

GRANITOIDS MARKING THE END OF THE BRASILIANO (PAN - AFRICAN) OROGENY WITHIN THE CENTRAL TECTONIC DOMAIN OF THE BORBOREMA PROVINCE

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ABSTRACT The studied syenogranite and granodiorite intrusions have a similar U-Pb zircon age (*ca* 570 Ma). They are intruded in the Central Tectonic Domain of the Borborema Province, forming an S-type belt in relation to the Patos and Pernambuco Lineaments. The studied granitoids are clinopyroxene biotite leuco-syenogranites of the Solidão Pluton; amphibole biotite syenogranites from the Queimadas Pluton; biotite granodiorite and amphibole biotite granodiorite, which occur as dikes cutting the Itapetim Complex and leuco-syenogranites from the Serra Branca Pluton. They show geochemical data transitional between shoshonitic and alkaline series. Deep troughs at Nb, Sr, P and Ti and high LILE/HFSE ratios characterize the spiderdiagram patterns. The ϵ_{Nd} (0.6 Ga) values are extremely negative (-11 to -16; except for the Itapetim dykes \sim -3) and Nd model ages (T_{DM}) range from 2.0 Ga to 2.5 Ga (the Itapetim dykes \sim 1.4Ga). Biotites of the studied granitoids are Fe-rich with Fe/(Fe+Mg) ratios in the 0.62 to 0.84 range. Biotites from older granitoids (640 Ma - 580 Ma) of the Pajeú - Paraíba Terrane, have Fe/(Fe+Mg) ratios < 0.60. The isotopic and geochemical data suggest that the studied granitoids correspond to a *trans*-alkaline, ferro-potassic plutonism, originated by partial melting of Paleoproterozoic and Mesoproterozoic crusts, emplaced during the final stage of the Brasiliano Orogeny in the Central Tectonic Domain of the Borborema Province.

Keywords: granites, Brasiliano, post-collision

INTRODUCTION The principal magmatic feature of the Brasiliano in the Borborema Province, Northeastern, Brazil, is a large number of granitic intrusions coeval with the development of continental-scale transcurrent shear zones and high-grade metamorphism (Vauchez *et al.* 1995). Geochronological data indicated a long period of granitic magmatism within the Borborema Province, during the Brasiliano Orogeny: 640Ma - 520Ma (Guimarães *et al.* 1998, Da Silva Filho *et al.* 1997).

In the past few years, we have been investigating granitoids from the Pajeú Paraíba Belt, Central Tectonic Domain (CTD) of the Borborema Province and here, we summarize the field features geochemical and isotopic data of granitoids that form an S-type belt between the Patos Lineament (North) and Pernambuco Lineament (South).

REGIONAL SETTING The Borborema Province represents one of the Neoproterozoic collisional belts of Gondwana that may have evolved in two-stages during the Pan-African / Brasiliano Orogeny: 750-660Ma and 650-580Ma (Liégeois *et al.* 1994). However, the precise timing of the Brasiliano Orogeny is poorly constrained.

The evolution of the Borborema Province has been described in the last few years, as a collage of terranes during different orogenic events (Santos 1995, Medeiros *et al.* 1997). According to Santos *et al.* (1997), the collage of terranes in the CTD occurred in two orogenic events: Cariris Velhos- Kibaran (1.1 - 0.95Ga) and Brasiliano - Pan-African (0.75-0.57Ga). Within the so-called Pajeú-Paraíba Belt (Brito Neves 1983), which is part of the CTD, Santos (1995) and Medeiros *et al.* (1997) recognized three distinct terranes: The Alto Moxotó Terrane (AMT), Alto Pajeú Terrane (APT) and Rio Capibaribe Terrane (RCT). The studied granitoids are located in the APT and AMT.

PETROGRAPHIC AND FIELD CONSIDERATIONS The **Queimadas Pluton** is an elongated intrusion cropping out in an area of about 50Km². It has been interpreted as a megadike deformed under high temperature conditions (Almeida 1999). Later transcurrent shear zones (N60E) cut the intrusion giving a megaboudin shape to the body. Petrographically, it is very monotonous, consisting of coarse-grained leucocratic monzogranites to granodiorites, which contains rare small mafic enclaves. The main mafic phase is biotite (2%). Small modal volume of amphibole (< 1%) was recorded. The accessory phases are sphene, allanite, apatite, zircon and opaques.

