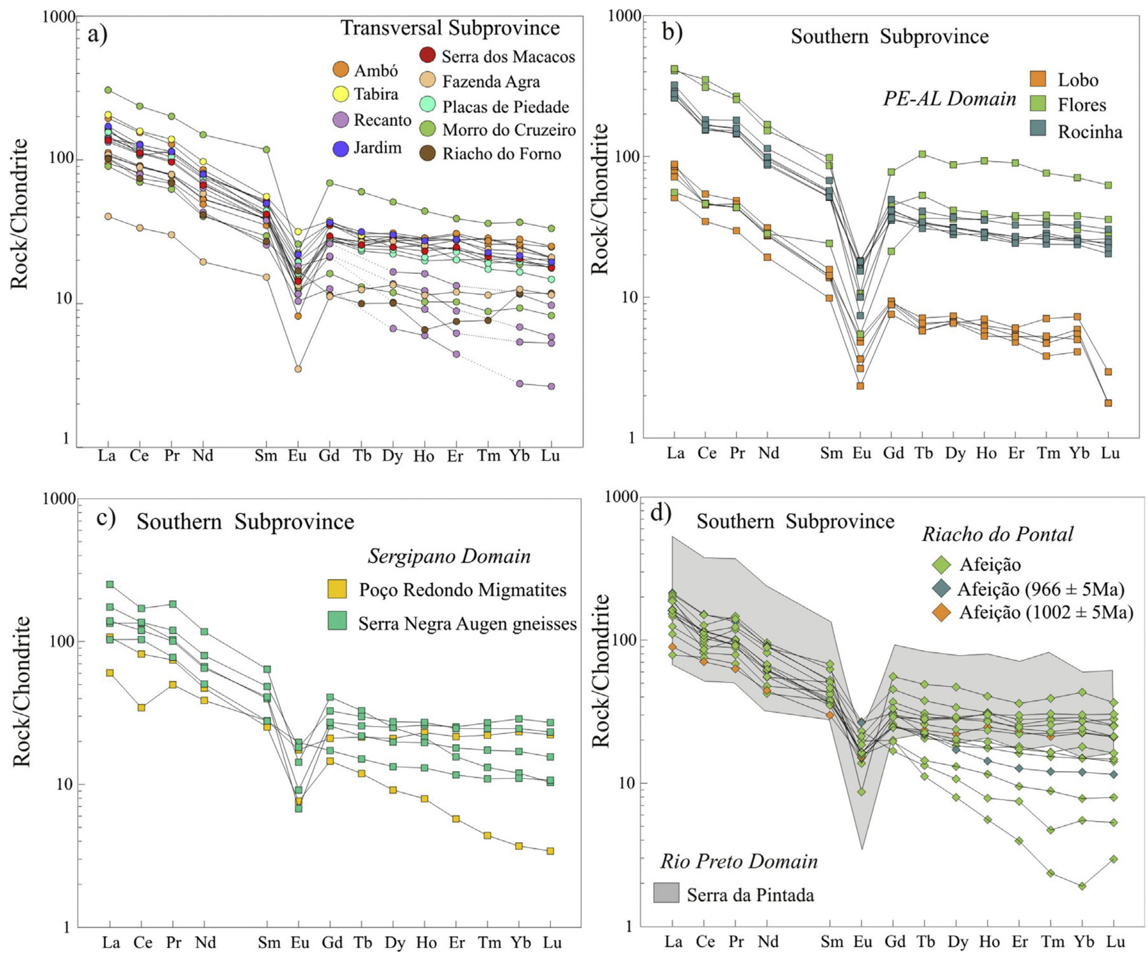

Fig. 8. Chondrite normalized REE plots for the studied orthogneisses. Chondrite values from Nakamura (1974).

Velhos belt in the Transversal subprovince (Guimarães et al., 2012; Kozuch, 2003); from the South subprovince (Oliveira et al., 2010; Oliveira personal communication; Caxito et al., 2014; Cruz et al., 2014). However, there is no data available for the orthogneisses with crystallization ages younger than 900 Ma, and those from the Serra da Pintada pluton from the Rio Preto domain. The geochemical data from the Serra da Pintada augen - gneisses, we used the data presented in diagrams by Aquino and Batista (2011).

