POST-COLLISIONAL MULTISTAGE MAGMATISM IN THE RIBEIRA MOBILE BELT: GEOCHEMICAL AND ISOTOPIC STUDY OF THE VÁRZEA ALEGRE INTRUSIVE COMPLEX, ESPÍRITO SANTO, BRAZIL

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ABSTRACT The Várzea Alegre Intrusive Complex (VAIC) corresponds to a post-collisional (late orogenic) pluton, related to the Brasiliano cycle, situated in the central part of the Espírito Santo State. It intrudes amphibolite to granulite facies metamorphic rocks of the Ribeira Belt. Two distinct domains were recognised in this zoned pluton: an inner domain with opx-gabbro, monzogabbro, diorite, quartz-diorite and megaporphyritic granite, and an outer one comprising an irregular and large ring of charnockitic rocks. Geochemical data from the former reveal medium to high-K calc-alkalic rocks, enriched in incompatible elements, mainly Ba, Sr, La, Ce and Pb and partially depleted in HFS elements. The charnockitic rocks show a high-K alkali-calcic signature; they are rich in Ba, K and some HFS elements, such as Zr, P and Nb. The incompatible element enrichment detected in the rocks of the VAIC has been reported for several intrusions from this part of the Ribeira Belt. A Rb-Sr isochronic age of 508±12 Ma was determined for the megaporphyritic granite. The T_{DM} model age varies from 1.3 Ga (opx-gabbro) to ca. 1.67 Ga (charnockitic rocks), which can be related to an important Mesoproterozoic crustal event. The calculated T_{CHUR} model ages of the cogenetic opx-gabbros and intermediary rocks is ca. 1.0 Ga, interpreted as the time when the basic magma was extracted from the source.

Keywords: post-collisional, high K calc-alkalic, multistage magmatism

INTRODUCTION The Espírito Santo State corresponds to the northern portion of the Ribeira Belt, which is the continuation of the Neoproterozoic Araçuaí orogen (Pedrosa-Soares and Wiedemann-Leonardos, subm.). In a late orogenic stage of the Brasiliano cycle (535 - 490 Ma), several complexly zoned plutons intrude the enclosing high-grade gneisses, highlighting the post-collisional magmatism of this region (Wiedemann *et al.* 997). The Várzea Alegre Intrusive Complex, located in the central part of Espírito Santo, is an example of this event. According to Pedrosa-Soares and Wiedemann-Leonardos (subm.), it is included in the G5 suite, which corresponds to the latest magmatic event of the orogen, and is characterized by several plutons with compositions varying from opx-gabbro to granite. This suite comprises meta-aluminous, high-K calc-alkaline, I-type granitoids originated in the lowermost continental crust with important mantle contributions. The VAIC has an outcropping area of 150 Km^2 and was studied by Mendes (1996). and Medeiros (1999). This paper presents the first Sm-Nd data of this type of magmatism in the Espírito Santo.

GEOLOGICAL AND PETROGRAPHIC ASPECTS The Várzea Alegre Complex corresponds to an inversely zoned pluton with an almost circular shape (Fig. 1). Its enclosing rocks are ortho and paragneisses of amphibolite to granulite metamorphic grade.

