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U-Pb (LA-ICPMS) zircon ages and Nd isotopes for granitoids of the Tamboril-Santa Quitéria Complex, Ceará Central Domain: implication for neoproterozoic syncollisional magmatism in north Borborema Province

Idade U-Pb (LA-ICPMS) em zircão e isótopos de Nd para granitoides do Complexo Tamboril-Santa Quitéria, Domínio Ceará Central: implicações para magmatismo neoproterozoico sin-colisional no domínio norte da Província Borborema

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Abstract

The Tamboril-Santa Quitéria Complex (TSQC) is one of the largest Neoproterozoic plutonic manifestations in the north Borborema Province (NE Brazil). It represents an anatectic/igneous association characterized by a number of magmatic pulses that occurred in the 650-610 Ma interval. In this paper, we present U-Pb (LA-MC-ICP-MS) zircon ages and Nd isotopes for quartz monzonites and quartz diorites of the southern part of TSQC. The quartz monzonites belong to a hybrid granitoid association, including monzonites, syenites and quartz syenites, all with abundant mafic magmatic enclaves. A quartz monzonite sample yielded a U-Pb zircon age of 634 ± 10 Ma and a TDM age of 2.69 Ga. The quartz diorites are much more homogeneous in composition and yielded a U-Pb zircon age of 618 ± 23 Ma and a TDM age of 2.19 Ga. The presence of coeval mantle-derived magmatism and diatexites (crustal anatexis) post-dating high-pressure metamorphism (*ca.* 650 Ma), and together with high-temperature metamorphism (*ca.* 630-610 Ma), suggests that this large magmatic manifestation evolved in a collisional setting, probably related to slab breakoff during the Western Gondwana amalgamation.

Keywords: Borborema Province; Neoproterozoic magmatism; Continental collision.

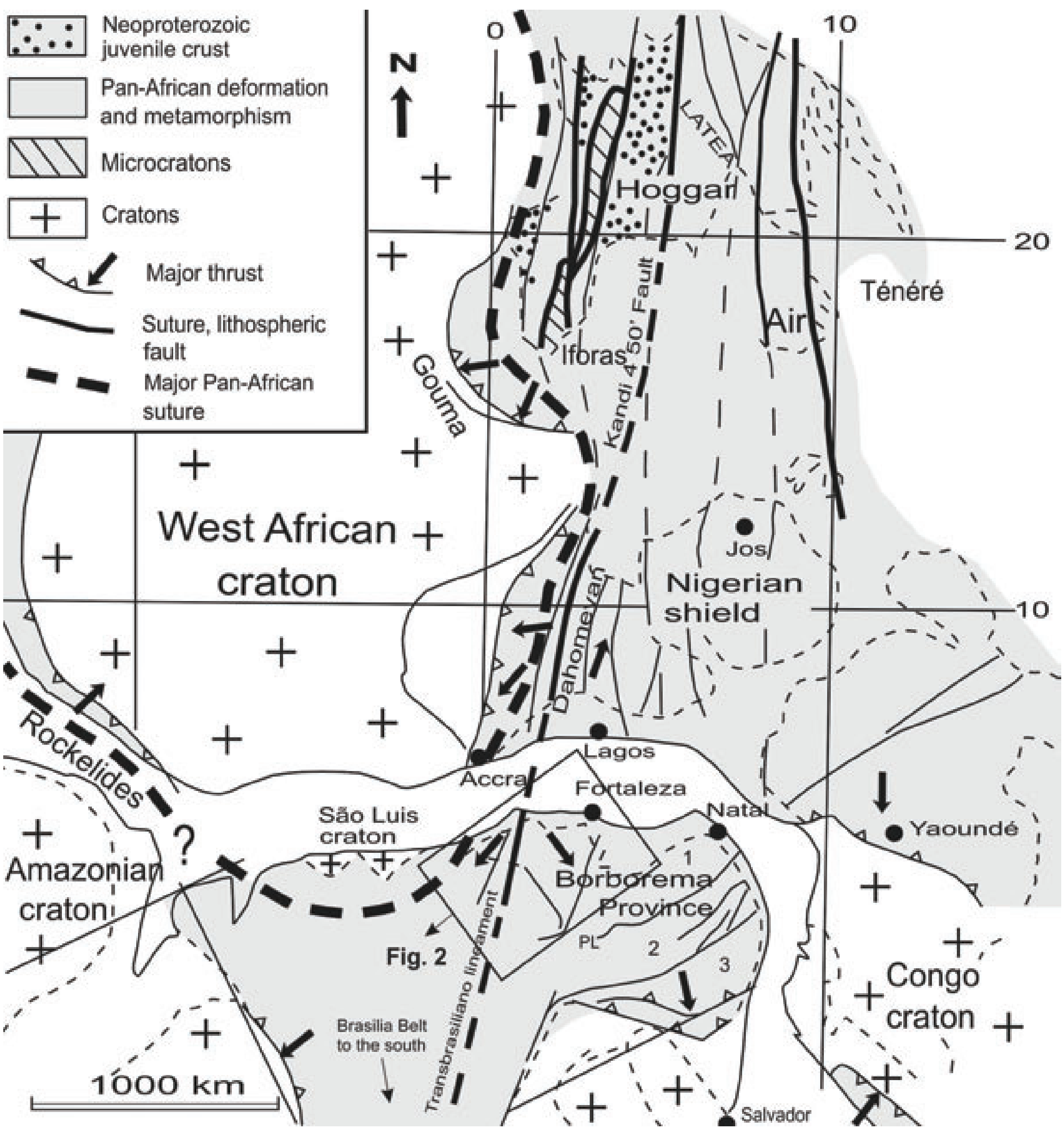
Resumo

O Complexo Tamboril Santa-Quitéria (CTSQ) é uma das maiores manifestações plutônicas do Neoproterozoico na porção norte da Província Borborema (NE Brasil). Corresponde a uma associação granito-migmatítica envolvendo granitoides diversos no intervalo de 650-610 Ma. Neste trabalho, são apresentadas idades U-Pb (LA-MC-ICP-MS) em zircão e isótopos de Nd para quartzo-monzonitos e quartzo-dioritos da porção sul do CTSQ. Os quartzo-monzonitos fazem parte de uma associação de granitoides híbridos, incluindo monzonitos, sienitos e quartzo-sienitos, todos com abundante ocorrência de enclaves máficos magmáticos. Para uma amostra de quartzo-monzonito, foram obtidas idade U-Pb em zircão de 634 ± 10 Ma e idade TDM de 2,69 Ga. Os quartzo-dioritos são bem mais homogêneos em composição, e, para uma amostra, foram obtidas idade U-Pb em zircão de 618 ± 23 Ma e TDM de 2,19 Ga. A presença simultânea de magmatismo com afinidade mantélica e diatexitos (fusão crustal), após o metamorfismo de alta-pressão (*ca.* 650 Ma) e junto com o metamorfismo de alta temperatura (*ca.* 630 – 610 Ma), sugere que esta grande manifestação magmática evoluiu em um ambiente colisional, provavelmente associado ao processo de *slab breakoff* durante a amalgamação da porção oeste do supercontinente Gondwana.

