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New U-Pb (SHRIMP) and first Hf isotope constraints on the Tonian (1000-920 Ma) Cariris Velhos event, Borborema Province, NE Brazil

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Abstract

Orthogneisses associated with metavolcanosedimentary successions related to the 1000 – 920 Ma Cariris Velhos event occur mainly in a ca. 700 km-long sigmoidal-shaped belt that crosscuts the Transversal Zone of the Borborema Province and extends to the fold belts located in its southern or external zone (part of the Riacho do Pontal and Sergipano orogens). Despite its importance, the tectonic setting and the role of those rocks in the geological evolution of the Borborema Province are contentious and not yet well understood. New zircon U-Pb SHRIMP data on an augen-gneiss sill of the Afeição Suite intruding mica-schists mapped as part of the Santa Filomena Complex yielded a Concordia Age of 974 ± 11 Ma, indicating that at least part of the metasedimentary rocks in the internal zone of the Riacho do Pontal Orogen are Tonian or older and possibly related to the Cariris Velhos event. Hf-in-zircon isotope data are presented for the first time for Cariris Velhos-related ortho-derived rocks of the Afeição Suite. Analyzed samples yielded εHf(t) in a narrow range between -1.51 and +2.41, with associated T_{DMHf} of 1.6-1.4 Ga, similar to previously obtained Nd isotope data with εNd(t) = -1.0 to +3.1 and T_{DMNd} of 1.5-1.2 Ga. A possible scenario to explain both the geochemical features and the moderately juvenile to slightly evolved, near-chondritic Hf and Nd isotope signatures is a continental arc setting, where fractionated melts produced in the supra-subduction zone mantle wedge carrying a Tonian juvenile signature became contaminated with discrete amounts of Archean-Paleoproterozoic continental crust during ascent, producing Mesoproterozoic model ages which represent the mixture of those two end-members.

KEYWORDS: *U-Pb SHRIMP geochronology; Hf isotope analysis; Cariris Velhos; Borborema Province.*

INTRODUCTION

The Borborema Province of northeastern Brazil (Fig. 1) and its counterparts in northwestern Africa (the Tuareg Shield, the Benino-Nigerian Shield, and related provinces in Cameroon) are part of the broad orogenic network involved in the amalgamation of West Gondwana during the Ediacaran-Cambrian (ca. 630 – 500 Ma) Brasiliano/Pan-African Orogeny (Almeida *et al.* 1981, Brito Neves *et al.* 2000). Although broad continuity of structural, stratigraphic and tectonic features was recognized for decades between the Borborema Province and provinces in NW Africa (Hurley *et al.* 1967, Caby 1989, Trompette 1994, 1997, Brito Neves *et al.* 2002, Oliveira *et al.* 2006, Arthaud *et al.* 2008, Dada 2008, Van Schmus *et al.* 2008, Araújo *et al.* 2014, 2016), there are still some major correlation problems between them. One of the major issues lies in the recognition and definition of ca. 1000 – 920 Ma plutonic and metavolcanosedimentary rocks within the central and southern Borborema Province, encompassing the Cariris Velhos event (Brito Neves *et al.* 1995, Kozuch 2003, Santos *et al.* 2010). Rocks in this age range have not yet been unequivocally recognized in NW Africa, and interpretations of its geodynamic setting and role in the Borborema Province are contentious, resulting in the proposition of both continental arc (Kozuch 2003, Medeiros 2004, Santos *et al.* 2010, Caxito *et al.* 2014b) and intracontinental rift (Neves 2003, Guimarães *et al.* 2012) models.

In this paper, we present new U-Pb SHRIMP data on zircon crystals from an augen-gneiss sill of the Afeição Suite that intrudes mica-schists mapped as part of the Santa Filomena Complex within the internal zone of the Riacho do Pontal Orogen, representing the Cariris Velhos event in the southern Borborema Province. We also present the first Hf isotope data for this and other occurrences of the Afeição Suite previously studied by Caxito *et al.* (2014b). The aim of the study is to contribute with new geochronological and isotopic data which will help to constrain the tectonic setting, petrological evolution and meaning of the Cariris Velhos event in the evolution of the Borborema Province.

Geological context

For descriptive purposes, the Borborema Province is generally subdivided into three broad tectonic zones (Northern,

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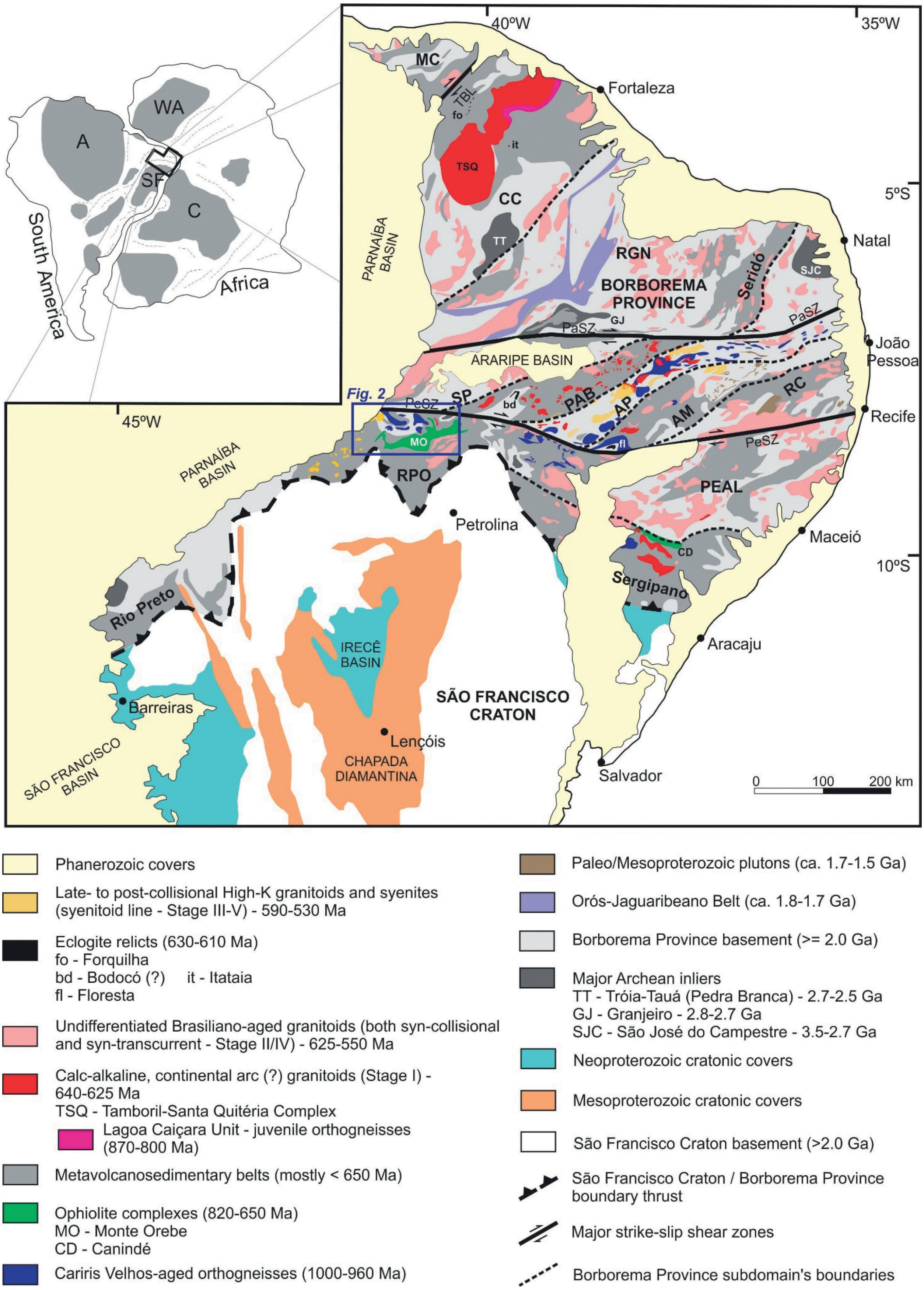
Transversal, and Southern subprovinces; Brito Neves *et al.* 2000, Van Schmus *et al.* 2011) separated by major (continental-scale) late-orogenic structural lineaments (the Patos and Pernambuco shear zones; Fig. 1). The tectonic arrangement of the province results largely from the assembly of the major São Francisco-Congo, São Luís-West African and Amazonian



PeSZ: Pernambuco Shear Zone; PaSZ: Patos Shear Zone; TBL: Transbrasiliano Lineament.

Figure 1. Simplified geological framework of the Borborema Province. Modified from Caxito *et al.* (2016), and references therein. Domains and sub-domains of the Borborema Province: PEAL: Pernambuco–Alagoas, RC: Rio Capibaribe, AM: Alto Moxotó, AP: Alto Pajeú, PAB: Piancó-Alto Brígida, SJC: São José do Caiano, RGN: Rio Grande do Norte, CC: Ceará Central.

paleoplates, and smaller, intervening continental blocks such as the concealed Parnaíba block during the Neoproterozoic. As part of the Southern subprovince, the Riacho do Pontal Orogen (Brito Neves 1975, Caxito *et al.* 2016, 2017) borders the northern São Francisco craton margin in the southernmost Borborema Province.