The **Serra Branca Pluton** is an approximately 300Km² E-W elongated pluton, which intrudes mainly gneisses and migmatites (including mylonites) of possible Archean age. It is bounded in the south by the E-W Coxixola transcurrent dextral Shear Zone. It is composed of fine-grained gray biotite leuco-syeno to monzogranites showing banded flow structures and near solid state foliation, suggesting that the emplacement of this pluton involved distinct

batches of magmas during shearing. Biotite is the only major mafic phase and occurs as isolate flakes or, as oriented clots, following the magmatic flux direction. It constitutes less than 10% of the mode. The accessory minerals are allanite sometimes showing epidote rims, zircon and apatite.

The **Solidão Pluton** is a 250km² pluton, intruded into sillimanite bearing biotite-gneiss, locally migmatized, and is associated to the Solidão transcurrent dextral shear zone (Araújo *et al.* 1996). It is constituted by medium to coarse-grained monzogranites to granodiorites. The main mafic phases (\sim 10 % of the mode) are clinopyroxene (salite) and amphibole. Biotite constitutes less than 2% of the mode. The accessory phases are allanite, sphene, zircon and apatite.

The **Itapetim late dykes** are medium-grained granodiorite, which crosscut the porphyritic monzogranite and the country rocks of the Itapetim Complex (Guimarães & Silva Filho 2000), corresponding to the Itapetim-type granite described by Almeida *et al.* (1967). Widths range from centimeters to dozens of meters. Most of the dikes occupy brittle fractures. Banded flow magmatic structures are common. The granodiorites can be divided into two sub-facies: biotite granodiorite and amphibole-biotite granodiorite. The most abundant mafic mineral is biotite (< 15%). Sphene, epidote, apatite and zircon are the accessory phases.

GEOCHRONOLOGY AND Sm - Nd DATA U/Pb zircon analysis for the Solidão, Queimadas and Serra Branca Plutons were performed in the Isotope Geochemistry Laboratories-Kansas University - USA, following the methodology described by Van Schmus *et al.* (1995).

Four zircon fractions from the Solidão Pluton give a minimum age of 572 \pm 21 Ma. (Fig. 2A). There is a large inherited component present in the rock that has a minimum age of 2.1 \pm 62 Ga. These results are similar to those recorded by Kozuch *et al.* (1997). The minimum age of the inherited component is similar to the Sm-Nd TDM ages recorded in the Solidão granitoids (2.07 to 2.14 Ga)

Four zircon fractions from the Queimadas Pluton give an upper intercept age of 570 \pm 24 Ma (Fig. 2B) when the lower intercept is forced to zero. The Queimadas granitoids have Sm-Nd TDM ages similar to those recorded in the Solidão granitoids (2.04 - 2.17Ga.)

The Serra Branca granitoids contain zircons which give an age of 575 \pm 16 Ma. These granitoids show Sm-Nd TDM ages higher (2.3 to 2.5 Ga) than those recorded in the Solidão and Queimadas Plutons. It suggests that an Archean component may have been involved in the source of the Serra Branca granitoids.

Geochronological data are not available for the Itapetim dikes. However, the field relationships, mineral chemistry and whole rock geochemistry, suggest that they are co-magmatic with the *ca* 570Ma