Palavras-chave: Província Borborema; Magmatismo neoproterozoico; Colisão continental.

INTRODUCTION

The Tamboril-Santa Quitéria Complex (TSQC) is one of the largest Neoproterozoic plutonism in the northern Borborema Province (Fetter et al., 2003; Castro, 2004; Arthaud et al., 2008) (Figures 1 and 2). It is an anatectic/igneous association characterized by a number of magmatic pulses that occurred in the 650-610 Ma interval (e.g. Fetter et al. 2003; Castro, 2004; Santos et al., 2007; Araujo et al., 2012a) (Table 1). This large granite-migmatitic complex has a tabular shape and is probably an allochthonous unit related to nappe tectonics (Caby and Arthaud, 1986). The structural pattern points to magma emplacement concomitant with tangential deformation, with a ubiquitous syn- to late-magmatic deformation followed by injection of less deformed, younger magmas



PL: Patos Lineament; 1: North Borborema Province; 2: Transversal Zone; 3: Sergipano Belt. Figure 2 is also represented.

Figure 1. Pre-drift reconstruction of NE Brazil and NW Africa in the late Neoproterozoic – early Paleozoic interval (Arthaud et al., 2008).

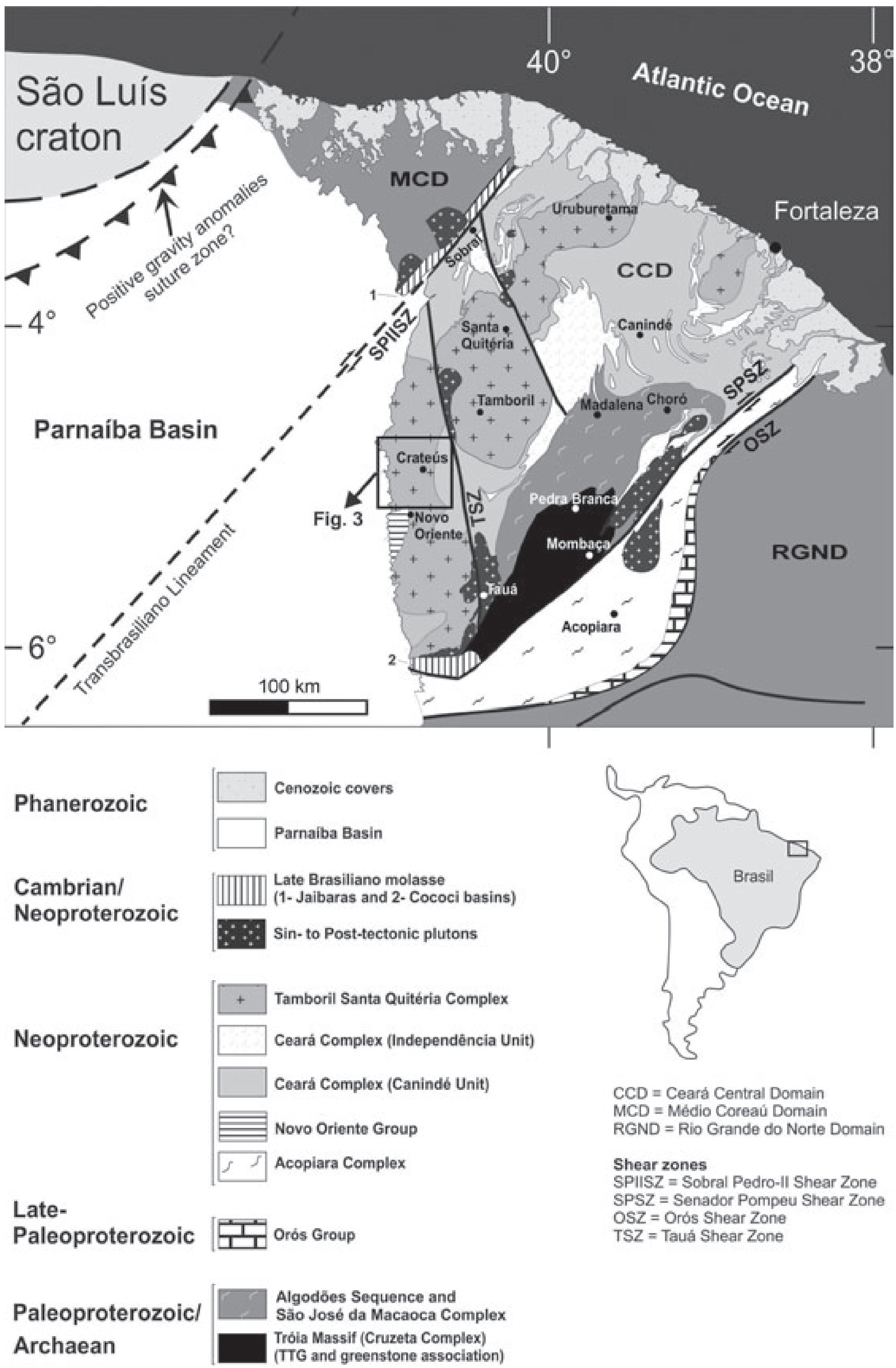


Figure 2. Geological map of the Ceará Central Domain (CCD) and the surrounding geological framework adapted from Fetter et al. (2003) and Cavalcante et al. (2003). Figure 3 is also represented.

(Fetter et al., 2003; Arthaud et al., 2008). In general, granitic/granodioritic pink granitoids and diatexites predominate, with some local participation of less evolved dioritic to tonalitic rocks (Fetter et al., 2003; Santos et al., 2007). The Nd isotopic signatures [ε_{Nd} (600 Ma) -20 to +4] are consistent with variable mixtures between juvenile Neoproterozoic magmas and crust-derived magmas of the surrounding Paleoproterozoic gneisses (Fetter et al., 2003). Regarding the basis of these isotopic characteristics and the proximity of this magmatism to the probably Brasiliano/Pan-African suture zone (Figure 2), Fetter et al. (2003) suggested a continental-margin magmatic arc as the tectonic setting for TSQC. However, geochronological constraints on regional high-grade metamorphism (Castro, 2004; Amaral, 2010; Amaral et al., 2012) overlap the TSQC plutonism interval (~650 – 610 Ma), which suggests that metamorphism and magmatism essentially resulted from the same thermal anomalies. This linking between high-grade metamorphism and magmatism led to the interpretation of a continent-continent collisional setting for the TSQC magmatic evolution (Costa et al., 2010; Amaral, 2010; de Araujo et al., 2010a). In terms of petrology, it has been suggested that the pinkish diatexites and many evolved biotite-granites in TSQC were probably generated by partial melting of an intermediate crustal source (de Araújo et al., 2012a). However, coeval to this crust-derived granites and diatexites, mantle-derived magmatism also occurs in TSQC, and it is a very important subject to be investigated in order to discuss petrogenesis and tectonic processes at this large granite-migmatite complex. In this paper, we present U-Pb zircon ages and Sm-Nd isotope data for deformed quartz monzonites and quartz diorites of the southern part of TSQC and discuss their contribution to a regional geodynamic model.