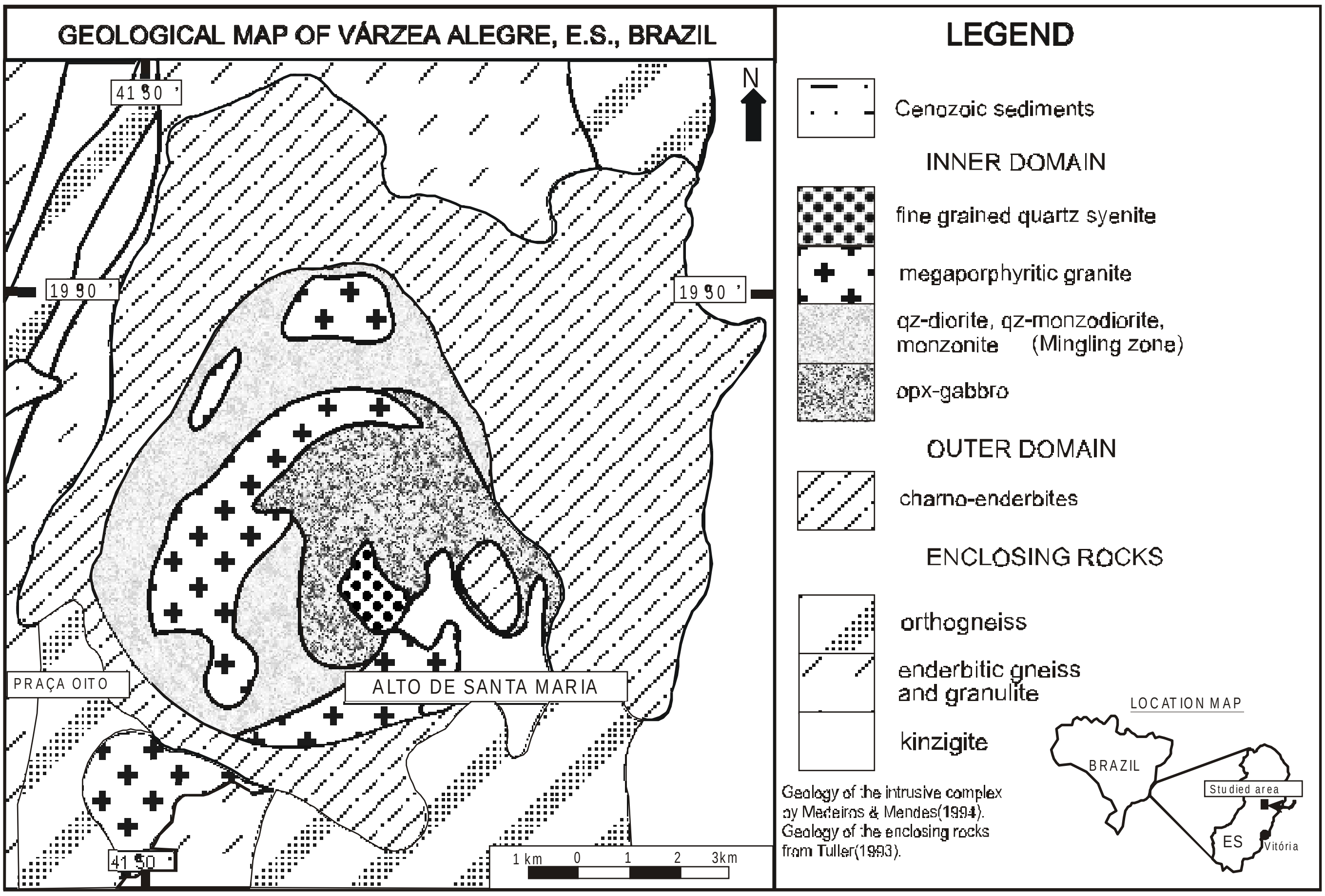

Figure 1 - Geological map of Várzea Alegre Intrusive Complex - ES

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The intrusion has opx-gabbro/monzogabbro at the eroded center surrounded by diorite/quartz-diorite-monzodiorite and megaporphyritic granite. A small stock of sphene-bearing granite occurs close to the opx-gabbro (Medeiros 1999). The contact between the megaporphyritic granite and the diorite is a mingled/mixed zone, and the hybridization process (Medeiros et al.1996) probably produced quartz-diorite and quartz-monzodiorite.

The younger intrusion of Várzea Alegre is involved by a large, early emplaced, ring of dark green color and megaporphyritic charnockitic rocks. This outer domain varies in width from hundred meters, at the S and W borders, to almost 4 Km, at the E and N borders, forming expressive topography. Their mineralogy is made up of plagioclase (An_{32} to An_{40}), quartz, K-feldspar ($Or_{89}Ab_{11}$ to $Or_{69}Ab_{31}$), biotite, hypersthene ($Wo_{1,5-2,5}$; En_{30-41}; Fs_{57-67}), calcic amphibole (Mg-hastingsitic hornblende and magnesian hastingsite), zircon, apatite, magnetite, ilmenite and pyrite (Mendes *et al.* 999).

