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ISOTOPIC SIGNATURES OF PALEOPROTEROZOIC GRANITOIDS OF THE GAVIÃO BLOCK AND IMPLICATIONS FOR THE EVOLUTION OF THE SÃO FRANCISCO CRATON, BAHIA, BRAZIL

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ABSTRACT Intense granitic plutonism of peraluminous and metaluminous calc-alkaline affinity took place in the northern sector of the São Francisco Craton, during the Paleoproterozoic. Rb-Sr and ^{207}Pb/^{206}Pb(zircon) radiometric data for the granitoids yield crystallization ages at ca. 2.0 Ga. The calculated ^{87}Sr/^{86}Sr initial ratios (up to 0.727), T_{DM} model ages (between 2.6 and 3.5 Ga) and the range in the $e_{Nd(t)}$ values (-5.8 to -13.4) are all compatible with participation of variable proportions of Archean crust material in the magma genesis of such plutons. Technically, these granites originated due to the Transamazonian collisional orogeny, which developed within large terranes of the Craton along the edge of the Archean Gavião Block.

Keywords: isotope geochemistry, geochronology, granites, crustal evolution

INTRODUCTION In the northern São Francisco Craton (SFC), several granitoids associated with syn and late- tectonic phases of the Transamazonian collisional orogeny (e.g., Carnaiba, Campo Formoso, Flamengo, Riacho de Pedras, Lagoinha, Lagoa Grande, and Caetano) have been identified (Sabate *et al.* 1990, Santos-Pinto 1996) (Figs. 1A and B). They comprise a string of plutons bearing predominant peraluminous and subordinate metaluminous affinities, which are closely associated with a major NS structure of the Paleoproterozoic Contendas Mirante-Jacobina belt, which makes up the collision front due to tectonic convergence between the Archean Gavião and Jequie blocks. The mineralogical, chemical, and isotopic characteristics of the granitoids (e.g., Serra da Franga, Mariana, Umburanas, Rio of Paulo, Iguatemi, Cacule, Espírito Santo), at the southern portion of the Gaviao Block (GB), near Brumado, reveal that the Archean gneiss-migmatite terrain played an important role in the genesis of the parental magmas of these granitoids (e.g. Santos-Pinto 1996, Bastos Leal 1998).

Here we present a synthesis of ^{207}Pb/^{206}Pb(single zircon, evaporation), Rb-Sr, Sm-Nd and K-Ar determinations carried out on four Transamazonian granitoids (Rio do Paulo-RP, Cacule-CA, Iguatemi-IG, Espírito Santo-ES) that intrude the GB - Fig. IB. Based on isotopic and geochemical data, the sources of these plutonic rocks are constrained, leading to discussion of the tectonic implications for the evolution of SFC.

GEOLOGICAL FRAMEWORK The GB comprises three main geological units (Fig. IB): (i) granite-gneiss-migmatite terranes, dominated by associations of TTG-type orthogneisses and Archean granites with zircon U-Pb and ^{207}Pb/ Pb ages varying from 3403 ± 5 Ma to 3146 ± 24 Ma; (ii) Archean greenstone belts with Sm-Nd (T) and zircon ^{207}Pb/^{206}Pb ages varying from 3,0 to 2,5 Ga; (in) Paleoproterozoic granitoids (Bastos Leal 1998).

The Paleoproterozoic granites investigated (e.g., RP, CA, IG, ES) as well as many other granites are intrusive into both the greenstone belts and gneiss-migmatite terranes of the GB. These granitoids are gray to pink, coarse- to fine-grained, porphyritic, often slightly deformed. Their compositions vary from granodiorite to granite. In areas affected by Neoproterozoic regional shear zones, these plutons become pervasively lineated and/or foliated according to the orientation of the regional structures. In addition, the RP and CA granitoids host enclaves of mafic rocks, para- and orthogneisses, whereas the IG and ES bodies include enclaves of gneiss-migmatite rocks. A distinct compositional characteristic among the granitoids is the presence of amphibole and biotite in the essential mineralogy of the RP and CA massifs, whereas the IG and ES massifs are marked by the occurrence of muscovite.