REGIONAL GEOLOGY

The Borborema Province was defined by Almeida et al. (1981) as a complex region of tectono-stratigraphic domains, structured during the Neoproterozoic. This province covers an area of approximately 450,000 km^2 in northeastern Brazil and its final configuration results from the convergence of the Amazon, São Luis/West African and São Francisco/Congo cratons during the Brasiliano/Panafrican collage of West Gondwana (Brito Neves and Cordani, 1991; Trompette, 1994) (Figure 1). Recently, several isotopic studies, specially U-Pb and Sm-Nd data, have helped distinguish different tectono-magmatic domains in the Borborema Province (e.g., Van Schmus et al., 2003, 2008; Arthaud, 2007; Arthaud et al., 2008; Neves et al.,

Table 1. Summary of available U-Pb and Pb-Pb geochronological data for the Tamboril-Santa Quitéria Complex.

Rock type	Method	Age (Ma)	Reference
Hb-bt-diatexite	U-Pb in zircon (isotopic dilution)	658 +/- 6 (protolith)	(Teixeira, 2005)
Granitic orthogneiss	Pb-Pb in zircon (evaporation)	657 +/- 4 (crystallization)	(de Araujo et al., 2012a)
Granitic orthogneiss	Pb-Pb in zircon (evaporation)	643 +/- 10 (crystallization)	(de Araujo et al., 2012a)
Porphyritic granite	U-Pb in zircon (isotopic dilution)	641 +/- 15 (crystallization)	(Santos et al., 2007)
Granitic orthogneiss	U-Pb in zircon (isotopic dilution)	639 +/- 4 (crystallization)	(Santos et al., 2007)
Metatonalite	U-Pb in zircon (isotopic dilution)	639 +/- 2 (crystallization)	(Santos et al., 2007)
Granitic orthogneiss	Pb-Pb in zircon (evaporation)	639 +/- 4 (crystallization)	(de Araujo et al., 2012a)
Granitic orthogneiss	U-Pb in zircon (LA-MC-ICP-MS)	638 +/- 3 (crystallization)	(de Araujo et al., 2010b)
Metadiorite	U-Pb in zircon (isotopic dilution)	637 +/- 6 (crystallization)	(Fetter et al., 2003)
Meta-quartz monzonite	U-Pb in zircon (LA-MC-ICP-MS)	634 +/- 10 (crystallization)	This study
Bt-diatexite	U-Pb in zircon (isotopic dilution)	629 +/- 22 (crystallization)	(Castro, 2004)
Metagabbro	U-Pb in zircon (isotopic dilution)	628 +/- 1 (crystallization)	(Teixeira, 2005)
Metagranodiorite	U-Pb in zircon (isotopic dilution)	624 +/- 1 (crystallization)	(Fetter et al., 2003)
Metagabbro	U-Pb in zircon (isotopic dilution)	623 +/- 4 (crystallization)	(Santos et al., 2007)
Granitic orthogneiss	Pb-Pb in zircon (evaporation)	620 +/- 9 (crystallization)	(de Araujo et al., 2012a)
Hb-bt-diatexite	U-Pb in zircon (isotopic dilution)	620 +/- 8 (crystallization)	(Castro, 2004)
Meta-quartz diorite	U-Pb in zircon (LA-MC-ICP-MS)	618 +/- 23 (crystallization)	This study
Bt-diatexite	U-Pb in zircon (isotopic dilution)	618 +/- 11 (crystallization)	(Castro, 2004)
Bt-diatexite	U-Pb in zircon (isotopic dilution)	611 +/- 2 (crystallization)	(Castro, 2004)

2009, 2012; Oliveira, Windley, Araújo, 2010; de Araujo et al., 2010b, 2012b; Santos et al., 2010; Van Schmus, Kozuch, Brito Neves, 2011).

On the basis of U-Pb ages and crustal Nd signatures, the northern Borborema Province (northward of the Patos lineament) can be divided in three main geological domains (Fetter et al., 2000): (i) Médio Coreaú Domain (or NW Ceará), (ii) Ceará Central Domain and (iii) Rio Grande do Norte Domain (Figure 2). For a review of the northern Borborema Province geology and its correlation with the African counterpart, see Arthaud et al. (2008) and Santos et al. (2009). The limits of the domains cited above are not well constrained in the literature, but there is strong evidence that they may represent tectono-stratigraphic terranes accreted to the São Luis/West Africa continental margin during the Neoproterozoic. The gravimetric anomalies (Lesquer, Beltrão, Abreu, 1984) found under the Parnaíba Basin (Figure 2) indicate that there is a prolongation of the major Pan-African suture zone (Caby, 1989; Trompette, 1994; El-Hadj et al., 1997; Fetter et al., 2003) that bends parallel to the Transbrasiliano-Kandi lineament and to the Brazilian portion of the West African craton (São Luis craton) (Figures 1 and 2).

The Ceará Central Domain (CCD) (Figure 2) encompasses a geological mosaic composed of an Archean inlier (Tróia Massif 2.8 – 2.7 Ga) (Fetter, 1999) which is enveloped by Paleoproterozoic orthogneisses and migmatites of the Cruzeta Complex, São José da Macaoca Complex and juvenile plutonic-volcanic-sedimentary sequences of the Algodões Unit and Madalena Suite, all with ages falling in the range from 2.17 to 2.13 Ga (Fetter et al., 2000; Martins, Oliveira, Lafon, 2009). These Archean to Paleoproterozoic rocks were the basement for Neoproterozoic supracrustal volcano-sedimentary rocks represented by the Ceará Complex and the Novo Oriente Group (Arthaud et al., 2008; de Araujo et al., 2010b, 2012b) (Figure 2). In general, all these units (basement and supracrustal rocks) were strongly deformed and migmatized during the Brasiliano/Panafrican tectono-thermal event. The structural patterns observed in CCD are dominated by early low-angle foliation related to a nappe tectonics (Caby and Arthaud, 1986) that probably took place at 650 – 610 Ma, followed by the late development of large NNE-SSW transcurrent shear zones at ~590 – 530 Ma (e.g., Vauchez et al., 1995; Neves, Vauchez, Archanjo, 1996; Monié, Caby, Arthaud, 1997). The high-grade metamorphism in CCD is represented by local high-pressure granulite facies (~650 – 640 Ma) (Castro, 2004; Amaral, 2010; Amaral et al., 2012), some relict eclogite facies (Santos et al., 2009), and subsequent regional high-temperature granulite/amphibolite metamorphism (630-610 Ma) (Arthaud, 2007; Amaral, 2010; Amaral et al., 2012).

Magmatism around 650 – 610 Ma in CCD is mainly represented by TSQC, as described in the introduction, followed by large syn-transcurrent batholith emplacement (e.g., Quixadá-Quixeramobim) at *ca*. 590 – 560 Ma (Fetter, 1999; Nogueira, 2004). Finally, the intrusion of slightly deformed late-transcurrent batholiths (e.g., Mucambo and Meruoca) took place at *ca*. 540 – 520 Ma (Fetter, 1999; Archanjo et al., 2009, Santos et al., 2013), and isotropic anorogenic plutons, at 490 – 460 Ma (Castro et al., 2012).