The coarse-grained opx-gabbro and monzogabbro, showing intergranular to glomeroporphyritic and granular texture, contain more than 50% modal plagioclase (An_{40-60}). The hypersthene ($Wo_{1-2}En_{59-46}$ Fs_{40-52}) is the most common mafic phase, followed by biotite, salite/augite (Wo_{48-46} $En_{41-35}Fs_{11-19}$), ilmenite and Ti-magnetite. The mafic minerals are frequently associated forming aggregates with apatite and zircon. The pyroxenes show evidence of subsolidus reactions, like exsolution lamellae, coronas of amphibole intergrowth with quartz and simplectites with opaque minerals. Curved, fractured and poligonized plagioclase and pyroxenes with kink bands are features of deformation in the opx-gabbro.

In the intermediary rocks, the mineralogical composition is oligoclase/andesine, amphibole (tchermackitic to Fe-pargasite), biotite, ferrihypersthene, salite, K-feldspar, ilmenite, magnetite, apatite and zircon. They show a subhedral inequigranular fabric, fine- to medium grained.

The megaporphyritic granite shows a coarse-grained matrix consisting of plagioclase (An_{24}), microcline, quartz, mesoperthite and biotite. Microcline as megacrystal is usually corroded, with abundant quartz, biotite and plagioclase inclusions. Zircon, sphene, epidote/allanite and apatite are normally euhedral and tend to be concentrated in the biotite-rich domains, which surround the microcline megacrystals.

GEOCHEMISTRY

The charnockitic rocks of the VAIC are hypersthene-bearing quartz-diorites, granodiorites, quartz-monzodiorites and quartz-monzonites. They present medium to high incompatible elements-contents, including REE and HFS elements, such as Zr and Nb, when compared to N-Morb values. The REE patterns are fractionated and show small positive Eu anomalies. The chemical signature of the rocks is high-K calc-alkalic, and in the spidergrams they present negative Ti and P anomalies, suggesting an origin related to a subduction process (Fig. 2). Mendes (1996) and Mendes *et al.* (1997) geochemically distinguished two groups of rocks by means of incompatible versus compatible element diagrams. One of these groups evolved mainly by fractional crystallization of an intermediate magma and the other one by magma mixing, under anhydrous and reducing conditions. Geochemical modeling confirms this hypothesis. The mixing probably occurred after the partial melting of the lower crust, induced by underplating of a basaltic magma. The formation of such basaltic magma is probably related to partial melting of a previously enriched mantle source.

The geochemical behavior of the inner domain rocks indicates a large predominance of metaluminous, Hy-normative, silica-oversaturated lithotypes. When compared to N-MORB (Sun and McDonough 1989), they are enriched in Ba, Sr, K, La and Ce, and depleted in HFS elements (Ta, Nb, Zr, Hf and Ti). Anomalous values are not observed among the less incompatible elements (Fig. 2). Using the normalization values suggested by Pearce (1983), the pattern obtained for the incompatible element is similar to those of ocean islands calc-alkalic basalts. The whole major and trace element data (including REE) give a medium (basic/intermediate rocks) to high-K (megaporphyritic granite) calc-alkalic signature for the Várzea Alegre inner domain rocks. Two groups of rocks are clearly separated in the variation diagrams in Figure3: the basic to intermediate group (from opx-gabbro to quartz-monzodiorite) and the acidic group (granite). The compositional gap observed shows a lack of rocks in the 54% to 61% SiO_2 interval. The petrographic similarity and the differentiation trend in all diagrams indicate that the basic and intermediate lithotypes formed by differentiation. Their identical REE and incompatible element patterns confirm a genetic link between them (Figures 1 and 3). The granitic rocks have different mineralogy and chemical signature. They define a different trend and their REE and incompatible elements patterns are quite distinct (Fig. 4).