GEOCHEMICAL FEATURES The geochemical characteristics of the studied granitoids vary from I-type granodiorites to S-type granites and define two different compositional groups in the AFM diagram (Fig. 2A). RP and CA rocks show metaluminous character with a light peraluminous tendency in the case of RP. IG and ES rocks are dominantly peraluminous (Fig. 2B). It is also noticeable that the granitoids of all four massifs show a range of composicional variation similar to other Transamazonian granitoids of the GB and those closely associated with the CMJ (Figs. 2A and 2B).

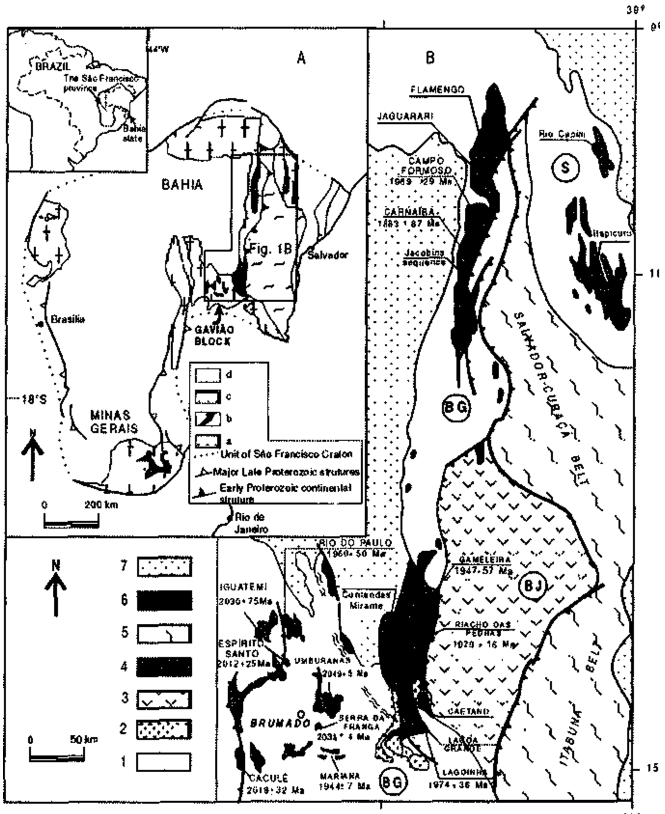

Figure 1 - Geological map of the studied area in the São Francisco Craton. A: a - Archean and Paleoproterozoic granitic-gneissic-migmatitic terranes; b - Archean and Paleoproterozoic greenstone belts; c - Archean and Paleoproterozoic high grade rocks; d - Post-Paleoproterozoic sedimentary covers (After Bastos Leal 1998, with modifications). B: 1 - Archean gneissic-migmatitic terranes of the TTG suite; 2 - Archean granitoids; 3 - Jequie Block (Archean high grade gneiss); 4 -Archean/ Paleoproterozoic supracrustal sequence; 5 - Paleoproterozoic mobile belt; 6 - Transamazonian granitoids; 7- Meso/Neoproterozoic and Cenozoic covers (After Sabate et al. 1990, with modifications).