LOCAL GEOLOGY

During the Geological Survey of Brazil mapping program in the Crateús topographic sheet area (scale 1:100.000), which partly covers the southern portion of TSQC (Figures 2 and 3), three main magmatic units were recognized, according to their field and petrographic characteristics: (i) diatexites, (ii) hybrid granitoids, and (iii) quartz-dioritic plutons.

(i) Diatexites are the predominant rock type in the area (Figure 3), represented by medium- to coarse-grained, alkali feldspar rich, pink granitic rocks containing biotite as the main mafic mineral. Minor hornblende is commonly present. A typical feature of this diatexite is the abundance of fine-grained mafic/intermediate enclaves (restites?) and schlieren structures. Some mafic/intermediate enclaves characterize schollen-type structures (Figure 4A) and may represent metamorphic xenoliths derived from either nearby country-rock or from deep sources. Diatexite hand samples generally resemble granitoids and show only a weak foliation. However, migmatitic textures can be recognized in the outcrops, from (1) layered variations in grain size and biotite content; (2) schlieren structures, and, most importantly, (3) the widespread presence of mafic to intermediate gneissic enclaves in various stages of arrested dissolution (Figures 4A and B). The diatexite petrographic analyses show granodioritic to granitic compositions, essentially alkali feldspar (20 – 30%), plagioclase (15 – 25%), biotite (10 – 20%) and quartz (15 – 25%). The enclaves show dioritic to tonalitic composition, with plagioclase (20 – 30%), alkali feldspar (5 – 10%), quartz (5 – 15%), biotite (10 – 20%) and hornblende (5 – 10%).

(ii) We use the term "hybrid granitoids" in the TSQC for the association represented by monzonites, quartz monzonites and quartz syenites emplacing the diatexite. These granitoids are characterized by the presence of mafic, hornblende-bearing enclaves and syn-plutonic mafic dykes, evidencing magma mingling processes (Figure 4C). Therefore, its petrogenesis advocates a dual source contribution, displaying characteristics compatible to those of hybrid, mixed-origin "H" granitoids of Barbarin (1990). In the study

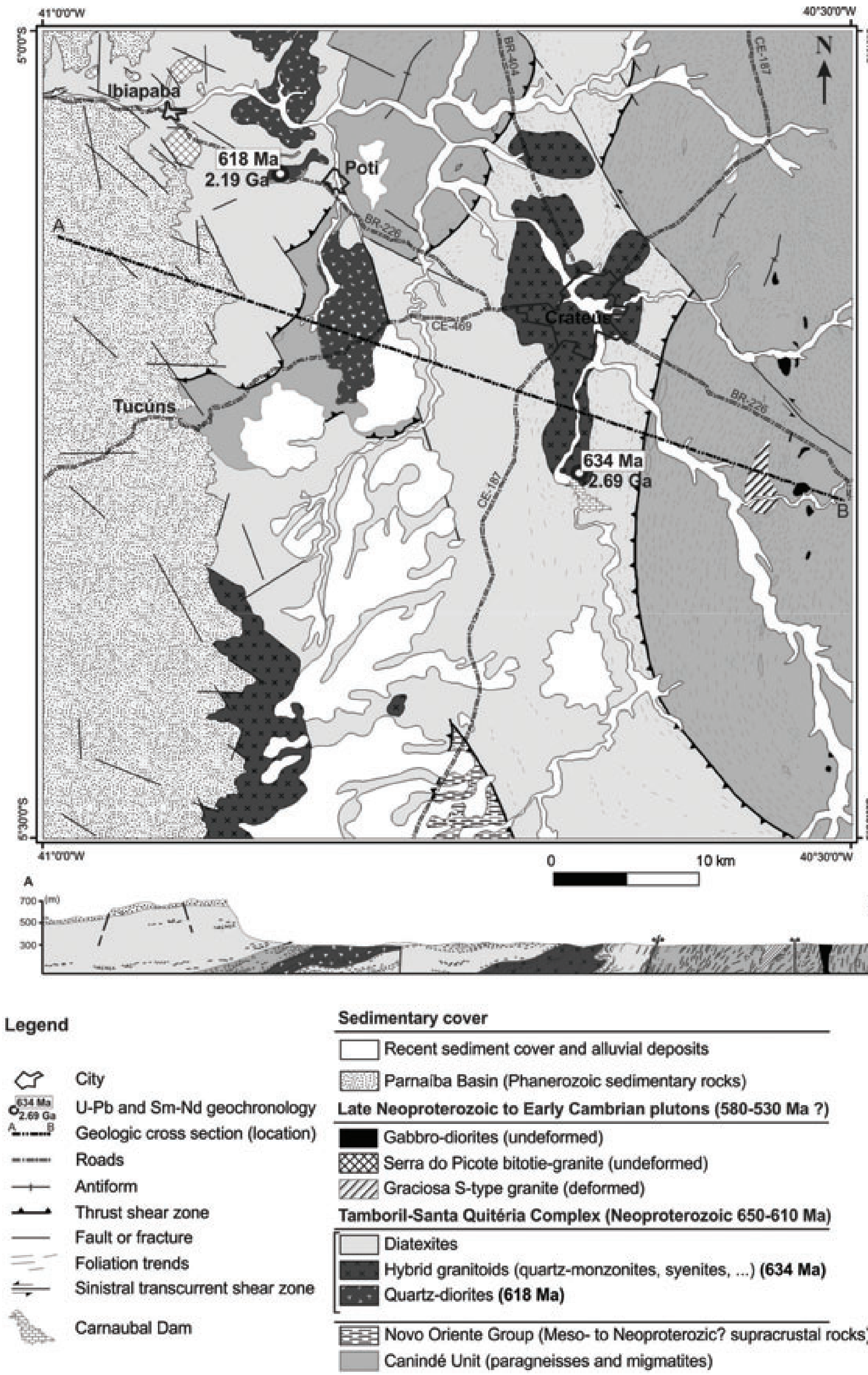


Figure 3. Geological map and geologic cross section of the study area (simplified from Costa, 2011).