Most occurrences of Cariris Velhos' aged rocks have been documented in a narrow and elongated sigmoidal belt in the central portion of the Borborema Province (roughly 100 km wide × 700 km-long), comprising the Alto Pajeú and Riacho Gravatá domains of the Transversal Zone (Fig. 1; Santos *et al.* 1997, Kozuch 2003, Brito Neves *et al.* 2005, Van Schmus *et al.* 2008, 2011, Santos *et al.* 2010), but other important occurences have also been documented within the Southern subprovince, in the Poço Redondo-Marancó domain of the Sergipano Orogen (Carvalho 2005, Oliveira *et al.* 2010), in the Pernambuco-Alagoas domain (Silva Filho *et al.* 2002, 2014, Cruz *et al.* 2014), and in the northern portion of the Riacho do Pontal Orogen (Jardim de Sá *et al.* 1988, 1992, Van Schmus *et al.* 1995, Caxito *et al.* 2014b) where it comprises the Afeição augen-gneiss Suite.

In this work, samples of the Afeição Suite were studied as representatives of the Cariris Velhos event. Thus, a brief review of the geology of the Riacho do Pontal Orogen is here presented. For detailed descriptions, the reader is referred to Caxito (2013) and Caxito *et al.* (2016, 2017). According to the geophysical, sedimentary, igneous, metamorphic and structural characteristics, the Riacho do Pontal Orogen can be divided into three tectonostratigraphic zones or domains (Fig. 2): external, central, and internal (Oliveira 1998, Caxito 2013, Caxito *et al.* 2016).

The southernmost external zone is characterized by a south-verging nappe system, composed of supracrustal rocks that override the São Francisco craton basement in the Sobradinho dam area. They are composed mainly of metasedimentary clastic rocks of the Barra Bonita and Mandacaru formations, comprising, respectively, a platformal succession composed mainly of quartzite, garnet-mica schist, and marble intercalations, and a syn-orogenic basin composed of metagreywacke and garnet-mica schist, locally containing staurolite and kyanite, and with minor metavolcanoclastic intercalations (Caxito *et al.* 2016). The syn-orogenic metavolcanosedimentary rocks of the Mandacaru Formation contain ca. 650 Ma detrital zircon grains (Brito Neves *et al.* 2015, Caxito *et al.* 2016) which attest for provenance from the Borborema Province (hinterland), while those are absent from the passive margin sedimentary rocks of the Barra Bonita Formation, characterized by provenance from the cratonic sources to the south (Caxito *et al.* 2016). The distinct sources and tectonic settings preclude joining the two formations in a single group, as previously proposed ("Casa Nova Group", see Caxito *et al.* 2016).

The central zone is characterized by complex deformation involving both south-verging thrusts and E-W strike-slip shear zone systems, and is composed of the metavolcanosedimentary Monte Orebe Complex. This unit bears important metamafic rocks (actinolite-plagioclase greenschists) with MORB-like lithogeochemistry and juvenile εNd(t) signatures of +4.4 (Caxito *et al.* 2014c) interleaved with deep-sea metasedimentary rocks including exhalites and local metaultramafic lenses. This unit is interpreted as composed of remnants of a Neoproterozoic ophiolite complex of ca. 820 Ma (Sm-Nd whole-rock isochron), marking the development of new oceanic crust separating the Borborema Province from the São Francisco paleocontinent to the south. The geophysical signature of the central zone is marked by the inflection of a paired positive-negative Bougher anomaly which is typical of Precambrian suture zones (Oliveira 2008, Oliveira and Medeiros 2018) representing the site where ancient plates agglutinated. In this case, the lower plate (São Francisco paleocontinent) is represented by lower Bouguer values to the south while the upper one (western edge of the Pernambuco-Alagoas domain) is represented by higher Bouguer values to the north (Oliveira 2008, Caxito *et al.* 2014c, 2016, Oliveira and Medeiros 2018).

The internal zone, to the north, is characterized by abundant augen-gneiss intrusions (Afeição Suite), highly reworked Archean/Paleoproterozoic migmatitic basement slices, and predominantly metasedimentary units with important mafic volcanic and plutonic contributions (Paulistana and Santa Filomena complexes). It is bounded, to the north, by the E-W trending dextral strike-slip western branch of the Pernambuco shear zone.

The Santa Filomena Complex is composed of mica schist with abundant garnet, staurolite and sillimanite, quartzite, marble lenses, and minor metamafic intercalations. Detrital zircon contents suggest that at least part of the Santa Filomena Complex is younger than ca. 650 Ma, although samples collected in different sites yield distinct provenance patterns without the specific Cryogenian zircon grains and bearing only older, basement-derived grains (Brito Neves *et al.* 2015, Santos *et al.* 2017). Peak metamorphic conditions are estimated at ca. 640ºC and 12 kbar (Santos *et al.* 2018).

The Paulistana and the Santa Filomena Complexes differ from one another by the absence of marble and by the abundance of mafic (metagabbros, amphibolites, and actinolite-schists) and ultramafic (talc-schist and pyroxenite) rock intercalations in the former. Zircon crystals extracted from a metagabbro yielded a Concordia age of 882.8 ± 4 Ma (Caxito *et al.* 2016), and detrital zircon contents suggest deposition after ca. 900 Ma (Brito Neves *et al.* 2015, Santos *et al.* 2017). Based on the geochemical signatures of metabasalts and metagabbros, Caxito *et al.* (2016) interpreted the Paulistana Complex as part of a continental rift setting.

The western portion of the internal zone is dominated by a metavolcanosedimentary sequence, the Morro Branco Complex, composed mainly of metarhythmite with intercalations of metabasalt, metarhyolite, and mafic to intermediate metatuff. This sequence is intruded by the Brejo Seco Complex, a mafic-ultramafic intrusion that bears Ni-Cu-PGE deposits crystallized at ca. 900 Ma (Sm-Nd whole-rock isochron; Salgado *et al.* 2016). The Brejo Seco Complex is interpreted as intruded in a continental extension setting related to the emplacement of a mantle plume (Salgado *et al.* 2016).

The whole supracrustal package of the Riacho do Pontal Orogen is intruded by multiple generations of pre-, syn- and post-collisional granitic and syenitic plutons. The calc-alkaline Betânia Granite in the internal zone is interpreted as part of a continental arc. Zircon crystals from this granite yielded a 628.7 ± 2.3 Ma Concordia Age (LA-ICPMS, Perpétuo 2017). The syn-collisional two-mica Rajada orthogneisses are dated at ca. 610 Ma (Brito Neves *et al.* 2015, Caxito *et al.* 2016). The post-collisional Serra da Aldeia syenites are dated at ca. 586 – 576 Ma (Caxito *et al.* 2016, Perpétuo 2017).

The Afeição augen-gneiss Suite crops out in the internal zone of the Riacho do Pontal Orogen, about 100 km southwestward of the closest Cariris Velhos occurrence within the Transversal Zone. Those rocks became a major target for the study of the Cariris Velhos Belt after a Rb-Sr whole-rock isochron of 968 ± 35 Ma was presented (Jardim de Sá *et al.* 1988) as the first Tonian age obtained in the Southern subprovince of the Borborema Province. This age was later confirmed by a U-Pb TIMS age of 966 ± 10 Ma on zircon crystals from an augen-gneiss of the Afeição Farm, type-locality for the Afeição Suite (Van Schmus *et al.* 1995), by LA-ICPMS dating of augen-gneisses near São Francisco de Assis, Piauí, at 985 ± 18 Ma (Freitas and Sachs 2012), and by two LA-ICPMS zircon U-Pb Concordia ages of a granitic sill at 1001.8 ± 4.5 Ma and of a different augen-gneiss body at 966 ± 4.6 Ma (Caxito *et al.* 2014b).