The REE quantities of the inner domain rocks are high, mainly the LREE. The granite is different from the others in that it has a negative Eu anomaly and slightly more fractionated patterns. The patterns of the basic and intermediate rocks resemble those of basanites and magmatites from the anomalous portion of the mid-ocean ridge, related to an enriched mantle, E-MORB type (Frey 1984). Such geochemical signatures are also reported by Ludka *et al.* (1998) for many intrusive rocks of the Ribeira Belt.

The SiO_2-contents of the charnockitic rocks range from 54% to 65% (Fig. 3). In spite of this silica interval be partially coincident with the gap observed between the granites and basic/intermediate rocks from the inner domain, they probably do not have cogenetic relation. The general geochemical behavior of the inner domain lithotypes and charnockitic rocks differ considerably in the TiO_2, Fe_2O_3, CaO, K_2O, Sr, Ba, Nb and Zr-contents. Also, the distinct patterns revealed by the incompatible elements and REE diagrams (Figures 2 and 4), besides the lower whole rock #Mg of the charnockites (strong reducing conditions) can be still used as evidence of different magma sources for the inner and outer domain rocks of VAIC.

ISOTOPIC DATA

Rb-Sr and Sm-Nd isotopic analyses were carried out at the Laboratory of Geochronology at the Institute of Geosciences of the University of São Paulo (IG-USP). Seventeen samples were dosed for Rb-Sr determination: 2 opx-gabbros, 2 quartz-diorites, 1 quartz-monzonite, 6 megaporphyritic granite and 6 charnockites (Table 1). Sm-Nd data were obtained for 7 samples selected from those already dosed for Rb-Sr (Table 2). The Rb-Sr data made possible the attainment of an isochron only for the

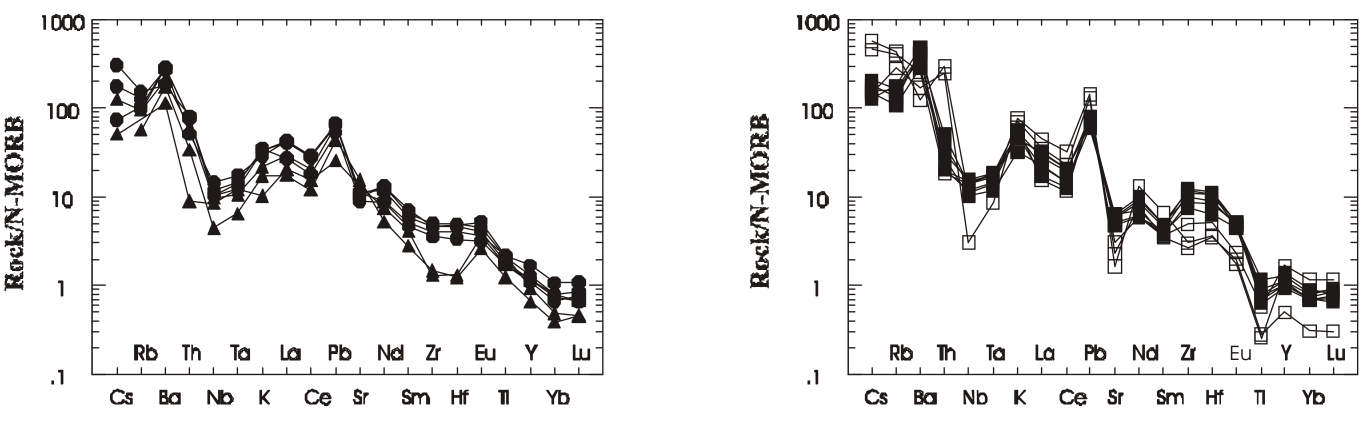

Figure 2 - N-MORB-normalized (Sun and McDonough 989) spidergram for the rocks of VAIC. Symbols: (s) opx-gabbro, monzogabbro; (l) diorite/quartz-diorite, quartz-monzodiorite; (n) megaporphyritic granite; (•) charnockitic rocks.