The Tonian augen-gneisses have a high SiO_2 (>71%). When migmatized the SiO_2 values vary widely but values lower <70 wt% dominate. The augen-gneisses plot mainly in the alkali-calcic and calc-alkaline fields of the MALI (Modified Alkali-Lime index) versus SiO_2 diagram of Frost and Frost (2008) (Fig. 5a). The migmatites plot in all fields of the MALI versus SiO_2 diagram as expected, due to the alkalis (K_2O and Na_2O) mobility during migmatization. They have high FeO/(FeO + MgO) ratios usually >0.8 and most of them are classified as Ferroan granitoids (Fig. 5b) in the FeO/(FeO + MgO) versus SiO_2 diagram (Frost et al., 2001). They range from slightly peraluminouos to slightly metaluminouos according to the Shand index (Fig. 6). According to the geochemical diagrams presented by Aquino and Batista (2011), the Serra da Pintada augen-gneisses have high SiO_2, K_2O and low MgO contents. Their classification into magnesian or ferroan granitoids (Frost et al., 2001) is not possible, because Fe contents are not provided. However, from the diagrams, it is possible to know that the majority of them have FeO/MgO ratios >20, which point to ferroan granitoids.

In the ternary diagram Al_2O_3/(FeO + MgO) - 3*CaO − 5* (K_2O/Na_2O), with fields representing compositions of potential sources (Laurent et al., 2014), the studied granitoids show an origin involving melting of distinct lithologies (Fig. 7). However, the Rocinha, Serra Negra, and Flores orthogneisses have composition point to an origin through melting of metasediments. The most part of the Recanto orthogneiss samples and few samples of the Poço Redondo migmatites fall in the field of metasedimentary source. All the other orthogneisses and migmatites plot in all fields of igneous source rocks, with composition of high-K mafic rocks (mainly Afeição augen-gneisses), low − K mafic rocks (few samples) and tonalities (most of the Cariris Velhos belt samples and Lobo orthogneisses). The Poço Redondo samples plot in the fields of high-Ca (mafic rocks) and low-Ca (metasedimentary) of the Al_2O_3/(FeO + MgO) - 3*CaO − 5* (K_2O/Na_2O) diagram. This geochemical behavior suggests that the Poço Redondo migmatites represent distinct rocks, migmatized during the Ediacaran period. The Poço Redondo sample with available geochronological data, plot into the field of magmas originated by melting of metasedimentary rocks, similar to those recorded in the Serra Negra augen - gneisses (Fig. 7).

Trace element variations within and between the studied plutons are likewise extensive. They show low Sr (20–150 ppm) and Nb (12–22 ppm) contents, variable Ba (100–1260 ppm), Rb (164–400 ppm) and Zr (144–408 ppm) contents and high abundances of Y (41–80 ppm) and Ga (19–30 ppm).

The chondrite normalized REE patterns for the studied granitoids from all domains show many similarities (Fig. 8a–d). They are

