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Geochemical and isotopic characterization of the granitic magmatism along the Remígio - Pocinhos shear zone, Borborema Province, NE Brazil

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Two granitoid plutons (Pilõezinhos and Curral de Cima) intruded along the Remígio - Pocinhos shear zone, eastern part of the Borborema Province. The Pilõezinhos and Curral de Cima granites were dated at 566 ± 3 Ma and 618 ± 5 Ma respectively. The granitoids from both plutons have distinct initial $^{143}Nd/^{144}Nd$ ratios, expressed by εNd(t) values, i.e. the granitoids of Pilõezinhos pluton have lower εNd(t) values (−15.47 to −15.81) and negative εHf (t = 570 Ma) values (−16.0 to −18.6), while the granitoids of the Curral de Cima pluton have εNd(t) values between −1.12 and −5.23. The granitoids of the Curral de Cima pluton are epidote bearing, magnesian calcalkaline I-type granitoids, crystallized under high fO_2 conditions. The granitoids of the Pilõezinhos pluton are alkaline, low-fO_2, ferroan, ilmenite-series, A2-type granite intrusions. The geochemical and isotopic signatures suggest that the origin of magma of the Curral de Cima granitoids involved mixing/mingling at depth between crustal and mantle magmas, associated to decompression (lateral escape) during the convergent stage of Brasiliano/Pan/African orogeny, which lead the asthenosphere melts to rise into the lower crust. The source of magma of the granitoids of the Pilõezinhos pluton involved a strong crustal component with geochemical and isotopic signatures similar to the orthogneisses of the Serrinha-Pedro Velho Complex, and small mantle component. The emplacement of the Pilõezinhos pluton is associated to an extensional space formed during high-T strike-slip shearing developed by the synchronic movement of the Matinhas sinistral shear zone and Remígio - Pocinhos dextral shear zone.

1. Introduction

Granitic magmatism is one of the main features associated to the Brasiliano Orogeny (= Pan-African 0.65–0.55 Ga) in the Borborema Province, NE Brazil (Fig. 1A). The granitic magmatism is mainly associated to the development of E-W and NE-trending shear zones. According to their relationships with the shear zones, they are classified as early-, syn-, late- and post-transcurrent. Within the Borborema Province, the majority of them are syn-transcurrent (Neves et al., 2006).

Van Schmus et al. (1995) suggested that the E-W dextral Patos and Pernambuco shear zones divided the Borborema into three domains, later denominated subprovinces (Van Schmus et al., 2011): i) Northern, north of the Patos shear zone, ii) Transversal, between the Patos and Pernambuco shear zones and iii) Southern, south of the Pernambuco shear zone. Each subprovince was divided in many domains.

The EW- trending dextral Remígio - Pocinhos shear zone (Fig. 1B) has been interpreted as the east branch of the Patos shear zone, dividing the northern and transversal subprovinces. In pre-drift reconstructions (Fig. 2), the Patos shear zone continues into East Nigeria (De Witt et al., 1998; Van Schmus et al., 2008) or into Cameroon as the Central Cameroon and Adamaoua shear zones (Nzina et al., 2010). The Remígio Pocinhos shear zone is associated with terminations of smaller scale shear zones of generally sinistral

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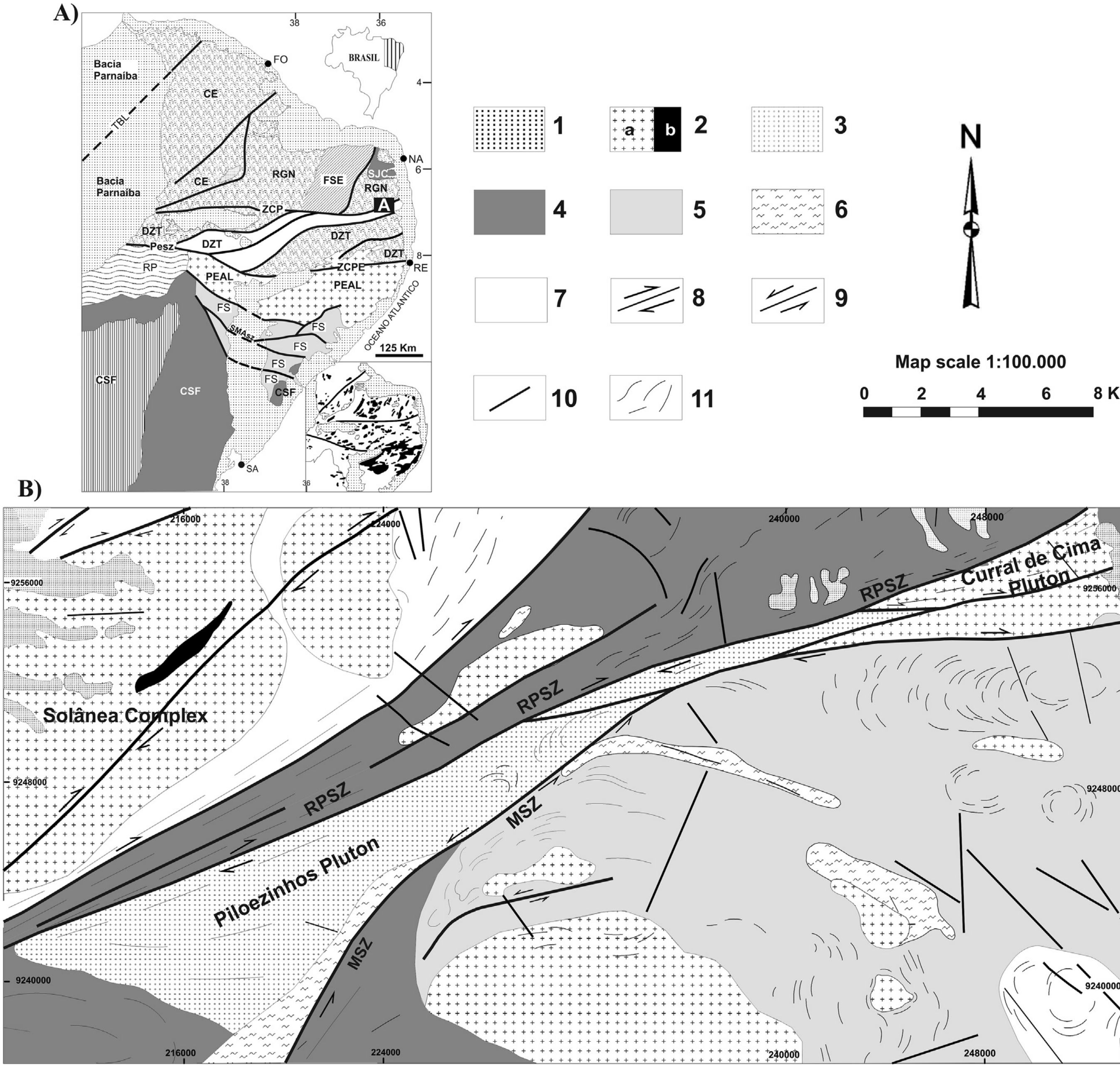

Fig. 1. A) Major domains and subdomains of the Borborema Province (Van Schmus et al., 2008). CSF= São Francisco craton; FS: Sergipana Belt; FRP = Riacho do Pontal Belt; PEAL = Pernambuco-Alagoas subdomain; FSE = Seridó belt; SJC = São José do Campestre Archean core; CE = Ceará domain; RGN = Rio Grande do Norte domain; ZCPE = Pernambuco Shear Zone; ZCP = Patos Shear Zone; A = Study area. Insert - Distribution of Brasiliano granites of the Borborema Province after Santos et al. (1997); B) Simplified geological map of the study area, modified from the Solânea/SB.25-Y-A-IV (Guimarães et al., 2008) and Guarabira/SB.25-Y-A-V (Guimarães and Bittar, 2011) maps. 1 = Phanerozoic covers; 2a = Brasiliano granites, 2b = diorites; 3 = Pilõezinhos Pluton; 4 = Brasiliano metasedimentary rocks; 5 = Metasedimentary rocks of undefined age (Sertânia Complex); 6 = Tonian orthogneisses; 7 = Rhyacian orthogneisses; 8 = dextral shear zone; 9 = sinistral shear zone; 10 = fractures; 11 = photo lineaments; ZCM = Matinhas Shear Zone; ZCRP = Remígio - Pocinhos shear zone.

kinematics sense and shows a southwest displacement direction, which gradually changes to the south defining a half-negative flower geometry (Jardim de Sá, 1994). Many granitic plutons are emplaced along the Remígio-Pocinhos shear zone.

Based on mineral composition, geochemical signature and geochronological data, Guimarães et al. (2004) divided the granitoids from the Transversal subprovince of the Borborema Province into four groups: 1) Calc-alkaline granitoids with crystallization ages within the 610–644 Ma interval, modified to ~ 620Ma by Guimarães et al. (2011); 2) High-K calc-alkaline and shoshonitic granitoids with U–Pb TIMS zircon age ranging from 590 to 581 Ma, associated the transition between flat-lying foliation event and transcurrence; 3) Post-collision alkaline granitoids with U–Pb zircon age of ~570 Ma and 4) A-type granitoids associated to the subvolcanic bimodal magmatism, with ages within the 540 - 512 Ma interval.

Along some E-W trending dextral shear zones, the granitic magmatism with distinct ages, geochemical signatures and fO_2 crystallization conditions has been identified, telling the evolutionary history of the shear zone.

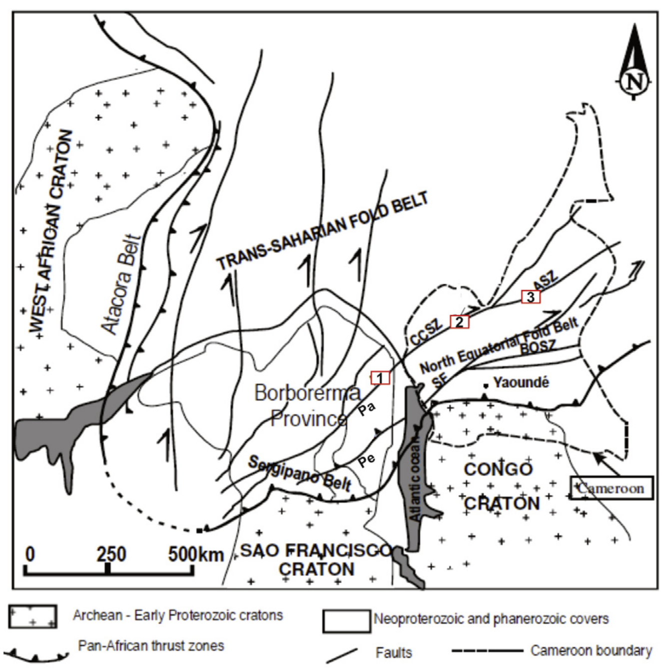

Fig. 2. Pre-drift reconstruction of Pan-African and Brasiliano terranes (Nzina et al., 2010): CCSZ: Central Cameroon Shear Zone; ASZ: Adamaoua shear zone; BOSZ: Betaré-Oya Shear Zone; SF: Sanaga Fault; Pa: Patos shear zone; Pe: Pernambuco shear zone; 1: Study area; 2: Studied granitoids by Nzina et al., 2010; 3: Studied granitoids by Ferré et al., 1998.

This work deals with the geochemical and isotopic characterization of granitoids intruded along the eastern part of the dextral Remígio - Pocinhos shear zone (east branch of the Patos Shear Zone). Geochemical, U–Pb zircon geochronology and Nd–Hf isotopic analyses on selected samples are presented. A genetic model of the tectonic framework of the Pilõezinhos pluton, compatible with A-type magmatism in a transcurrent setting, is proposed. In this genetic model, we also add some discussion on the source of the Curral de Cima pluton, intruded along the same shear zone, based on geochemical data from the literature and some data from this work.

2. Geological setting

2.1. Borborema Province

The ~450.000 km^2 Borborema Province (Almeida et al., 1977) comprises the Northeast region of Brazil and is located north of the São Francisco Craton, and westwards of the Central African Orogenic Belt. The actual structural framework of the Borborema Province resulted from the Brasiliano/Pan African Orogeny (640-580 Ma; Van Schmus et al., 2008). The Borborema Province comprises a Paleoproterozoic basement, with small Archean nuclei (3.4 Ga - 3.1 Ga), composed of Rhyacian (2.2 Ga – 1.8 Ga) gneisses and migmatite (Hackspacher et al., 1990; Brito Neves et al., 1995; Van Schmus et al., 1995; Dantas et al., 1998), Tonian and Ediacaran supracrustal sequences, granitic magmatism and E-W and NE-SW trending shear zones.