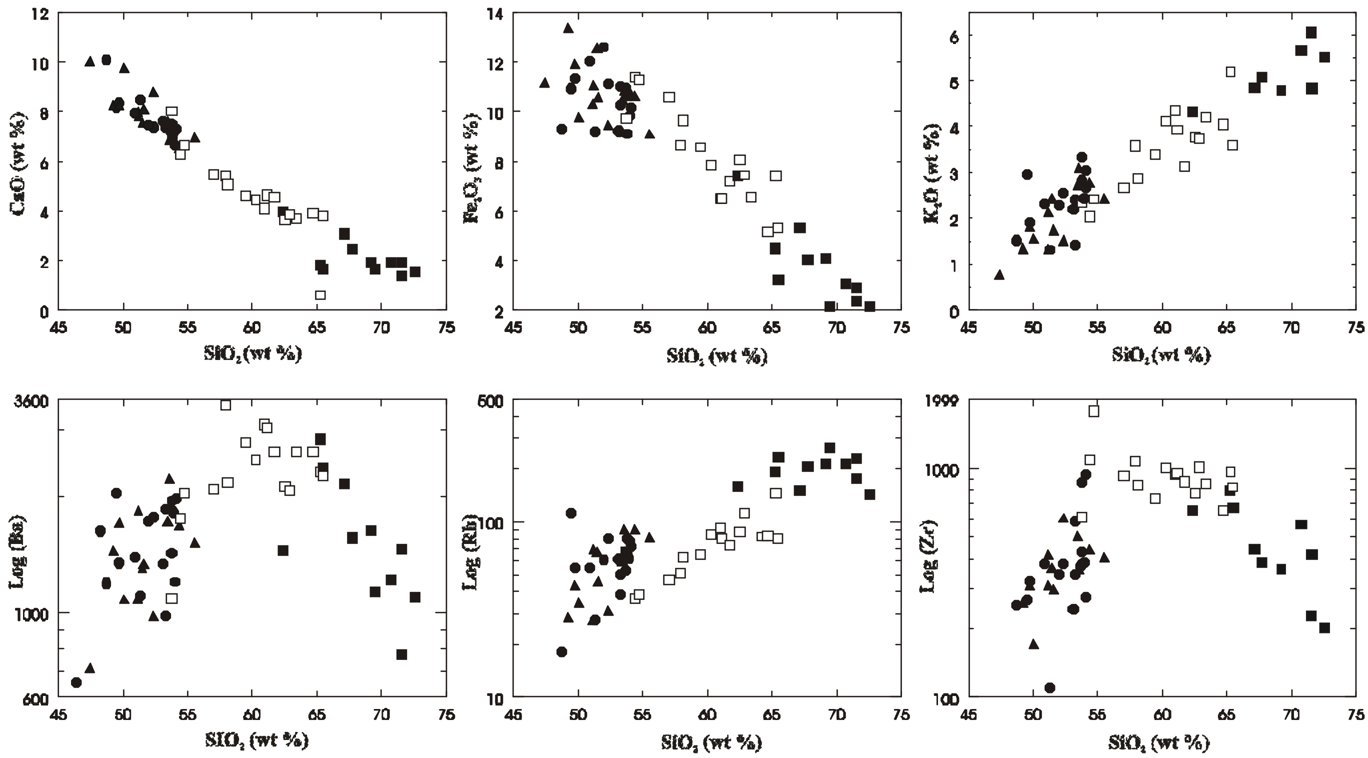

Figure 3 - Variation diagrams for the rocks of VAIC. Symbols: (▲) opx-gabbro, monzogabbro; (●) diorite/quartz-diorite, quartz-monzodiorite; (■) megaporphyritic granite; (□) charnockitic rocks.

