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FURTHER SIGNS OF AN ENRICHED MANTLE SOURCE UNDER THE NEOPROTEROZOIC ARAÇUAÍ-RIBEIRA MOBILE BELT

ISABEL PEREIRA LUDKA[1] AND CRISTINA MARIA WIEDEMANN-LEONARDOS[1,2]

ABSTRACT Isolated small bodies of Neoproterozoic coronitic gabbros crop out in the states of Espírito Santo (Jacutinga and Itaoca) and Rio de Janeiro (Amparo), in the central portion of the Araçuaí-Ribeira Mobile Belt. The rocks from Jacutinga and Itaoca are mainly gabbronorites and show a wide range of modal/textural varieties recording crystal-setting processes normally found in layered intrusions. The Amparo intrusion is formed by a coronitic rock, also present as layers in Jacutinga and Itaoca. The primary mineral assemblage consists of olivine, opx, cpx, plagioclase, ilmenite, Ti-magnetite and sulphides. Coronitic overgrowths related to the olivine-plagioclase reaction form concentric rims of opx, amphibole and simplectitic amphibole-spinel around olivine cores. They are all very similar in shape and composition pointing towards similar physical-chemical crystallization conditions. Different geothermometric measurements yielded crystallization temperatures around 800°C, which are close to those calculated for primary opx-cpx pairs (800/940°C). The absence of regional deformational and metamorphic paragenesis is compatible with their intrusion into the middle/ lower crust during a late collisional phase. A long lasting cooling environment at a late magmatic stage induced the sub-solidus reactions.
Low K sub-alkaline signatures with clear enrichment in some incompatible elements such as Ba, Sr and LREE associated with high $^{87}Sr/^{86}Sr$ initial ratios (around 0.706-0.708) are anomalous chemical characteristics of these gabbros. Enriched mantle types (EM1, EM2 and HIMU) with high Sr-initial ratios are frequently found in the Southern Hemisphere. The chemical anomalies obtained in this study could be related to large-scale phenomena, similar to the Dupal anomaly.

Keywords: mantle geochemistry, gabbro-norites, olivine coronas.

INTRODUCTION The Jacutinga and Itaoca gabbros are located in the southern region of Espírito Santo State and the Amparo outcrop lies in the Nova Friburgo mountainous region of Rio de Janeiro (Fig.1). Despite the absence of geochronology data, field evidence shows they are part of the late- to post-collisional magmatism of the Araçuaí-Ribeira Mobile Belt, formed at the end of the Pan-African-Brasiliano orogeny. The preservation of primary igneous structures and only weak signs of deformation, restricted to few lineaments, show that the compressional effects of the Brasiliano event are trivial. The country rocks of the gabbro intrusions are 580-590 Ma old ortho and paragneisses (Söllner *et al.* 1991).

Field, petrographic and preliminary geochemical data of the Jacutinga gabbroic intrusion were previously discussed by Fontes *et al.* (1981), Wiedemann and Lammerer (1983), Wiedemann and Ludka (1984), Wiedemann *et al.* (1986a), Wiedemann *et al.* (1986b), Ludka (1991) and Wiedemann *et al.* (1995). Preliminary chemical analyses of the Itaoca gabbros (Ladwig 1988, Offman 1990) were compared to other mafic occurrences of this region. Braun and Cavalcante (1980) first mapped Amparo.

Comparing geochemical data from several examples within the literature, Ludka *et al.* (1998) showed the unique regional geochemical signature of the underlying mantle. In this study complementary field, petrographic, geochemical and isotopic data characterized these basic rocks as well preserved mantelic differentiates.

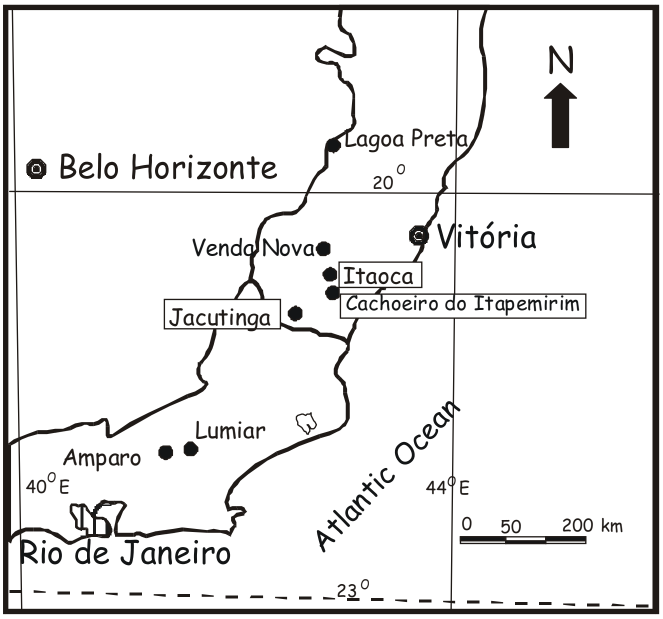

Figure 1 - Location map of the studied gabbroic occurrences in the states of Rio de Janeiro and Espírito Santo.