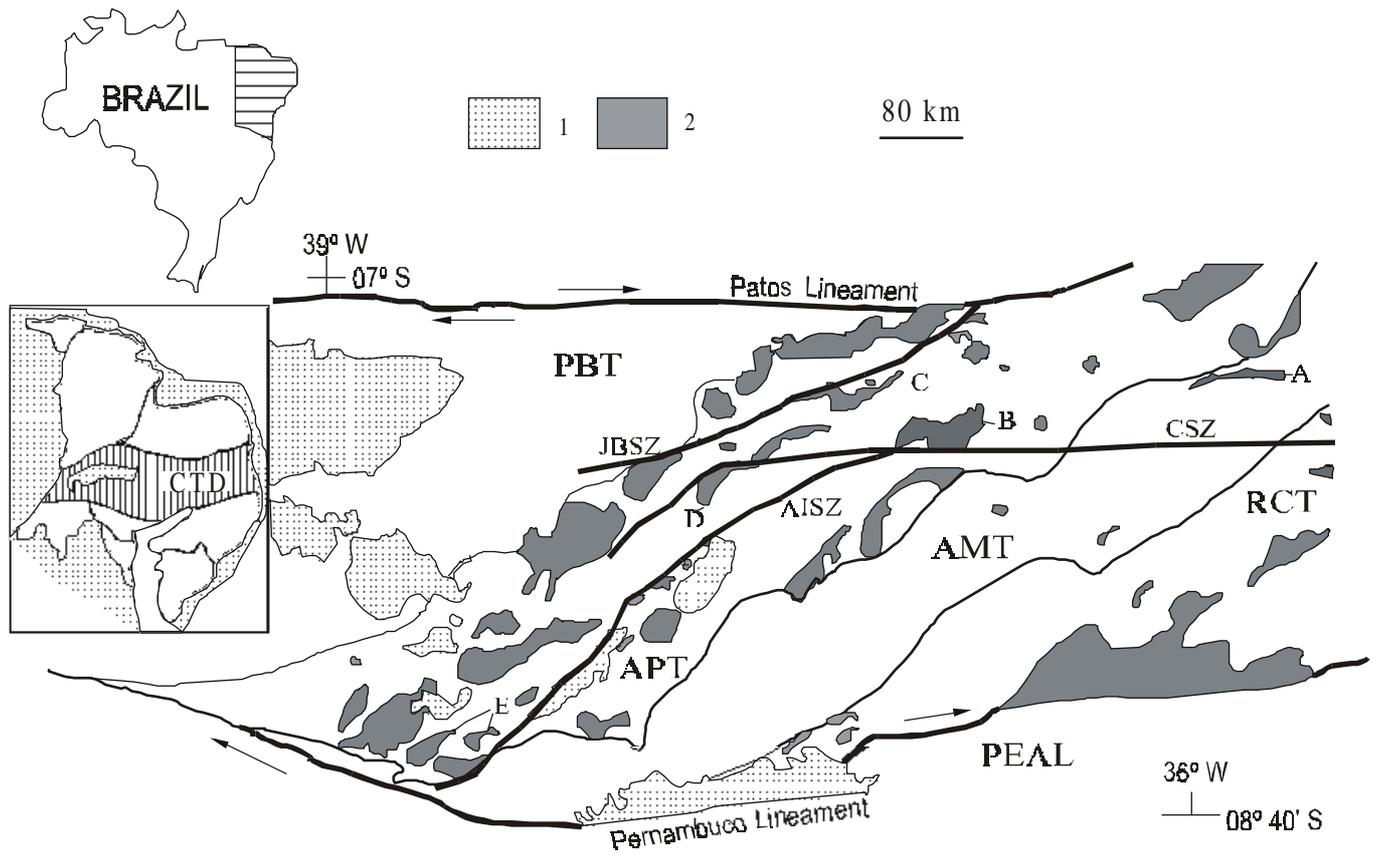


Figure 1-The location map of the studied granitoids. A = Queimadas Pluton; B = Serra Branca Pluton; C = Itapetim Dykes (cut the Itapetim Complex); D = Solidão Pluton and E = Serra Grande and Serra do Arapuá Plutons. Modified from Medeiros et al. (1996) and Santos et al. (1996). CSZ = Coxixola Shear Zone; AISZ = Afogados da Ingazeira Shear Zone; JBSZ = Jurú - Belem Shear Zone. PBT = Piancó Alto Brígida Terrane; AMT = Alto Moxotó Terrane; APT = Alto Pajeú Terrane; RCT = Rio Capibaribe Terrane. CTD = Central Tectonic Domain; 1 = Pherozoic Covers and 2 = Brasiliano/Pan-African granitoids