The Brasiliano orogeny within the Transversal zone of the Borborema Province was responsible for granitic magmatism, showing distinct geochemical signatures (Almeida et al., 1967; Guimarães and Da Silva Filho, 1998; Neves and mariano, 1997; Ferreira et al., 1998). The majority of granitic intrusions is associated to the synchronic movement of the E-W dextral shear zones and NE-SW sinistral shear zones (Vauchez and Egydio-Silva, 1992; Guimarães and Da Silva Filho, 1998; Ferreira et al., 1998; Neves and Mariano, 1999; Neves et al., 2000; Silva and Mariano, 2000).

The Transversal subprovince, first defined as the Transversal zone (Ebert, 1970), corresponds to a megastructure located between the Patos and Pernambuco shear zones. This subprovince includes from West to East, the belts: Cachoeirinha or Piancó-Alto Brígida, composed of metapelites metamorphosed under greenschist conditions, intruded by calc-alkaline granitoids; Alto Pajeú composed of Neoproterozoic supracrustal sequences, Neoproterozoic (Tonian) and Paleoproterozoic (Rhyacian) orthogneisses; Alto Moxotó comprising Paleoproterozoic orthogneisses and few Ediacaran plutons, and Rio Capibaribe or East Pernambuco (Neves et al., 2006), composed of supracrustal sequences and Brasiliano plutons.

The Rio Grande do Norte domain is part of the northern subprovince. It is located just north of the Remígio - Pocinhos shear zone and is limited to the west by the Orós West/Aiuaba shear zone and its east and north limits are covered by sedimentary rocks of the Coastal Province. The Rio Grande do Norte basement comprises Middle Paleoproterozoic (2.2–2.0 Ga) complex, composed of orthogneisses with local lenses of mafic and ultramafic rocks, including olivine gabbro, wehrlite, clinopyroxenite and hornblendite (Dantas, 1997; Ferreira et al., 2015). An Archean core, São José do Campestre, is located in the northeast portion of the Rio Grande do Norte domain (Fig. 1A).

The basement is overlain by a thick metavolcanic-sedimentary sequence, the Ediacaran Seridó Group (deposition age of 640–620 ma; Van Schmus et al., 2003). Accordin to Archanjo and Salim (1986), the Seridó Group comprises: 1) paragnaisses and metavolcanic basic rocks of the basal Jucurutu Formation; 2) quartzites from the intermediate Equador Formation and 3) micashists from the Seridó Formation in the top.

Van Schmus et al. (2003) reported Nd T_{DM} model ages ranging from 1.8 to 2.2 Ga for metasedimentary rocks of the Jucurutu Formation while the metasedimentary rocks of the Seridó Formation have Nd T_{DM} model ranging from 1.2 to 1.6 Ga. The differences in the isotopic Nd signatures show that the Jucurutu Formation received detritus from the Paleoproterozoic basement, while the detritus of the Seridó Formation were derived from younger and distal sources. The contacts between supracrustal units and basement are mainly made through shear zones.

During the Ediacaran, the Rio Grande do Norte domain was affected by extension-related high-temperature metamorphism, which reached upper amphibolite to granulite facies (Souza et al., 2006; Archanjo et. Al., 2013; Viegas et al., 2014).

2.2. Pilõezinhos and Curral de Cima plutons

The Pilõezinhos pluton (Fig. 1B) comprises an ENE - elongated intrusion of ca. 100 km^2, along the Remígio - Pocinhos Shear Zone, the east branch of the Patos Shear Zone, which limits the Northern and Transversal subprovinces of the Borborema Province. The granitoids of the Pilõezinhos pluton intruded Neoproterozoic metasedimentary rocks and Tonian orthogneisses. The metasedimentary rocks represent slices the Seridó Formation (Jardim de Sá, 1994). The structural context of the Pilõezinhos pluton intrusion involved the synchronous movement of the E-W dextral Remígio - Pocinhos and the NE-SW left-handed Matinhas shear zone. It is compatible with an extensional setting that enabled the opening of space (extensional site) for the accommodation of the granitic magmas.

The Curral de Cima pluton comprises an E-to NE-elongated body intruded by Pilõezinhos pluton and making contact to the west with metasedimentary rocks, along the Remígio - Pocinhos shear zone, and partially covered to the east by the sedimentary deposits of the Paraiba Basin. The Curral de Cima pluton is a magmatic epidote-bearing pluton that carries hornblende, biotite, titanite, and epidote. Ferreira at al. (2011) reported a U–Pb zircon SHRIMP age of 618 ± 5 Ma for the granitoids of the Curral de Cima pluton. This age is similar to the U–Pb conventional age (623 ± 4 Ma) reported by Brito Neves et al. (2008).

3. Analytical procedures

3.1. Mineral chemistry

Major element compositions of mineral phases were determined by electron microprobe analysis using a JEOL, JXA-8230 model electron microprobe at Brasilia University. The samples were metallized with carbon in a vacuum chamber.

The analytical conditions used an acceleration voltage of 15 kV and current of 10 nA.

3.2. Whole-rock geochemistry

Representative samples from the Pilõezinhos pluton and three enclaves of the Curral de Cima pluton were analyzed by ICP-AES (Inductively Coupled Plasma Emission Spectrometry) for major elements and ICP-MS (Inductively Coupled Plasma Mass Spectrometry) for trace elements at ACME Laboratories in Canada. Analyses of representative samples are shown in Table 1.

3.3. U–Pb isotopes

For in situ U–Pb and Lu–Hf analyses, the zircon concentration was performed at NEG-LABISE Laboratory, of the Pernambuco Federal University, using conventional techniques. Zircon grains from the non-magnetic fractions were hand-picked and mounted along with chips of the Temora 2 and FC1 zircon standards onto double-sided tape. Zircon grains and the standards were enclosed by epoxy resin and polished to expose internal structures.

The U–Pb and Lu–Hf isotopic analyses were performed on zircon grains from the same sample (PP3), using a Thermo-Fisher Neptune MC-ICP-MS coupled with a Nd:YAG UP213 NewWave Laser Ablation System at the Laboratory of Geochronology of the Brasilia University.

The analytical procedures of U–Pb analyses on zircon grains followed the procedure detailed by Bühn et al. (2009). During the analytical session, zircon standard Temora-2 was analyzed as an unknown sample.

The cathodoluminescence (CL) images were obtained at the Geosciences Institute of the Pará Federal University, using an electronic microscope LEO-ZEISS 1430 with Mono-CL Gatan system and Sirius-SD EDS detector.

Table 1
Representative whole–rock compositions of the Piloezinhos and Curral de Cima Plutons. PP: Pilõezinhos Pluton; CCP: Diorites of the Curral de Cima Pluton (For detection limits see ACME Laboratories brochure).

Sample	PP1	PP4	PP8	PP12	PP21	PP18B	PP5	PP9	CCP3	CCP4	CCP2
SiO_2	68.73	65.08	63.36	68.09	70.81	71.35	64.41	67.82	57.32	51.88	54.55
Al_2O_3	14.53	15.14	14.43	14.24	14.09	13.39	14.59	15.45	14.33	14.8	13.41
MnO	0.05	0.07	0.11	0.07	0.05	0.04	0.09	0.05	0.15	0.2	0.23
MgO	0.57	1.04	0.98	0.68	0.44	0.46	1.25	2.25	4.96	5.75	6.29
CaO	1.8	2.91	3.85	1.92	1.64	1	3.49	2.71	5.85	6.55	7.65
Na_2O	2.93	3.27	3.06	2.79	2.87	2.4	3.02	4.64	2.99	2.71	2.68
K_2O	5.36	4.1	4.09	5.16	5.55	6.11	4.22	1.89	2.26	2.79	1.69
TiO_2	0.53	0.93	1.16	0.64	0.41	0.46	1.07	0.51	0.95	1.15	0.76
P_2O_5	0.19	0.33	0.38	0.2	0.13	0.12	0.47	0.21	0.18	0.22	0.14
Fe_2O_3	4.26	5.57	7.04	4.76	3.29	3.31	6.45	3.2	9.03	11.88	10.26
Total:	99.65	99.64	98.46	98.55	99.28	98.64	99.06	98.73	98.02	97.93	97.66
Trace elements (ppm)											
Ba	1694	1633	2226	1578	1109	1293	2016	696	415	387	180
Cs	4.1	2.7	3.1	1.8	2.1	1.4	4.9	12.9	5.7	11.2	4
Ga	23.4	25.5	23.2	22.8	20.7	19.1	28.3	24.1	21.1	27.4	21.1
Hf	15.3	18.2	27.1	15.2	10.3	13.3	22.7	4.6	4.4	6.1	4.3
Nb	26.1	34.7	58.3	32.1	18.8	19.3	52.2	11.2	10.8	10	10.8
Rb	210.9	232.3	151.8	202.6	217.3	209.3	197.1	179.2	106.4	142.3	80.4
Sr	262.2	332.3	423.6	283.3	215.7	216.9	414.3	411.2	222.8	218.3	234
Ta	1.4	1.8	3.3	0.9	0.9	0.7	3.6	0.8	0.4	0.3	0.4
Th	44.2	44.6	31.2	52	39.8	64.6	39.3	12.7	5.2	5.7	2.9
U	2	2.4	3.9	2	2.9	3.1	4.2	3.5	1.6	2.2	3.6
V	16	34	44	27	19	18	52	71	157	209	153
Zr	616	706	1183	630	372	489	904	146	167	197	140
Y	40.7	60.9	68.5	32.4	23.1	44.0	72.2	8.8	24.0	17.6	40.5
La	167.4	228	186.7	230.9	116.9	292.1	208	35.1	20.9	23	16.2
Ce	393.5	491.9	380.5	452.2	229.4	523.2	429.1	65.5	45.3	43.5	33.5
Pr	37.49	49.61	46.08	49.8	26.6	61.38	50.11	7.93	6.56	5.99	6.4
Nd	130.9	170.9	169.5	165.4	94.3	203.5	192.2	27.2	29.1	24.7	31.3
Sm	20.4	26.3	28.53	22.4	13.95	29.8	28.53	5.04	6.89	5.61	9.63
Eu	2.03	2.29	3.69	1.92	1.29	1.68	3.05	1.09	1.13	1.08	1.44
Gd	10.9	14.67	20.54	14.71	9.25	19.37	21.35	3.77	6.39	5.1	9.44
Tb	1.68	2.43	2.79	1.66	1.09	2.37	2.74	0.44	0.9	0.73	1.5
Dy	8.57	11.84	14.26	8.36	5.29	11.14	14.93	1.90	4.88	3.85	8.29
Ho	1.51	2.06	2.57	1.29	0.89	1.70	2.53	0.31	0.93	0.66	1.56
Er	3.51	5.46	6.49	3.12	2.16	3.97	6.76	0.79	2.15	1.78	3.64
Tm	0.53	0.76	0.99	0.41	0.29	0.52	0.98	0.11	0.29	0.23	0.54
Yb	2.77	4.9	6.12	2.53	1.76	3.32	6.04	0.56	1.76	1.46	3.61
Lu	0.46	0.64	0.86	0.34	0.23	0.41	0.82	0.08	0.27	0.24	0.5

3.4. Lu–Hf isotopes

The Lu–Hf isotopes analysis followed the procedures of Matteini et al. (2010). The εHf(t) values and Depleted Mantle model age were calculated using the decay constant (λ) of $1.867*10^{-11}$ (Söderlund et al., 2004). Chondritic values of $^{176}Hf/^{177}Hf = 0.0336$ and $^{176}Lu/^{177}Hf = 0.282785$ (Bouvier et al., 2008). Model depleted mantle 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) and $^{176}Lu/^{177}Hf$ ratios of mafic and felsic crust from Pietranik et al. (2008) were used. The Hf model ages were calculated using double stage. Hf isotope data were obtained in zircon grain spots with well-defined magmatic crystallization age, because the different age components will have different Hf isotope compositions (Vervoort and Kemp, 2016).

3.5. Sm–Nd isotope

The bulk rock Sm–Nd isotopic analyses were carried out at the Geochronology Laboratory of the University of Brasília. Sample preparation followed the technique of Richard et al. (1976), in which first the REE are separated as a group, using cation-exchange columns, and then Sm and Nd are separated using columns loaded with HDEHP (di-2-ethylhexyl phosphoric acid) supported on Teflon powder. The spike used was a mixed $^{149}Sm/^{150}Nd$. Sm and Nd samples were loaded onto Re filaments and the isotopic analyses were carried out in a Finnigan MAT-262 mass spectrometer. Procedures details can be found in Gioia and Pimentel (2000). Uncertainties on Sm/Nd and $^{143}Nd/^{144}Nd$ ratios were based on repeated analyses of international rock standards BCR-1 and BHVO-1.