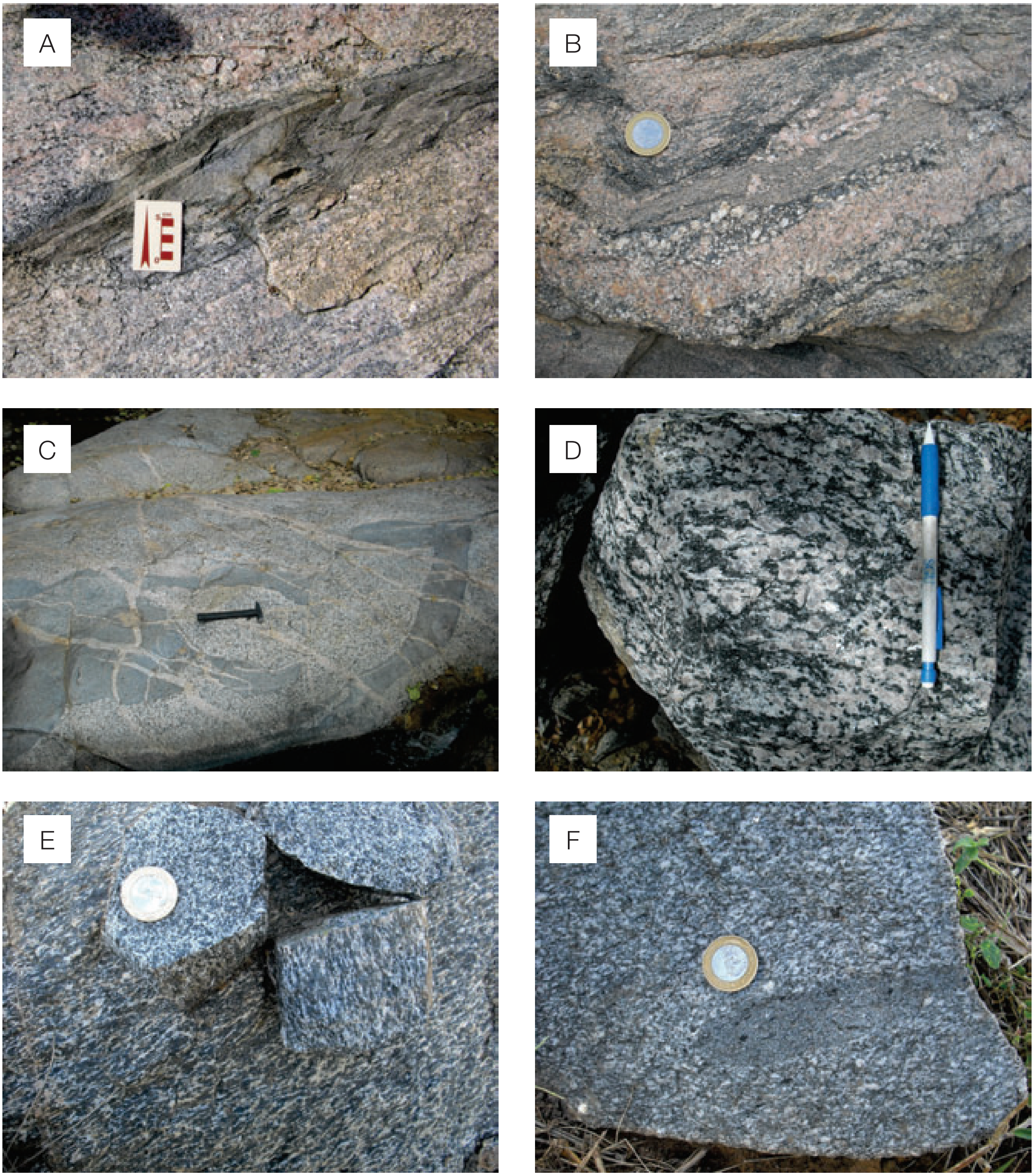


Figure 4. (A) Diatexite with mafic/intermediate gneissic enclaves characterizing schollen-type structure; (B) pink diatexite with schlieren structure, showing oriented biotite-rich gneissic bands (paleosome?), partially dissolved into the anatectic magma (*flow banding diatexite*); (C) syn-plutonic mafic dyke host by a hornblende-bearing quartz syenite; (D) typical quartz monzonite from the hybrid granitoid association that outcrops at the Carnaubal dam (sample FC-162B); (E) meta-quartz diorite with milonitic foliation; (F) felsic intermediate magmatic enclave in less deformed quartz-dioritic rock.

area, quartz syenites and quartz monzonites are the predominant rock type in this association (Figures 4C and D). These plutonic rocks are deformed medium-grained rocks, generally with equigranular phaneritic textures, and locally porphyritic textures with alkali feldspar phenocrysts. Hornblende is the main mafic mineral, but biotite can also be abundant. Felsic (granitic) magmatic enclaves can also be found in these granitoids. Petrographic analyses for this hybrid granitoid reveal that the monzonites and quartz monzonites are mainly composed of plagioclase (~30%), alkali feldspar (~15%), quartz (~5 – 10%), hornblende (~25%) and biotite (~10%). The quartz syenites are composed of alkali feldspar (~40%), plagioclase (~10%), hornblende (~20%), biotite (~10%) and quartz (~5%). Mafic magmatic enclaves are generally monzonitic to monzodioritic in composition and contain variable amounts of biotite (10 – 30%), clinopyroxene (0 – 18%), hornblende (5 – 20%), alkali feldspar (10 – 15%) and plagioclase (10 – 20%).

(iii) The quartz diorites are the least evolved plutonic rocks in the area. They occur as small intrusions within the diatexite domain, are slightly aligned according to a NW-SE trend, and are locally juxtaposed to paragneissic-migmatitic rocks of the Canindé Unit (Figure 3). They are dominantly represented by medium-grained, dark-gray granitoids, generally showing low-angle foliation and locally strong mineral stretching lineation (Figure 4E). The quartz diorites are mainly composed of plagioclase (~40%), hornblende (~30%) and clinopyroxene (~15%), with less abundant biotite (~5%), alkali feldspar (~5%) and quartz (~5%). Except for a few magmatic enclaves with the same composition of the host quartz diorites (Figure 4F), neither mafic magmatic enclaves nor primitive igneous facies have been found in the field, attesting for a dominant homogeneous, intermediate composition of these rocks.

ANALYTICAL METHODS

U-Pb zircon geochronology

The analytical procedures were carried out at the Geochronology Laboratory of the Brasília University (UnB). Samples selected for laser ablation multiple-collector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) zircon analyses were crushed with a jaw crusher and powdered to approximately 500 μm. Heavy mineral concentrates were obtained by panning and were subsequently purified using a Frantz isodynamic separator. Zircon grains were selected from the least magnetic fraction. The grains were set in epoxy resin mounts and polished. The U-Pb analyses by LA-MC-ICP-MS were carried out using a Finnigan Neptune mass spectrometer coupled to a Nd-YAG laser (λ = 213 nm) ablation system (New Wave Research, USA) at the Geochronology Laboratory of the UnB. The analytical procedures followed those proposed by Bühn et al. (2009), in which the mounts were cleaned in a HNO_3 solution (3%) and in an ultraclean water bath. The ablation was performed adopting a 30-μm spot size, a frequency of 9-13 Hz and an intensity of 0.19 – 1.02 J/cm^2. The ablated material was carried by Ar (~0.90 L/min) and He (~0.40 L/min) in analyses of 40 cycles of 1 s. Unknowns were bracketed by measurements of the international standard GJ-1, following the sequence 1 blank, 1 standard, 4 unknowns, 1 blank, and 1 standard. The accuracy was controlled using the standard UQZ. Raw data were reduced using a home-made spreadsheet and corrections were done for background, instrumental mass bias drift and common Pb. The ages were calculated using ISOPLOT 3.0 (Ludwing, 2003).