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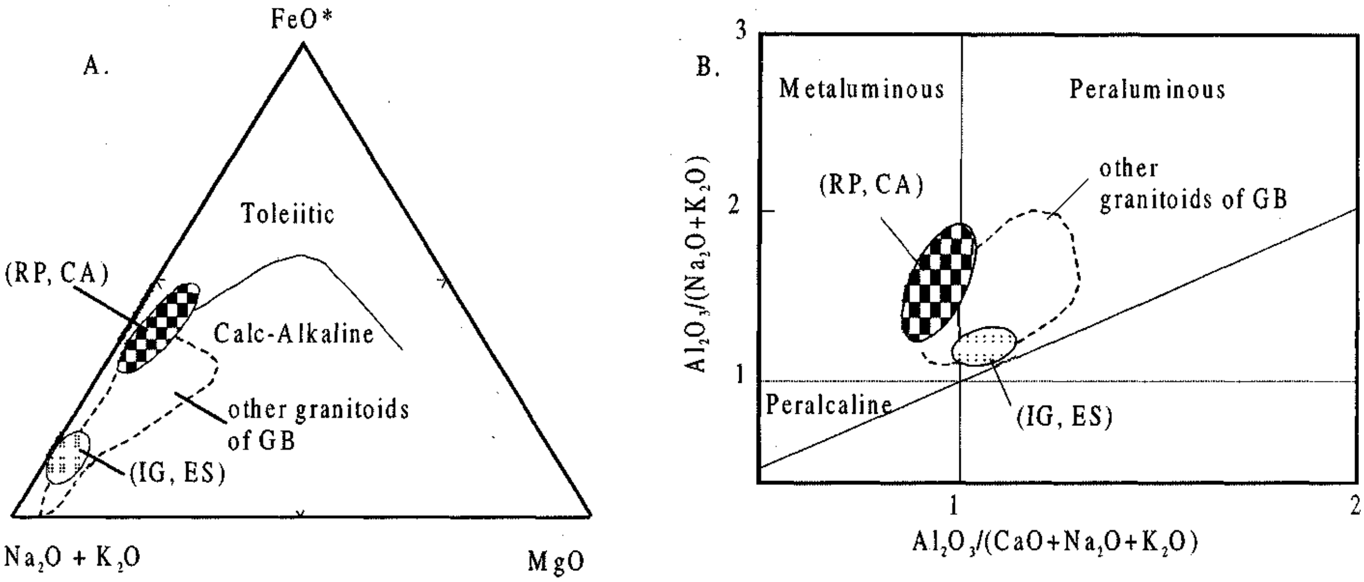

Figure 2 - (A) AFM diagram showing the calc-alkaline trend of the granitoid plutons. (B) The granitoids plutons in $Al_2O_3/(Na_2O+K_2O)$ vs. $Al_2O_3/(CaO+Na_2O+K_2O)$ diagram.

The two groups of granitoid differ in their relationships between the LIL and HFS elements. The ratios from members of the RP and CA bodies include, respectively: Rb/Sr (0,8 and 0,5), Rb/Zr (0,28 and 0,16), Rb/Hf (13,2 and 8,3), K/Rb (228,7 and 277,5) Ta/Hf (0,11 and 0,12) and Ta/Zr (0,003 and 0,002) respectively. In contrast, the SE and IG rocks show, respectively: Rb/Sr (4,7 and 3,2), Rb/Zr (2,4 and 1,9), Rb/Hf (94,0 and 60,2), K/Rb (135,0 and 165,0), Ta/Hf (0,84 and 0,64) and Ta/Zr (0,03 and 0,02). Such contrasts are thought to result from fundamental differences in the nature of the sources of these granitoids. In this context, geochemical data from RP and CA are compatible with those observed in calk-alkaline, I-type granitoids, while the geochemistry of IG and ES granitoids is similar to peraluminous granitoids formed in collisional orogens.

Table 1 - Rb/Sr analytical data of the granitoids. The initial $^{87}Srfi^{6}Sr$ were calculated for the crystallization time of the rocks.