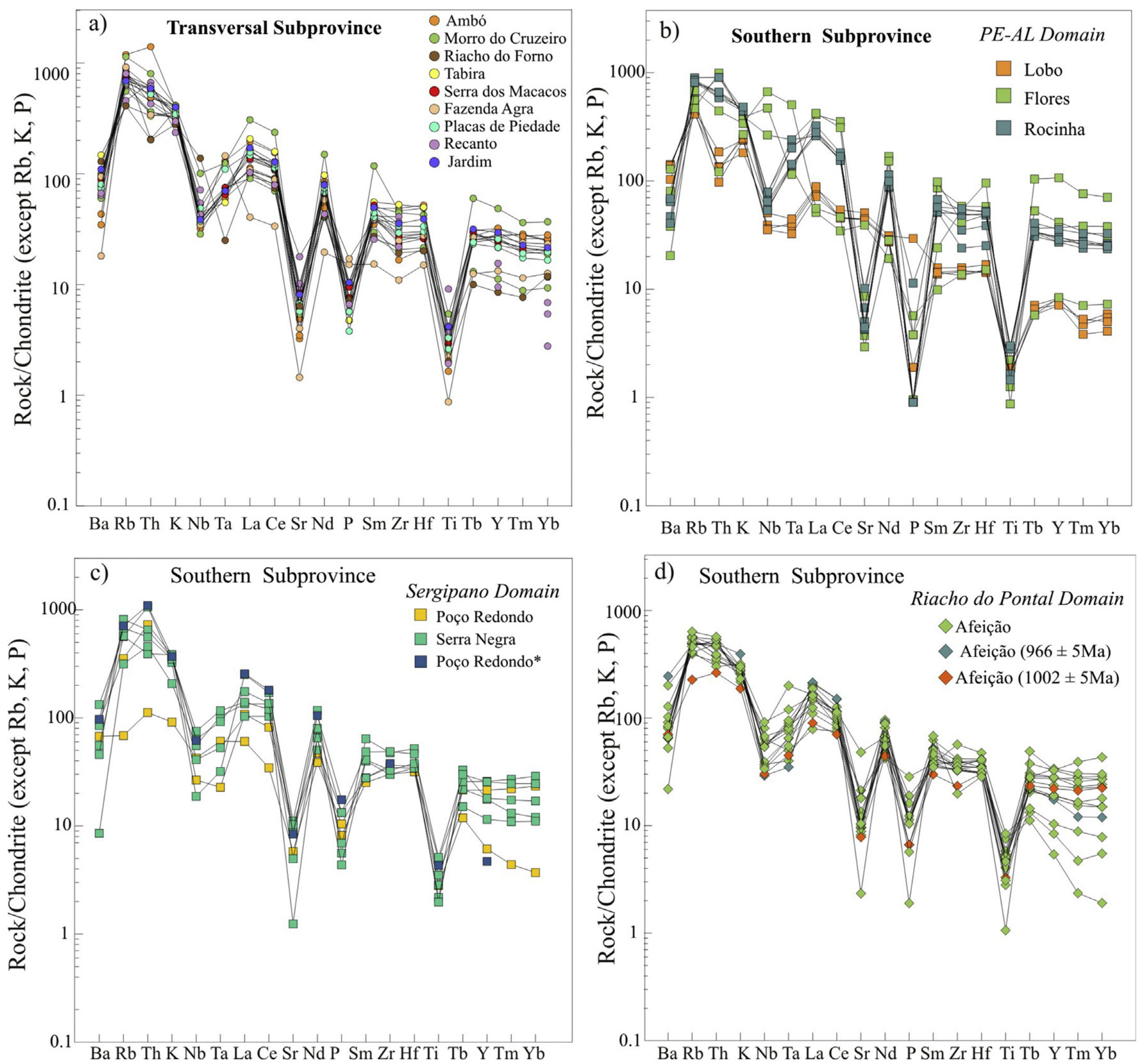

Fig. 9. The spidergram patterns of the studied Tonian orthogneisses, normalized to the values suggested by Thompson (1982), from the Transversal (a) and Southern subprovinces (b, c, d). In c) age of Poço Redondo from Carvalho (2005) and in d) ages from Caxito et al. (2014).

characterized by negative Eu anomalies and low $(Ce/Yb)_N$ ratios. The Lobo orthogneisses have the lowest, while the Flores orthogneisses have the highest total REE contents (Fig. 8b). The deeper negative Eu anomalies, with Eu/Eu* ranging from 0.12 to 0.4, were recorded in the Pernambuco – Alagoas domain. The Serra da Pintada augen-gneisses have REE patterns (Fig. 8d) similar to those recorded in the orthogneisses from the Cariris Velhos belt and Afeição suite of the Riacho do Pontal domain.

The spidergram patterns of the orthogneisses from all domains normalized to the values suggested by Thompson (1982) (Fig. 9 a–d) show many similarities: troughs at Ba, Sr, P and Ti and, variable troughs at Nb and Ta. The Lobo orthogneisses also show troughs at Ba, Ti, Nb and Ta, however, they differ from the others orthogneisses patterns by troughs at Th and no troughs at Sr (Fig. 9b). They have patterns similar to those recorded in others fine - grained orthogneisses as Sitio do Icó, and some of the Poço Redondo migmatites. However, the dated sample from the Poço Redondo migmatite, has spidergram pattern similar to those recorded in the Serra Negra augen - gneisses (Fig. 9c). The spidergram patterns recorded in the studied augen-gneisses and most of the migmatites are similar to those recorded in extension-related granitoids (Thompson et al., 1984). The Serra da Pintada augen - gneisses have primitive mantle spidergram patterns characterized by deep troughs at Sr, P and Ti, smaller troughs at Ba and peaks and smaller troughs at Nb (Aquino and Batista, 2011). These patterns are also similar to those recorded in extension-related granitoids.