Nd isotopes

Sample preparation and isotopic analyses were made at the Geochronology Laboratory of the UnB. Sm-Nd isotopic measurements were carried out using a multicollector Finnigan MAT 262 mass spectrometer in static mode and according to Gioia and Pimentel (2000). Whole-rock powders (*ca.* 50 mg) were mixed with a ^{149}Sm-^{150}Nd spike solution and dissolved in HF, HNO_3 and HCl in Savillex capsules. The cation exchange technique was used to extract Sm and Nd from whole-rock samples by means of Teflon columns containing LN-Spec resin (HDEHP – di-ethylhexil phosphoric acid supported on PTFE powder). Sm and Nd samples were loaded on Re evaporation filaments of a double filament assembly. Uncertainties for Sm/Nd and ^{143}Nd/^{144}Nd ratios are better than ± 0.5% (2σ) and ± 0.005% (2σ), respectively, based on repeated analyses of international rock standards BHVO-1 and BCR-1. The ^{143}Nd/^{144}Nd ratios were normalized to ^{146}Nd/^{144}Nd of 0.7219, and depleted mantle model age (TDM) values were calculated using De Paolo (1981) model.

RESULTS (ISOTOPE GEOLOGY)

Quartz monzonite (FC-162B)

Sample FC-162B (utm: 315160, 9416336) was collected in a huge outcrop located in the Carnaubal reservoir area, 10 km south of the Crateús city, Ceará state (Figure 3). The rock corresponds to a slightly deformed quartz monzonite, showing medium to coarse grained phaneritic texture (Figure 4C). Its estimated mineralogical composition is alkali feldspar (35%), hornblende (25%), plagioclase (15%), biotite (15%) and quartz (10%). Zircon grains extracted from sample FC-162B are typically medium sized (100 – 150 μm long), elongated euhedral to subhedral prisms (3:1 to 4:1). The crystals are colorless to slightly pink, often translucent, with rare inclusions. The age obtained from 10 zircon grains is 634 ± 10 Ma (Figure 5). U-Pb data are listed in Table 2. Alternatively, the weighted average calculated for $^{207}Pb/^{206}Pb$ values yielded an age of 630 ± 14Ma (2σ, mean squared weighted deviation – MSWD = 1,09) (Figure not shown). For this weighted average, we use only the most concordant data (grain spot: z06, Z16, Z18 and z15), with concordance between 95 – 105% (Table 2). Sm-Nd isotopic measurements of sample FC-162B yielded a TDM model age of 2.69 Ga and $\varepsilon_{Nd\ (634)}$ of -14.10 (Table 3).

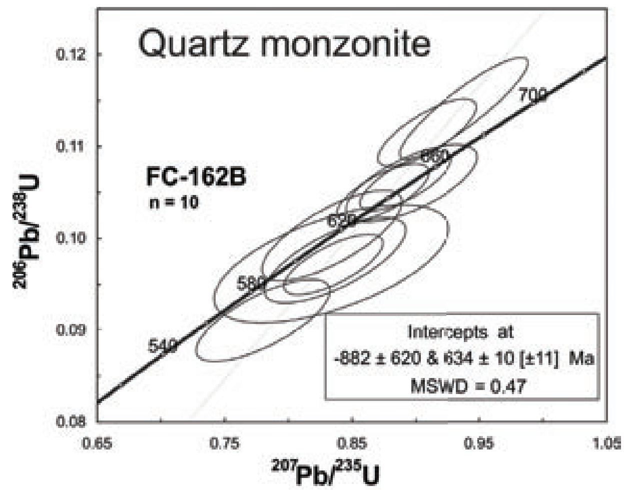


Figure 5. Concordia diagram from zircons of quartz monzonite (FC-162B).

Table 2. U-Pb analytical data from zircons of sample FC-162-B (quartz monzonite).

Grain.spot	f206(%)	Th/U	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	err (%) 1σ	$^{207}Pb/^{235}U$	err (%) 1σ	$^{206}Pb/^{238}U$	err (%) 1σ	Rho	$^{207}Pb/^{206}Pb$	(Ma)	$^{207}Pb/^{235}U$	(Ma)	$^{206}Pb/^{238}U$	(Ma)	Conc.(%)
Z01	0.05	0.39	32305	0.062146	1.87	0.780	2.75	0.091048	2.01	0.73	679	40	586	12	562	11	82.71
Z06	0.04	0.34	40455	0.061359	1.71	0.897	2.35	0.106003	1.62	0.68	652	36	650	11	649	10	99.64
Z07	0.05	0.44	32784	0.062167	1.88	0.837	2.70	0.097610	1.94	0.71	680	40	617	12	600	11	88.31
Z10	0.08	0.60	21678	0.062189	3.62	0.834	4.51	0.097239	2.69	0.59	681	75	616	21	598	15	87.89
Z12b	0.03	0.47	56256	0.062346	1.31	0.835	1.90	0.097160	1.38	0.72	686	28	616	9	598	8	87.14
z15	0.02	0.59	91260	0.060400	1.17	0.874	1.69	0.104961	1.22	0.71	618	25	638	8	643	7	104.12
Z16	0.03	0.90	54235	0.060313	1.79	0.834	2.69	0.100304	2.00	0.74	615	38	616	12	616	12	100.22
Z18	0.02	0.49	90836	0.060906	1.08	0.892	1.64	0.106220	1.23	0.74	636	23	647	8	651	8	102.33
z19	0.02	0.49	107430	0.059572	0.96	0.938	2.20	0.114165	1.98	0.90	588	21	672	11	697	13	118.51
Z20	0.02	0.43	85739	0.059121	1.11	0.909	1.74	0.111507	1.34	0.76	572	24	657	8	681	9	119.24

Table 3. Sm-Nd isotopic composition of the quartz monzonite (FC-162B) and quartz diorite (CR-011).

Amostra	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ (± 2SE)	$\varepsilon_{Nd\ (0)}$	TDM (Ga)	$\varepsilon_{Nd\ (t)}$
FC-162B	7.148	31.953	0.1352	0.511659 +/- 16	-19.09	2.69	-14.10
CR-011	8.793	48.604	0.1094	0.511537+/- 11	-21.48	2.19	-14.56

t: crystallization age.

Quartz diorite (CR-011)

Sample CR-011 (utm: 294594, 9437217) was collected from a small body of quartz-dioritic rocks cropping out as boulders on the BR-226 highway about 25 km from Crateús city, toward Ibiapaba city. Sample CR-011 corresponds to a quartz diorite showing well developed stretching lineation (Figure 4E). Mineralogical composition is plagioclase (50%), hornblende (30%), clinopyroxene (18%) and quartz (~5%). The zircon grains extracted from this rock are clean, colorless to pink, small and prismatic. The ages obtained were reasonably concordant, yielding 618 ± 23 Ma with 18 points (Figure 6), interpreted as crystallization age. Analytical data are listed in Table 4. Alternatively, the weighted average calculated for $^{207}Pb/^{206}Pb$ values yielded an age of 610 ± 31Ma (2σ, MSWD = 18) (Figure not shown). For this weighted average, we use all data of Table 4, excluding the low

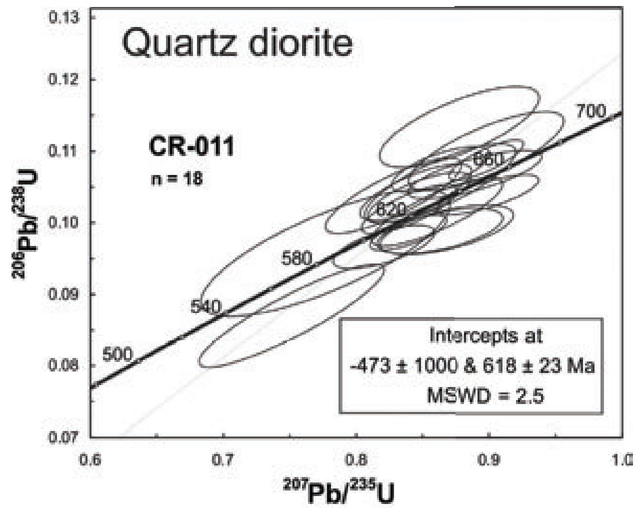


Figure 6. Concordia diagram from zircons of quartz diorite (CR-011).