Granitoid	sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$ ± error	$^{87}Sr/^{86}Sr$ ± error	$^{87}Sr/^{86}Sr(i)$ (Ri)
RP	BR-JC-68A	108,0	203,9	1,540 ± 0,043	0,75548 ± 0,00013	0.7120
	BR-JC-68E	105,1	169,3	1,807 ± 0,051	0,76525 ± 0,00007	0.7142
	BR-JC-68G	445,1	181,8	7,242 ± 0,200	0,93150 ± 0,00008	0.7030
	BR-JC-68I	156,2	181,4	2,508 ± 0,070	0,77378 ± 0,00009	0.7271
	BR-JC-68M	225,0	126,6	5,216 ± 0,145	0,84982 ± 0,00008	0.7026
	BR-JC-68N	148,3	126,8	3,417 ± 0,096	0,80339 ± 0,00010	0.7069
CA	BR-JC-234	145,9	342,2	1,239 ± 0,035	0,74539 ± 0,00009	0.7097
	BR-JC-229	203,0	298,1	1,982 ± 0,056	0,76252 ± 0,00009	0.7054
	BR-JC-237A	174,0	300,2	1,686 ± 0,047	0,75860 ± 0,00011	0.7100
	BR-JC-237AA	203,5	321,9	1,839 ± 0,052	0,76144 ± 0,00009	0.7085
	BR-JC-237BB	176,5	276,8	1,855 ± 0,052	0,75750 ± 0,00011	0.7041
	BR-07A	166,9	301,8	1,608 ± 0,045	0,75580 ± 0,00007	0.7095
ES	BR-01A	349,7	56,8	18,722 ± 0,504	1,22205 ± 0,00009	0.6827
	BR-01G	349,8	62,1	17,083 ± 0,461	1,19327 ± 0,00080	0.7011
	BR-01L	337,5	69,4	14,653 ± 0,398	1,12419 ± 0,00060	0.7021
	BR-01P	383,8	56,8	20,637 ± 0,553	1,26848 ± 0,00043	0.6734
IG	BR-JC-304C	279,3	80,5	10,340 ± 0,284	1,00888 ± 0,00007	0.7110
	BR-JC-304D	300,6	84,0	10,668 ± 0,293	1,01208 ± 0,00009	0.7048
	BR-JC-304F	269,3	60,5	13,347 ± 0,364	1,07357 ± 0,00009	0.6891
	BR-JC-304G	198,8	66,3	8,910 ± 0,245	0,97824 ± 0,00011	0.7216
	BR-JC-304J	264,7	97,5	7,881 ± 0,222	0,93770 ± 0,00013	0.7107
	BR-JC-309	242,9	135,9	5,248 ± 0,146	0,85406 ± 0,00008	0.7028

ANALYTICAL METHODS Rb-Sr, Sm-Nd and K-Ar isotopic analyses (Tables 1, 2 and 4) were carried out at the Geochronologic Research Center of the University of São Paulo (CPGeo-USP), whereas zircon ^{207}Pb-^{206}Pb analyses (Table 3) were carried out at the Isotopic Geology Laboratory of the Federal University of Pará, Brazil (LGI-UFPA).

Rb and Sr, and Sm and Nd contents in whole rocks (wr) were determined by X-ray fluorescence and isotopic dilution, respectively. The spectrometric readings of the ratios were done with a CPGeo's VG-354 mass spectrometer. The $^{143}Nd/^{144}Nd$ values were normalized using $^{146}Nd/^{144}Nd$=0.7219. Sm-Nd model ages (T_{DM}) were calculated using the depleted mantle model proposed by DePaolo (1988). $^{207}Pb/^{206}Pb$ analyses using the single zircon evaporation technique followed the procedures proposed by Gaudette *et al.* (1998).

Table 2 - Sm/Nd analytical data for granitoids. The isotopic ratios are at 2-sigma level, and the $e_{Nd(t)}$ were calculated for the time of emplacement of the rocks using De Paolo (1988) model.

Granitoid	sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$ ± error	$^{143}Nd/^{144}Nd$ ± error	fSm/Nd	T_{DM}	εNd(t) t=2.0 Ga	εNd(o)
RP	BR-JC-68A	14,731 ± 0,008	80,945 ± 0,032	0,1107 ± 0,0001	0,511214 ± 0,000028	-0,44	2,73	-6,1	-27,8
CA	BR-07A	45,590 ± 0,024	323,333 ± 0,123	0,0858 ± 0,0001	0,510849 ± 0,000039	-0,56	2,63	-6,8	-34,9
	BR-JC-234	2,990 ± 0,001	18,682 ± 0,006	0,0974 ± 0,0001	0,510944 ± 0,000037	-0,50	2,77	-7,9	-33,0
ES	BR-01L	5,769 ± 0,004	33,972 ± 0,016	0,1033 ± 0,0001	0,510860 ± 0,000024	-0,47	3,05	-11,1	-34,7
	BR-01S	7,947 ± 0,003	48,061 ± 0,019	0,1006 ± 0,0001	0,510778 ± 0,000024	-0,49	3,09	-12,0	-36,3
IG	BR-JC-309	13,519 ± 0,008	76,148 ± 0,029	0,1080 ± 0,0001	0,511034 ± 0,000023	-0,45	2,93	-8,9	-31,3
	BR-JC-304J	10,939 ± 0,004	55,369 ± 0,021	0,1202 ± 0,0001	0,510963 ± 0,000025	-0,39	3,46	-13,4	-32,7