A detailed study comprising the petrography, geochemistry, and isotope geology of the Afeição Suite was presented by Caxito

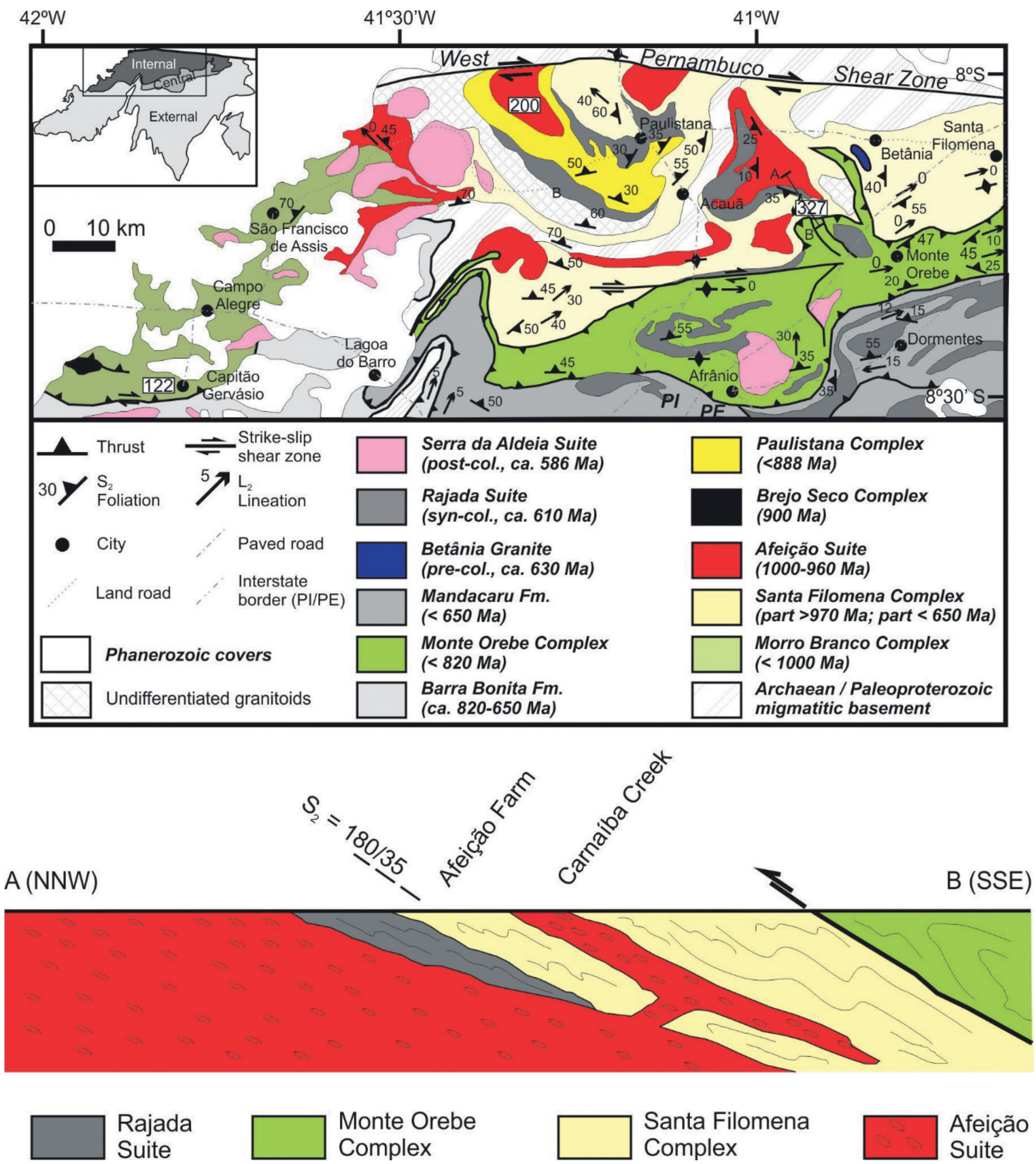


Figure 2. Simplified map of the internal zone of the Riacho do Pontal Orogen (see location in Fig. 1) and transect of the Carnaíba Creek area. Location of samples used in this study are marked by a white stripe; the numbers are for sample identification (sample code = FRP + number shown). Modified from Caxito *et al.* (2014c).

et al. (2014b) and a brief description of its results is presented herein. The Afeição Suite is composed mostly of calc-alkaline, high-K, slightly metaluminous to slightly peraluminous (mol $Al_2O_3/(CaO + K_2O + Na_2O) = 0.94$ to 1.16, mean 1.04 — please note that samples are plotted incorrectly in Fig. 5B of Caxito *et al.* (2014b) due to a graphics error), high-silica ferroan and magnesian granites. Chondrite-normalized REE patterns are moderately to highly fractionated, with a pronounced negative Eu anomaly. Incompatible element spidergrams show a negative Nb-Ta anomaly, normally resulting from Nb-Ta-bearing phases such as magnetite, titanite, rutile, biotite, among others, left on the cumulate or in the restite, akin to convergence setting (Cordilleran-type) granites. Values of εNd(t) between -1.0 and +3.1 and T_{DM} of 1.2 – 1.5 Ga suggest variable mixing of Tonian juvenile sources with older crustal sources involving Archean/Paleoproterozoic basement. According to previous models proposed for the Cariris Velhos event (*e.g.*, Kozuch 2003, Medeiros 2004, Santos *et al.* 2010), Caxito *et al.* (2014b) interpreted the Afeição Suite as the southwestern edge of a continental margin magmatic arc accreted to this portion of West Gondwana during the early Tonian. Late-Brasiliano dextral displacement through the western branch of the Pernambuco shear zone separated these Cariris Velhos occurrences from their equivalents within the Transversal Zone of the Borborema Province (*e.g.*, the Recanto-type augen-gneiss of the Alto Pajeú Domain; Santos *et al.* 2010).

Caxito *et al.* (2016) interpreted the development of a complete Wilson Cycle during the Neoproterozoic in the Riacho do Pontal Orogen area. A five-stage model is proposed:

1. rift phase, with the development of a triple junction system at ca. 900 – 820 Ma ago, leading to intense mafic–ultramafic magmatism of the Brejo Seco Ni-Cu-PGE mineralized layered intrusion probably related to a plume head. This was followed by development of the Paulistana Complex metavolcanosedimentary sequence, with metagabbros and metabasalts dated at ca. 882 Ma and younger detrital zircons at ca. 900 Ma;
2. drift phase: evolution of the rift system to a broad passive margin in the northern São Francisco paleocontinent edge, represented by the Barra Bonita Formation platformal sediments. This drift phase caused by continued continental stretching culminated in the development of new oceanic crust, represented by the Monte Orebe ophiolitic complex around 820 Ma ago;
3. convergence phase: started at ca. 630 – 620 Ma, with emplacement of the calc-alkaline Betânia granite, probably related to a continental magmatic arc setting, culminating in inversion of the basins, obduction of oceanic crust slices, and sedimentation of the Mandacaru Formation syn-orogenic greywackes, with younger detrital zircon populations at ca. 650 Ma;
4. collisional phase: continental collision between the São Franciscopaleocontinent (lower plate) and the Pernambuco-Alagoas block (upper plate) around 620 – 590 Ma, with stacking of the external nappes upon the lower plate, crustal thickening, deformation, metamorphism, melt generation and intrusion of the syn-collisional Rajada Suite two-mica granites;
5. lateral escape phase — this stage occurred around 590 – 530 Ma, generating the western branch of the E-W trending Pernambuco Shear Zone, which truncates the northern part of the orogen. This phase was accompanied by extensive alkaline magmatism of the Serra da Aldeia suite, at 586 – 576 Ma.

In this scenario, the São Francisco paleocontinent would represent the lower, subducted plate, while the western edge of the Pernambuco-Alagoas domain would represent the upper plate. The Afeição augen-gneiss intrusions would be part of the latter, as augen-gneisses of this age range are absent from the São Francisco Craton region. Thus, the lower and upper plates present distinct geological features, which are reflected in distinct geophysical signatures (Oliveira 2008, Oliveira and Medeiros 2018).

MATERIALS AND METHODS

U-Pb Sensitive High-Resolution Ion Microprobe (SHRIMP) analysis (Tab. 1) was performed in zircon crystals separated through standard crushing, sieving, magnetic, and gravimetric methods from homogeneous portions (*i.e.*, bearing no veins, fractures or alteration fronts) of ca. 15 kgs of sample FRP327G in the *Laboratório de Separação Mineral de Alta Pureza* (SEPURA) at CPMTC, IGC-UFMG. Zircon crystals from samples FRP122 and FRP200 have previously been analyzed for U-Pb isotopes through Laser Ablation - Induction Coupled Plasma Mass Spectrometry (LA-ICPMS) at Laboratório de Estudos Geodinâmicos e Ambientais, UnB, and results and preparation methods were previously reported by Caxito *et al.* (2014b). Zircon crystals from all of those samples were further analysed for Hf isotopes at Laboratório de Geoquímica Isotópica, UFOP. Sample coordinates are presented along with Hf isotope results in Table 2.