4. Results

4.1. Field aspects, petrography and mineral chemistry

4.1.1. Pilõezinhos Pluton

The granitoids of the Pilõezinhos pluton were divided into two distinct textural/petrographic facies (Fig. 3A and 3B): facies 1 - coarse-grained porphyritic syenogranite to monzogranite, containing rare enclaves of granodioritic composition and xenoliths of the country rocks; 2 - equigranular, fine-grained monzogranite facies. In the contact zone between the two petrographic facies, mafic enclaves show typical texture of magmatic stage interaction processes (Fig. 3 C). However, in the vicinity of the north outer contact, close to the Remígio - Pocinhos shear zone, the Pilõezinhos granitoids show typical solid state deformation features (Fig. 3D), as mylonitic foliation. The studied granitoids contain quartz as anhedral crystals, sometimes recrystallized and/or as aggregates of subgrains, usually displaying undulose extinction. Locally, chess-board subgrain pattern in quartz occurs, denoting subsolidus deformation under high temperature conditions.

The elongated shape of the Pilõezinhos Pluton, associated to the presence of magmatic foliation, running parallel to the Remígio - Pocinhos shear zone (Fig. 3 E) and, evidences for deformation features, ranging from magmatic state to typical features of high temperature solid state deformation, suggest that the Pilõezinhos pluton is a syn-transcurrent intrusion. According to Neves et al. (2006), many of the Ediacaran plutons in the Borborema Province are syn-transcurrent.

The granitoids of the Pilõezinhos Pluton have phenocrysts of microcline with composition ranging from $Or_{59}An_0Ab_{41}$ to $Or_{92}An_0Ab_{08}$. Plagioclase occurs as subhedral crystals, locally zoned, with composition ranging from oligoclase to andesine (An_{17}-An_{39}) (Fig. 4A). The biotite compositions are characterized by high fluorine (2.20%–1.10%) and chlorine (0.27%–0.01%) contents, and high Fe (Fe # 0.72 to 0.82) (Fig. 4B), with composition similar to those of alkaline anorogenic granites. The amphiboles have composition ranging from hastingsite to Fe-tchermakite (Fig. 4C and D), with fluorine and chlorine contents ranging from 0.22% to 0.79% and from 0.25% to 0.45%, respectively. Titanite occurs as either a primary early phase, mostly included by biotite, and as a late phase, surrounding an opaque phase; both phases have low REE contents (Lima et al., 2017). Allanite is REE – rich (13–67% oxide) and occurs as euhedral zoned crystals. The opaque minerals are mainly ilmenite, occurring as euhedral crystals. Magnetite occurs in small modal amount, as a late phase. High – Fe chlorite, of pseudothuringite composition, occurs as a secondary phase originated from the destabilization (hydrothermal alteration) of the ferromagnesian minerals.

4.1.2. Curral de Cima Pluton

This pluton comprises medium-grained inequigranular, grading to slight porphyritic leucotonalites to granodiorites enclosing enclaves of diorites (Fig. 3F). These granitoids show magmatic foliation running parallel to the Remígio - Pocinhos shear zone and in the northern part of the pluton is strongly sheared.

The granitoids of the Curral de Cima pluton show anhedral crystals of quartz with strong ondulose extinction, plagioclase as subhedral to euhedral crystals, locally zoned, with composition ranging from oligoclase to andesine (An_{23-39}) (Fig. 4A), and small modal volume of perthitic microcline, occurring as phenocrysts. The biotite is siderophyllite molecule-rich (Fe# 0.51–0.53) (Fig. 4B), with F contents ranging from 0.35 to 0.65. The amphiboles occur as subhedral crystals with composition ranging from edenite to Mg-hornblende (Fig. 4C and D). The amphiboles from the granitoids of the Curral de Cima pluton are chemically distinct from the granitoids of the Pilõezinhos pluton by low- Fe, low-F (0.11–0.42) and low-Cl (0–0.05) contents. The accessory mineral phases are titanite, epidote, zircon and apatite, mostly included in biotite.

4.2. P-T, fO_2 crystallization conditions

The mafic mineral phases of the granitoids from the Pilõezinhos pluton are Fe– and halogen-rich compared to the mafic minerals of the granitoids from the Curral de Cima pluton. The differences reflect crystallization under distinct fO_2 conditions, low for the granitoids of the do Pilõezinhos pluton and high for the granitoids of the Curral de Cima pluton (Lima et al., 2017). The presence of magmatic epidote in the granitoids of Curral de Cima pluton also suggests high - fO_2 conditions during the crystallization of the granitoids of the Curral de Cima pluton, between NNO and QFM buffers (Ferreira et al., 2011).

Solidification temperatures were calculated using the semi empirical thermometer of Holland and Blundy (1994), which uses chemical analyses of coexisting plagioclase and amphibole. The temperatures are pressure dependent and the pressures were defined using the Al-in-hornblende barometer of Anderson and Smith (1995). The estimated crystallization temperatures for the granitoids of the Pilõezinhos pluton are within the 795 - 745 °C interval (Lima et al., 2017). The granitoids of the Curral de Cima pluton show crystallization temperatures ranging from 663 to 559 °C (Ferreira et al., 2011).

Zircon saturation temperatures were estimated using the equation of Watson and Harrison (1983) that takes into account Zr contents of whole rock. Zircon is an early crystallized phase in the Pilõezinhos pluton and in the Curral de Cima pluton, and the calculated temperatures should be close to liquidus conditions. Calculated temperatures for the Pilõezinhos pluton vary from 872 °C to 1004 °C and from 795 °C to 821 °C in the granitoids of the

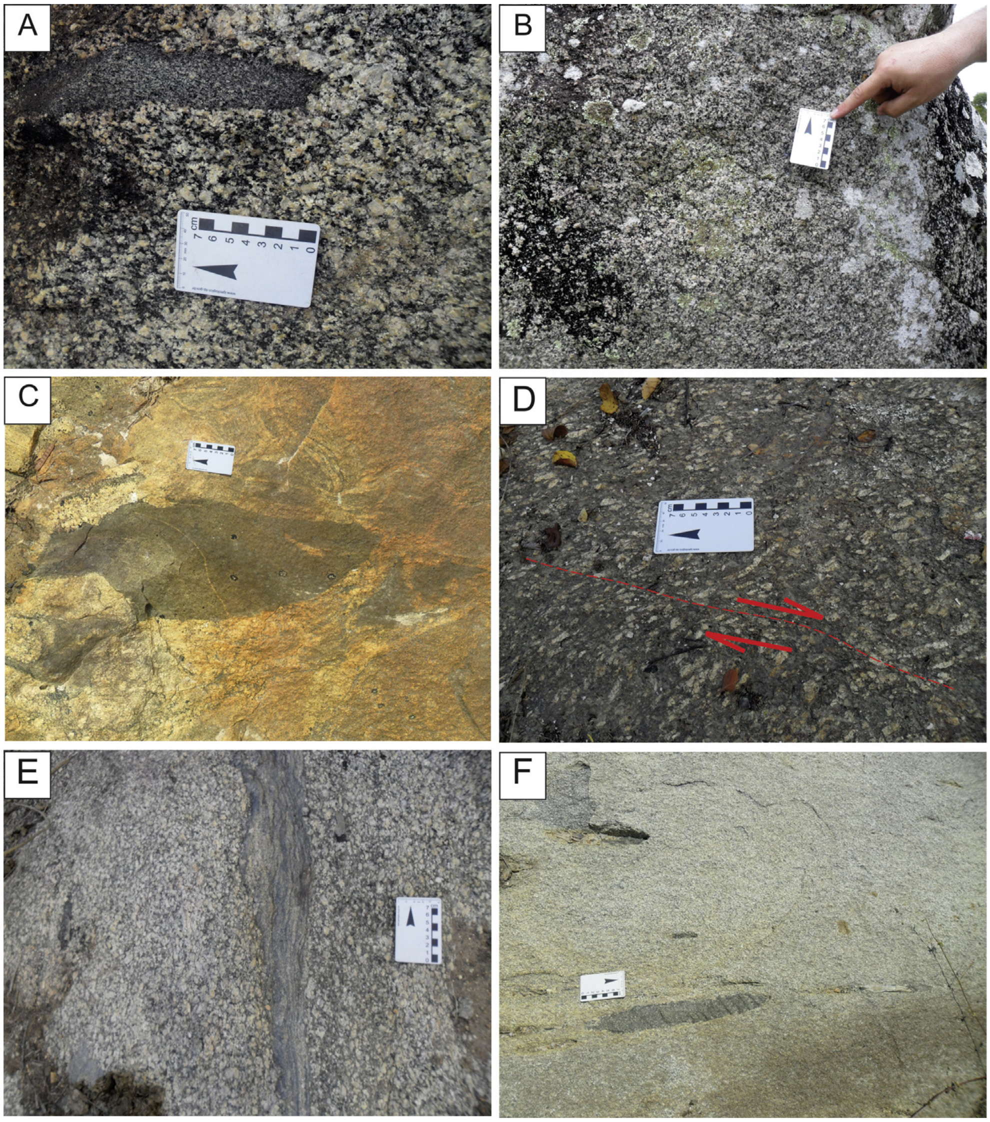

Fig. 3. A) Porphyritic syenogranite enclosing dioritic enclave; B) Fine-grained granitic rock of the facies 2; C) Mafic enclaves showing typical features of magmatic stage interaction processes; D) Shear band indicating dextral kinematics in the porphyritic granite facies; E) Magmatic foliation defined by the alignment of euhedral to subhedral K-feldspars and plagioclase phenocrysts; F) Dioritic enclave hosted in the Pluton Curral de Cima granite.

Curral de Cima Pluton (Ferreira et al., 2011; Lima et al., 2017).

The lower temperatures estimated by the thermometer of Holland and Blundy (1994) for the granitoids of the Pilõezinhos pluton should be close to the solidus temperature, while the low temperatures recorded in the granitoids of the Curral de Cima pluton suggest reequilibration between amphibole and plagioclase in sub-solidus state.

Total Al contents in hornblende were used as pressure indicator on calc-alkaline granitic rocks containing the mineral assemblage in equilibrium: quartz + hornblende + plagioclase (oligoclase or andesine) + K-feldspar + biotite + titanite + magnetite or ilmenite (Hammarstrom and Zen, 1986; Hollister et al., 1987; Anderson and Smith, 1995). The Pilõezinhos granites have all of these phases.

The pressure calculated by the equation of Anderson and Smith (1995) takes in consideration crystallization under higher temperatures, which can increase the Al^{IV} in amphibole, and low fO_2 conditions. Both conditions match with the crystallization conditions of the Pilõezinhos granites.

The pressure of crystallization, using the equation by Anderson and Smith (1995), was estimated within the 4.28–5.95 ± 0.6 kbar interval for the granites of the Pilõezinhos pluton (Lima et al., 2017). The estimated crystallization pressures for tonalites from the Curral de Cima pluton, calculated by Ferreira et al. (2011), using the equation of Anderson and Smith (1995), are lower, varying from 2.2 to 3.3 kbar. Ferreira et al. (2011) explain the low temperatures and pressures recorded in the Curral de Cima granitoids as resulting from either: 1) exchange of Al between coexisting hornblende and plagioclase during crystallization and/or 2) the analyzed amphibole resulted from the disaggregation of amphibole-rich mafic enclaves (clots) derived from the source. The petrographic features favor hypothesis 1.