ISOTOPIC RESULTS AND DISCUSSION

Rio do Paulo Rb-Sr analyses of six samples from RP yielded a crystallization age of 1959 ± 50 Ma and initial ratio $^{87}Sr/^{86}Sr$. (IR) = 0.7108 ± 0.0017 (MSWD = 9.2) (Fig. 3A; Table 1). A Sm/N'd model age (T_{DM}) of 2.73 Ga and a calculated $\varepsilon_{Nd(t)}$ value of-5.8 were also obtained (Table 2). The high values of the IR coupled with the negative $\varepsilon_{Nd}(t)$ suggest the involvement of crustal material in the genesis of this granitoid.

K-Ar analysis in biotite from the RP body yielded 507 ± 6 Ma (Table 4), indicating a thermal overprint and complete argon loss during the Neoproterozoic.

Cacule Isotopic analyses in six zircon crystals of the CA granitoid produced a $^{207}Pb/^{206}Pb$ crystallization age of 2019 ± 32 Ma (2s) (Fig. 3B; Table 3). Rb-Sr analyses of six samples yielded an errochron of 1734 ± 127 Ma and high IR = 07146 ± 00030 (Table 1). There is a significant age difference between the $^{207}Pb/^{206}Pb$ and Rb/Sr methods within the error, suggesting that the Rb-Sr system was isotopically disturbed after emplacement of the CA. We interpret such a disturbance as possibly linked to the late Meso- to Neoproterozoic

Table 3 - Evaporation data for zircons from the granitoids.

Granitoid	sample/ nº zircon	nº of rations	$^{204}Pb/^{206}Pb$ ± error	$^{207}Pb/^{206}Pb$ ± error	Age (Ma) ± error
CA	BR-JC-237/6	42	0,000833 ± 0,000119	0,119651 ± 0,003688	1956 ± 56
	BR-JC-237/9	42	0,000553 ± 0,000173	0,122033 ± 0,003693	1988 ± 54
	BR-JC-237/10	36	0,000175 ± 0,000113	0,123969 ± 0,001915	2015 ± 27
	BR-JC-237/15	30	0,000101 ± 0,000102	0,127521 ± 0,005508	2070 ± 72
	BR-JC-237/19	66	0,000270 ± 0,000066	0,123630 ± 0,002173	2012 ± 31
	BR-JC-237/20	18	0,000634 ± 0,000643	0,122569 ± 0,012870	1999 ± 186
ES	BR-01/2	30	0,000167 ± 0,000173	0,122033 ± 0,003693	1997 ± 32
	BR-01/6	78	0,000291 ± 0,000055	0,124444 ± 0,001849	2023 ± 26

Table 4 - K/Ar analytical data of the granitoids

Granitoid	sample	mineral	% k ± error	$^{40}Ar_{rad}$ ($X10^{-6}$) ccSTP/g	$^{40}Ar_{atm}$ %	Age ±error (Ma)
RP	BRJC-68G	Biotite	7,56 ± 0,5	172,0	6,4	507 ± 6
CA	BRJC-237D	Amphib.	2,68 ± 0,5	151,0	1,1	1064 ± 12
	BRJC-237D	Biotote	7,06 ± 0,5	176,7	5,6	551 ± 6
ES	BR-01A	Biotite	7,64 ± 2,3	167,2	2,9	490 ± 12
IG	BRJC-304A	Biotite	7,34 ± 0,5	157,8	4,9	483 ± 6