The majority of the studied granitoids, including those from Serra da Pintada (see Aquino and Batista, 2011), plot in the A-type granites field (Fig. 10a) in the (FeO/MgO) versus (Zr + Nb + Ce + Y) tectonic discriminant diagram of Whalen et al. (1987). However, some samples plot in the field of fractionated granites, while the fine-grained migmatite sample from Sitio do Icó, and another one dated at ~1.0 from Afeição suite, fall in the field of unfractionated M–, I- and S-type granites. The A-type Tonian granitoids are, with rare exception, distinct from OIB (Fig. 10b) in the Y/Ta versus Y/Nb diagram (Eby, 1992). This chemical signature is typical of A_2-type granitoids (Eby, 1992). The A_2-type signature is also recorded in the majority of the studied granitoids, when they are plotted in the Nb–Y–Z/4 and Nb–Y–Ce diagrams (Fig. 10c,d) with fields after Eby (1992). However, although the Flores granitoids fall in the A_2-type granites field in the Nb–Y–Ce diagram, their high-Y and Nb contents are typical of A_1-type granitoids.

The Sitio do Icó analyzed migmatite sample is magnesian, and plot within the calc-alkaline field of the MALI versus SiO_2 diagram

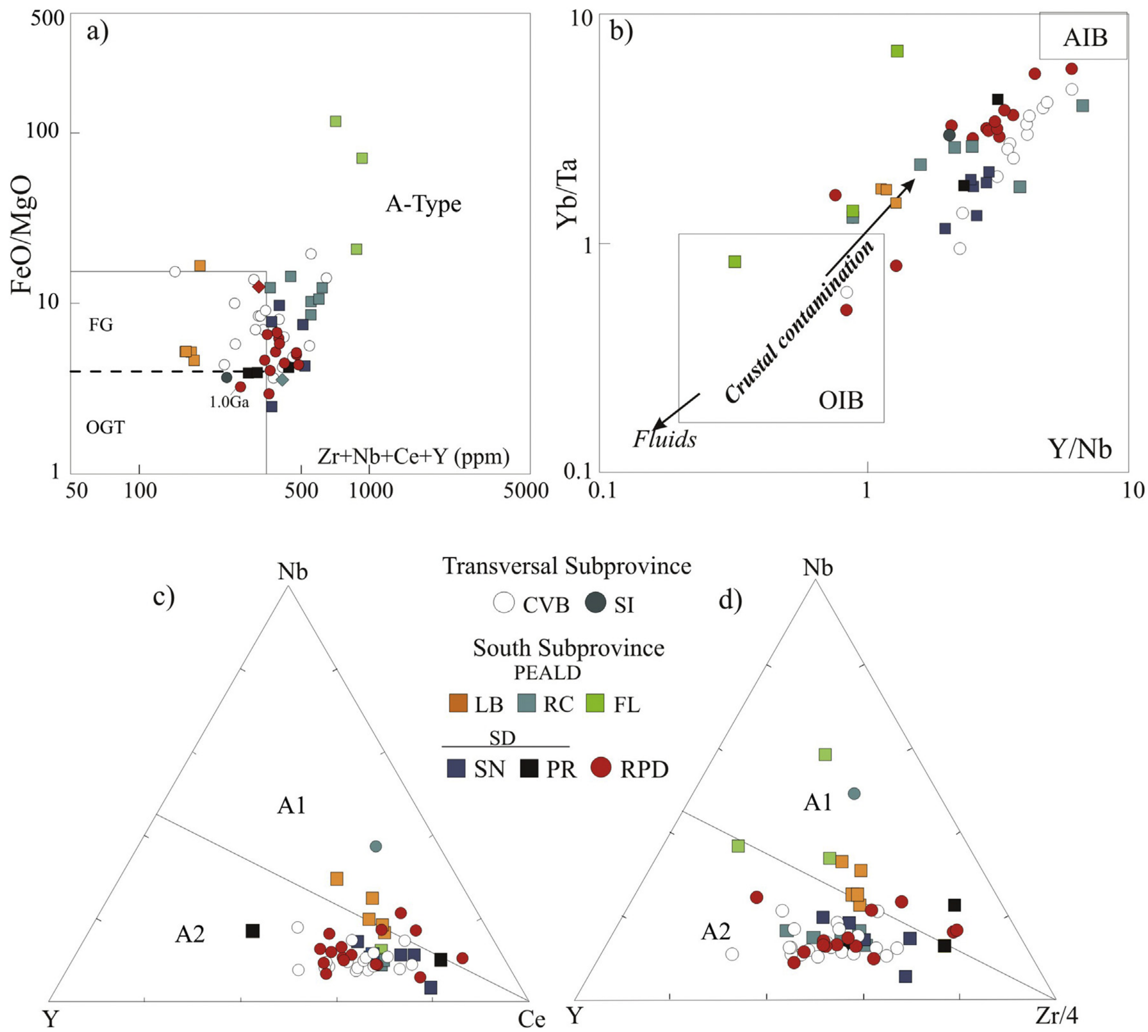

Fig. 10. The Tonian orthogneisses in the tectonic discriminant diagram of a) Whalen et al. (1987); and b) The Yb/Ta versus Yb/Nb diagram with fields of ocean island basalts (OIB) and island arc basalts (IAB) (Eby, 1992), and c) and d) A1 and A2 subgroups discrimination of A-type granites after Eby (1992). CVB – Cariris Velhos belt; SI – Sitio do Icó; PEALD – Pernambuco Alagoas domain; LB – Lobo pluton; RC – Rocinha pluton; FL – Flores pluton; SD – Sergipano domain; SN- Serra Negra; PR – Poço Redondo migmatites; RPD = Riacho do Pontal domain.

(Fig. 5a). It is distinct from the other Tonian granitoids from the Borborema Province, because it has low SiO_2 and HFSE contents. The analyzed sample shows spidergram pattern (Fig. 8a) with smaller troughs at Sr and Ti and lower HSFE contents, compared to the augen-gneisses. There is no geochemical data available for the Tonian orthogneisses from the east part of the PEAL domain and also for those of crystallization age younger than 0.9Ga.