After mounting in epoxy and polishing, zircon crystals were imaged through standard Scanning Electron Microscopy (SEM) techniques such as Secondary Electrons (SE), Back-Scattered Electrons (BSE) and Cathodoluminescence (CL) in a TESCAN Vega SEM in the Centre for Microscopy and Microanalysis (CMCA) at the University of Western Australia, Perth. The images were used for spot positioning based on the study of crystals features such as cores and rims, zones of damage by U radioactive decay, zones of inclusions, etc. The FRP327G sample mount was analysed for U-Pb isotopes and concentrations at the SHRIMP II Laboratory of the John de Laeter Centre, Curtin University, Perth, Australia. The mount was cleaned following internal standards of the centre and coated with gold for SHRIMP analyses, with a microprobe spot size of 20 μm. Six scans were performed for each spot, with nine peaks analysed at masses $^{196}Zr_2O$, ^{204}Pb, background, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, ^{248}ThO, and ^{254}UO. The NBS611 glass standard was used to identify the peak position of mass ^{204}Pb, whereas the calibration of the U contents and Pb/U ratios were conducted using zircon standard Temora II (417 Ma; Black *et al.* 2004), which analysis was bracketed after each three or four unknows, yielding a Concordia Age of 416.4 ± 3.3 Ma (2σ;

MSWD = 1.5; n = 25). The $^{207}Pb/^{206}Pb$ zircon standard used to monitor both instrument-induced mass fractionation and accuracy was OGC (3467 ± 3 Ma; Stern *et al.* 2009) yielding a Concordia Age of 3462.1 ± 6.8 Ma (2σ; MSWD = 0.73; n = 7) and a $^{207}Pb/^{206}Pb$ mean age of 3464.3 ± 6.6 Ma. SHRIMP data were reduced using SQUID 2.5 software (Ludwig 2009) and plots were prepared using ISOPLOT 4.15 (Ludwig 2008).

Hf-isotope analyses (Tab. 2) were carried out in a Thermo-Finnigan Neptune multicollector ICPMS coupled to a Photon-Machine laser system that delivers a beam of 193 nm UV light from a frequency-quintupled Nd:YAG laser hosted in *Laboratório de Geoquímica Isotópica, Universidade Federal de Ouro Preto*. The analyses were performed with a beam diameter of 50 μm, a repetition rate between 4 and 6 Hz and 50% of laser output. Depending on the conditions and Hf contents, the Hf signals were between 1 to 6x10^{-11} A and ablation time lasted 60 s. Ar carrier gas transported from the ablated sample from the laser ablation cell via mixing chamber to the ICPMS torch. To correct for the isobaric interferences of ^{176}Lu and ^{176}Yb on ^{176}Hf, masses 172, 173, and 175–180 were measured

Table 1. SHRIMP U-Pb data for sample FRP327G.

Spot Name	U (ppm)	Th/U	f_{206}(%)	$^{207}Pb/^{235}U$	±1σ (%)	$^{206}Pb/^{238}U$	±1σ (%)	ρ	$^{207}Pb/^{206}Pb$	±1σ (%)	$^{206}Pb/^{238}U$ Age (Ma)	±1σ	$^{207}Pb/^{206}Pb$ Age (Ma)	±1σ	Disc. (%)
FRP327G-1.1	163	0.30	0.040	1.6336	2.55	0.162994	2.25	0.88	0.072688	1.21	973	20	1005	25	3.42
FRP327G-2.1	192	0.50	0.758	1.4189	2.93	0.141710	2.11	0.72	0.072619	2.04	854	17	1003	41	15.85
FRP327G-4.1	377	0.27	0.120	1.5940	2.03	0.160707	1.81	0.89	0.071936	0.91	961	16	984	19	2.56
FRP327G-5.1	614	0.08	0.357	1.4605	1.99	0.147117	1.67	0.84	0.072002	1.09	885	14	986	22	10.98
FRP327G-6.1	400	0.44	0.000	1.5740	1.93	0.159503	1.79	0.93	0.071569	0.70	954	16	974	14	2.18
FRP327G-7.1	142	0.35	0.265	1.5870	3.10	0.169753	2.39	0.77	0.067804	1.98	1011	22	863	41	-18.57
FRP327G-8.1	2,011	0.11	0.694	1.5576	1.55	0.158283	1.35	0.87	0.071372	0.77	947	12	968	16	2.32
FRP327G-9.1	82	0.29	0.548	1.4380	4.20	0.156374	2.85	0.68	0.066695	3.09	937	25	828	64	-14.05
FRP327G-9.2	22	0.05	1.821	0.9294	14.7	0.115319	5.10	0.35	0.058453	13.8	704	34	547	301	-30.28
FRP327G-10.1	143	0.22	0.084	1.6405	2.67	0.167663	2.31	0.86	0.070963	1.35	999	21	956	28	-4.84
FRP327G-11.1	597	0.51	0.207	1.5446	1.93	0.157111	1.70	0.88	0.071302	0.90	941	15	966	18	2.82
FRP327G-12.1	319	0.84	0.154	1.6025	2.18	0.162188	1.89	0.87	0.071662	1.09	969	17	976	22	0.82
FRP327G-13.1	192	0.64	0.214	1.4893	2.92	0.148600	2.17	0.74	0.072689	1.95	893	18	1005	40	11.95
FRP327G-14.1	45	0.33	0.604	1.1513	7.04	0.113985	3.85	0.55	0.073257	5.89	696	25	1021	119	33.59
FRP327G-14.2	242	0.64	0.555	1.4714	2.73	0.152853	2.03	0.74	0.069815	1.83	917	17	923	38	0.70
FRP327G-15.1	22	0.91	15.065	0.2274	79.1	0.045820	5.91	0.07	0.035989	78.9	289	17	-632	2159	149.08
FRP327G-16.1	127	0.31	0.000	1.6354	2.80	0.165294	2.49	0.89	0.071757	1.29	986	23	979	26	-0.78
FRP327G-17.1	76	0.32	0.000	1.3818	3.14	0.148652	1.90	0.60	0.067417	2.50	893	16	851	52	-5.38

Table 2. Hf isotope data for the analyzed samples.

Spot Name	$^{176}Lu/^{177}Hf$ (present)	±2σ	$^{176}Hf/^{177}Hf$ (present)	±2σ	t(Ma)	$^{176}Hf/^{177}Hf(t)$	eHf(t)	±2σ	T_{DM}
Sample FRP327-G (Lat 8°13’53” / Long 40°53’01”)									
FRP327G-1.1	0.00183	0.000046	0.282163	0.00011	973 ± 20	0.282129	-1.40	0.06	1.6
FRP327G-4.1	0.00051	0.000016	0.282179	0.00003	961 ± 16	0.282170	-0.25	0.01	1.5
FRP327G-16.1	0.00109	0.000035	0.282218	0.00007	954 ± 16	0.282198	0.61	0.03	1.4
FRP327G-6.1	0.00114	0.000033	0.282164	0.00007	969 ± 17	0.282143	-1.01	0.05	1.5
FRP327G-12.1	0.00104	0.000026	0.282170	0.00006	986 ± 23	0.282151	-0.36	0.02	1.5
Sample FRP122 (Lat 8°29’25” / Long 41°50’47”)									
FRP122-z11	0.00112	0.000017	0.282240	0.00007	1000 ± 6	0.282219	2.38	0.05	1.4
FRP122-z24	0.00173	0.000036	0.282247	0.00011	999 ± 6	0.282214	2.20	0.06	1.4
FRP122-z3	0.00129	0.000016	0.282238	0.00010	1010 ± 7	0.282213	2.41	0.05	1.4
Sample FRP200 (Lat 8°3’56” / Long 41°18’41”)									
FRP200-z27	0.00063	0.000020	0.282169	0.00004	971 ± 5	0.282158	-0.46	0.02	1.5
FRP200-z23	0.00038	0.000013	0.282180	0.00002	959 ± 5	0.282173	-0.17	0.01	1.5
FRP200-z16	0.00036	0.000015	0.282173	0.00004	956 ± 6	0.282166	-0.47	0.02	1.5
FRP200-z6	0.00057	0.000015	0.282148	0.00005	971 ± 6	0.282138	-1.16	0.04	1.5
FRP200-z9	0.00048	0.000017	0.282141	0.00004	964 ± 6	0.282132	-1.51	0.06	1.5
FRP200-z11	0.00129	0.00002	0.282164	0.0001	983 ± 7	0.282141	-0.80	0.02	1.5

in static- collection mode and simultaneously monitored. The ^{177}Hf signal intensity was ca. 10 V. LA-ICP-MC data were reduced using In-house Excel Spreadsheets.

The accuracy and external reproducibility of the Lu–Hf results were monitored through the analysis of zircon standards Temora ($^{176}Hf/^{177}Hf = 0.282680 \pm 0.000031$; Black *et al.* 2003, Wu *et al.* 2006), Blue Berry ($^{176}Hf/^{177}Hf = 0.281674 \pm 0.000018$; Santos, M.M. *et al.* 2017), Mud Tank ($^{176}Hf/^{177}Hf = 0.282504 \pm 0.000044$; Black and Gulson 1978, Woodhead and Hergt 2005), GJ-1 ($^{176}Hf/^{177}Hf = 0.282000 \pm 0.000005$; Jackson *et al.* 2004) and Plešovice ($^{176}Hf/^{177}Hf = 0.282482 \pm 0.000013$; Sláma *et al.* 2008), which yielded $^{176}Hf/^{177}Hf$ mean ratios of 0.282654 ± 0.000014 (n = 1), 0.281673 ± 0.000017 (n = 8), 0.282519 ± 0.000015 (n = 9), 0.282006 ± 0.000019 (n = 7) and 0.282485 ± 0.000014 (n = 9), respectively (±2SD); all values within the uncertainties and in good agreement with the accepted standard ratios.