4.3. Geochemistry

The granitoids of the Pilõezinhos pluton show SiO_2 contents ranging from 64 wt% to 72 wt%. The Pilõezinhos granitoids have high total alkalis ($Na_2O + K_2O$) values, with K_2O/Na_2O ratios > 1. The granitoids of the Curral de Cima pluton have lower SiO_2

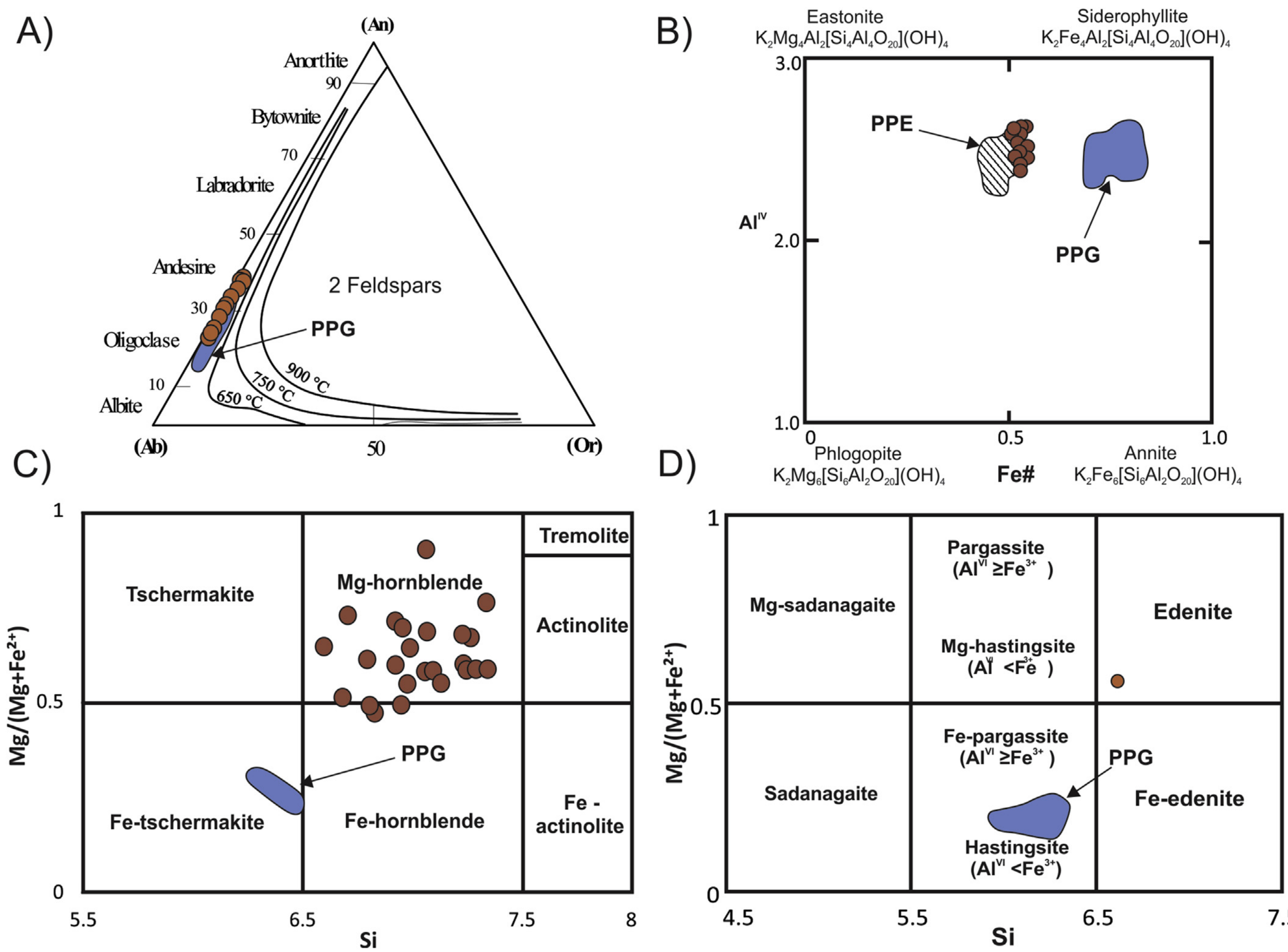

Fig. 4. A) Chemical diagram for feldspars classification; B) *Fe# x Al^{IV}* chemical diagram for the classification of studied biotite crystals; C) and D) Diagrams for the classification of amphiboles crystals according to Leake et al. (1997). Circles = Curral de Cima Pluton diorites; PPG = Pilõezinhos Pluton granites; PPE = Pilõezinhos Pluton enclaves. Fields after Lima et al. (2017).

contents, 58 wt% to 52 wt% for the dioritic enclaves, and 68 wt% to 64 wt% in the tonalites. The granitoids from both plutons are metaluminous to slightly peraluminous, with Alumina Saturation Index (ASI) varying between 0.66 and 1.08 (Fig. 5A). The enclaves analyzed from the Pilõezinhos pluton are all slightly peraluminous.

In the AFM diagram, the granitoids from the Pilõezinhos pluton develop a trend parallel to the AF side of the triangle (Fig. 5B), reflecting crystallization under low fO_2 conditions. This trend is also recorded in the granitoids with similar ages from the central, north domains of the Borborema Province (Galindo, 1993; Guimarães et al., 2008) and in granitoids from eastern Nigeria (Ferré et al., 1998). The granitoids, including the diorite enclaves, from the Curral de Cima pluton show a trend typical of calc-alkaline rock series.

According to Sylvester (1989) the $(A1_2O_3 + CaO)/(FeO_t + Na_2O + K_2O)$ vs. $100(MgO + FeO_t + TiO_2)/SiO_2$ plot (Fig. 5C) is effective in discriminating alkaline granites, calc-alkaline and strongly peraluminous granites. However, it does not discriminate between highly fractionated calc-alkaline granites and "normal" alkaline (A-type). The granitoids of the Pilõezinhos pluton fall in the field of alkaline rocks while the granitoids of the Curral de Cima plot within the calc-alkaline field (Fig. 5C). In the diagram SiO_2 versus MALI (modified alkali lime index - Frost et al., 2001), the Pilõezinhos and Curral de Cima granitoids plot within the alkali-calcic and calc-alkaline rock fields respectively (Fig. 5D).

The Pilõezinhos pluton granitoids display Fe-number ($FeO_t/[FeO_t+MgO]$) close to 0.9, and belong to the Ferroan series of granitoids (Frost et al., 2001) (Fig. 5E), which are commonly associated to magmas that evolved under reducing conditions (low fO_2), generating ilmenite-series granites (Ishihara, 1977). In contrast, the granitoids from the Curral de Cima pluton and mafic enclaves of the Pilõezinhos pluton exhibit Fe-number within the 0.58–0.73 interval, which is typical of the magnesian-series (Fig. 5E).

The granitoids from the Pilõezinhos pluton exhibit negative trends for MgO, FeO, CaO, Na_2O, TiO_2, P_2O_5, Zr, Y, Nb, Sr, Ba and, a strongly positive trend for K_2O e Rb (Fig. 6A-N). Al_2O_3 does not show systematic chemical variation. The recorded trends suggest that crystal fractionation was the major process controlling the magmatic evolution, and that plagioclase, biotite, amphibole, ± ilmenite, ± titanite were the fractionated phases and K-feldspar was not fractionated during magma evolution.

The granitoids of the Curral de Cima pluton exhibit the major elements behavior similar to those recorded in the granitoids from the Pilõezinhos pluton except for their low contents of SiO_2 (64%–68%), K_2O (1.69–3.81%) and higher MgO and Al_2O_3. The granitoids of the Pilõezinhos pluton show higher contents of Ba, Rb, Nb, Zr, Y and similar Sr contents compared to those recorded in the Curral de Cima granitoids for similar SiO_2 contents (Fig. 6I-N).

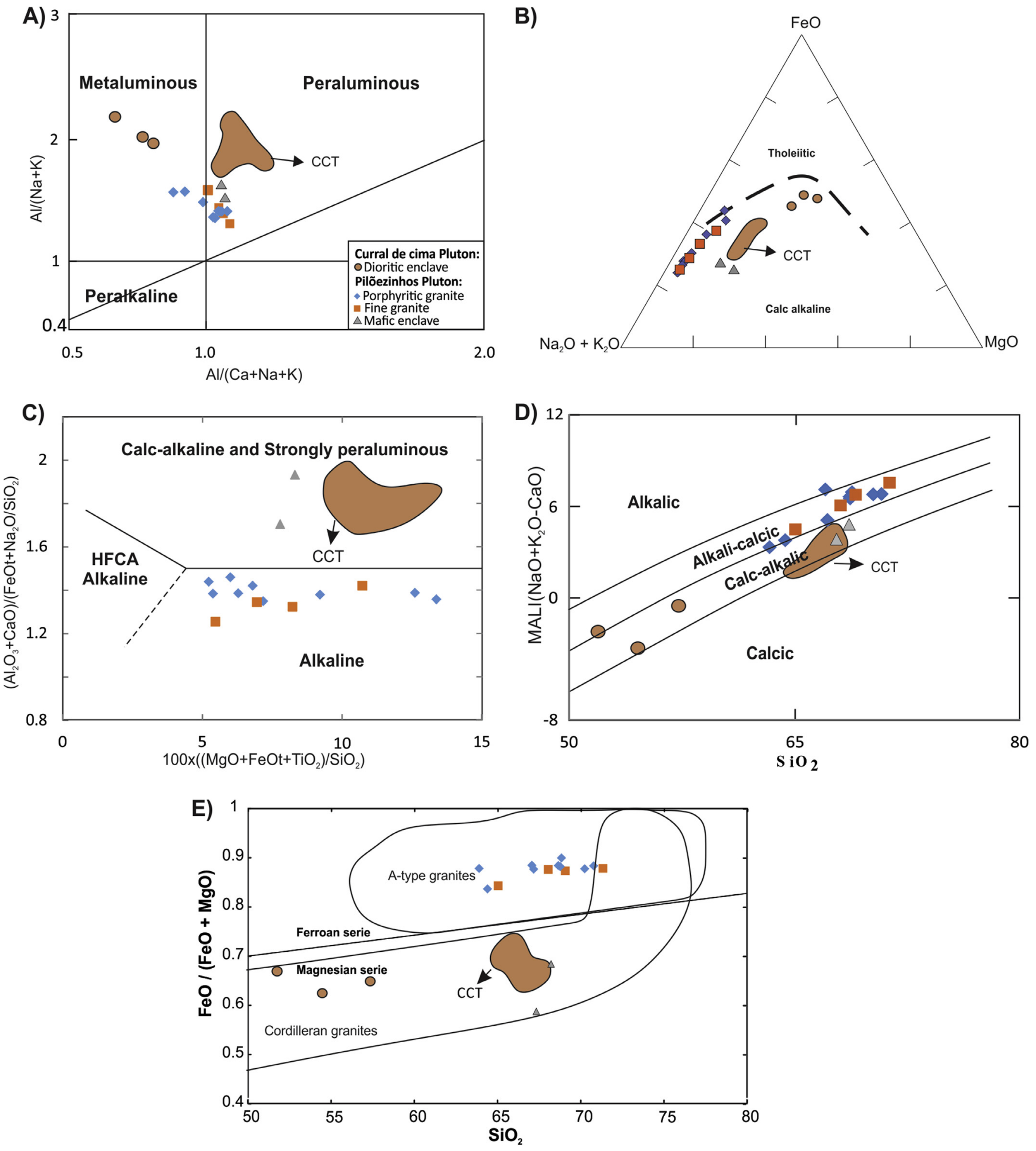

Fig. 5. A) Shand's Index for the studied granitoids; fields after Maniar and Piccoli (1989). B) The studied granitoids in the AFM diagram; fields after Irvine and Baragar (1971). C) The studied granitoids in the $(A1_2O_3 + CaO)/(FeO_t + Na_2O + K_2O)$ vs. $100(MgO + FeO_t + TiO_2)/SiO_2$ diagram from Sylvester (1989). D) SiO_2 x Mali (modified alkali lime index) diagram (Frost and Frost, 2008) for the studied granitoids. E) Studied granitoids in the $FeO_{tot}/(FeO_{tot} + MgO)$ versus weight percent SiO_2 diagram; fields of ferroan and magnesian series from Frost et al. (2001). CCT = Curral de Cima tonalites (data from Ferreira et al., 2011).

Mafic enclaves incorporated by the Pilõezinhos pluton exhibit major and trace elements signatures similar to the tonalites of the Curral de Cima pluton, suggesting that they share similar sources.