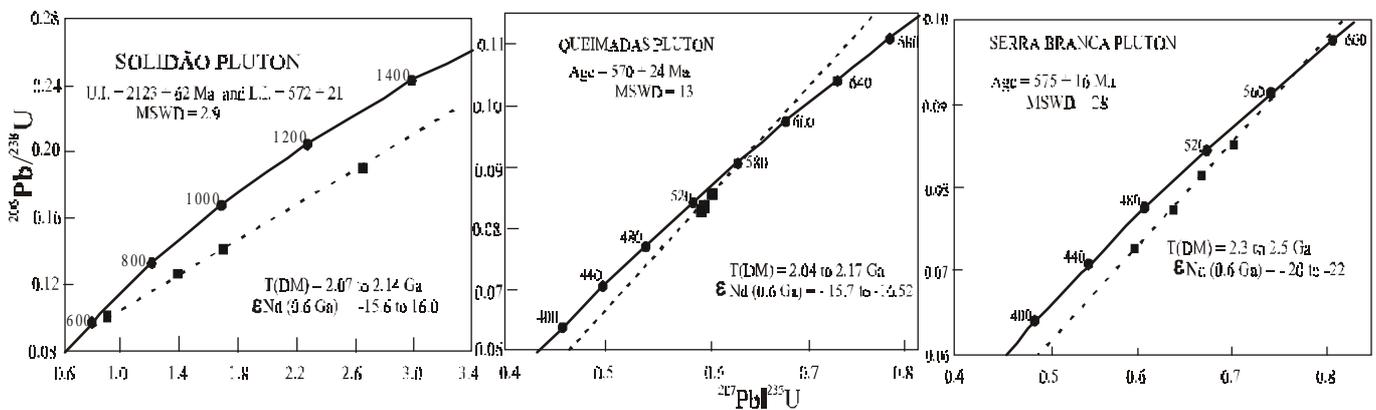


Figure 2-U-Pb zircon age determination and Sm-Nd isotopic data for the ca 570Ma granitoids from the Central Tectonic Domain of the Borborema Province.

granitoids from the Pajeú Paraíba Belt. Sm-Nd TDM ages of ~1.4Ga for these granitoids, suggest a Mesoproterozoic source (Guimarães & Silva Filho 2000).

MINERAL CHEMISTRY Biotite and amphibole compositions were determined on the JEOL- Superprobe at the Institute of Geosciences University of São Paulo.

Biotite The biotites from the studied granitoids are iron-rich with FeO contents in the 25% - 28% range and Fe/(Fe + Mg) ratios ranging from 0.62 to 0.85 (Fig. 3A). The Mg-poorer biotites are those from the amphibole and clinopyroxene-free granitoids (Queimadas and Serra Branca Plutons).

According to Abdel-Rahman (1994), FeO/MgO ratios in biotites define three compositionally distinct fields: 1) biotites from alkaline anorogenic suites are iron-rich siliceous annites, with mean FeO/MgO

= 7.04; 2) biotites from the peraluminous granitoids, including the S-type, are siderophyllite with mean FeO/MgO ratio = 3.48; and 3) biotites from the calc-alkaline granitoids are moderately Mg-enriched, with FeO/MgO ratios of 1.76 on average. Biotites from the free-amphibole and clinopyroxene studied granitoids show FeO/MgO ratios ranging from 6.4 to 8.4. Biotites from the amphibole clinopyroxene bearing granitoids show FeO/MgO ratios ranging from 2.5 to 3.7.

High temperature conditions favor accommodation of Ti instead of Al^{IV} in the biotite structure (Albuquerque 1973). Low Ti contents in biotite correspond to low fO₂ (Buddington & Lindsley 1964). Accordingly, the low Ti and high Al^{IV} in the biotites of the studied granitoids, suggest crystallization under relatively low temperatures and low fO₂. These evidences agree with the petrographic observation that biotite is a later crystallized phase.

Within the CTD, biotites with FeO > 22 wt.% and Fe/(Fe+Mg) > 0.61 are not recorded in granitoids older than 570 Ma (Fig 3A). On the other hand, higher FeO values (> 30%) have been reported in biotites from younger granitoids (ca 520Ma) (Melo 1997).

Biotites from the studied granitoids plot into the field of biotites from sub-alkaline granites (Fig. 3B) in the Al^{IV} versus Mg diagram (Nachit *et al.* 1985) or mildly alkaline (Ferré *et al.* 1998).