6. Sm–Nd data

The Transversal subprovince concentrated most of the Sm–Nd whole rock data for the Tonian granitoids. The majority of them were obtained at the University of Kansas (Kozuch, 2003; Van Schmus et al., 2011), although a few were done at the Institute of Geosciences, São Paulo University (USP) and at the Geochronological Laboratories, Brasilia University.

The Tonian orthogneisses of the Cariris Velhos belt (Transversal subprovince) show Nd T_{DM} model ages ranging from 1.98 to 1.24Ga (Kozuch, 2003; Van Schmus et al., 1995, 2011). However, the majority of them have T_{DM} model ages within the 1.43–1.76 Ga interval (Fig. 11a,b). Those with T_{DM} model ages >1.8 Ga were recorded in the southwest part of the Cariris Velhos belt. Younger T_{DM} model ages were recorded in the Sítio do Icó migmatized orthogneisses (T_{DM} = 1.23Ga with εNd(t) of 2.89) and in the Serra Talhada orthogneisses (1.39 Ga and εNd(t) of 0.74).

In the Sergipano domain, Carvalho (2005) and Silva Filho et al. (1997) reported T_{DM} model ages ranging from 1.75 to 1.48Ga and εNd(t) values varying from 1.01 to −1.40 for the Poço Redondo migmatites. The Serra Negra pluton has T_{DM} model ages ranging from 1.53 to 1.66 Ga, and εNd(t) of −1.05 to −2.48 (Carvalho, 2005; Oliveira et al., 2010; Silva Filho et al., 1997).

Within the Pernambuco Alagoas domain, the Rocinha orthogneisses have T_{DM} model ages of 1.5Ga and εNd(t) value of −0.8 (Cruz and Accioly, 2013). Data from Silva Filho et al. (2014b) for migmatized orthogneisses (samples SI-100 and 125) show T_{DM} model ages ranging from 1.44 to 1.16Ga and εNd (980Ma) values ranging from 0.24 to 2.93.

The Sm–Nd data from the Riacho do Pontal domains, including migmatites and augen gneisses, show T_{DM} model ages ranging between 1.2 and 1.5 Ga, with εNd(t) from −1.0 to 3.1 (Caxito et al., 2014; Van Schmus et al., 1995, 2011).

Sm–Nd T_{DM} model ages recorded in the Tonian metaplutonic rocks (Fig. 11a,b) suggest participation of older crustal component in the genesis of their magmas. As pointed out by Van Schmus et al.