The REE patterns (Fig. 7) normalized to the chondrite values of Nakamura (1974) of the granitoids from the Pilõezinhos pluton are fractionated, display $(Ce/Yb)_N$ ratios ranging from 16 to 68 and are characterized by strong negative Eu anomalies, with Eu/Eu* ratios ranging from 0.21 to 0.77, similar to the REE patterns recorded in A-

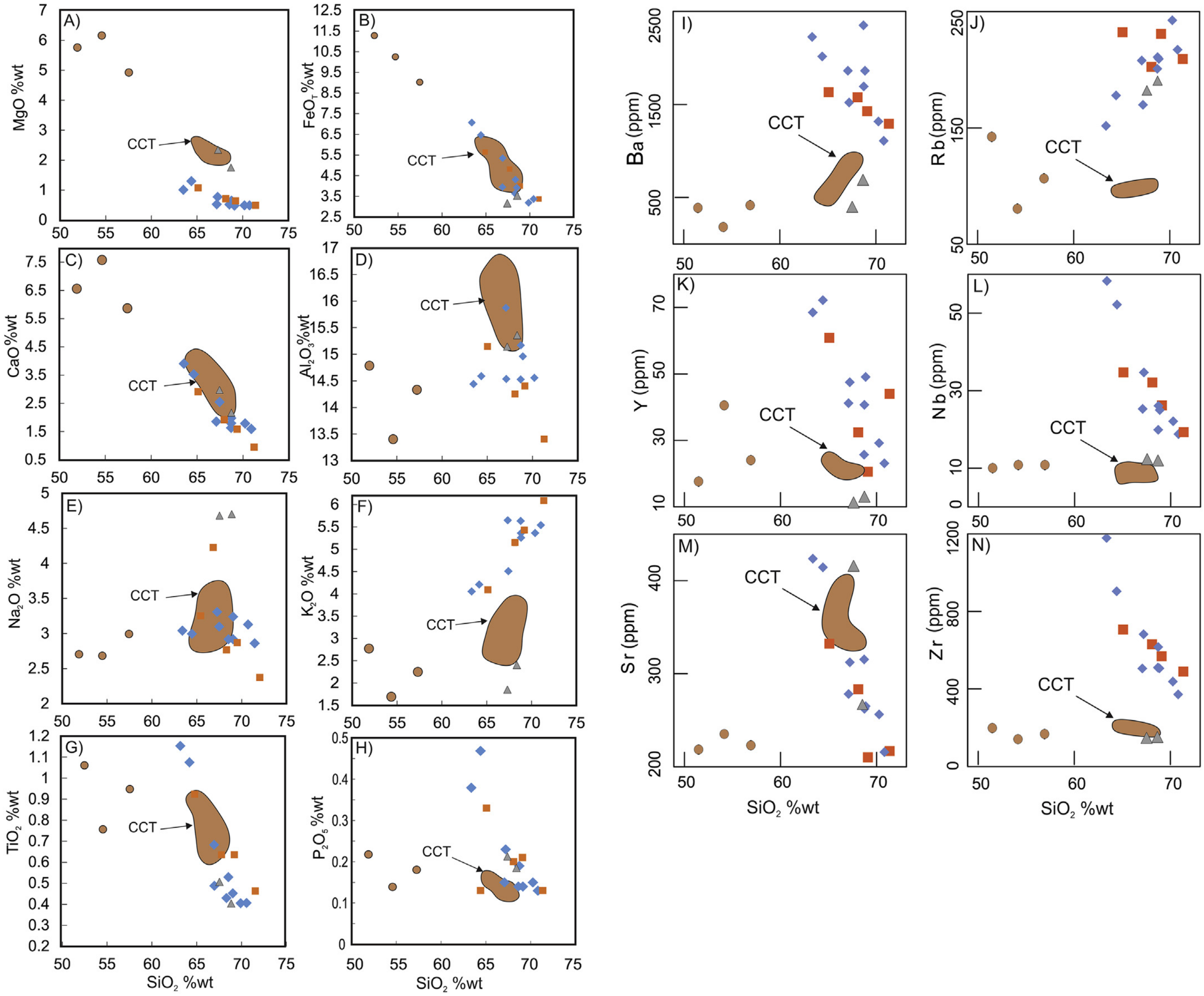

Fig. 6. Variation diagrams for major and trace elements in the studied granitoids. Symbols as in Fig. 5.

type granites. The negative Eu anomalies suggest plagioclase fractionation during magma evolution of the Pilõezinhos granites. In contrast, the tonalites from the Curral de Cima pluton exhibit lower contents of REE and lack significant Eu anomalies (Fig. 7) while their dioritic enclaves display horizontal patterns, with negative Eu anomalies, Eu/Eu* ratios ranging from 0.45 to 0.53, and HREE contents similar to those recorded in the granites of the Pilõezinhos pluton. The enclaves of the Pilõezinhos pluton have REE patterns similar to those recorded in granitoids from Curral de Cima pluton (Fig. 7). Plagioclase fractionation during the evolution of the Pilõezinhos pluton granitoids magma is also suggested by the samples plot in the Sr vs. Rb/Sr diagram (Fig. 8).

Trace element distributions patterns (spidergrams), normalized to the values suggested by Thompson (1982), are characterized by troughs at Ba, Nb, Ta, Sr, P and Ti (Fig. 9). These patterns are typical of alkaline granites, while the patterns of the granitoids from the Curral de Cima pluton are typical of calc-alkaline granitoids (Fig. 9). However, the dioritic enclaves from the Curral de Cima pluton display spidergram patterns similar to the granitoids of the Pilõezinhos pluton, except for smaller troughs at Sr, P and Ti and deeper trough at Ba.

The granitoids of the Pilõezinhos pluton fall in the within plate granites field (WPG), with few of them plotting within the syn-collision (Syn-COLG) + volcanic arc granites (Fig. 10A) in the Y vs Nb diagram (Pearce et al., 1984), and they plot in the post-collisional granites field, but within the WPG (Fig. 10B) side in the (Y + Nb) vs. Rb diagram (Pearce, 1996). The granitoids from the Curral de Cima granitoids plot within the Syn-COLG + VAG and Post-collisional field but within the VAG side of the diagram (Fig. 10B). As pointed out by Pearce (1996), the post-collisional granites are the most difficult to classify, due to some having subduction-like mantle sources and others showing within-plate granite character. Pearce (1996) also emphasized that interaction between mantle-derived sources and crust tends to move the granite composition towards the volcanic arc field. In the Whalen et al. (1987) diagram the granitoids from Pilõezinhos and Curral de Cima plutons plot within the A-type granites and (I,S,M)- type fields respectively (Fig. 10 C and D).

According to Eby (1992), A-type granites with mantle related origin, from anorogenic environments (A_1-type) have Y/Nb ratios of

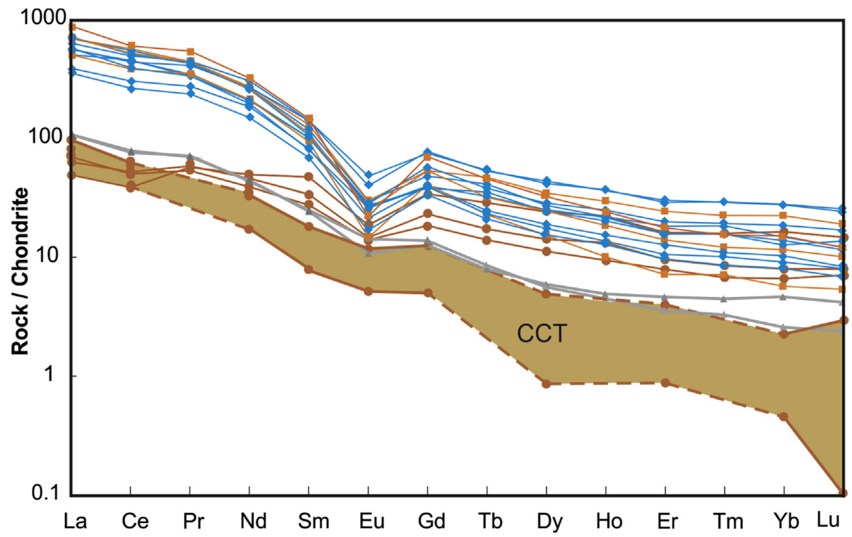

Fig. 7. Chondrite-normalized REE patterns (Nakamura, 1974) of the studied granitoids. Symbols as in Fig. 5.

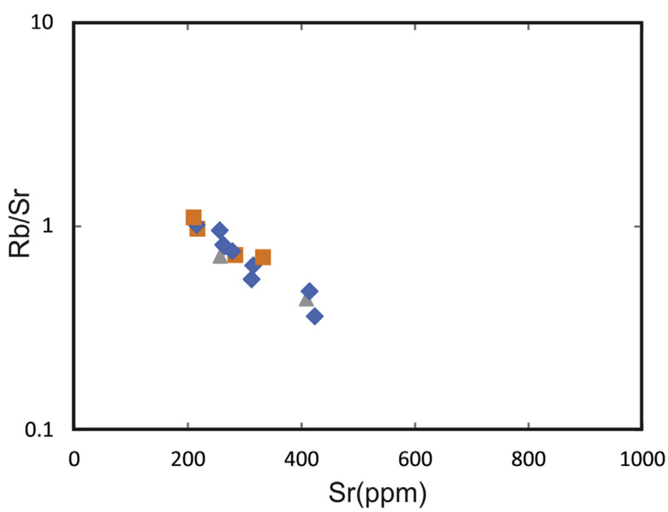

Fig. 8. The studied granitoids plotted in the Sr versus Rb/Sr diagram. Symbols as in Fig. 5.

1.2 (A_2 -type). The granitoids from the Pilõezinhos pluton have Y/Nb ratios >1.2, and plot in the A_2-type granites field of the Eby (1992) diagrams (Fig. 11A), which are distinctive from OIB (Fig. 11B).

4.4. U–Pb zircon dating

Zircon grains were extracted from a sample of the porphyritic facies of the Pilõezinhos granite. They are euhedral to subhedral pale pink crystals, with rare inclusions, usually elongate, prismatic, length/width ratio ranging from 5:1 to 5:3 and show strong oscillatory zoning (Fig. 12A). Inherited cores and overgrowths were not recorded. Eighteen spots were analyzed from twelve grains. All the analyses show variable contents of common Pb, as revealed by the array of data in the Tera-Wasserburg diagram (Fig. 12B). The correction of common Pb followed the method of Compston (1999), fitting the array and considering the lower intercept date as representing the crystallization age. Twelve analyses plotted on the Tera-Wasserburg concordia diagram yielding an age of 566 ± 3Ma (Fig. 12B).

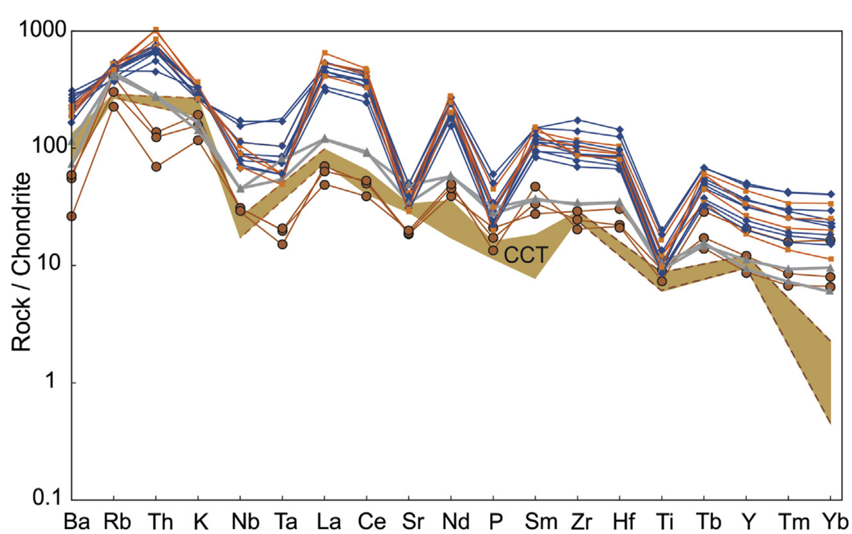

Fig. 9. Chondrite-normalized (Thompson, 1982), trace element abundance diagrams (spidergrams). Symbols as in Fig. 5.

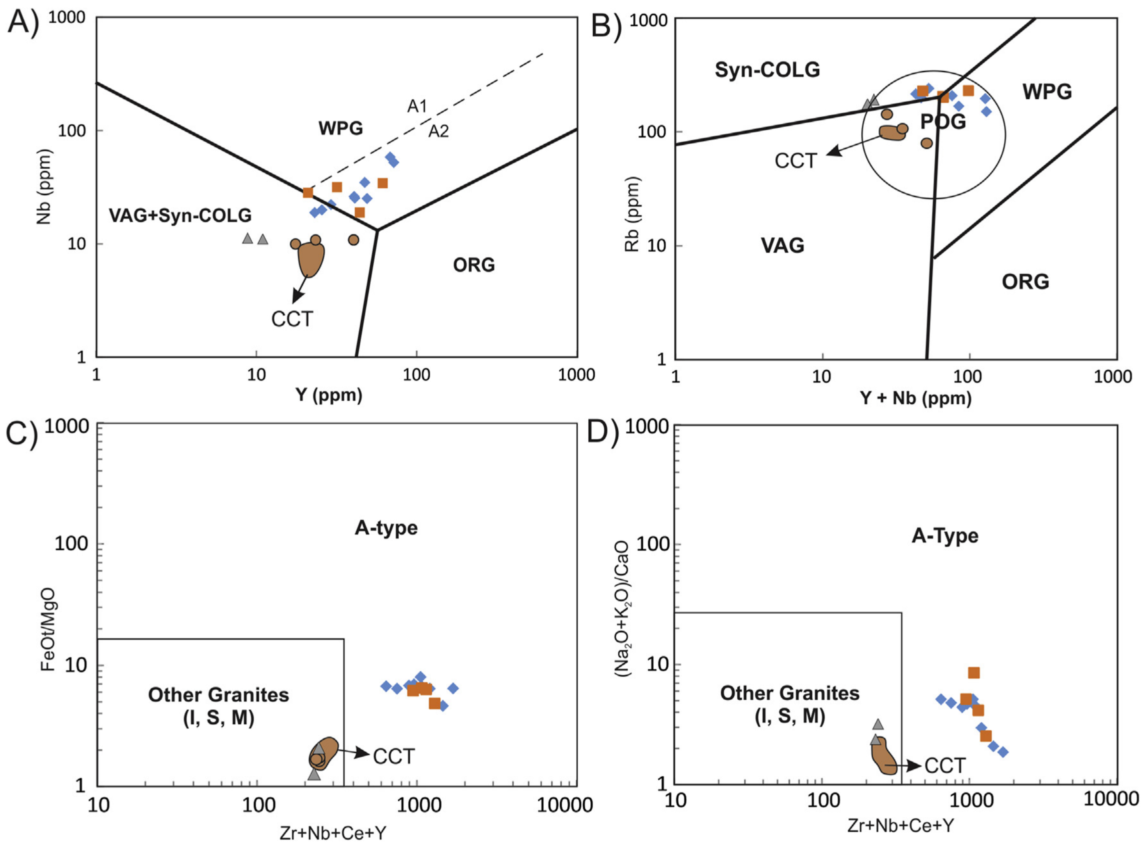

Fig. 10. The studied granitoids plot in the tectonic discriminant diagrams. (A) and (B), fields after Pearce et al. (1984) and Pearce (1996), respectively; (C) and (D), after Whalen et al. (1987). WPG = Within Plate granites; POG= Post-orogenic granites; ORG = Ocean Ridge Granites; VAG = Volcanic Arc Granite. Symbols as in Fig. 5.