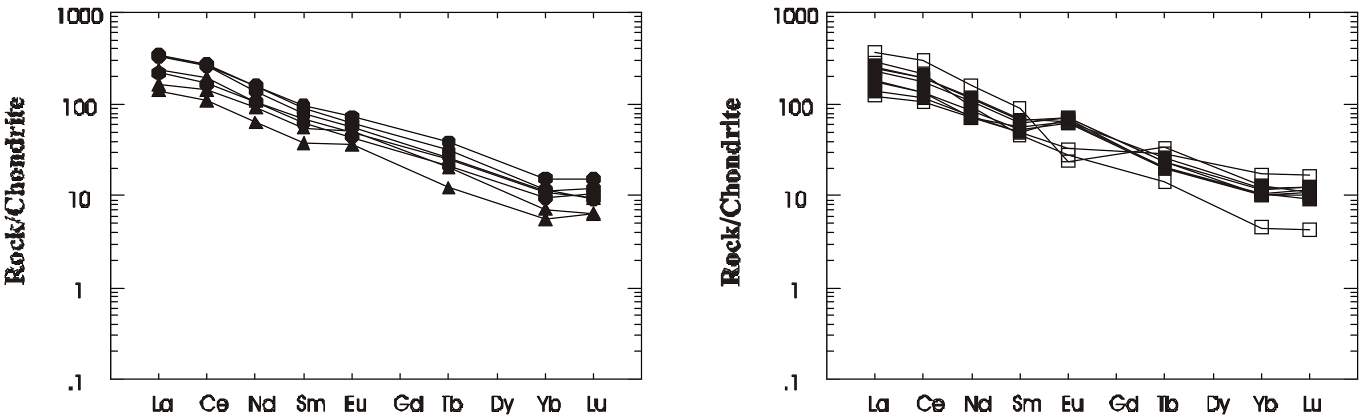

Figure 4 - Chondrite-normalized (Boynton 984) REE-spectra (or patterns) for the rocks of VAIC. Symbols: (▲) opx-gabbro, monzogabbro; (●) diorite/quartz-diorite, quartz-monzodiorite; (■) megaporphyritic granite; (□) charnockitic rocks.

Table 1 - Rb-Sr isotopic selected results for the rocks of the VAIC

Rocks types	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	Erro	$^{87}Sr/^{86}Sr^{(f)}$	Erro	$^{87}Sr/^{86}Sr^{(i)}$	$\varepsilon_{Sr}^{(0)}$	$\varepsilon_{0,55GaSr}$
Quartz-diorite	65.92	952.40	0.1995	0.0028	0.708690	0.000130	0.707126	-	-
Quartz-diorite	53.24	955.61	0.1613	0.0024	0.708330	0.000080	0.707065	47.23	45.66
Quartz-monzonite	50.79	1300.86	0.1130	0.0018	0.707420	0.000130	0.706534	34.32	38.12
Opx-gabbro	15.71	1033.81	0.0440	0.0006	0.707610	0.000080	0.707265	37.02	48.50
Opx-gabbro	34.52	1108.48	0.0901	0.0013	0.707120	0.000130	0.706414	30.07	36.41
Granite	204.20	182.60	3.2440	0.0920	0.731560	0.000160	0.706125	-	32.31
Granite	242.20	155.30	4.5280	0.1280	0.740730	0.000110	0.705228	-	19.56
Granite	159.60	365.60	1.2650	0.0360	0.717530	0.000060	0.707612	-	53.43
Charnockite	109.80	666.20	0.4770	0.0130	0.715390	0.000190	0.711650	147.37	110.80
Charnockite	59.79	665.12	0.2602	0.0037	0.710740	0.000160	0.708700	81.41	68.89
Charnockite	75.61	674.14	0.3262	0.0050	0.711980	0.000120	0.709422	99.01	79.15