GEOLOGY AND PETROGRAPHY The rocks from Jacutinga and Itaoca are mainly gabbro-norites. They grade from leucogabbronorite to pyroxenite, covering a wide range of modal/textural/grain-size varieties. The contrasting aspects (color index and grain size) in these rocks show several processes of crystal setting normally found in layered intrusions such as: igneous lamination, poikilitic textures, cumulates, adcumulates and heteroadcumulates crystals (Cox *et al.*1979) and interlayering of contrasting minerals (rhythmic layering). Olivine, opx, cpx, plagioclase, ilmenite, Ti-magnetite and sulphides form the common primary mineral assemblage. In few areas, along lineaments or within the intrusion margins, amphibole and ilmenite/Ti-magnetite exsolutions replace both the pyroxenes. In the Jacutinga intrusion, biotite (meroxen/lepidomelan) and garnet was locally observed.

Poikilitic (oikocrysts of opx, cpx, plagioclase and amphibole) and coronitic texture are abundant in all 3 bodies. Coronites occur as interlayers in the Jacutinga and Itaoca gabbros. The Amparo intrusion consists exclusively of this coronitic rock, also known as hyperite. Its mineral proportion varies from place to place. This rock is characterized by a coronitic overgrowth that resulted from the olivine-plagioclase reaction, forming concentric layers of bronzite II, pargasitic amphibole and spinel symplectite around olivine. The modal analysis shows that Jacutinga and Amparo coronites are very similar, the Itaoca is more mafic. Very similar coronas are also found in the Lagoa Preta gabbroic massif (Vieira *et al.* 1993), and in the hyperites gabbros from the Bamble area, in the Caledonides of Norway (Dam 1995).

Microprobe analysis from the three intrusions records homogeneous mineral compositions. Primary crystals show no significant chemical zoning. This is a clear indication of crystal-liquid equilibrium and, in the case of the corona formation, well-developed sub-solidus reactions. Low forsterite contents (> Fo70) of olivine together with very high anorthite contents (> An94) in plagioclase suggest high degree of Mg diffusion during the corona reaction or the modification of a primary, mantle-derived melt by a complex differentiation process.

Comparative geologic, petrographic and mineralogical data are presented on Table 1.

GEOTHERMOMETRY The crystallization temperature of the primary orthopyroxene-clinopyroxene pair was calculated using three different methods (Wood and Banno 1973, Weels 1977, and the software QUILF from Andersen, 1992). The results are coherent for each sample, under the range of the uncertainties expected for these methods (Table 2). The coronitic rocks from Amparo give the highest temperature for the pyroxenes pairs.

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1 - Departamento de Geologia, UFRJ, Rio de Janeiro, Brazil. E-mail: ludka@igeo.ufrj.br
2 - Instituto de Geociências, UNB, C.P. 04350, 70919-970 Brasília, Brazil. E-mail: wiedeman@unb.br

Table 1 - Main geological and petrographic features of Amparo, Jacutinga and Itaoca