For the calculation of the εHf values, the chondritic values reported by Bouvier *et al.* (2008) of $^{176}Hf/^{177}Hf = 0.282785 \pm 11$ and $^{176}Lu/^{177}Hf = 0.0336 \pm 1$ were used. To calculate the model ages (T_{DM}) based on a depleted mantled source, the present-day ratios of $^{176}Hf/^{177}Hf = 0.28325$ and $^{176}Lu/^{177}Hf = 0.0388$ were used (Griffin *et al.* 2000, updated by Andersen *et al.* 2009). εHf(t) values were calculated using $^{206}Pb/^{238}U$ ages of each analysed spot. The λ decay constant for ^{176}Lu used is 1.867×10^{-11}/yr (Söderlund *et al.* 2004).

RESULTS

Sample FRP327G

This sample is from a meter-thick augen-gneiss sill of the Afeição Suite interleaved within garnet-mica schist mapped as part of the Santa Filomena Complex at Carnaíba creek, at the Acauã-Monte Orebe road (Figs. 2 and 3). Both schist and sill were later folded and deformed, presumably during the Brasiliano Orogeny. The close proximity to the main Afeição augen-gneiss pluton (near Afeição farm) suggests that this sill represents an apophysis projected from the batholith (Fig. 2). Recovered zircon crystals are euhedral bipyramidal < 250 μm long prisms and needles with up to 5:1 aspect ratio, conspicuous internal zoning (Fig. 4) and high Th/U ratios (0.22 – 0.84), typical of igneous crystals (Tab. 1). Zircon crystals are mostly clear (translucid) with brownish colours and localized inclusions. Some of the crystals display a discrete few μm-thick low-U (< 45 ppm) bright border in CL images (Fig. 4). Eighteen spots were analysed in sixteen different crystals. Sixteen spots yielded a Discordia with an upper intercept at 953 ± 30 Ma and a high uncertainty close-to-zero lower intercept, all of the spots in high-U cores but one (14.1, in a low-U border). The six most concordant crystals yielded a Concordia age of 974 ± 11 Ma (2σ; MSWD = 0.59; Fig. 5). The slightly discordant points are interpreted as due to recent Pb-loss, as hinted by the close-to-zero lower intercept of the Discordia. Thus, the Concordia age of 974 ± 11 Ma is interpreted as the best estimate for crystallization age of the magmatic protolith. The other two high-uncertainty spots (large ellipsis in Fig. 5A) are from bright low-U borders. Those are generally too thin for microprobe spot placement and yielded highly discordant data with $^{207}Pb/^{206}Pb$ ages between 547 and 1000 Ma (Tab. 1), hinting they might be metamorphic rims with variable Pb-loss related to the Brasiliano Orogeny.

Five of the most concordant zircon crystals were selected for Hf isotope analysis (Tab. 2). Those yielded homogeneous initial $^{176}Hf/^{177}Hf_{(t)}$ ratios of 0.282129–0.282198, corresponding to moderately juvenile to slightly evolved $εHf_{(t)}$ of -1.40 to +0.61 (Fig. 6) and with T_{DMHf} of 1.4 – 1.6 Ga.

Sample FRP122

This sample is from a metric granite sill concordantly interleaved within pelitic metarhythmite of the Morro Branco Complex in the Maravilha creek, near Capitão Gervásio Oliveira, Piauí (Fig. 2). Zircon crystals are stubby (2:1 aspect ratio), euhedral-subhedral bipyramidal prisms < 250 μm long, mostly clear and transparent, but some showing minor inclusions. In CL images, the crystals show typical patterns of igneous internal zoning (Fig. 4) and Th/U ratios, between 0.3 and 0.6, are typical of primary (igneous) zircon crystals. This sample was dated by LA-ICPMS and the results were presented

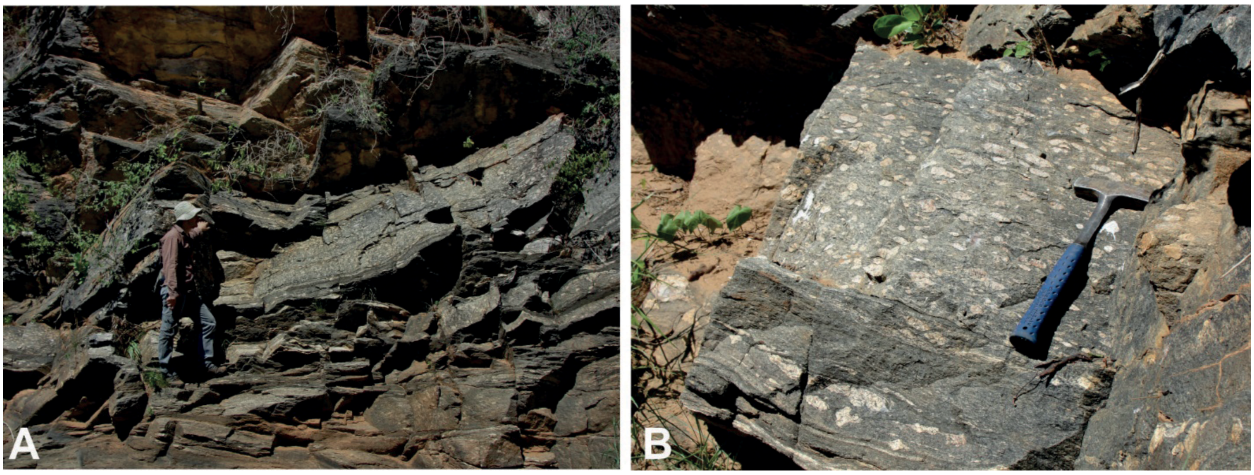


Figure 3. Metric augen-gneiss sill of the Afeição Suite intruding mica-schist mapped as part of the Santa Filomena Complex at station FRP327, Carnaíba Creek (Lat 8º13'53"S / Long 40º53'01"W). In (B), detail of (A).

by Caxito *et al.* (2014b). The U-Pb isotope ratios of the analyzed zircon crystals cluster in a single coherent population in the Concordia diagram, and the eight most concordant zircon crystals yield a Concordia age of 1001.8 ± 4.5 Ma (2σ; MSWD = 1.2), which is interpreted to be the magmatic age of the granite, and also the minimum age of sedimentation of the metarhythmites within which it is interleaved.

Three of the most concordant zircon crystals were selected for Hf isotope analysis (Tab. 2). Those yielded homogeneous initial $^{176}Hf/^{177}Hf_{(t)}$ ratios of 0.282214-0.282219, corresponding to moderately juvenile εHf(t) of +2.20 to +2.41 (Fig. 6) and with T_{DMHf} of 1.4 Ga.

Sample FRP200

This sample is from an augen-gneiss to the northwest of Paulistana, Piauí, between this town and São Francisco de Assis (Fig. 2). It is a NW-SE elongated body thrust upon the metavolcanosedimentary rocks of the Paulistana Complex. While in the central portion of the pluton it might be only slightly deformed, in its borders it is strongly foliated. Especially toward the north, the elongated body suffers a bending toward NE, which is related to the late-Brasiliano dextral shearing of the western branch of the Pernambuco shear zone; this is represented in the field by the progressive mylonitization of the augen-gneiss, developing an E-W trending anastomosing