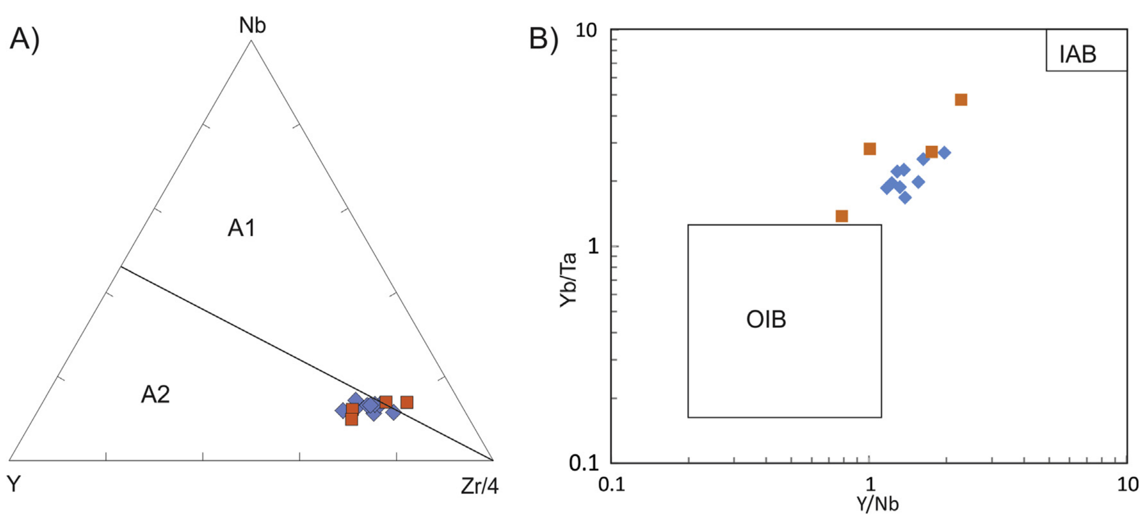

Fig. 11. A) Trace elements for the studied granitoids in the tectonic discriminant diagrams of Eby (1992); B) The studied granitoids in the Y/Nb versus Yb/Ta diagram. OIB = Oceanic Island Basalts; IAB = Island Arc Basalts. Symbols as in Fig. 5.

4.5. Lu–Hf isotopes in zircon

Five zircon grains, the same analyzed for U–Pb, were used to define Lu–Hf isotopic compositions. The results are presented in Table 2 and Fig. 13. The analyzed grains yielded relatively uniform $^{176}Hf/^{177}Hf$ initial ratios, ranging from 0.281898 to 0.281976. They show Paleoproterozoic Hf T_{DM} model ages, varying between 1.74 and 1.86 Ga, and negative εHf (t = 570 Ma) values between −16.0 and −18.6.

4.6. Sm–Nd isotopic systematics

Sm–Nd data were obtained for eight samples from the Pilõezinhos Pluton and one enclave from the Curral de Cima pluton. The results are presented in Table 3 and Fig. 14.

The granitoids of the Pilõezinhos pluton have Sm–Nd (T_{DM})

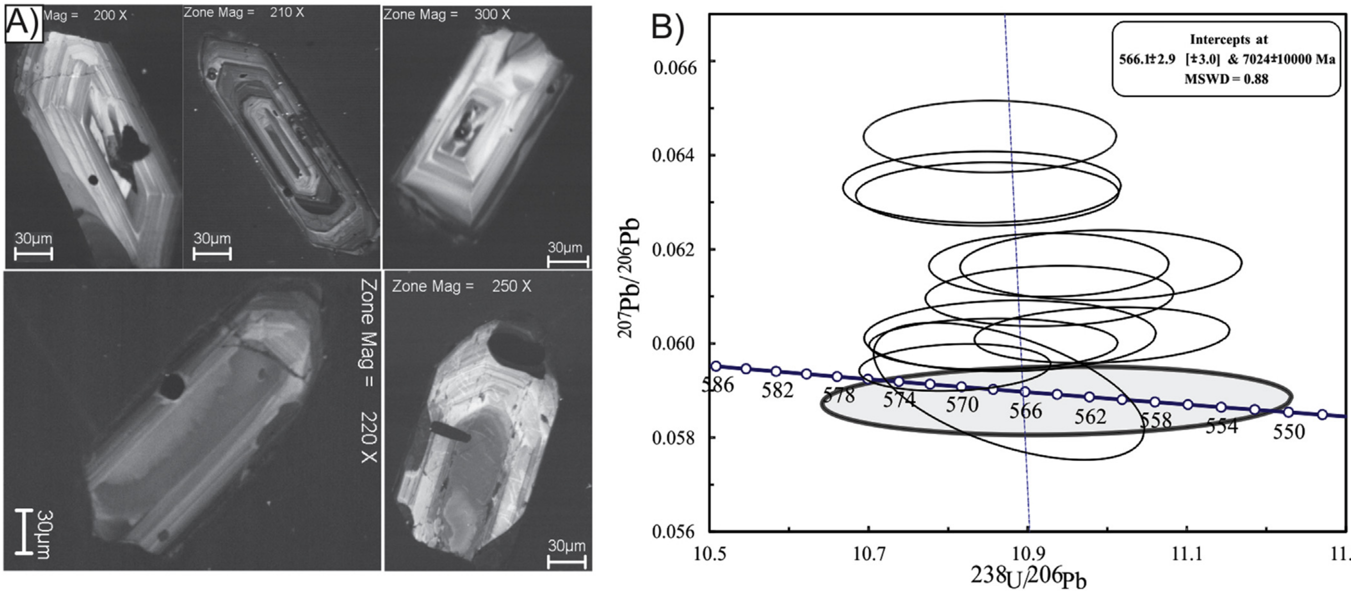

Fig. 12. A) Cathodoluminescence (CL) images showing strong oscillatory zoning in the zircon grains; B) Concordia diagram for a granite sample (PP3) of the Pilõezinhos Pluton.

Table 2
Lu–Hf Isotopic data of the granites from the Pilõezinhos Pluton.

Sample	$^{176}Hf/^{177}Hf$	±2SE	$^{176}Lu/^{177}Hf$	±2SE	$^{176}Hf/^{177}Hf(t)$	εHf(t)	T_{DM} (Ga)
003-Z1	0.2819066	0.000118	0.0007970	4.8E-05	0.281898022	−18.64	1.86
004-Z6	0.2819399	6.66E-05	0.0006494	8.44E-06	0.281933016	−17.52	1.81
005-Z8	0.2819792	9.11E-05	0.0003380	5.1E-06	0.281975627	−16.01	1.74
006-Z9	0.2819287	0.00014	0.0004012	6.57E-06	0.281924446	−17.90	1.81
007-Z14	0.2819138	0.000135	0.0004367	2.45E-05	0.281909071	−18.23	1.83

Table 3
Sm–Nd Isotopic data of the granites and one enclave from the Pilõezinhos Pluton (PP) and diorite from the Curral de Cima Pluton (CCP).

Sample	($^{147}Sm/^{144}Nd$)	($^{143}Nd/^{144}Nd$)i	εNd(T)	T_{DM}
PP2	0.0906	0.511099	−15.81	2.030
PP3	0.0921	0.511116	−15.47	2.026
PP4	0.0898	0.511114	−15.52	2.003
PP7	0.0940	0.511132	−15.17	2.031
PP8	0.0848	0.511105	−15.69	1.961
PP9B	0.1089	0.511812	−1.88	1.293
PP12	0.0828	0.511142	−14.98	1.900
PP21	0.0907	0.511154	−14.73	1.967
CCP4	0.1340	0.511851	−1.12	1.438

model ages, calculated with respect to the depleted mantle average in the 1.9–2.03 Ga range, and εNd (at 570 Ma) ranging from −14.73 to −15.81 (Fig. 14). These values are identical to many other granite intrusions in the Serrinha–Pedro Velho Complex (Japi Pluton, Hollanda et al., 2003; Solânea and dona Inês plutons – Guimarães et al., 2008) and from eastern Nigeria (Dada et al., 1995; Ferré et al., 1998).

The Sm–Nd model ages recorded in the Pilõezinhos granitoids are close to a granulite metamorphic event of 2.2 Ga in the Rio Grande do Norte domain (Dantas, 1997) and also in the correlative pre-drift basement of Nigeria (Bertrand et al., 1986; Dada, 1998) and north-central Cameroon (Toteu et al., 1991). A major calc-alkaline magmatic event with similar ages in the same time span (2.15–2.2 Ga) has been described in the Rio Grande do Norte domain (Dantas, 1997; Souza et al., 2016) and in the Transversal subprovince (Neves et al., 2015).

The Sm–Nd data presented by Ferreira et al. (2011) for the granitoids of the Curral de Cima pluton show higher εNd(at 600 Ma) values (−1.12 to −5.23) and Mesoproterozoic T_{DM} model ages (1.38–1.50 Ga). One mafic enclave hosted by the granitoids from the Pilõezinhos pluton show εNd value (−1.88) and T_{DM} model age (1.29 Ga) similar to those reported by Ferreira et al. (2011) for the granitoids of the Curral de Cima pluton. The granitoids of the Curral de Cima pluton have Sm–Nd isotope signatures similar to the so-called Conceição-type granitoids of Almeida et al. (1967), within the Transversal subprovince (Sial, 1990; McReath et al., 1998; Guimarães et al., 2004, 2011; Long et al., 2005).

The Paleoproterozoic basement, orthogneisses/migmatites of the so called Serrinha - Pedro Velho Complex, crop out just north of the Remígio - Pocinhos shear zone, have εNd (at 2.0 Ga) values varying from −17.73 to − 26.47, and T_{DM} model ages between 2.0 and 2.6 Ga (Van Schmus et al., 1995; 2003, 2011; Dantas et al., 2004). In the east part of the Transversal domain, Neves et al. (2015) suggest that island arc formation took place around 2.2 Ga, leading to a volcanic arc edifice by 2.13–2.10 Ga.

The Nd evolution paths for the granitoids (Fig. 14), including the mafic enclave, of the Pilõezinhos pluton are intermediate between those of the Serrinha Pedro Velho Complex and the granitoids from the Curral de Cima pluton. It suggests that the magma source of the Pilõezinhos granitoids involved components with Nd isotopic signatures similar to the Paleoproterozoic basement and granitoids of the Curral de Cima pluton.