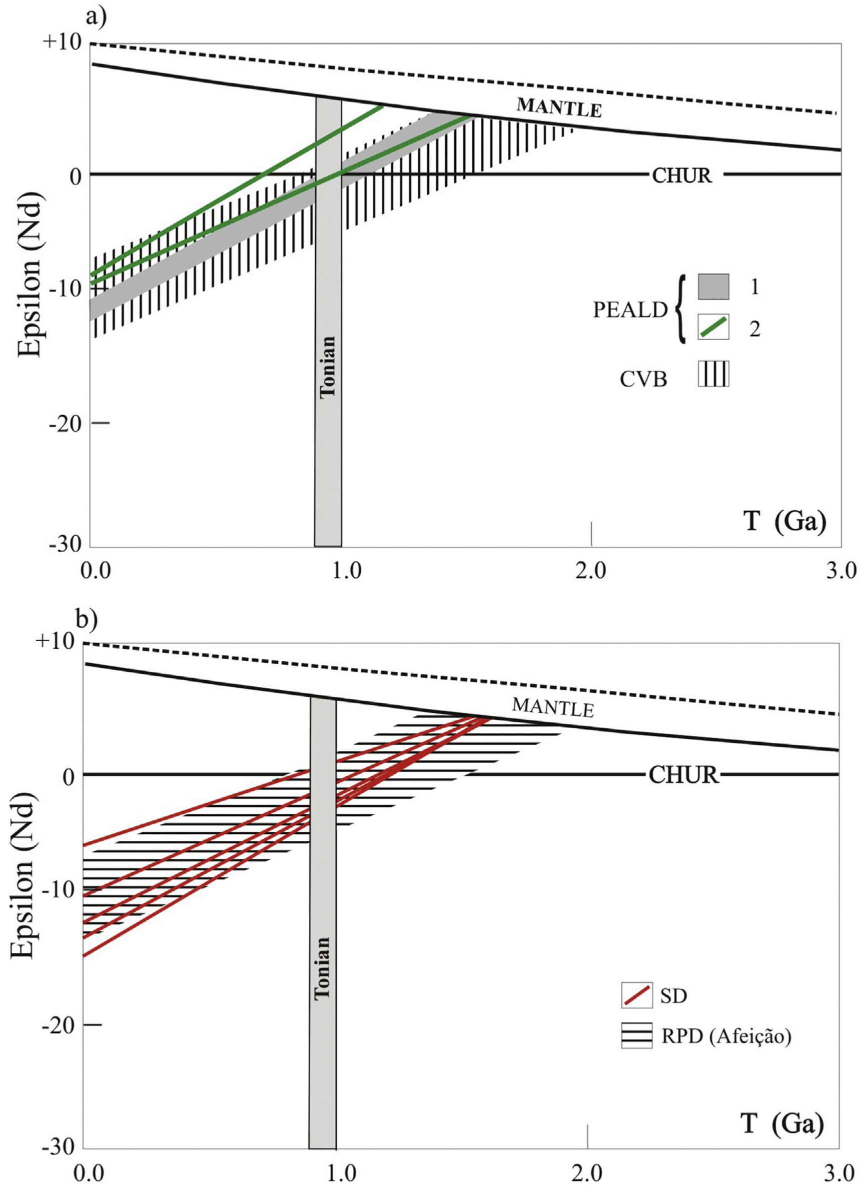

Fig. 11. Nd evolution paths for orthogneisses of the Tonian ages from the Borborema Province. a) CVB – Cariris Velhos belt data are from Van Schmus et al. (2011), Kozuch (2003). PEALD – Pernambuco Alagoas domain data are from (1) Cruz et al. (2014); (2) Silva Filho et al. (2014a,b). b) SD – Sergipano domain (Carvalho, 2005; Oliveira et al., 2010; Silva Filho et al., 1997). Depleted mantle curve of De Paolo (1981). Dashed line shows the upper limit of depleted mantle curves proposed by various authors (see Van Schmus et al., 2011).