Characteristics	Amparo	Jacutinga	Itaoca
shape	ellipsoidal	Elongated ellipsoid	ellipsoidal
cropping out area	4 Km^2	14 Km^2	11 Km^2
field occurrence	cm/metric boulders	cm/decametric boulders	cm/decametric boulders
rock classification	olivine leucogabbro-norite	olivine leuco/melagabbronorite	olivine leuco/ melagabbro-norite/pyroxenite
mineral orientation	not observed	igneous lamination	igneous lamination
evidence of igneous layering	not observed	sharp contact between contrasting compositional layers	centimetric rithmic layering
poikilitic texture	Cpx and opx oikocrysts	Amphibole oikocrysts	opx oikocrysts, plagioclase and amphibole
primary paragenesis	ol-opx-cpx-plg-op	ol-opx-cpx-plg-op-biot?(meroxeno/lepido-melano)	ol-opx-cpx-plg-op
cumulate minerals	ol-cpx-opx-plg	ol-cpx-plg	ol-cpx-opx
primary minerals	chrysolite/hyalosiderite (Fo$_{67-73}$) enstatite (Wo$_{0.6-3.4}$ En$_{69.8-75.8}$-Fs$_{23-29.}$) diopside(Wo$_{46-47}$ En$_{42-44}$ -Fs$_{9-10}$) plagioclase (An$_{87-98}$)	hyalosiderita (Fo$_{68}$) enstatite(Wo$_{0.8-4.2-}$En$_{40-52}$-Fs4$_{6-58}$) diopside(Wo$_{44-77}$En$_{33-44}$-Fs$_{8-21}$) plagioclase (An$_{38-93}$) biot?(meroxen-lepidomelane)	Chrysolite (Fo$_{78}$) enstatite(Wo$_{0.5-4.-}$En$_{62-79}$-Fs4$_{19-35}$) diopside(Wo$_{46-48}$En$_{40-45}$-Fs$_{6-12}$) plagioclase(An$_{82-92}$)
signs of mineral deformation	not observed	elongated and breached coronas and pyroxenes along the Iurú-Mimoso do Sul lineament	slightly deformed minerals along restrict lineaments
sub-solidus paragenesis	amphibole, opx, spinel, ore minerals	amphibole, opx, spinel, ore minerals	amphibole, opx, spinel, ore minerals
composition of secondary corona minerals	enstatite(Wo$_{0.2-0.8}$-En$_{69-76}$ Fs$_{23-30.}$) XMg amphibole:69-81 XMg spinel:45-59	enstatite(Wo$_{0.5}$-En$_{76-}$Fs$_{23}$) XMg amphibole:73-76 XMg spinel:47	enstatite(Wo$_{0.5-0.6}$-En$_{77-79}$ Fs$_{21-23}$) XMg amphibole: 87-90 XMg spinel:56

The equilibrium temperature for the corona minerals was calculated using the software QUILF for the olivine-orthopyroxene-spinel system and the method proposed by Perchuck *et al.* (1985). This method is based on the Fe/Mg ratio (#Mg) between the coexistent orthopyroxene and amphibole in the corona. The observed differences for each sample are in the error range. Due to the higher Mg-content of olivine, Amparo rocks show again the highest temperatures (Table 3). These temperatures are very close to those found by Bas Dam (1995) for the coronitic gabbros from the Bamble area, in Norway.

GEOCHEMISTRY Major, minor and trace element geochemistry, including rare-earth elements (REE) and Sr-isotopes analyses were performed at the laboratories of the Institut für Allgemeine und Angewandte Geologie of the Maximillian University (IAAG/LMU), in Munich, Germany, and at GEOSOL/Brazil. XRF, ICP-AES and mass spectrometries were the techniques used.

From the total of 29 analysis, 11 were selected and are on Table 4. Using traditional rock classification diagrams a low-K sub-alkaline signature was obtained even when different indicators were chosen, such as: Na$_2$0 + K$_2$O X SiO$_2$ diagram from Cox *et al.* (1979) and Irvine and Baragar (1971), K$_2$O X SiO$_2$ from Middlemost (1975), P$_2$O$_5$ X Zr diagram from Winchester and Floyd (1976), Cr X Ti from Pearce (1975), SiO$_2$ X Zr/TiO$_2$ from Winchester and Floyd, (1977). The chemical classification proposed by Middlemost (1985) and Le Maitre (1989) classifies these rocks as basalt, tholeiitic basalt, picrobasalt and picrite.

The spidergrams of figure 2 show similar chemical signatures. Ba, Sr and LREE enrichments and Rb, K and HREE depletions are comparable for all three rock-types in the three intrusions.

The REE-patterns of all investigated samples show strong LREE enrichments (Fig. 3) and absence of Eu anomalies, despite the high plagioclase content in some rocks. The high positive La$_{cn}$/Lu$_{cn}$ ratio varies from 9 to21 for Amparo, from 2.8 to 15 for Jacutinga and 3.6 to 8.5 for Itaoca. When normalized to OIB values, the REE pattern from all intrusions is horizontal and with comparative lower total REE values. The OIB normalized spidergrams show depletion for some incompatible elements, especially Rb and K. Compared to continental crust values; these rocks show LREE-enrichments, and HREE depletion. The HREE depletion suggests a generation process through relative small degrees of mantle partial melting, as proposed by Bellieni et al. (1984) for the Mesozoic basalts from the Paraná basin.