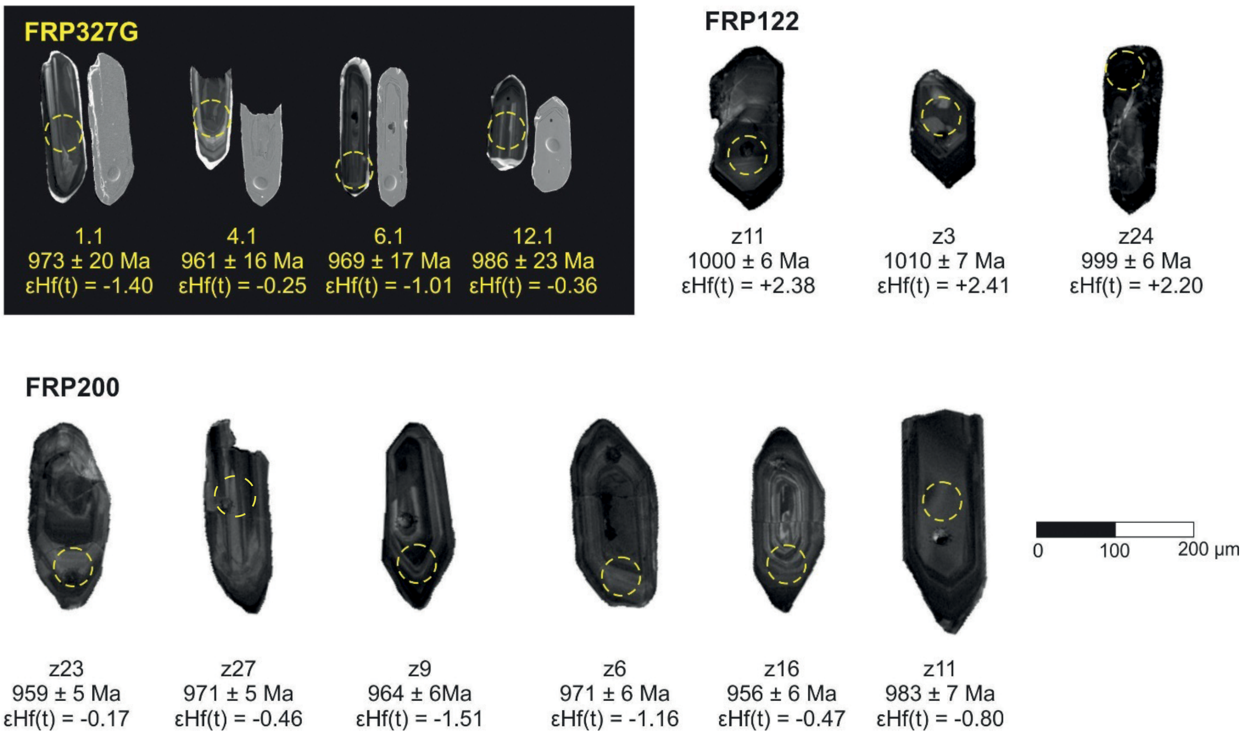


Figure 4. CL and SE (FRP327G) images of selected zircon crystals from the studied samples. The doted circle represents spot placement for Hf analysis (50 μm diameter). Previous SHRIMP spots (20 μm diameter) are visible on SE images of zircon crystals from sample FRP327G, and laser ablation spots (20 μm diameter) for U-Pb analysis are visible on CL images of samples FRP122 and FRP200. Quoted ages are $^{206}Pb/^{238}U$ dates.

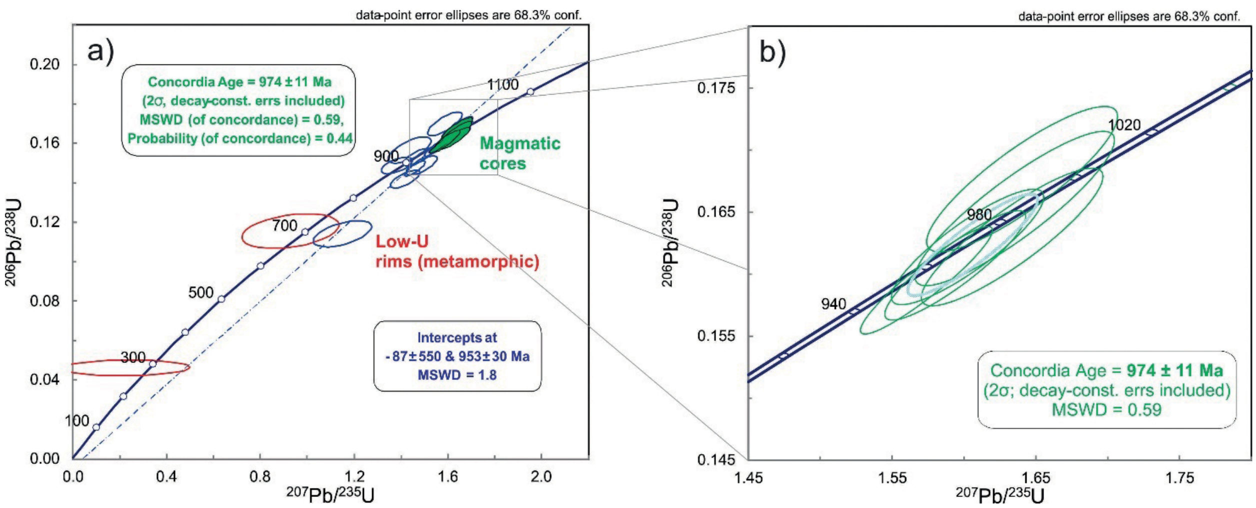


Figure 5. Concordia diagrams for sample FRP327G. The diagram in (B) represents a zoom into the grey square area in (A). Spots are color-coded to represent the analysis used in calculation of the Discordia (upper intercept) age (blue), of the Concordia age (green) and low-U high-uncertainty rims not used for age calculation (red).

foliation which involves the dextral-sense rotated feldspar porphyroclasts of the augen-gneiss.

Sample FRP200 is from the central and most undeformed portion of the pluton. Zircon crystals are clear, inclusion-free needle-like elongated euhedral prisms (up to 5:1 aspect ratio), with conspicuous concentric internal zoning (Fig. 4). The zircon crystals show typically igneous Th/U ratios, between 0.1 and 0.4. Those were dated by Caxito *et al.* (2014b) by LA-ICPMS, yielding a Concordia age of 966 ± 4.6 Ma (2σ, MSWD = 2.3), which is interpreted to be the magmatic age of the granitic protolith.

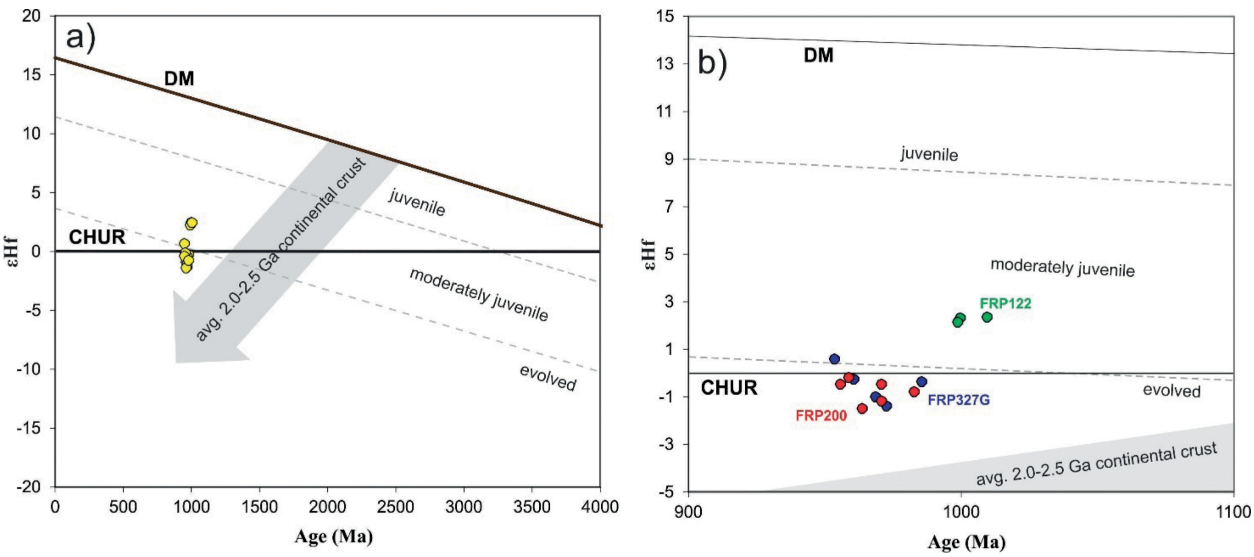
Six spots in the most concordant zircon crystals were selected for Hf isotope analysis (Tab. 2). Those yielded initial $^{176}Hf/^{177}Hf_{(t)}$ ratios of 0.282132–0.282173 (Fig. 6), corresponding to slightly evolved $\varepsilon Hf_{(t)}$ of -1.51 to -0.17 and with T_{DMHf} of 1.5 Ga.

DISCUSSION

The new U-Pb data adds to the amassed dataset that shows the presence of ca. 1000-960 Ma rocks related to the Cariris Velhos event within the internal zone of the Riacho do Pontal Orogen (Caxito *et al.* 2014b and references therein). The augen-gneiss sill dated at 974 Ma intrudes metasedimentary rocks, and thus at least part of what is currently mapped as Santa Filomena Complex must be older than that, and probably related to the Cariris Velhos event. The fact that, in other parts of the internal zone of the Riacho do Pontal Orogen, samples of metasedimentary rocks also mapped as Santa Filomena Complex yield detrital zircon grains as young as ca. 650 Ma (Brito Neves *et al.* 2015, Santos *et al.* 2017) highlights the difficulty of separating metasedimentary successions of distinct age and tectonic setting which were subjected to strong deformation and metamorphism during the Brasiliano Orogeny in this area. Probably, what is today mapped as Santa Filomena Complex encompasses both sedimentary basins related to the Tonian Cariris Velhos and the Ediacaran Brasiliano syn-orogenic sedimentation.