Table 4. U-Pb analytical data for sample CR-011 (quartz diorite).

Grain.spot	f206(%)	Th/U	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{206}Pb$	err (%) 1σ	$^{207}Pb/^{235}U$	err (%) 1σ	$^{206}Pb/^{238}U$	err (%) 1σ	Rho	$^{207}Pb/^{206}Pb$	(Ma)	$^{207}Pb/^{235}U$	(Ma)	$^{206}Pb/^{238}U$	(Ma)	Conc.(%)
Z01	0.54	0.44	3297	0.062660	1.70	0.752	3.79	0.086987	3.39	0.89	697	36	569	16	538	17	94.48
Z02	0.16	1.16	6583	0.061602	1.41	0.821	1.91	0.096633	1.28	0.66	660	30	608	9	595	7	97.73
Z03	0.23	0.95	7469	0.063323	1.82	0.863	2.24	0.098852	1.31	0.57	719	38	632	10	608	8	96.18
Z04	0.10	0.58	17966	0.062735	1.36	0.899	1.75	0.103922	1.09	0.75	699	29	651	8	637	7	97.88
Z06	1.02	0.57	1770	0.058830	3.16	0.777	4.93	0.095789	3.78	0.77	561	67	584	22	590	21	101.01
Z07	0.07	0.42	24008	0.061721	0.97	0.839	1.41	0.098613	1.02	0.71	664	21	619	6	606	6	97.99
Z08	0.32	1.80	5520	0.063578	1.88	0.868	2.36	0.099038	1.43	0.60	728	39	635	11	609	8	95.93
Z09	0.21	1.22	11593	0.058777	1.33	0.845	2.03	0.104270	1.54	0.75	559	29	622	9	639	9	102.81
Z10	0.24	0.50	7221	0.059330	1.62	0.863	2.69	0.105524	2.15	0.79	579	35	632	13	647	13	102.34
Z11	0.15	2.56	12063	0.060418	1.93	0.889	2.32	0.106733	1.29	0.74	619	41	646	11	654	8	101.21
Z12	0.20	0.77	8599	0.059780	1.08	0.840	1.75	0.101910	1.38	0.78	596	23	619	8	626	8	101.04
Z13	0.18	2.42	6803	0.059360	1.25	0.847	1.86	0.103541	1.38	0.73	580	27	623	9	635	8	101.91
Z14	0.30	0.73	5941	0.061507	1.34	0.861	2.34	0.101524	1.92	0.82	657	28	631	11	623	11	98.84
Z16	0.39	0.66	6836	0.056134	1.92	0.878	2.80	0.113392	2.03	0.72	458	42	640	13	692	13	108.24
Z17	0.30	1.39	5876	0.059187	1.70	0.898	2.66	0.110016	2.04	0.77	574	36	651	13	673	13	103.43
Z19	0.29	0.79	6116	0.058290	1.26	0.864	1.75	0.107451	1.22	0.68	541	27	632	8	658	8	104.09
Z20	0.39	0.92	3131	0.057877	1.44	0.828	2.52	0.103780	2.07	0.82	525	31	613	12	637	13	103.91
Z21	0.05	0.63	35943	0.059870	0.73	0.898	1.28	0.108767	1.05	0.81	599	16	651	6	666	7	102.31

concordant (94,49%) Z01 grain spot. The Sm-Nd isotopic measurements resulted in a TDM model age of 2.19 Ga and $\varepsilon_{Nd\ (618)}$ of -14.54 for sample CR-11 (Table 3).

INSIGHTS INTO MAGMA SOURCES

Most of the rocks in the granitic-migmatitic TSQC are represented by an anatectic phase, enclosed evolved migmatites (diatexites) and deformed granites. According to de Araujo et al. (2012a), the diatexites of the southern part of TSQC are slightly peraluminous, sub-alkaline rocks and belong to the high-K calc-alkaline series. These chemical characteristics and field evidences show that these diatexites probably resulted from partial melting of a crustal source. Fragments of this source rock, which may be represented by the enclaves (schollens) in the diatexites, correspond to ortho-derived tonalitic/dioritic gneisses. For example, some high-K calc-alkaline granites with a slightly peraluminous signature can result from partial melting of ortho-derived tonalitic rocks, as attested by experimental data (e.g., Patiño Douce and Beard, 1995) or interpreted from field relationships (e.g., Petcovic and Grunder, 2003). On the other hand, for the hybrid granitoids described here, contribution from a mantle source, at least for their most primitive mafic magmatic enclaves, is suggested for this magmatism. Some preliminary geochemical data reveal that this hybrid magmatic association has a shoshonitic to ultrapotassic affinity (Costa et al., 2011a; Zircone, 2011), attesting for partial melting of an enriched mantle source (subcontinental lithospheric mantle). The age of 634 ± 10 Ma obtained here for the quartz monzonite evidences the contemporaneity of this magmatism with the ~650 – 630 Ma segregated pink diatexites, dated (Pb-Pb in zircon, isotopic dilution) by de Araujo et al. (2012a). Therefore, it is quite possible that the hybrid granitoids, including syenites, monzonites and quartz monzonites, were emplaced close in time with crustal anatexis at low crustal levels and probably mixed with some of these crust-derived melts. The TDM model age of 2.67 Ga obtained here for the quartz monzonite is much older than previously TDM ages obtained for TSQC (Fetter et al. 2003; Castro, 2004; Santos et al., 2007). It may have resulted from contamination with (hidden) lower to middle Archean crust or basement-derived metasediments, or even be an inherited Nd imprinting of the subcontinental lithospheric mantle signature. For example, the hypothesis of metasomatism in the subcontinental mantle during collision has been proposed by Janousek and Holub (2007) to explain the link between high-grade metamorphism and potassic-ultrapotassic magmatism in collisional orogens. According to these authors, subduction of mature crustal material caused direct contamination and metasomatism in the overlying lithospheric mantle wedge. Shortly after the high-grade metamorphic peak, these metasomatized and contaminated mantle domains can be melted by advected heat from the invading asthenosphere, generating potassic-ultrapotassic intrusions, closely related to the granulite occurrences in space and time (Janousek and Holub, 2007).

The age of 618 ± 23 Ma makes the quartz diorite closely related in time to the diatexites and the hybrid magmatism. Its dominant mafic/intermediate composition precludes partial melting of felsic meta-igneous rocks so that partial melting of mafic/ultramafic sources seems necessary. Previous preliminary geochemical data for these quartz diorites evidence a low-K calc-alkaline signature (Costa et al., 2011a). In general, there are two main possibilities for the origin of these quartz diorites: (1) melting of mafic lower crust, or (2) melting of a less enriched or even depleted mantle. However, the absence of more primitive end-members (mafic magmatic enclaves) and the negative $\varepsilon_{Nd\ (618)}$ of -14.10 suggest that a mafic lower crust should be a source candidate.