5. Discussion

The granitoids from the Pilõezinhos pluton show many features

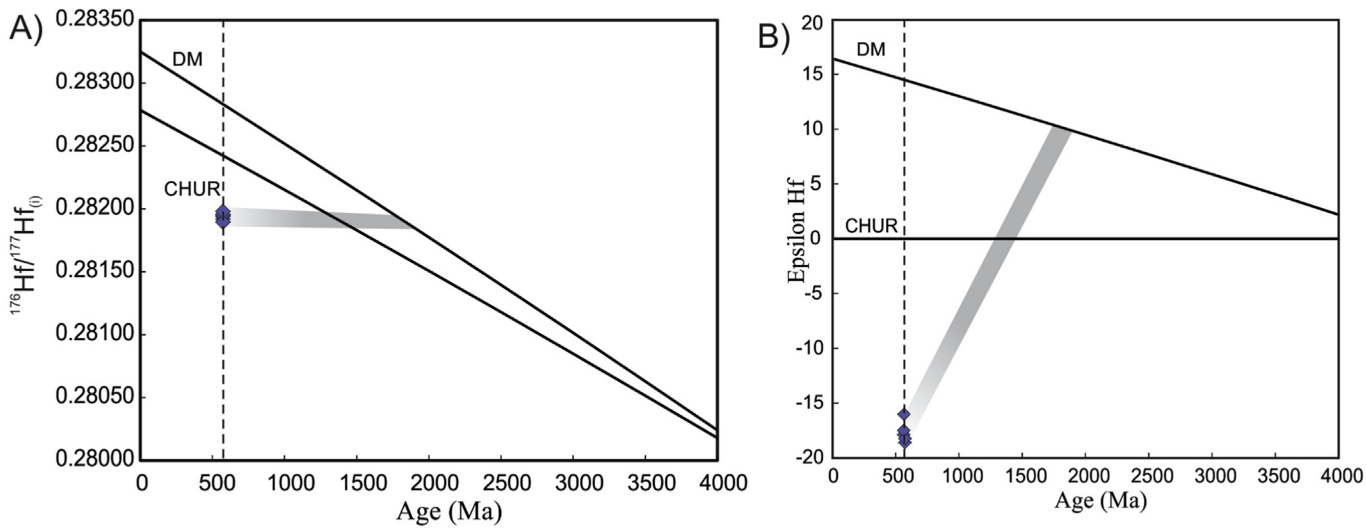

Fig. 13. A) Isotopic evolution of Hf for zircon crystals from the Pilõezinhos pluton sample; B) Epsilon Hf(t) plots for zircon grains from granite sample of the Pilõezinhos Pluton.

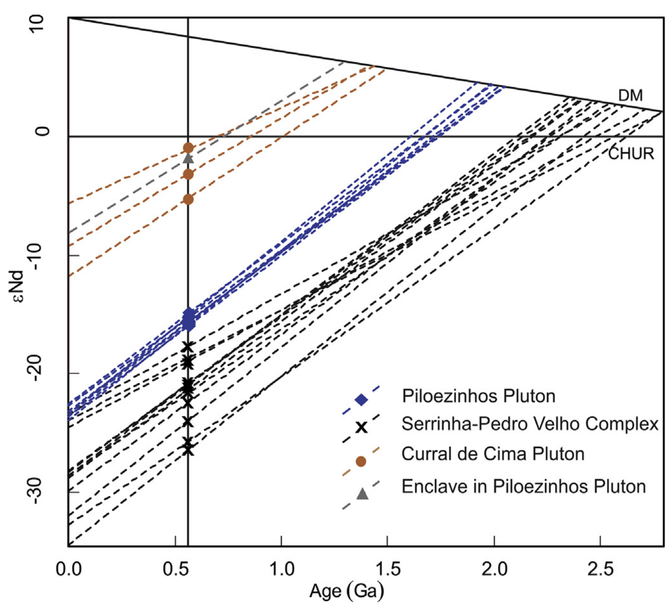

Fig. 14. Nd isotopic composition of the studied granitoids, the Curral de Cima granitoids (Ferreira et al., 2011) and orthogneisses from Serrinha-Pedro Velho Complex (Dantas et al., 1998). Isotopic notations, model ages and reference mantle reservoirs are from De Paolo (1988).

of A-type granites (Loiselle and Wones, 1979; Whalen et al., 1987) i.e., they have high-Fe mafic phases, high contents of total alkalis (K_2O +Na_2O) and high Fe# values, low CaO, high F content, high REE, HFSE and trace elements, in general, compatible with magmas generated in extensional setting. Their REE patterns are characterized by strong negative Eu anomalies, which are features reported in A-type granites. On the other hand, the granitoids from the Curral de Cima pluton have geochemical signature typical of I-type calc-alkaline granitoids (Ferreira et al., 2011). The Pilõezinhos and Curral de Cima plutons are in contact and were intruded along the Remígio - Pocinhos shear zone.

A-type granitoids were defined by Loiselle and Wones (1979). They are granitoids emplaced in extensional environment, i.e., post-collisional or within plate settings, and the magma generated by the melting of a lithospheric source from which a previous melt had been extracted, or by differentiation of a basalt magma. Geochemically they are characterized by high total alkalis, halogens, particularly high F, high FeO/MgO ratios and lower CaO, compared to I— and S-types. Their mineralogy is characterized by iron-rich mafic silicates or alkali-rich mafic silicates in peralkaline suites. A-type granites probably result mainly from partial melting.

According to Eby (1992), A-type granites are divided into two groups: 1) granites resulted from differentiation of basalt magma derived from an OIB-like source (A_1-type) associated with anorogenic settings, and 2) granites derived from the subcontinental lithosphere or lower crust, often emplaced in post-collisonal or postorogenic settings (A_2-type).

The granitoids of Pilõezinhos pluton show many geochemical and mineralogy characteristics of A_2-type, post-collisional, alkaline, ferro-potassic granites which correspond to the aluminous A-type granites of King et al. (1997). Magmatism with such geochemical signature and crystallization age has been reported in the Rio Grande do Norte domain, the Solânea Complex (Guimarães et al., 2009), just north of the Pilõezinhos intrusion, associated to the splay of the Remígio - Pocinhos shear zone; within the Transversal subprovince, along the E-W trending dextral, Coxixola Timbaúba shear zone, the Marinho pluton (Guimarães et al., 2015). In pre-drift reconstruction of Pan-African and Brasiliano terranes (Castaing et al., 1994), the Remígio-Pocinhos shear zone continues in Africa as the Central Cameroon and Adamaoua shear zones. In the central domain of Cameroon Pan-African fold belt, along the Central Cameroon shear zone (Fig. 2), Nzina et al. (2010) report synkinematic ferro-potassic magmatism. However, geochronological data are not available. Granitic magmatism with similar geochemical signature and age is reported in eastern Nigeria by Ferré et al. (1998).

5.1. Origin of the Pilõezinhos Pluton

The Pilõezinhos granitoids show many mineralogical and geochemical characteristics of A-type granitoids. The geochemical and mineralogical varieties of the A-type suites are due to the distinct geotectonic settings in which the A-type granitoids are intruded. They have been recorded within continents and ocean floor (Bonin, 2007). The Pilõezinhos pluton granitoids are A_2-type and intruded during a post-collisional stage of the Brasiliano/Pan-African Orogeny, associated to transcurrence. Similar A-type intrusions are reported in Algeria (Taourirt – Hoggar, suite -Azzouni-Sekkal et al., 2003), Mali (Adrar des Iforas, - Liégeois and Black, 1984), Post-kinematic suite of Finland (Nironen et al., 2000), Provincia Borborema, Brazil (Bravo Pluton - Lages et al., 2016; Solanea Pluton, Guimarães et al., 2009).

Many petrogenetic models have been proposed for the source of A-type granites. Partial melting of F and/or Cl enriched dry, lower crust granulitic residue resulting from previous extraction of orogenic granite (I-type calc-alkaline magmas) was proposed as the origin of the A-type granites by many authors (Collins et al.,1982; Clemens et al.,1986; Whalen et al.,1987). However, alkali feldspar and biotite cannot be residual phases during the generation of I-type magmas from partial melting of basaltic to tonalitic source (Rutter and Wyllie, 1988), because biotite and alkali feldspar have melting temperatures lower than those necessary to melt hornblende. Magmas produced from such residue have low SiO_2 and K_2O contents (Rudnick and Taylor, 1987), which are characteristics distinct from those recorded in the Pilõezinhos pluton.

Melting experiments on biotite- and amphibole-bearing tonalitic gneisses at 10 kbar (Skjerlie and Johnston, 1992) produced a granulitic residue and F-rich granitic melt chemically similar to A-type granites, except for lower SiO_2 and slightly higher Al_2O_3 contents. This model does not require a previous melting event, dehydroxylation (OH↔F) of the source biotite is sufficient. The presence of F-rich biotite and amphibole in the granitoids of the Pilõezinhos pluton and their lower SiO_2 contents, compared to those recorded in typical felsic A-type (>74 %wt) granites (Whalen et al., 1987) could support their crystallization from F-rich melt.

The Nd and Hf isotopic signatures favor the generation of the Pilõezinhos granitoids magma by melting of a Paleoproterozoic felsic lower crust, similar to the tonalitic gneisses described by Dantas (1997).

However, the younger Hf T_{DM} model ages and εNd values slightly higher than those recorded in the Palaeoproterozoic tonalitic gneisses of the Serrinha Pedro Velho Complex suggest that the source of the Pilõezinhos granitoids magma also involved a younger component. This younger component could be associated to mafic magma input in the lower crust during extension, which can also be the heat source required for the partial melting. Halogen-rich fluids from the mantle (Bayley, 1980) can respond for the F-rich mafic phases recorded in the granitoids from the Pilõezinhos pluton. The Pilõezinhos granitoids plot in the field of infracrustal source in the La/Nb versus Th/Nb diagram (Fig. 15) with fields after Planck (2005).

Viscosities of fluorine-bearing aluminosilicate melts are temperature dependent. The viscosity decreases as the fluorine and SiO_2 content increase, and also by the melt depolymerization caused by replacement of Si–O-(Si,Al) bridges with Si–F bonds (Dingwell et al., 1985). High-F content during melting processes promotes a complexing effect (Collins et al., 1982), generating melting with high contents of HFSE, mainly Zr, Nb and Y and REE. High temperatures (>900 °C) can also respond for high HFSE and REE recorded in A-type granites. The high Ga/Al ratios recorded in the Pilõezinhos granitoids and in many A-type suites are also explained by the presence of F. During melting in the presence of F, Ga forms stable octahedrons (GaF_6^{3-}) while Al forms stable octahedrons AlF^{3-} only in SiO_2 saturated melts (Cotton and Wilkinson, 1980; Manning et al., 1980).

According to Cocherie (1986), the projection of Rb versus Ba, Sr, Sm and La can indicate the process involved in the magma evolution. If the partial melting dominates the samples plot according to a curve of low inclination while fractional crystallization favors the samples plotting according to high angle negative trends. The granitoids of the Pilõezinhos pluton show strong negative correlation in the Rb versus Ba, Sr, Sm and La diagrams (Fig. 16), suggesting that fractional crystallization was the dominant process during the Pilõezinhos granitoids magma evolution. The Harker diagrams (Fig. 6) associated to the spidergram patterns (Fig. 9) suggest that the fractional crystallization involved plagioclase, amphibole, titanite, allanite, ilmenite and apatite fractionation.

The Pilõezinhos granitoids were crystallized under temperatures varying from 745 to 1003 °C, and pressures of 4.28–5.95 kbar, which correspond to depth of ~15–20 km, close to the brittle/ductile transition, i.e., upper part of the medium crust (Bonin, 2007). High temperature, associated to high-F and Cl contents, promoted the fractionation processes and lowered the magma viscosity (Dingwell and Mysen, 1985).

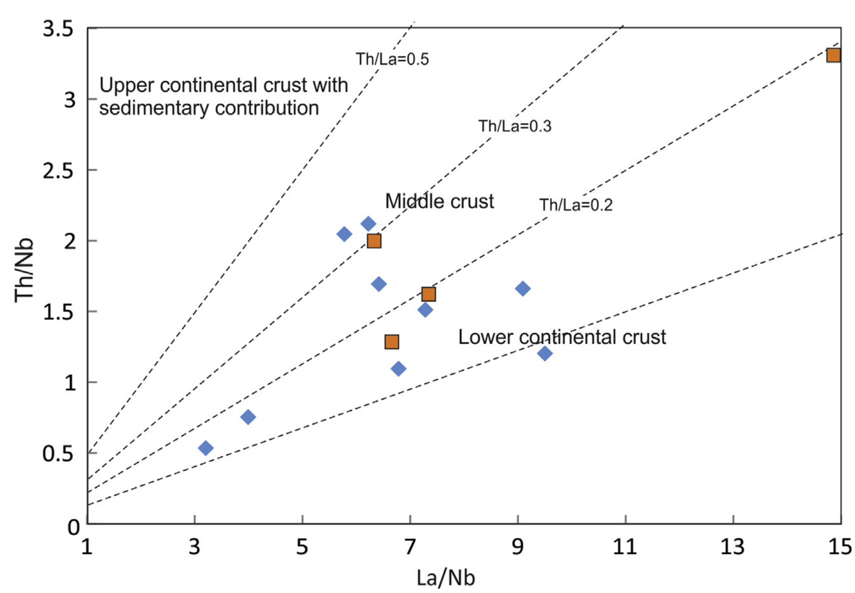

Fig. 15. The studied granitoids plotted in the La/Nb versus Th/Nb diagram; fields after Planck (2005). Symbols as in Fig. 5.