(2011), large degrees of partial melting of a source having Sm/Nd model ages of 1.4–1.9 Ga (Mesoproterozoic lithosphere) can respond for such T_{DM} model ages recorded in the Tonian granitoids. However, this hypothesis is defeated by Van Schmus et al. (2011), using the argument that rocks with ages within this interval have a restrict occurrence in the Borborema Province and, that many of the plutons are hosted by Paleoproterozoic basement, with older Sm-Nd model ages (2.1–2.7 Ga). Another evidence that the Mesoproterozoic T_{DM} model ages of the Tonian granitoids reflect an old crustal component in their source, comes from the U–Pb data from the Riacho do Forno analyzed sample (Fig. 3). This sample has Paleoproterozoic zircon grains and Sm–Nd T_{DM} model age of 1.61Ga (Van Schmus et al., 2011). Thus, the Sm–Nd signatures recorded in the Tonian granitoids appear to reflect magmas formed by mixing of juvenile magmas within the 925 to 1000 Ma interval, with magmas generated by varying degrees of partial melting of Paleoproterozoic to Archean crust.

7. Discussions

The majority of the Tonian orthogneisses of the Borborema Province are ferroan granitoids. Ferroan magmas are formed by extreme differentiation or partial melting of tholeiitic to alkaline mafic magmas under reducing and relatively dry conditions in intraplate environments (Loiselle and Wones, 1979; Frost et al., 2001, 2008). The ferroan rocks in the SiO_2 versus MALI diagram are mostly alkali, although they can be alkali-calcic or even calc-alkaline as those from the Lachlan Fold Belt, described by Collins et al. (1982) and King et al. (2001). The ferroan granitoids from the Lachlan Fold Belt are aluminous (King et al., 1997) as the Tonian orthogneisses from the Borborema Province. Assimilation of high SiO_2 melts from the country rocks drives the magma to more calcic and peraluminous compositions (Frost and Frost, 2008).

The probably metasedimentary sources of the protoliths of the Serra Negra, Rocinha, Flores and some rocks of the Poço Redondo

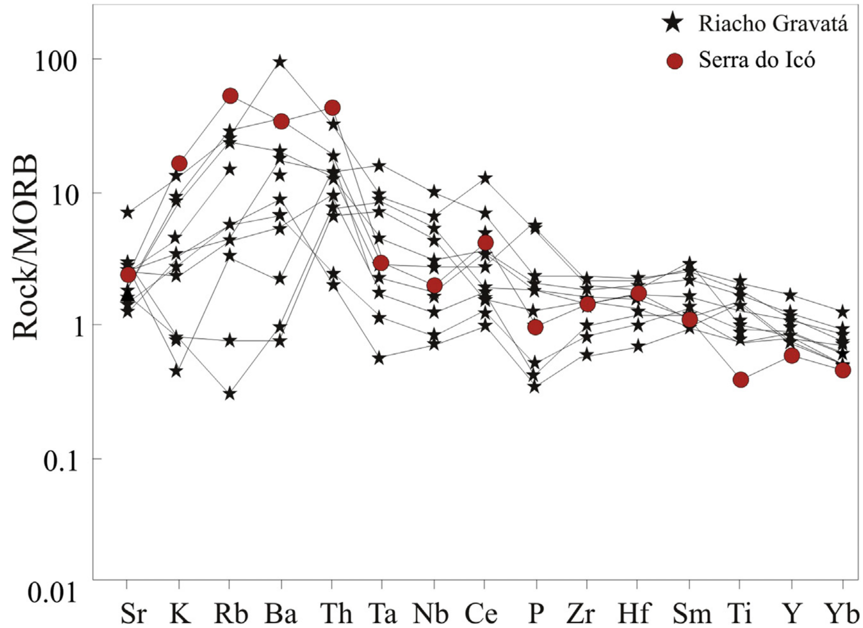

Fig. 12. - Spidergram pattern of the Sitio do Icó sample compared to the patterns of Tonian metamafic volcanic rocks of the Riacho Gravata Complex (Guimarães et al., 2012) normalized to the MORB values (Pearce, 1983).

migmatites and Recanto orthogneisses are difficult to explain at present day. The metasediments in the Riacho Gravatá Complex and Marancó subdomain have a Tonian maximum deposition age, and Tonian metamorphic event was not identified, up to now, in the Borborema Province. On the other hand, assimilation of deep-seated Paleoproterozoic sediments or melts produced by their fusion, could respond for the metasedimentary signature of these granitoids. The temperature required to produce an extractable magma may have been produced by either, mantle upwelling or mafic magmas influx during extension. The T_{DM} model ages >1.5Ga, recorded in these granitoids, require some juvenile magma involved in their protolith.