TECTONIC DISCUSSION

The linear occurrence of plutonic rocks, the parallelism with the Transbrasiliano Lineament and the close relationship with high-grade metamorphic rocks have drawn the attention of many researchers to the tectonic setting of this large igneous/anatectic complex (Fetter et al., 2003; Castro, 2004; Santos et al., 2007; Costa et al., 2010; Amaral, 2010; Zincone, 2011; de Araújo et al., 2012a). The evolution of this plutonic activity has been interpreted as the record of a continental magmatic arc around 650 – 610 Ma (Fetter et al., 2003; Castro, 2004; Santos et al., 2007), and more recently of a collisional setting (Costa et al., 2010; Amaral, 2010; de Araújo et al., 2010a; 2012a). Geochronological constraints on regional metamorphism (Castro, 2004; Arthaud, 2007; Amaral, 2010) concordant with the ~650 to 610 Ma interval for the plutonism in TSQC suggest that metamorphism and magmatism essentially resulted from the same thermal anomalies. The most direct evidence for the timing of collision in the CCD comes from the age of high-pressure (HP) and high-temperature (HT) granulitic rocks (Santos et al., 2009; Amaral, 2010; Amaral et al., 2012). The age of the early HP metamorphism is ~650 – 640 Ma and leads directly to inferences about when the greatest thickening took place at the continent-continent collision (Amaral, 2010; Amaral et al., 2012). The pressure *versus* temperature (PT) clockwise metamorphic trajectory evidences that metamorphism evolved from HP to HT at the CCD (Santos et al., 2009), and the age constraints for the HT metamorphism suggest a peak at 630 – 610 Ma (Arthaud, 2007; Amaral, 2010; Amaral et al., 2012). The age of most

TSQC granitoids and diatexites post-dates this HP metamorphism, suggesting that magmatism began after the major crustal thickening, and was in great part coeval with the HT metamorphism. Mafic plutonism is rare in TSQC but can probably account for the high temperatures close to the peak of metamorphism because the ages of some tholeiitic gabbros (e.g. 623 ± 5 Ma, Santos et al., 2007; 628 ± 1 Ma, Teixeira, 2005; 640 ± 17 Ma, Costa et al., 2011b) are broadly coeval to the HT metamorphism. Therefore, the large amount of granites s.s. in TSQC, coeval with minor gabbro, diorite, quartz diorite, syenite and quartz monzonite intrusions, may have resulted from melting of distinct crustal and mantle sources during special thermal circumstances during orogeny.

REGIONAL CORRELATION AND GEODYNAMICAL MODEL

Recently, several works in Borborema Province recognized that magmatism at 630 – 610 Ma is largely distributed and generally associated with regional metamorphism and flat-lying foliation (Oliveira et al., 2010; Guimarães et al., 2011; Ferreira et al., 2011; Van Schmus et al., 2011; Neves et al., 2012). Therefore, in the CCD, the ~650 – 610 Ma magmatism of the TSQC does probably have some relationship with this regional plutonism.

Taking into consideration only the U-Pb LA-MC-ICP-MS zircon ages for the TSQC (Table 1), the age interval reduces to 638 – 618 Ma, which may be more realistic, because older zircon ages done by U-Pb (isotopic dilution) or Pb-Pb (evaporation) may probably be attributed to the presence of inherited grains or cores.

At the Zona Transversal, Central Domain of Borborema Province (Figure 1), the (LA-ICPMS) zircon age of 618 ± 4 Ma for the Caruaru orthogneiss (Neves et al., 2012); the 616 ± 5 Ma SHRIMP zircon age for the Timbaúba pluton (Guimarães et al., 2011) and the SHRIMP U-Pb zircon age of 618 ± 4 Ma for the Curral de Cima tonalite (Ferreira et al., 2011) all match with the ages obtained in this work for the quartz monzonite (634 ± 10 Ma) and quartz diorite (618 ± 23 Ma) from the TSQC.

According to Guimarães et al. (2011) and Neves et al. (2012), the plutonic rocks around 630 – 610 Ma, in the Central Domain of Borborema Province (Zona Transvesal), can be interpreted as records of syncollisional magmatism coeval with regional metamorphism, and are also regarded as dating development of a regional flat-lying foliation. These authors suggest that this syncollisional magmatism developed in an intracontinental orogen, not in a “classical” orogen formed after closure of large oceanic basins.

At the Sergipano belt, south of Borborema Province (Figure 1), compressional deformation related to the Brasiliano/Pan-African Orogeny also occurred around 640 – 630 Ma ago (e.g., Bueno et al., 2009; Oliveira et al., 2010). For this region, Oliveira et al. (2010) proposed that continental deformation and granite emplacement at 630 – 617 Ma resulted from closing of an oceanic domain that separated the Pernambuco-Alagoas block from the São Francisco-Congo craton.

In the CCD, at north Borborema Province, even without considering the TSQC as a pre-collisional magmatism, we believe that it may be related to the final stage evolution of an oceanic closure, when large volume of syn-to post-collisional mantle- and crust-derived plutonic rocks evolved in response to Slab Breakoff process (Costa et al., 2010). An important information to reinforce this proposed collisional model is the recent discovery of older (~890 – 830 Ma), strongly deformed and migmatized juvenile plutons in TSQC (de Araujo et al., 2012c). According to these authors, these Early Neoproterozoic plutons may be the record of pre-collisional arc magmatism, similar to other parts of the Transbrasiliano-Kandi lineament in Brazil (e.g., Junges et al., 2002; Matteini et al., 2010) and in the African counterpart (e.g., Caby, 2003). Therefore, it is quite possible that arc development at this long transcontinental active margin ends up in a diachronic continental collision following delamination of the subducted oceanic crust.

CONCLUSIONS

The U-Pb zircon ages of 634 ± 10 and 618 ± 23 Ma for deformed quartz monzonite and quartz diorite, respectively, evidence that such plutonic activity is coeval with the magmatic interval (~650 – 610 Ma) of granite-migmatite evolution in the TSQC.

The TDM model ages of 2.69 and 2.19 Ga obtained for the quartz monzonite and quartz diorite, respectively, evidence the contribution of Archaean/Paleoproterozoic crustal material in the genesis of these rocks, distinct from previous TDM ages reported in literature for the TSQC (~0.9 – 1.9 Ga).

Despite the predominance of crust-derived granite/diatexites, mantle sources also participated in the TSQC magma genesis: an enriched lithospheric mantle source for the hybrid granitoids (syenites, monzonites and quartz monzonites) and a less enriched mantle source or a mafic lower crust for the quartz diorites.

The age of TSQC magmatism (~650 – 610 Ma) post-dates HP metamorphism (*ca*. 650 – 640 Ma) and is expressively coeval with the HT metamorphism (630 – 610 Ma), suggesting that this igneous/anatectic complex evolved during a collisional setting, probably related to a slab breakoff process.

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