Amphibole The amphiboles from the studied granitoids show Fe/(Mg+Fe) ratios ranging from 0.93 to 0.68, similar to that of the whole rock and low Fe³⁺ / (Fe²⁺ + Fe³⁺) ratios (0.14 - 0.20). Fe/(Fe+Mg) ratios > 0.6 and Fe³⁺ / (Fe²⁺ + Fe³⁺) ratios < 0.25 are typical of granitoids crystallized under intermediate to low-fO₂ conditions (Anderson & Smith 1995). The amphiboles from the Queimadas granitoids show the highest Fe/(Fe + Mg) ratios (0.82-0.93). It implies that this pluton was emplaced at low levels of fO₂ below QFM. The amphiboles from the Itapetim dikes show Fe/(Fe + Mg) ratios in the

0.67 - 0.68 range, suggesting that the dikes were emplaced at intermediate levels of fO₂, above QFM. In the Pajeú-Paraíba Belt (PPB), amphiboles from granitoids older than 570Ma have Fe/(Fe+Mg) ratios ≤ 0.58 (table 1).

Fe-rich amphiboles (FeO/(FeO + MgO) = 0.82 - 0.84) have also been reported (Zanon 1997) in clinopyroxene bearing leucocratic granitoids from the Serra do Arapuá and Serra Grande Plutons (Fig. 1), which are petrographically similar to the granitoids from the Solidão Pluton. These two plutons can be fitted in the same belt of the studied granitoids. However, geochronological data are not available.

GEOCHEMISTRY The studied granitoids are sub-alkaline (Fig. 4A) and range from metaluminous to slightly peraluminous (Fig. 4B). They show similar contents of SiO₂ (65% - 72%), Al₂O₃ (14 - 17%), MgO (0.2 - 0.6%) and Rb (100 - 300 ppm). The K₂O contents are high (5% - 6.5%), except in the granodiorites from the Itapetim dikes, which show K₂O contents lower than 3.2 (2.8 - 3.2%). With the exception of the granodiorites from the Itapetim dikes which have K₂O / Na₂O ratios < 1, the studied granitoids show K₂O / Na₂O ratios > 1. The granitoids from the Solidão Pluton are distinct from the others showing higher contents of Na₂O, Sr and Ba and, lower contents of TiO₂, CaO, Fe₂O_{3t}, Nb, Y, Hf and Zr. The FeO_t / (FeO_t + MgO) ratios

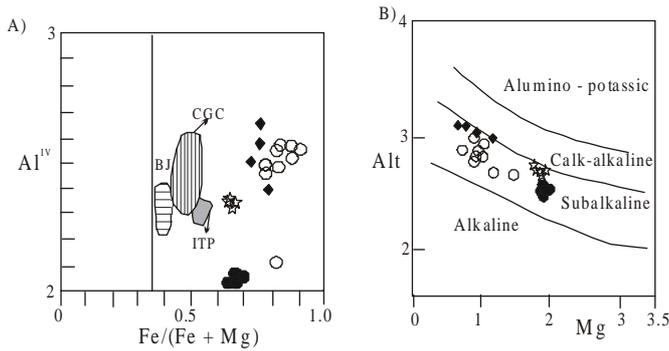


Figure 3-Biotite compositions of ca 570 Ma granitoids from the CTD, plotted in the Al versus Fe/(Fe + Mg) diagram (A) and Al-Mg diagram (B). BJ = Bom Jardim shoshonitic syenites (590 Ma); CCG - Campina Grande high-K calc-alkaline granitoids (580 Ma) and ITP = Itapetim high-K calc-alkaline granitoids (635 Ma) (Guimarães *et al.* 1998). Fields in B are from Nachit *et al.* (1985). Open circle = Queimadas Pluton; closed circle = Solidão Pluton; diamond = Serra Branca Pluton and stars = Itapetim Dykes.