Another characteristic of these rocks is the high ^{87}Sr/^{86}Sr initial ratios found for Jacutinga and Itaoca (Table 5). For Amparo no

Table 2 - Calculated temperatures of orthopyroxene-clinopyroxene pairs from Amparo, Jacutinga and Itaoca gabbros

	Wood & Banno	Wells	Quilf
Amparo			
A6.2	970° ± 60°C	940 ° ± 70°C	951 ° ± 64°C
A8.1	947° ± 60°C	958 ° ± 70°C	948 ° ± 94°C
Jacutinga			
J475	801° ± 6° °C	832 ° ± 7o°C	700 ° ± 40°C
J343	782° ± 6o°C	814 ° ± 7o°C	756 ° ± 40°C
Itaoca			
ita76	817° ± 6o°C	855 ° ± 7o°C	858 ° ±78°C

Table 3 - Calculated equilibrium temperatures of corona minerals from Amparo, Jacutinga and Itaoca coronites

Sample	minerals	ITA76	J348	A-2	A-8.1
QUILF	Ol-Opx-Sp	707°C ± 50°C	845°C ± 45°C	880°C ± 64 °C	847°C ± 72 °C
PERCHUCK	Opx-Amph	700°C ± 50°C	800°C ± 50°C	900°C ± 50°C	900°C ± 50°C

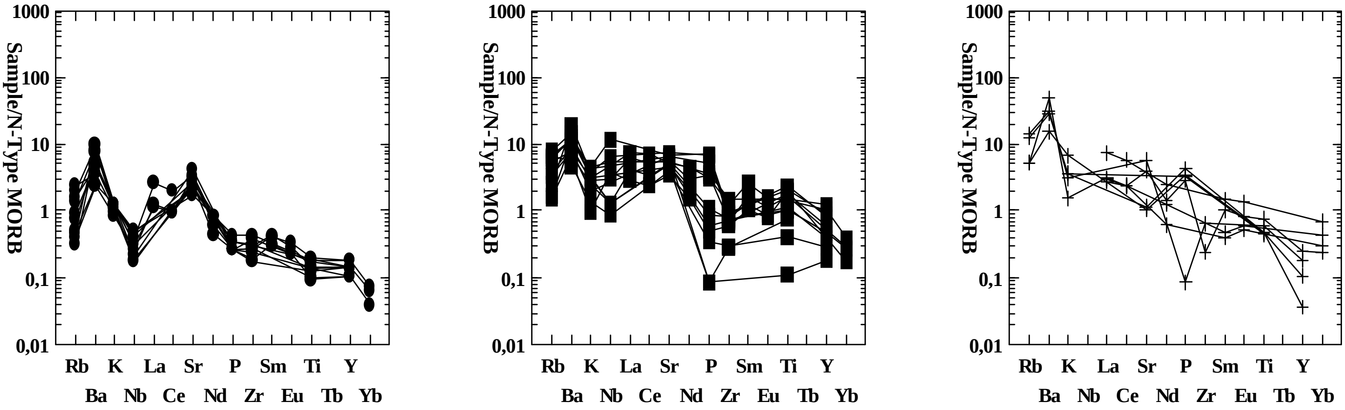

Figure 2 - N-type MORB (Sun & McDonough 1989) normalized spidergram for gabbroic rocks.- Legend: ***circle:*** *Amparo;* ***square:*** *Jacutinga; (+): Itaoca;*