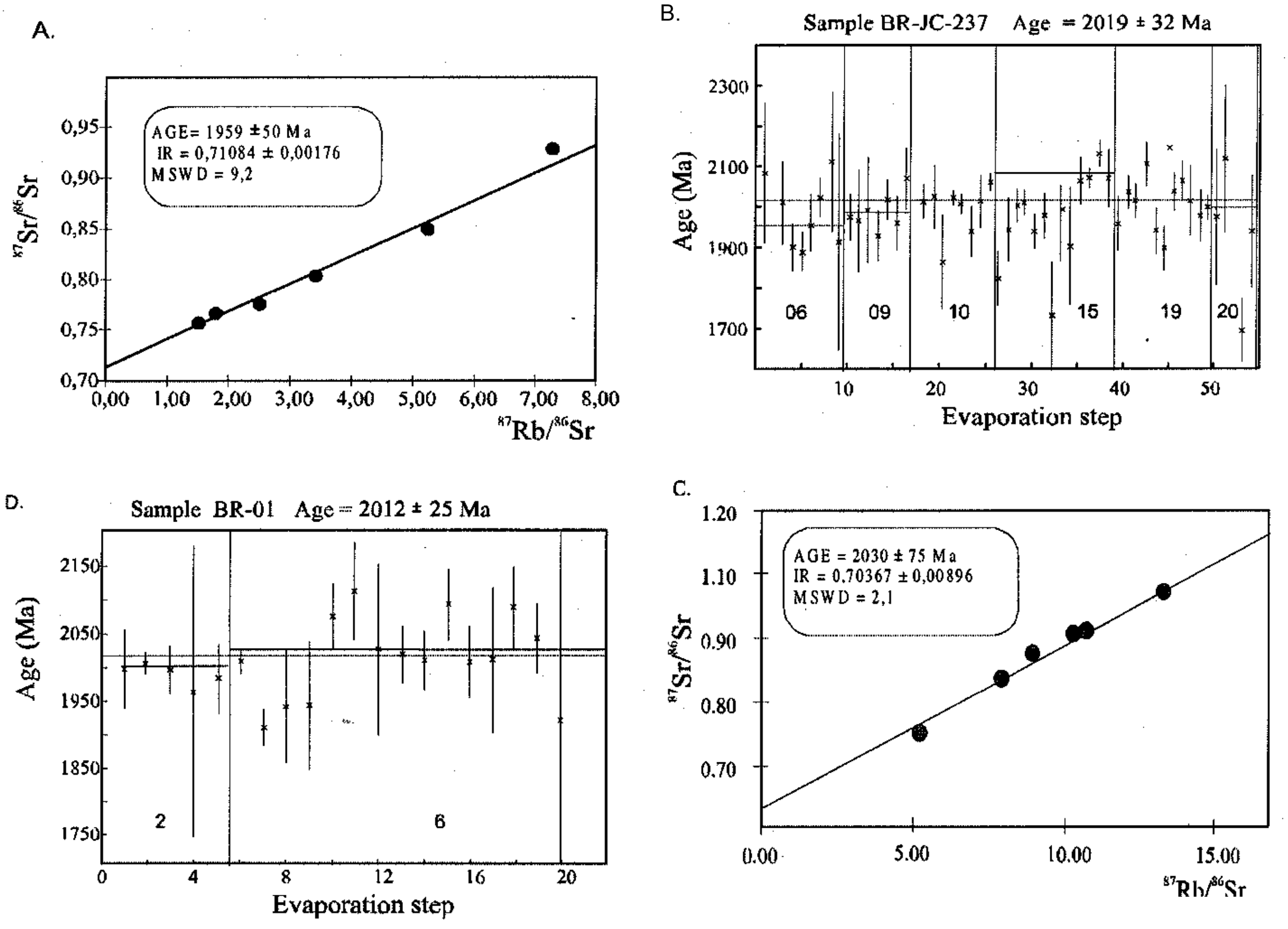

Figure 3 - (A) - Rb-Sr whole rock isochron of the Rio do Paulo granitoid; (B) - Diagram of Age vs. Number of blocks with six $^{207}Pb/^{206}Pb$ ratios for zircons of the Cacule granitoid, "x" - neglected blocks; the zircon grain number is indicated; (C) - Rb-Sr whole rock isochron of the Iguatemi granitoid; (D) - Diagram of Age vs. Number of blocks with six $^{207}Pb/^{206}Pb$ ratios for zircons of the Espirito Santo granitoid, "x" - neglected blocks; the zircon grain number is indicated.