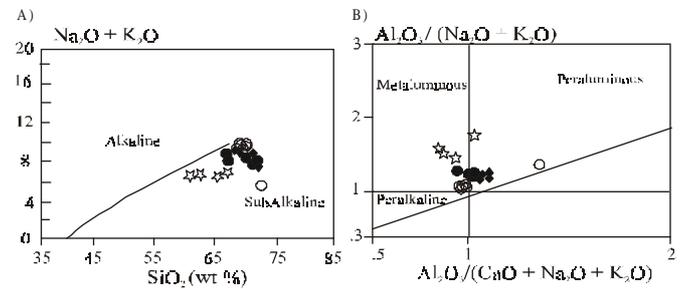


Figure 4-Geochemical plot of the ca 570 Ma granitoids from the CTD in the A/NK versus A/CNK, Shand diagram (A) and in the Na₂O + K₂O versus SiO₂ diagram (B) with fields from Irvine & Baragar (1971). Symbols as in Fig. 3

Table 1-Composition of amphiboles from Queimadas Pluton (Q); Itapetim Dykes (ID); and Solidão Pluton (CS) compared with average of amphiboles from the High-K Calc-Alkaline granitoids from Fazenda Nova Complex (FN - 588 Ma, Neves & Vauchez 1995), Campina Grande Complex (CCG -581 Ma, Almeida 1999); and Itapetim Complex (ITP - 635 Ma, Guimarães & Da Silva Filho 2000) from the CTD of the Borborema Province.

Sample	Q33	Q34	ID-32	ID-15	CS-144	CS-29A	FN	CCG	ITP
SiO ₂	40.53	40.34	41.10	39.98	43.59	42.62	46.22	43.68	42.59
TiO ₂	1.11	1.55	0.83	0.69	0.55	0.34	0.44	1.18	0.56
Al ₂ O ₃	9.96	9.77	12.30	12.27	7.33	9.45	8.57	9.49	10.81
FeO _t	27.01	28.45	21.27	23.03	24.49	25.58	16.26	18.39	20.53
MnO	0.56	0.54	0.24	0	0.66	0.57	0.35	0.36	0.54
MgO	3.23	3.06	6.45	6.14	6.05	5.82	10.50	9.55	7.86
CaO	11.00	10.51	11.67	11.59	11.01	11.09	11.88	11.61	11.51
Na ₂ O	1.32	1.03	1.36	1.40	1.27	1.38	1.32	1.30	1.20
K ₂ O	1.56	1.37	1.37	1.48	1.30	1.64	1.12	1.18	1.23
TOTAL	96.28	97.60	96.65	96.76	96.25	98.49	97.10	96.74	96.63
Structural formulae based on 23 Oxygens									
TSi	6.52	6.39	6.39	6.24	6.92	6.76	6.70	6.61	6.57
TAIV	1.48	1.63	1.62	1.76	1.08	1.30	1.31	1.38	1.43
CAIVI	0.43	0.32	0.67	0.49	0.29	0.48	0.14	0.31	0.53
CTi	0.14	0.19	0.10	0.08	0.06	0.04	0.16	0.14	0.06
CFe3+	0.24	0.36	0.21	0.47	0	0	0.56	0.37	0.27
CMg	0.77	0.73	1.49	1.43	1.42	1.34	1.57	2.15	1.81
CFe2+	3.39	3.40	2.54	2.53	3.22	3.15	1.37	1.95	2.30
BFe2+	0	0.05	0.02	0.004	0.04	0.17	0	0	0.05
BMn	0.07	0.07	0.01	0.02	0.09	0.08	0.001	0.05	0.02
BCa	1.88	1.80	1.94	1.94	1.86	1.76	1.85	1.85	1.90
BNa	0.33	0.26	0.38	0.39	0.013	0	0.09	0.28	0.05
ACa	0	0	0	0	0.01	0.14	0	0.04	0.31
ANa	0.08	0.07	0.03	0.04	0.38	0.42	0.30	0.09	0.24
AK	0.32	0.28	0.27	0.30	0.26	0.33	0.13	0.22	0.55
Fe/(Fe+Mg)	0.82	0.84	0.65	0.68	0.69	0.71	0.58	0.51	0.59

range from 0.78 (Itapetim dikes) to 0.92 (Queimadas Pluton). The FeO_t/MgO ratios recorded in the studied granitoids are higher than those of I- and S-type granitoids (Eby 1990).