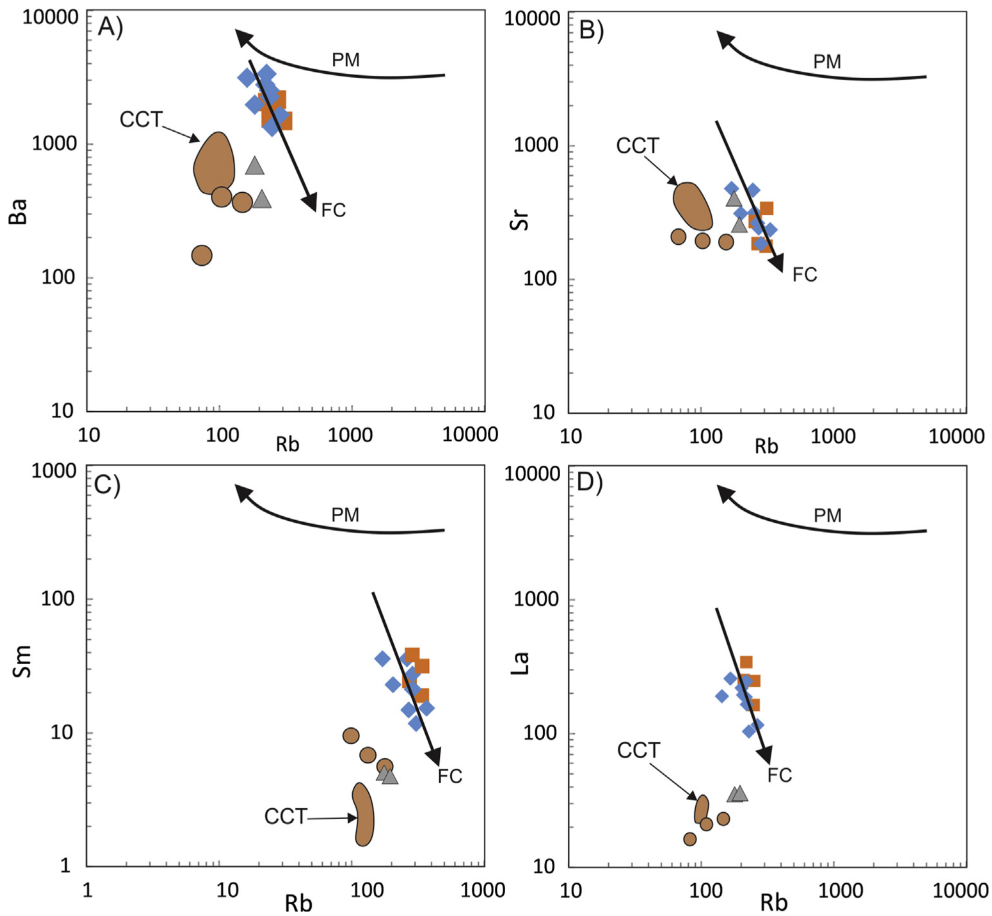

Fig. 16. The studied granitoids in the Rb versus Ba, Sr, Sm, La diagrams. PM = Partial melting; FC = Fractional crystallization. Symbols as in Fig. 5.

5.2. *Origin of the Curral de Cima Pluton*

The granitoids of the Curral de Cima pluton are magnesian, epidote bearing, I-type, calc alkaline granitoids (Ferreira et al., 2011). They show εNd values close to the reference values of the CHUR (εNd = 0), suggesting a strong juvenile component in their source.

Amphibole-rich enclaves are widespread within the Curral de Cima pluton and were interpreted by Ferreira et al. (2011) as source rock (metabasalt) fragments. The granitoids of the Curral de Cima pluton show $\delta^{18}O$ (average of 9.7‰) values within the intervals suggested by O'Neil et al. (1977) for granitoids generated by melting of igneous sources ($\delta^{18}O$ values up to 10‰). However, Ferreira et al. (2011) suggested that the $\delta^{18}O$ values are higher than those reported for the source of I-type granites, and suggest that partial melting of a previous hydrothermally altered metabasaltic source formed the Curral de Cima magma.

Other plutons with similar ages, geochemical and isotope signatures are reported in the Transversal (Sial, 1990; Guimarães et al., 2004, 2011) and South (Long et al., 2005; McReath et al., 1998) subprovinces.

We favor the hypothesis that the Curral de Cima granitoids magma was originated from a mixed source, involving partial melting of the lower crust due to basalt underplating associated to decompression during the compressive stage of the Brasiliano/PanAfrican Orogeny. The underplated basalt was the juvenile component involved in the magma source of the Curral de Cima granitoids, explaining in this way, the higher εNd compared to those recorded in the granitoids of the Pilõezinhos pluton.

5.3. *Tectonic model*

The Curral de Cima pluton intrusion is coeval with a flat-lying foliation event (630- 600 Ma) in the region (Guimarães et al., 2004, 2011; Archanjo et al., 2008; Archanjo and Fetter, 2004), associated to the compressive stage of the Brasiliano Orogeny. However, flat-lying foliation as recorded in other intrusions with ages in the same time spam is not recorded in the Curral de Cima pluton. The NE trending of the Remígio - Pocinhos shear zone, associated to crystallization age of the Curral de Cima granitoids and the NW-SE trend of the Brasiliano/Pan-African orogeny contractional structure (Neves et al., 2006) favor the hypothesis that the Remígio-Pocinhos shear zone represents a lateral escape of the Brasiliano/Pan-African orogeny compressive stage 620 Ma ago. The transtension gives way to the decompressional melting of the lithosphere mantle or possibly the asthenosphere. The Paleoproterozoic subduction-related metasomatic signature of the lithosphere mantle beneath the Borborema Province (Guimarães and Silva Filho, 1995; Guimarães et al., 2004; Hollanda et al., 2003; among others) associated to the Nd signatures reported by Ferreira et al. (2011), favor the decompression melting of the asthenosphere. The mantle melts rise to the lower crust promoting partial melting and mingling/mixing with the created crustal melts and rose to the mid-to upper-crustal levels (~15 km) were complete where the crystallization was completed under high fO_2 conditions. A cartoon explaining this model is shown in Fig. 17.

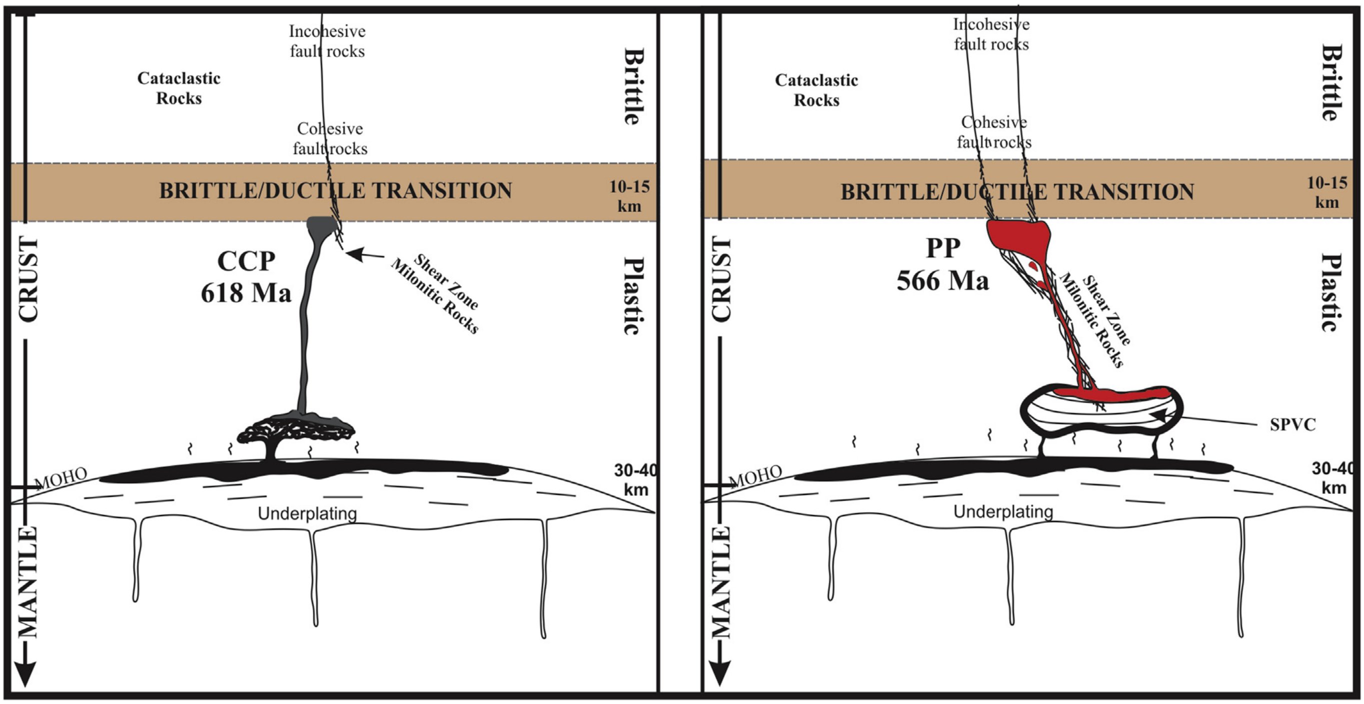

Fig. 17. Cartoon explaining the evolution model of the: (A) Curral de Cima Pluton, and (B) Pilõzinhos plutons. CCP: Curral de Cima Pluton; PP: Pilõezinhos Pluton; SPVC: Serrinha Pedro-Velho Complex.

Neves et al. (2005) and Neves et al. (2012) dated the beginning of the transcurrent regime in the Transversal subprovince at ca. 590 Ma. A HT/LP, ca. 575 Ma, post-collisional metamorphic event was recorded in the Seridó Belt of the Rio Grande do Norte domain, and in Igarra and Ilesha schist belts in south Nigeria (Archanjo et al. (2013). This event is not recorded in the Transversal and Southern subprovinces. There, the peak of high-T metamorphic conditions occurred at ca. 620 Ma.

Viegas et al. (2014) identified a 560–565 Ma high temperature metamorphic event, along the Patos shear zone, associated to anatexis, and postdating the peak of metamorphic event in the Seridó Belt. According to Viegas et al. (2014), this high − T metamorphism can be associated to localized deformation, that kept the mylonites under high temperatures after the peak of metamorphic conditions of the Seridó Belt or it represents a new shear deformation event under high temperature. The intrusion of the Pilõezinhos pluton (566 ± 3 Ma) coeval with the high-T reported by Viegas et al. (2014) suggests that the Pilõezinhos pluton was intruded during a later high-T deformation event, which reactivated the Remígio-Pocinhos and Matinhas shear zones after the peak of the high-T metamorphic event in the Seridó Belt.

The Nd and Hf isotope signatures associated to the geochemical signature strongly suggest that the magma source of the Pilõezinhos granitoids involved a dominant Paleoproterozoic crustal component of tonalite to granodiorite composition. The εNd values slightly lower than those recorded in the basement orthogneisses and also the presence of small and rare mafic enclaves showing higher εNd compared to the country granites and similar to the values recorded in the granitoids from the Curral de Cima pluton suggest small participation of a younger component in the magma source of the Pilõezinhos granitoids.

It is likely that mantle melts rising into the crust, through deep seated shear zone, promoting melting of the lower crust, but without extensive mixing/mingling processes. The high-halogens (F, Cl) contents in the magma, associated to the high-T liquidus, allowed the magma to rise up to mid-, upper-crustal levels, changing the composition through fractionation processes, where it finally crystallized.

6. Conclusions

On the basis of geochronological, geochemical and Nd − Hf isotopic data, the following conclusions can be drawn, regarding the origin and tectonic setting of the granitic intrusions along the east part of the Remígio-Pocinhos shear zone:

1) The granitoids of the Curral de Cima pluton were generated by magma mixing/mingling processes between crustal and a significant mantle melt generated by decompression (lateral escape) during the compressive regime of the Brasiliano Orogeny (618 ± 4 Ma).
2) The granitoids of the Pilõezinhos pluton were generated by melting of a source similar in composition to orthogneisses of the Serrinha Pedro Velho Complex, with small contribution of a mantle component, during a high-T deformation event at 566 Ma ago, that reactivated the Matinhas and Remígio-Pocinhos shear zones. The synchronic movement of the dextral Remígio-Pocinhos and sinistral Matinhas shear zones created an extensional site, allowing the magma of the Pilõezinhos granitoids to rise up to the upper middle crust, evolving through fractional crystallization, where it finally crystallized.
3) The similar crystallization ages, geochemical and isotopic signatures recorded among the granitoids of the Pilõezinhos pluton, Solânea Complex from the Rio Grande do Norte domain, granitoids from eastern Nigeria and Central Cameroon, suggest an extensive high-T transtensional deformation event. Their emplacement followed the peak of a high-T metamorphic event of the Seridó Belt, during the Gondwana consolidation.

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