Moderately juvenile to slightly evolved near-chondritic Hf isotope data presented here for the first time (Tab. 2 and Fig. 6) suggest that the Afeição augen-gneisses represent neither juvenile (*e.g.*, island-arc) rocks nor purely the remelting of ancient crustal rocks (Archean and Paleoproterozoic basement of the Transversal Zone). Instead, a scenario with the mixing of Tonian juvenile melts coming from a mantle wedge above a subduction zone with variable amounts of Archean and Paleoproterozoic basement is proposed to explain the Hf isotope characteristics of the Cariris Velhos augen-gneisses, generating intermediary Mesoproterozoic model ages (1.6 – 1.2 Ga) which are the result of the two end-member mixing process. A similar interpretation was presented for Nd isotope data available for Cariris Velhos-related rocks, which also yield Mesoproterozoic T_{DM} and positive to slightly negative εNd(t) (Kozuch 2003, Santos *et al.* 2010, Caxito *et al.* 2014b). Such scenario is coherent with a continental arc setting, as also suggested by the trace element patterns of Cariris Velhos gneisses (Kozuch 2003, Santos *et al.* 2010, Caxito *et al.* 2014b), which resemble Cordilleran granites. There is also an apparent slight tendency of the data to yield more juvenile εHf(t) for the oldest intrusions (ca. 1000), while the youngest (ca. 960) would yield more evolved data (Fig. 6). This trend, however, will only become clarified after more data is gathered and added to our pioneer dataset.

An alternative geotectonic model for the Cariris Velhos augen-gneisses was proposed by Neves (2003) and Guimarães *et al.* (2012, 2016), where those rocks would have been emplaced in an extensional, continental rift-related setting. It is interesting to notice that, interpreting similar lithogeochemical datasets, Neves (2003) and Guimarães *et al.* (2012, 2016) propose a distinct model and tectonic setting than Kozuch (2003), Santos



DM: Depleted Mantle; CHUR: Chondritic Uniform Reservoir.

Figure 6. Hf isotope evolution diagram for zircon samples of the Afeição Suite. The diagram in (B) represents a zoom in the area where the samples plot in the diagram in (A). Grey dashed lines classify fields of juvenile (0–5 ε-units below DM), moderately juvenile (5–12 ε-units below DM) and evolved (> 12 ε-units below DM; Bahlburg et al. 2011). The grey band represents the average evolution of typical continental crust generated around 2.0 – 2.5 Ga, with a $^{176}Lu/^{177}Hf = 0.010$ for felsic and $^{176}Lu/^{177}Hf = 0.022$ for mafic crust (Pietranik *et al.* 2008). Model DM with present day $^{176}Hf/^{177}Hf$ ratio of 0.28325 and $^{176}Lu/^{177}Hf$ ratio of 0.0388 (Griffin *et al.* 2000, updated by Andersen *et al.* 2009).

et al. (2010) and Caxito *et al.* (2014b). This highlights the difficulty of using lithogeochemical data to infer the tectonic settings of ancient metaigneous rocks. For instance, Caxito *et al.* (2014b) use diagrams that rely upon trace element data for the Afeição Suite augen-gneisses, which are generally thought to remain relatively immobile during post-crystallization processes, such as Th, Ta, Yb, Hf, Nb and Zr (Harris *et al.* 1986, Thiéblemont and Tegyey 1994, Gorton and Schandl 2000). In all of those diagrams, samples of the Afeição Suite augen-gneisses plot majoritarily in the Active Continental Margin, Volcanic Arc, or Collisional Calc-Alkaline/Syn-collisional fields, generally away from within-plate or anorogenic settings. Guimarães *et al.* (2016), on the other hand, uses the classic diagram of Eby (1992) for the discrimination of anorogenic granites where samples of the Afeição Suite, along with other Cariris Velhos samples, plot in the A2-type field.

As discussed by Guimarães *et al.* (2016), the majority of Tonian orthogneisses of the Borborema Province plot in the ferroan field in Frost *et al.* (2001) SiO_2x(FeO/FeO + MgO) diagram, specifically in the upper right part (SiO_2 > 70%) of the diagram. A scatter to the magnesian field is, however, evident, especially when using the SiO_2x(FeOtot/FeOtot + MgO) diagram, recommended by Frost *et al.* (2001) on the basis that most modern chemical analysis do not distinguish between ferric and ferrous iron. Although ferroan magmas are typical of intraplate environments, Frost *et al.* (2001) noticed that they are not exclusive of those tectonic settings. In fact, about 17% of the Cordilleran-type granitoids in the dataset (n = 538) of Frost *et al.* (2001) plot within the ferroan field. Excursions across the line that divide both fields are especially evident (although not exclusive) when SiO_2 > 70%, as its exactly the case for both the Afeição Suite and other granitoids related to the Cariris Velhos event (see Fig. 5D of Caxito *et al.* 2014b and Fig. 5B of Guimarães *et al.* 2012). For comparison, 96% of the A-type granitoids of the dataset (n = 486) of Frost *et al.* (2001) plot in the ferroan field, without significant scatter to any part of the magnesian field. Thus, although classifications based on the contents of FeO and MgO are normally useful, as it has long been recognized that there are fundamental differences between rock suites that undergo iron enrichment during differentiation and those that do not show significant FeO enrichment relatively to MgO while SiO_2 becomes enriched (Frost *et al.* 2001), samples of the Cariris Velhos augen-gneisses (and of the Afeição Suite) usually plot in the most ambiguous part of the proposed diagrams, and the scatter to the magnesian field hinders direct interpretation of the samples as typical ferroan A-type granites.

Plotting of Cariris Velhos samples in other diagrams that would allow separation between A-type and other types of granites are also ambiguous. For example, in the (FeO/MgO) *versus* (Zr + Nb + Ce + Y) tectonic discriminant diagram of Whalen *et al.* (1987), most samples plot in the borderline between the A-type granites field and the other fields (Fig. 10A of Guimarães *et al.* 2016), straddling the fractionated granites field and even the field of unfractionated M, I- and S-type granites.

Kozuch (2003), Santos *et al.* (2010) and Caxito *et al.* (2014b) interpret the fingerprints of subduction zones in normalized trace-element spidergram distributions of the Cariris Velhos orthogneisses. Kozuch (2003) and Santos *et al.* (2010) compiled data from different sources and proposed fields for typical extensional and convergent rock compositions, arguing that the Cariris Velhos orthogneisses plot within the convergent field, characterized by low Nb-Ta, Sm-Hf, and Tb-Yb segments, and away from typical extensional patterns. Those are, however, although characteristic, not exclusive of arc-related granitoids, as exemplified by the interpretation of Guimarães *et al.* (2016) of the same normalized trace-element spidergrams as typical of A-type granites.

There is a possibility that rocks originated and emplaced in distinct tectonic settings might have been considered and treated as similar, based only on the crystallization age range. This is not unlikely when dealing with rocks scattered in such a wide area and especially when comparing such distant regions as the Rio Preto, Riacho do Pontal and Sergipano Belts of the Southern Borborema Province, with occurrences in the Transversal Zone and PEAL block. Treatment of rock samples emplaced and evolved in distinct settings would lead to significant scatter in the diagrams discussed above, blurring the original relations and difficulting interpretation. Thus, both temporal and spatial distinction should be made.

Temporally, we disagree that all of the Tonian rocks within the Borborema Province should be treated and interpreted together (*i.e.*, as related to the Cariris Velhos event). For instance, in the Riacho do Pontal Belt, continental extension related to emplacement of a mantle plume and completely unrelated to the Cariris Velhos event was already underway at ca. 900 Ma (Salgado *et al.* 2016), leading to the development of the Paulistana rift basin at ca. 888 Ma and of new oceanic crust at ca. 820 Ma (Caxito *et al.* 2016). Those rocks are all related to the rift and drift stages which would evolve to a complete Wilson Cycle during the Neoproterozoic culminating in the Brasiliano Orogeny (Caxito *et al.* 2016). They are, thus, not related to the Cariris Velhos event, which should be understood in the Riacho do Pontal area as occurring between 1000 and 960 Ma; and perhaps as young as ca. 920 Ma in the remainder of the Transversal Zone (Santos *et al.* 2010). We disagree, then, with inclusion of rocks as young as ca. 870 Ma as Cariris Velhos-related (Guimarães *et al.* 2016). In effect, A-type orthogneisses dated at ca. 869 Ma in the eastern Transversal Zone (Neves *et al.* 2015) seem to be part of a middle Tonian rifting event similar to that discussed for the Riacho do Pontal area. In addition, based on the trace-element and isotope characteristics of the São Caetano supracrustal sequence of the Alto Pajeú Domain, Santos *et al.* (2019) described an extensional setting interpreted as a post-Cariris event at ca. 858 Ma. To our understanding, rocks related to the Cariris Velhos event are roughly bracketed between 1000 and 920 Ma, with middle Tonian rocks younger than that (ca. 900 – 820 Ma) being part of the rifting events in the Borborema Province related to Wilson cycles which would lead to the Brasiliano Orogeny.