Chondrite-normalized whole-rock REE abundance of the studied granitoids, is shown in Fig. 5B. Two distinct REE patterns were recorded: The patterns of the granitoids from Queimadas, Serra Branca Plutons and Itapetim dikes are characterized by (La/Yb)_N ratios in the 15 - 35 range and significant negative Eu anomalies (Eu^{*} = 0.3 - 0.7). The patterns of the granitoids from the Solidão Pluton show lack or small positive Eu anomalies and are more fractionated with (La/Yb)_N ratios in the 50 - 67 range.

The multi-element diagrams (Fig. 5B) also display the differences recorded between the Solidão and the others studied granitoids. In general, the spiderdiagrams are characterized by troughs at Nb and Ti. The granitoids from Queimadas and Serra Branca Plutons and Itapetim dikes also show troughs at Sr, while the spidergrams of the granitoids from the Solidão Pluton show peaks at Sr, deeper troughs at Ti and peaks at Ba.

In the Nb vs Y diagram of Pearce *et al.* (1984) the Queimadas granitoids plot within the WPG field while the other studied granites fall in the VAG + syn-COLG field (Fig. 6A). In the Rb vs (Nb+Y) diagram (Fig. 6B) of Pearce (1996) they cross the boundary of WPG and syn-COLG fields and occupy the post-COLG field. In the diagrams of Whalen *et al.* 1987 (Fig. 6C-D) some granitoid samples plot in the A-type field (Queimadas and Itapetim dikes) and others in the field of I, S, and M-type granitoids.

All granitoids investigated were emplaced after the last main phase of deformation. There is no evidence in the region indicating subduction of oceanic lithosphere contemporaneous with the emplacement of the granitoids. Thus, the VAG and syn-COLG

signature recorded in some of the studied plutons could be inherited from the source rock.

DISCUSSION AND CONCLUSION The granitoids with age *ca* 570 Ma within the Pajeú-Paraíba are subalkaline, show high contents of Ba, Rb, LREE, Zr and Y, high FeO/(FeO + MgO) and K₂O/Na₂O ratios and moderated to low Sr and Nb, which are common features of most alkaline granite suites. However, they have low SiO₂ contents (<70% in average), in contrast with alkaline granites, which usually have SiO₂ around 74.

The composition of biotite in granites reflects the composition of the melt from which they crystallized and indirectly the nature of their protholith (Nachit *et al.* 1985). The biotites of the studied granites fall mostly in the subalkaline field of Nachit *et al.* (1985) which corresponds to trans-alkaline compositions, according to Ferré *et al.* (1998).

All the previous features suggest that the granitoids of this study are similar to those described by Ferré *et al.* (1998) in eastern Nigeria, corresponding to *trans*-alkaline, ferro-potassic plutonism. The geochemical similarities between the studied granitoids (mainly the Queimadas Pluton) with those having similar ages in Eastern Nigeria (Ferré *et al.* 1998) suggest that this granitoids belt has a continuation in the African continent.

The fO₂ conditions estimated for these granitoids are lower than those recorded in older (³ 580Ma) granitoids from the PPB. The fO₂ of a magma reflects that of the source region (Carmichael 1991). Thus, the slightly higher Fe/(Fe + Mg) ratios recorded in the mafic silicates from Solidão Pluton and Itapetim dikes may reflect higher fO₂ in their source rocks. It reflects an apparent change in the state of oxidation, decreasing from west to east, in the source rocks of the *ca.* 570Ma granitoids of the PPB. It may suggest distinct uplift rates.