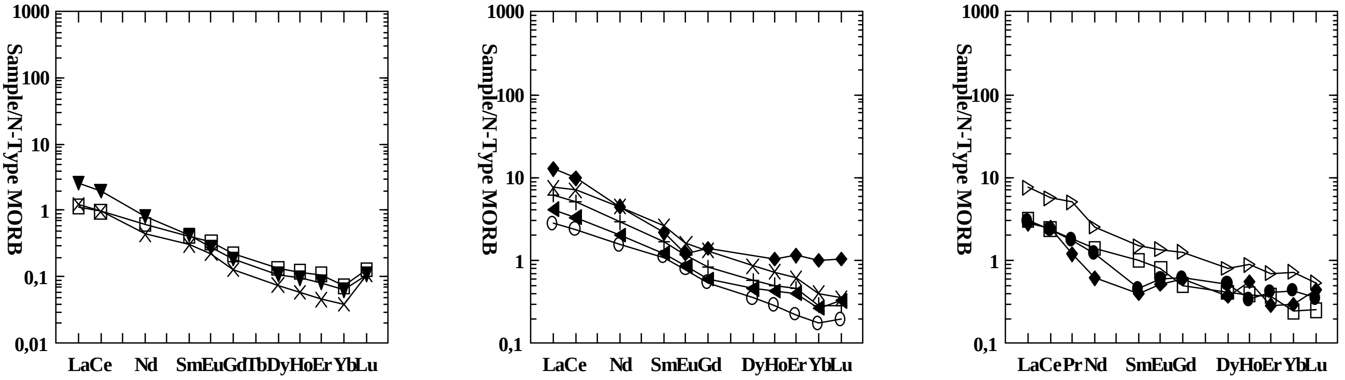

Figure 3 - N-type MORB (Sun & McDonough 1989) normalized REE-patterns of gabbroic rocks. Legend: left-Amparo: ***triangle****-A81;* ***square****-A2; (****X****) A6.2. center- Jacutinga:* ***triangle****-J470;* ***losangle:****J472;* ***circle****: J475;* ***cross****: J471; (****X****): J472; rigth-Itaoca:* ***triangle****-Ita25;* ***square****-Ita31;* ***losangle*** *Ita34;* ***circle****:Ita95.*

Table 4 - Selected chemical analysis of Amparo (Axx, coronite), Jacutinga (Jxxx, gabbro-norite) and Itaoca (Ita31 coronite, ita34 and 95 pyroxenite, Ita 25 gabbro-norite) rocks

sample	A2	A6.2	A8.1	J470	J471	J472	J475	Ita25	Ita31	Ita34	Ita95
SiO_2	41.46	42.06	43.40	46.46	45.72	44.70	41.90	46.82	45.88	48.39	48.54
TiO_2	0.17	0.12	0.24	1.27	2.08	1.83	2.50	0.75	0.96	0.57	0.59
Al_2O_3	15.98	19.09	18.01	17.57	18.34	18.20	15.00	22.63	21.02	6.47	8.78
Fe_2O_3	2.29	2.45	2.49	3.60	3.84	4.12	7.80	2.39	2.29	4.20	3.72
FeO	10.29	8.54	8.09	8.32	8.89	9.56	10.70	5.15	7.66	6.27	6.93
MnO	0.15	0.13	0.14	0.18	0.18	0.21	0.24	0.15	0.12	0.34	0.14
MgO	20.73	16.07	14.73	8.60	7.24	6.87	7.40	5.64	6.94	15.93	13.52
CaO	8.16	9.69	10.66	11.25	11.11	11.04	11.90	15.13	12.55	14.41	15.65
Na_2O	1.11	0.99	1.06	1.17	1.29	1.72	1.10	0.64	1.93	1.34	1.49
K_2O	0.08	0.06	0.09	0.23	0.21	0.31	0.07	0.22	0.11	0.26	0.49
P_2O_5	0.04	0.03	0.04	0.10	0.39	0.36	0.06	0.01	0.33	0.38	0.40
LOI	1.26	1.25	1.10	1.40	1.28	1.57	1.36	0.68	1.5	1.7	1.7
Summe	101.72	100.48	100.05	100.15	100.57	100.49	100.03	99.53	99.78	98.66	100.25
Ba	29	49	16	74	58	69	37	200	313		97
Rb	0.9	0.22	0.28	3.87	2.1	0.92	7	8	3		3
Sr	186	228	246	420	516	485	319	519	362		95
Zr	23	14	22	62	51	93	45	47	18		
Y	4	3	4	1.3	15	30	-	5	7		3
Cr	81	49	70	160	79	33	-	48	72		178
La	2.91	3.17	6.62	10.53	15.49	18.80	7.11	18.70	7.84	6.99	7.50
Ce	7.40	7.31	14.51	24.97	37.85	52.95	18.05	42.85	18.01	18.25	17.72
Nd	4.54	3.20	6.01	14.76	21.47	32.86	11.32	18.59	10.32	4.55	8.99
Sm	1.10	0.80	1.12	3.24	4.43	6.97	2.81	3.91	2.66	1.05	1.21
Eu	0.34	0.24	0.29	0.87	1.18	1.65	0.80	1.38	0.83	0.54	0.60
Gd	0.81	0.48	0.69	2.21	3.03	4.81	1.97	4.75	1.88	2.19	2.26
Dy	0.61	0.34	0.50	2.08	2.59	3.86	1.61	3.71	1.87	1.73	2.36
Ho	0.12	0.06	0.10	0.43	0.51	0.74	0.29	0.90	0.39	0.56	0.34
Er	0.33	0.14	0.25	1.19	1.36	1.85	0.66	2.07	1.12	0.87	1.25
Yb	0.22	0.12	0.20	0.82	0.87	1.21	0.53	2.19	0.74	0.91	1.33
Lu	0.058	0.05	0.05	0.15	0.13	0.16	0.09	0.25	0.11	0.20	0.16