Table 2 - Sm-Nd isotopic results for the rocks of the VAIC

Rock types	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$ (error)	$^{143}Nd/^{144}Nd$ (error)	$^{143}Nd/^{144}Nd^{(i)}$	$\varepsilon_{Nd}^{(0)}$	$\varepsilon_{0,55GaNd}$	T_{DM} (Ga)	T_{chur} (Ga)
Quartz-monzonite	16.203	98.014	0.099963 (315)	0.511902 (41)	0.511542	-14.36	-7.56	1.528	1.14
Quartz-diorite	17.071	100.657	0.102553 (343)	0.511925 (37)	0.511555	-13.91	-7.31	1.532	1.15
Opx-gabbro	6.866	41.867	0.099795 (71)	0.512047 (28)	0.511687	-11.53	-4.73	1.329	0.93
Opx-gabbro	11.477	70.094	0.099633 (84)	0.512002 (24)	0.511643	-12.41	-5.59	1.383	0.99
Charnockite	15.694	87.247	0.108774 (343)	0.511889 (37)	0.511497	-14.61	-8.44	1.675	1.29
Charnockite	12.433	70.400	0.106796 (336)	0.511971 (34)	0.511586	-13.01	-6.70	1.527	1.13
Charnockite	15.707	95.212	0.099754 (319)	0.511955 (39)	0.511596	-13.32	-6.51	1.455	1.07

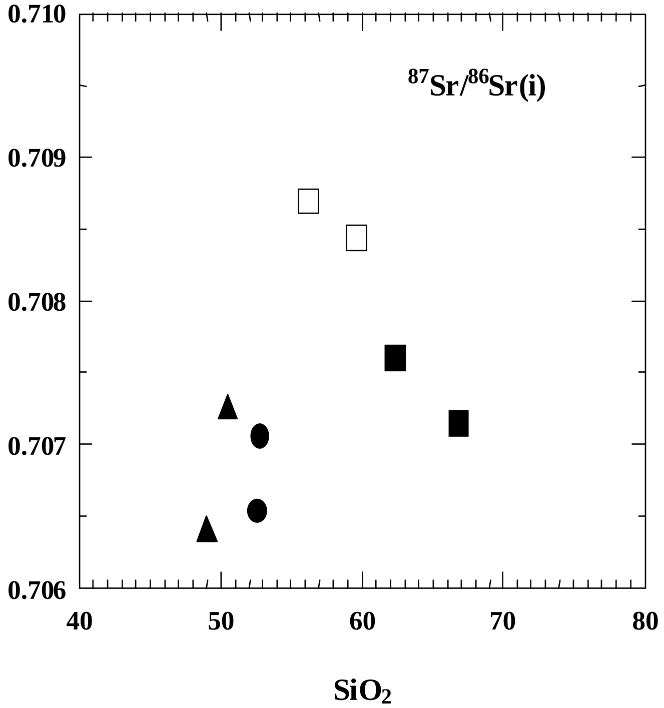

Figure 5 - SiO_2 x initial $^{87}Sr/^{86}Sr$ for the rocks of Várzea Alegre Intrusive Complex. Symbols: (▲) opx-gabbro, monzogabbro; (●) diorite/quartz-diorite, quartz-monzodiorite; (■) megaporphyritic granite; (□) charnockitic rocks.

megaporphyritic granite, which yield an age of 508±12 Ma. ($^{87}Sr/^{86}Sr$ initial ratio of 0.7084). Similar ages (513 Ma, $^{87}Sr/^{86}Sr_i$ = 0.7072) were obtained by Söllner *et al.* (1991) for calc-alkalic post-collisional intrusions from southern Espírito Santo, such as Santa Angélica, Iconha and Mimoso do Sul. A previously assumed crustal contribution for this granite is confirmed by the calculated initial $^{87}Sr/^{86}Sr$ ratio.

The $^{87}Sr/^{86}Sr$ initial ratios, calculated for an age of 550 Ma, plotted against SiO_2 (Fig. 5) plainly separate the basic/intermediate lithotypes, the granites and the charnockitic rocks, which show the highest Sr radiogenic and e550Sr values.