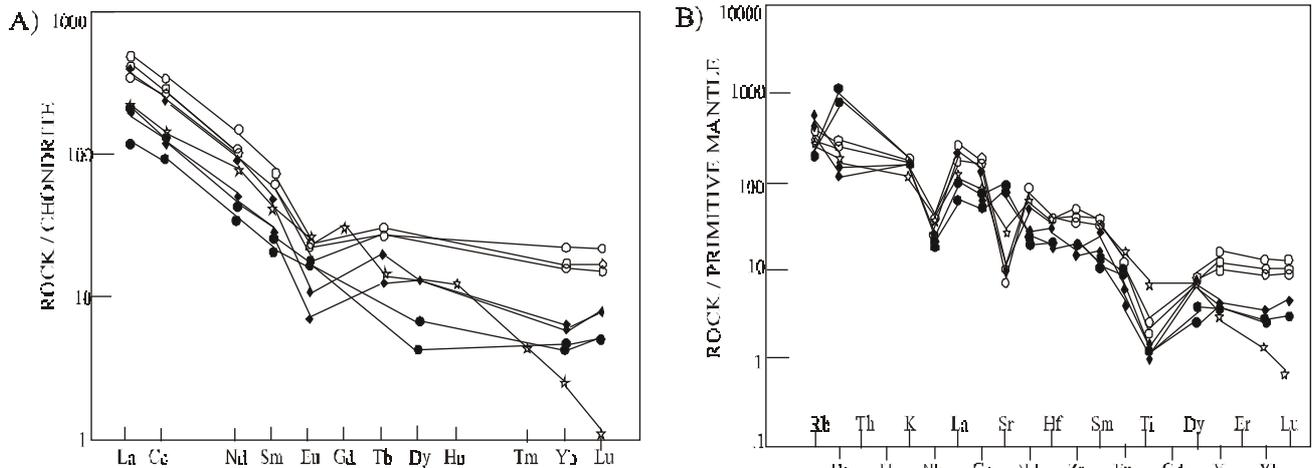


Figure 5-Chondrite (Sun 1980) normalized REE patterns (A) and multi-element diagrams of the *ca* 570Ma granitoids from the CTD. Symbols as in Fig. 3

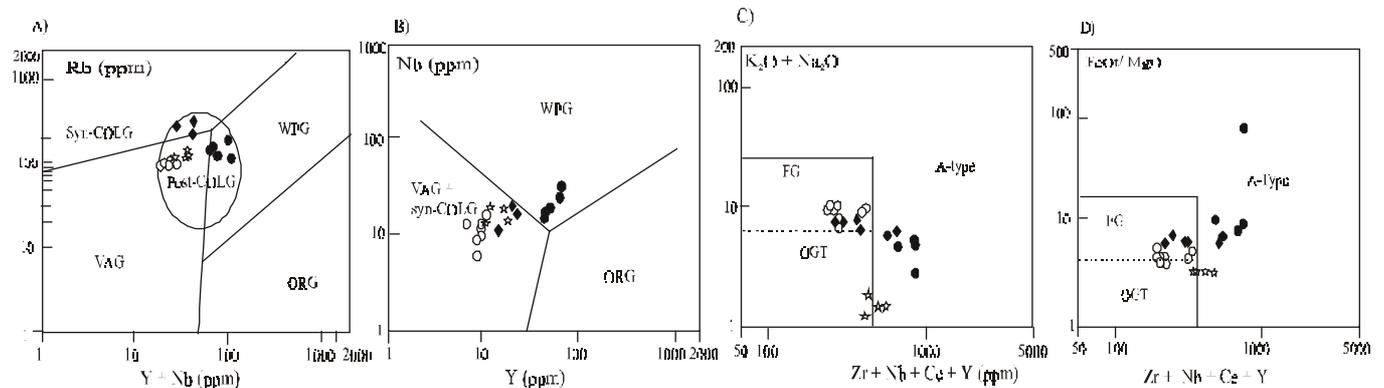


Figure 6-Trace element discrimination diagrams of the *ca* 570 Ma granitoids from the CTD. Fields after Pearce *et al.* 1984) (A); Pearce *et al.* 1996 (B); Whalen *et al.* (1987) (C and D). syn-COLG = syn-collision granite; VAG = volcanic arc granite; ORG = oceanic ridge granite; post-COLG = post-collision granite; FG = fractionated I-type granite; OGT = unfractionated I- S- and M-type granites. Symbols as in Fig. 3

The association of field relationship, geochemical isotopic and geochronology data suggest that the studied granitoids represent a belt of granitoids, generated from distinct sources (at least isotopically), during the later stage of the Brasiliano Orogeny within the CTB of the Borborema Province.

Acknowledgements We wish to thank Drs. W.R. Van Schmus (Isotope Geochemistry Laboratories – Kansas University – USA) I.P.G. is grateful for the financial support given by CAPES – Gov. do Brasil, through the grant BEX0742/96, for a post-doctoral program at Kansas University - USA.

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Contribution IGC-184
Received March 10, 2000
Accepted for publication May 10, 2000