Spatially, there is the possibility of distinct tectonic settings, coupled or not, being developed diachronolously over long distances. For instance, Kozuch (2003) and Santos *et al.* (2010) have made an interesting distinction of Tonian rocks emplaced in the Alto Pajeú domain (in a convergent arc setting) from those emplaced in the Riacho Gravatá subdomain (probably in an extensional, fore-arc or back-arc setting). Guimarães *et al.* (2016) consider the Serra da Pintada Suite of the Rio Preto Belt, in the extreme southwest of the Borborema Province, dated at 969 ± 11 Ma (Aquino and Batista 2011), as similar to the other Cariris Velhos occurrences in the Borborema Province. However, this is an alkaline suite composed of alkali-granites and syenites, with distinct normalized trace-element spidergrams (*e.g.*, with no Nb-Ta through), clearly plotting in the A-type field and in the within-plate granite fields of discrimination diagrams (Aquino and Batista 2011). Caxito *et al.* (2014a) and Alcântara *et al.* (2017) interpret the Serra da Pintada Suite as emplaced in an extensional setting related to the opening of a rift system which would be filled by the Canabravinha Formation sediments in the Rio Preto area. This setting is totally distinct from that occurring further northeast in both the Transversal Zone and in the Riacho do Pontal, Sergipano and PEAL areas, as also indicated by the distinct lithogeochemical signatures.

Another issue that deserves attention in future works is the petrogenesis and tectonic setting of mafic and ultramafic rocks which might be related to the Cariris Velhos event, including some retro-eclogitic remnants. For instance, Lages and Dantas (2016) studied the Floresta (Serrote das Pedras Pretas; Santos 1995) and Bodocó mafic-ultramafic units, which, according to the authors, constitute proto to marginal arc-back-arc basin systems that evolved between 1025 and 975 Ma, with arc cumulate rocks having evolved originally as picrite melts in suprasubduction ophiolite zones. Although the rocks related to the Cariris Velhos event are far from well understood, there is a larger dataset available for the felsic to intermediate augen-gneisses and metavolcanics than for the mafic and ultramafic rocks, and a clear picture of the belt's evolution will only be achieved by the study of the whole set of rocks.

As discussed by Neves (2003) and Guimarães *et al.* (2016), the lack of a well-defined metamorphic event related to the Cariris Velhos cycle is the main problem when trying to define an orogenic event of this age within the Borborema Province. However, accretionary processes and arc-continent collisions don't always produce significant deformation and metamorphism in the arc region. "Soft" collisions, where the arc region remains relatively undeformed, are not uncommon in the geologic record (Van Staal *et al.* 2011). Unfortunately, the low-U metamorphic rims in zircon crystals studied in this work are too thin and yielded results with too high uncertainties to be decisive in this case (Tab. 1 and Fig. 5). It is possible, as discussed by Medeiros (2004) and Caxito *et al.* (2014b), that metamorphism and structures related to the Cariris Velhos event (if this event is interpreted as a "hard" accretionary orogeny) have been largely obliterated by the late Neoproterozoic pervasive Brasiliano metamorphism and deformation. The definition of the existence and extent of the metamorphic event is a clear target for future research, and detailed petrographic and isotopic study of metamorphic rims and minerals should be conducted in order to clarify those issues. For instance, the 1.0 Ga metamafic-ultramafic rocks of the Serrote das Pedras Pretas Suite of the Alto Pajeu Domain are interpreted as a candidate of the oceanic remnants (Santos 1995) or arc-back-arc sequences (Lages and Dantas 2016) related to the Cariris Velhos event. Lages and Dantas (2016) interpreted a low Th/U (< 0.1) zircon crystal of this suite with a $^{206}Pb/^{238}U$ age of 967 ± 9 Ma as possible evidence of concomitant metamorphic processes during the Tonian (Lages and Dantas 2016). Further detailed geochronological work is necessary to confirm or dismiss a metamorphic event of this age.

Finally, recently acquired and processed magnetotelluric data suggest north-dipping crustal conductors as the dominant features in the Transversal Zone (Padilha *et al.* 2016). Considering the geometry and distribution of the conductors, Padilha *et al.* (2016) suggest that they represent remnants of an ancient subduction zone with enhanced conductivity associated with biogenic graphitized material originally deposited in a restricted oceanic environment. As the subsurface features correspond to the outcropping sites of Cariris Velhos-related rocks, including early Tonian rocks of oceanic affinity, Padilha *et al.* (2016) suggest that those are the relicts of an early Tonian subduction zone related to the Cariris Velhos event. Thus, geophysical data supports, in a first approximation, the continental arc model proposed by Kozuch (2003), Medeiros (2004), Santos *et al.* (2010), and Caxito *et al.* (2014b).

Based on the evidence discussed above, it is clear that from lithogeochemical data alone the tectonic setting of the Tonian orthogneisses of the Borborema Province is far from unambiguous and completely understood. However, we consider a continental arc setting for the Afeição augen-gneiss Suite and for most of the Cariris Velhos occurrences in the Alto Pajeú domain as the scenario that best explains the dataset gathered thus far. For instance, trace element data, which are usually regarded as immobile, point to a convergent setting in most discrimination diagrams. "Inheritance" of convergent-type lithogeochemistry due to the partial melting of older, Paleoproterozoic crust of arc affinity is not feasible because Hf and Nd isotope signatures clearly indicate the mixing of variable amounts of juvenile mantle and older crust, with important mantle input in the Tonian. This mantle input would strongly modify and obliterate the Paleoproterozoic geochemical signatures of the crustal sources. However, we recognize that further field, petrographic, geochemical, and isotopic work is necessary to characterize and fully understand the extent and importance of the Cariris Velhos event in the geology of the Borborema Province and of West Gondwana in general. In this process, it will be important to clearly separate, in both time and space, the rocks related to distinct tectonic settings and playing different roles, diachronously, throughout the Borborema Province.

Concluding remarks

The new U-Pb and Hf isotope data of the Afeição Suite presented here for the first time adds to the growing dataset that will help characterize and understand the tectonic setting and role of the augen-gneisses and metavolcanosedimentary rocks related to the Cariris Velhos event within the Borborema

Province and West Gondwana in general. Isotope data derived from both Nd and Hf datasets suggest the mixing of a Tonian juvenile mantle source with variable amounts of older, Archean and Paleoproterozoic basement of the Borborema Province.

Interpretation of the available lithogeochemical dataset for Tonian rocks of the Borborema Province is far from unambiguous. To help resolve this issue, some spatial and temporal distinctions should be made. Temporally, we suggest that only rocks in the 1000 – 920 Ma should be considered as possibly related to the Cariris Velhos event. Tonian rocks younger than that are clearly related to post-Cariris extensional events, which would evolve to continental breakup and drifting and ultimately to complete Wilson Cycles related to the Brasiliano Orogeny during the Neoproterozoic. Spatially, we stress that tectonic settings evolve diachronously in extensive regions and that extensional settings might develop coeval to adjacent compressional settings, coupled (*e.g.*, in the back-arc region) or not.

Even after those distinctions are done, interpretation of lithogeochemistry data will probably still be far from definitive in characterizing the geotectonic setting of Cariris Velhos-related rocks. To a first approximation, however, trace element data which are generally thought to be immobile (Th, Ta, Yb, Hf, Nb, Zr) all point to a convergent, arc-related setting for most of the Cariris Velhos occurrences, including the Afeição Suite. Interpretations that the subduction-related geochemical fingerprints would have been "inherited" from the remelting of arc-related Paleoproterozoic rocks are ruled out by Hf and Nd isotope data, which clearly suggest the important input of juvenile mantle-derived melts that would largely obliterate the geochemical signatures of remelted crustal sources during the Tonian.

Arguably, the greatest challenge to the interpretation of a convergent-type setting for the Cariris Velhos Belt is the lack of a well-defined metamorphic event related to this orogenic pulse. This is a clear target for further detailed petrographic and isotopic work, in search of metamorphic rims and minerals which would help clarify this and other issues in the geology of the Borborema Province. The possibility of "soft" accretionary processes, with relatively low deformation and metamorphism in the arc region, must also be investigated.

In order to achieve a better understanding of the evolution of the Cariris Velhos event in the Borborema Province, as a final remark we would like to stress the importance of studying, besides the felsic to intermediate orthogneisses and related metavolcanic rocks, also the mafic and ultramafic components, which are not as detailed as the first. Recent studies suggest the presence of arc-back-arc and suprasubduction zone mafic-ultramafic associations, and this is clearly a subject for further research. Also, the integration of surface geology with subsurface geophysical information will be crucial for further assessing the importance of the Cariris Velhos event for the evolution of the Borborema Province. Magnetotelluric data, for instance, suggest the presence of north-dipping conductors interpreted as remnants of ancient subduction zones corresponding to the outcropping sites of early Tonian rocks related to the Cariris Velhos event in the Transversal Zone, lending further support to the continental arc model.

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