The T_{DM} model age vary from 1.3 Ga (opx-gabbros) to 1.5 Ga (charnockitic rocks). The calculated εNd(t) range from ca. -5.0 (opx-gabbros) to ca. -7.3 (intermediary rocks), and it is ca. -6.5 for the charnockitic rocks. The T_{DM} age versus εNd(t) values represented as lines in the diagram of the Figure 6 exhibit a model Nd isotope evolution for the rocks of VAIC. Janasi *et al.* (1997) obtained similar Mesoproterozoic ages interval for syn-collisional calc-alkaline granitoids from São Paulo and Minas Gerais. They interpreted the results as an important crust-forming event for the area, possible in a subduction environment with lithospheric mantle metassomatism.

The calculated T_{CHUR} model ages for the cogenetic basic and intermediary rocks are around 1.0 Ga. This age is considered more appropriate for the extraction of the parental magma from the mantle, having in mind the enriched geochemical signature of the rocks here studied.

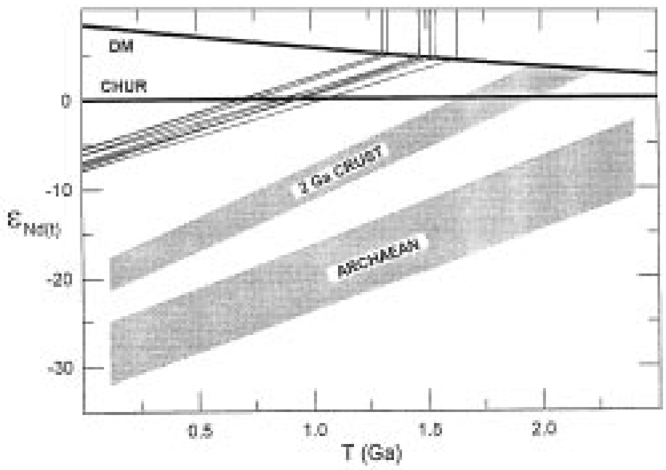

Figure 6 - *εNd vs. T(Ga) diagram showing model Nd isotope evolution for the rocks of VAIC (after De Paolo 988).*

DISCUSSION AND CONCLUSIONS The obtained Rb-Sr isochron for the megaporphyritic granite (508±12 Ma) reflects a crystallization age and confirms the post-collisional emplacement of the inner domain. Field relationships point to an early emplacement of the charnockitic outer shell. U-Pb in zircon yielded crystallization age of 535-520 Ma (Bilal *et al.* 1998) for the same charnockitic suite from the neighboring Ibituba and Itapina massifs, supporting our field inference. The highest Sm-Nd model age (T_{DM}) and εNd(t) values for the intermediary lithotypes, when compared to the opx-gabbro, must imply mixing ages once they are geochemically cogenetic. The εNd(t) of -6.5 and ε550Sr of 79-110 for the charnockitic rocks corroborate the proposal of Mendes *et al.* (1997) who suggested a partial melt of the lower crust induced by an underplating of an enriched basic magma, which was irregularly mixed with the crustal component. The behavior of some incompatible/HFS elements supports this mantle contribution.

Sm-Nd CHUR model age of around 1.0 Ga was calculated for the gabbro and intermediate cogenetic rocks. This age is related to the time when the basic magma was extracted from the mantle, and is here considered as having an important geological significance due to chemical enrichment already mentioned. Another interpretation for this age could be its relation with an episode of mantle enrichment. This episode can be associated to a continental rift phase in the northern part of the Araçuaí Belt, in response to the rising of a mantelic plume (Correa-Gomes and Oliveira 997, Martins-Neto 1998b), and recorded by basic dyke swarm, that yielded ages from ca. 1.05 to 0.9 Ga - U/Pb in zircon (Machado *et al.* 989).

This multistage magmatism records a progressive increase in the amount of mantelic melts mixed with different crustal melts, from around 530 to 490 Ma, suggesting an important mechanism of underplating and crustal delamination during the collapse of the orogen.

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