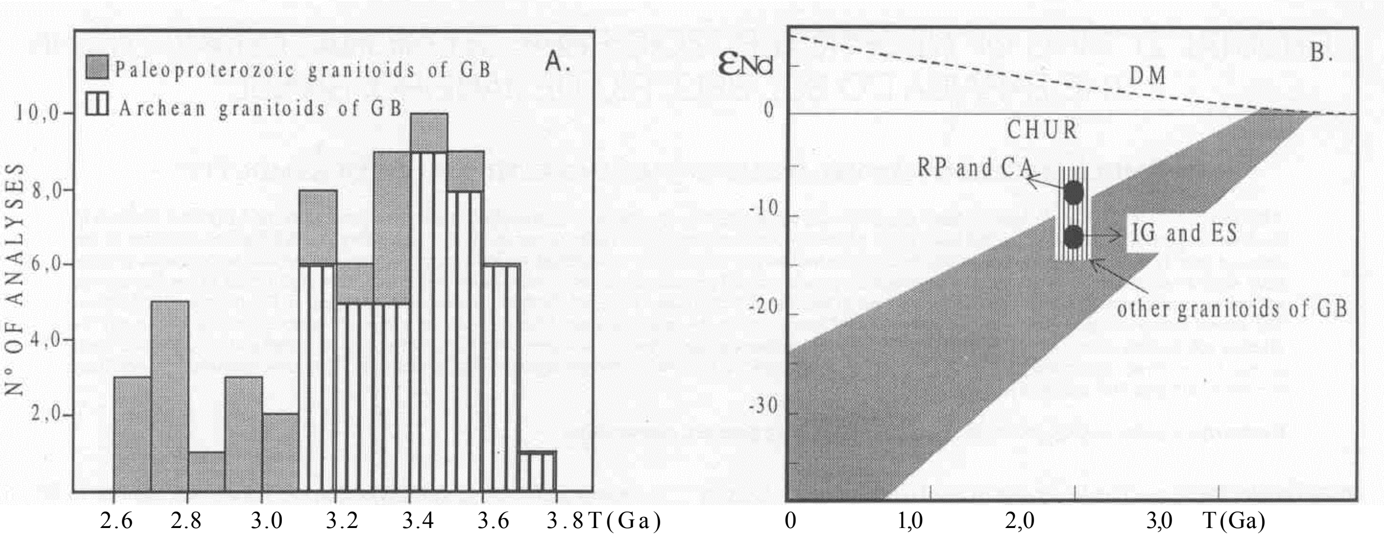

Figure 4 - (A) - Nd isotopic evolution for the Archean TTG gneissic-migmatitic rocks (GB) through time and variation of $\varepsilon_{Nd}(t)$ values (for t~2.0 Ga) of the granitoid plutons of Gavido block and Contendas Mirante-Jacobina belt. (B) - Sm-Nd model ages (Ga) for the Archean TTG gneissic-migmatitic and Transamazonic granitoid plutons of the BG and Contendas Mirante-Jacobina belt.

shear zones developed within this granitoid (see Fig. IB). Further evidence of the tectonism is given by the K-Ar ages on amphibole (1064 ± 12 Ma) and biotite (551 ± 6 Ma), as well as by the K-Ar date on the RP granitoid - see above and Table 4.

Two CA samples yielded T_{DM} model ages of 2.63 and 2.74 Ga with ^{e} values of-6.8 and -7.9, respectively (Table 2). These values, together with the calculated IRs for the six samples analyzed (0.7040-0.7100; see Table 1) suggest again the participation of different proportions of crustal components in the formation of this pluton.