isotopic data was available. According to the preliminary results two distinct groups of high $^{87}Sr/^{86}Sr$-initial ratios could be distinguished: around 0.708 and 0.705. The results confirm the separation into two main groups corresponding to those characterized for the Paraná basin basalts, 0.705-0.706 and 0.708-0-711(Cordani *et al.* 1988), and this seems to be a repetitive feature for the igneous basic and alkaline rocks from an extensive region.

CONCLUSIONS

The different gabbroic rocks from Amparo, Jacutinga and Itaoca revealed significant petrologic similarity. The mineralogy and textures are basically the same in the three intrusions. Microprobe analysis and geothermometric measurements confirmed similar physical-chemical crystallization conditions for the corona formation with temperatures around 800/900°C. These high temperatures are close to those calculated for the intramagmatic formation of opx-cpx pairs (800/ 940°C). The absence of consistent regional deformation and the lack of metamorphic paragenesis are compatible with the calculated temperatures. P-T conditions are compatible with the intrusion of the gabbros into the middle / lower crust, favoring the development of the sub-solidus reaction. The data is consistent with a slow cooling environment at a late magmatic stage.

Table 5- Sr isotopic analyses of Jacutinga and Itaoca rocks

	J470	J471	J472	J475
$^{87}Sr/^{86}Sr$	0.70832	070892	0.70831	0.70757
error	0.000012	0.000012	0.000039	0.000014
	Ita25	Ita31	Ita34	Ita95
$^{87}Sr/^{86}Sr$	0.70623	0.70621	0.705394	0.705655
error	0.000017	0.000017	0.000011	0.000012

Geochemical data show abnormal incompatible elements enrichment. Major, minor and trace element geochemistry and Sr-isotopic data, confirmed the enrichment process. The origin of such enrichment can be attributed to direct or indirect crustal contamination during the orogenic evolution. Nevertheless, in comparison to the values found in the basic rocks, the country rocks have equal to lower contents of Sr and LREE (Ludka *et al.*1998). The mantle enrichment through crustal contribution generally raises Ba, Rb, K, Sr and LREE, but not selectively Ba, Sr and LREE. The observed enrichment level in the tholeiites could point towards a large-scale crustal contamination. On the other hand, low SiO_2, Rb and K contents suggest that crustal contribution was limited. High Sr, Ba and LREE-contents together with lower Rb and K contents, as shown by Pearce (1983), are not currently accepted crustal contamination markers. This particular geochemical signature is a repetitive characteristic, observed in several igneous-derived rocks from this region (Ludka *et al.* 1998). In the paleoproterozoic orthogranulites from the Rio Preto (MG)-Vassouras (RJ) region, the common LILE depletion, typical for granulitic terranes is absent (Heilbron *et al.* 1997). This selective Rb removal observed in some granulite samples is once more similar to the low Rb contents found in the younger gabbros from Amparo, Jacutinga and Itaoca, from this work.

A further discussion point is the interpretation of the high Sr initial ratios, which is also considered by many authors as a strong sign of crustal contribution. The repetitions of this result (0.705-0.708), independent of igneous rock types (from tholeiitic to alkalic) and geological ages (from the Neoproterozoic to the present) are inconsistent with restricted crustal assimilation. Similar results for all intrusions may be rather a result of a mantle Dupal-type anomaly of the Southern Hemisphere (Hart, 1984). The two enriched mantle types end-members of Zindler and Hart (1986), EM1, with higher Ba and lower Sr initial ratio (lower than 0.706), and EM2, with higher isotopic initial ratio but lower Ba are frequently found all over the Southern hemisphere. The results of this study show mixed signatures between the two enriched mantle types. Further Sm/Nd and Pb isotopic analysis are needed to corroborate this correlation. A review of larger data sets from the literature will improve our knowledge of the phenomenon and may confirm the estimated long lasting mantelic geochemical anomaly.

The observed Ba, Sr and LREE enrichments and the anomalous isotopic ratios are interpreted in this work as an anomalous underlying mantle and not just an exclusive product of crustal contamination due to the Neoproterozoic subduction event.

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