Small degree of melting of such metasediments can produce high-SiO_2 melts, which were incorporated into juvenile Tonian magmas, increasing Ca- and Al-contents in the magma (Frost and Frost, 2008). Because, the studied granitoids are Ca-poor, plagioclase should be an important fractionated phase during the magma evolution, explaining in this way, the low Sr contents, and deep negative Eu anomalies recorded in these rocks, and explaining the Sm–Nd signature of these granitoids.

The Sítio do Icó migmatized orthogneisses sample is magnesian, and show mineralogy (high amount of modal amphibole) and geochemical signature distinct from others Tonian gneisses. Magnesian rocks are granitoids with composition ranging from calcic to alkali-calcic and are formed in arcs and post-collisional environments (Frost and Frost, 2008). However, magmas generated by partial melting of magnesian crustal rocks can inherit magnesian signature (Frost and Frost, 2008). The positive ε(Ndt) values, T_{DM} model age of 1.23Ga, and lack of rocks with ages ~1.2Ga within the Borborema Province, do not support the hypothesis of a magma originated by melting of continental crustal rocks. It appears to have been originated from a depleted mantle source that underwent some crustal contamination. In Fig. 12, the similarities between the spidergram pattern normalized to the MORB values of this sample and the metavolcanic mafic rocks from the Riacho Gravatá Complex of the Cariris Velhos belt, suggest that this rock is a metavolcanic migmatized rock.

According to the evolution model of Oliveira et al. (2010) for the Sergipano domain, the Poço Redondo migmatites protoliths are arc-related, while the Serra Negra orthogneisses are A-type granites. However, the dated migmatite sample and the Serra Negra orthogneisses share similar extension-related geochemical signature (Fig. 9). On the other hand, the Tonian granitoids were intruded as small plutons and the Poço Redondo migmatites comprise a belt of more than 8 km wide and more than 30 km long. As pointed out before, the available geochemical data show that the analyzed samples represent rocks of distinct compositions and probably distinct sources. The lack, up to now, of evidence of a Tonian metamorphic event, associated to the geochemical similarities between the dated sample from the Poço Redondo migmatites and the Serra Negra pluton, do not support the hypothesis that the Poço Redondo migmatites are arc-related.

8. Conclusions

Tonian granitoids constitute the main magmatic expression of the Cariris Velhos belt of the Transversal subprovince and occur in minor volume in all domains of the South subprovince of the Borborema Province. However, they are absent, or not yet recognized, in the North subprovince.

The crystallization ages of the Tonian orthogneisses protoliths show that the main granitic pulse occurred in between 925Ma to 970Ma. The fine-grained migmatized rocks show older crystallization ages (~1.0Ga), similar to those recorded in felsic metavolcanic rocks of the Riacho Gravatá Complex. It suggests that most of the fine-grained migmatites can be metavolcanic felsic rocks. Thus, detailed work in these migmatites is necessary to better define their sources.

The studied granitoids have extension-related geochemical signature and most of them were generated by melting of igneous source rocks. However, the granitoids from the Sergipano domain and some from the south part of the Pernambuco – Alagoas domain appear to have a sedimentary component in their source. Interaction between juvenile magmas and melts generated by melting (or assimilation) of deep-seated Paleoproterozoic sediments, followed by plagioclase fractionation, is a plausible interpretation for the genesis of the Tonian granitoids from the Sergipano and the south part of the PEAL domain. The Sm–Nd isotopic signatures also support this hypothesis. The heat sources is inferred to be mafic melts associated with crustal thinning. It is also important to emphasize the sediments input in the graniotids sources from south part of the Pernambuco – Algoas domain and north part of the Sergipano domain.

However, the Cariris Velhos event is still open to significant debate. More detailed geochronological and geochemical data from the South subprovince, and detailed field works in the most migmatized area are necessary to understand the tectonic meaning of this event.

The Riacho do Pontal (Afeição suite) and Rio Preto (Serra da Pintada pluton) Tonian orthogneisses have geochemical signatures and crystallization ages similar to those recorded in the Cariris Velhos belt from the Transversal subprovince. These evidence associated to the dextral sense of the Pernambuco shear zone, suggest that during the Tonian period they were part of the same belt, which was disrupted by the dextral Pernambuco shear zone during the Brasiliano orogeny. Van Schmus et al. (2011) already proposed a link between the Transversal subprovince and the Riacho do Pontal domain.

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