Iguatemi Rb-Sr isotopic analyses of six samples of the IG massif yielded an isochron with a crystallization age of 2030 ± 75 Ma (MSWD = 2.1) and IR = 0.7036 ± 0.0089 (Fig. 3C; Table 1). The *T* model ages are 2.93 and 3.46 Ga, with e_{Nd} values of-8.9 and -1374, respectively (Fig. 2). It is important to note the variations of IRs for each sample (from very low ones up to 0.7216; Table 1) and of model ages (see above) clearly showing heterogeneity in the crustal sources of the parental magmas, in agreement with previous interpretations (Sabate *et al.* 1990, Pimentel & Charnley 1991).

K-Ar analysis in biotite revealed an age of 483 ± 5 Ma (Table 4), confirming the superposition of Neoproterozoic tectonothermal events within large areas of the GB.

Espirito Santo Analyses of four zircon crystals from the ES massif yielded a $^{207}Pb/^{206}Pb$ crystallization age of 2012 ± 25 Ma (2s) (Fig. 3D; Table 3). In contrast, Rb-Sr analyses of four samples of this massif revealed poorly linear array with 1684 ±179 Ma, with IR = 0.7721 ± 0.0448 (Table 1). Similarly to the case of the CA massif (see above), the age differences between the $^{207}Pb/^{206}Pb$ and Rb-Sr methods in the ES granitoid probably reflects late partial re-equilibration of the Rb-Sr system.

$T_{\_M}$ model ages of 3.05 and 3.09 Ga and $e_{Nd(t)}$ values of -11,1 and -12,0 respectively (Table 2) suggest a crustal source for this granitoid, in conformity with the geochemical characteristics of the ES rocks (especially high Rb/Zr, Rb/Hf and Ta/Hf ratios) and mineralogical associations (biotite and muscovite). In addition, the K-Ar age on biotite for this granitoid is 490 ± 12 Ma (Table 4), confirming again the cooling of the isotopic system resulted from the recognized Neoproterozoic tectonics (see Fig. IB).

The four Paleoproterozoic granites clearly show the involvement of Archean gneissic-migmatitic materials of the GB in the magma genesis, as evidenced by Sm-Nd data compilation plotted in Figs 4 A and B. The isotopic feature is similar to that seen in the contemporary metaluminous and peraluminous granitoids which crop out along the Contendas-Mirante Jacobina belt (see Sabate *et al.* 1990).

Among the four plutons investigated, RP and CA exhibit the youngest T ages (2.6-2.7 Ga) and higher $\varepsilon_{Nd(t)}$ (-5.8 to -7.9) values. Their Sm-Nd data plot between the curves or me depleted mantle and of the BG crust, therefore providing evidence the mixture of crustal and mantle components in the generation of both plutons. In contrast, IG and SE samples yield the oldest T_{DM} ages (3.0-3.4 Ga) and lowest $\varepsilon_{Nd(t)}$ values (-11.1 to -13.4), clearly supporting a major crustal source for these granitoids (see Fig 4B).

SUMMARY AND CONCLUSIONS Petrographic, geochemical, and isotopic features presented for RP, CA, ES and IG granitoids allow subdivide them into two different plutonic groups. Our data also suggest that the genesis of the parental magmas of these granitoids, at about 2.0 Ga ago, was related to different sources and degrees of interaction between crustal and mantle materials. The plutonism was originated during the Transamazonian collisional tectonics within the northern São Francisco Craton.

RP and CA granitoids are characterized by amphibole- and biotite-bearing assemblages. They show metaluminous affinity, lower LIL/HFS ratios compared to ES and IG plutons, IRs between 0.703 and 0.727, $\varepsilon_{Nd(t)}$ values between -5.8 and -7.9, and T model ages of 2.6-2.7 Ga. From the above parameters the RP and CA granitoids probably originated from partial melting of a subducting lithosphere (juvenile), with involvement of the Archean continental material from the BG.

The ES and IG granitoids, however, have characteristic biotite + muscovite mineralogy, peraluminous character, higher LIL/HFS ratios, significantly older T model ages (3.0-3.4 Ga), and lower negative e values (-11,1 to -T3,4). These bodies were probably derived from analexis of the GB rocks including upper crust material.

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