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Cambro-Ordovician Magmatism in SE Brazil: U-Pb and Rb-Sr Ages, Combined with Sr and Nd Isotopic Data of Charnockitic Rocks from the Varzea Alegre Complex

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Abstract

In the central-southern region of Espírito Santo State, southeastern Brazil, several granitoids with a variable composition intruded high-grade metamorphic rocks, in the northern segment of the Ribeira fold belt. A close relationship between hydrous and anhydrous facies is present in some of the plutons, including the Varzea Alegre Igneous Complex, which has an inner domain formed by gabbro, diorite and granite, and an irregular outer ring of charnockitic rocks. These green megaporphyritic charnockites have primary anhydrous mineral assemblage, I-type and metaluminous character, and high-K calc-alkaline signature. U-Pb zircon single crystal ages obtained by TIMS indicate crystallization at about 500 Ma, similar to other late tectonic plutons of this part of the Ribeira belt. Sr and Nd isotopic ratios ranging from 0.7078 to 0.7096 and 0.5114 to 0.5116 respectively, are interpreted to be indicative of a hybrid origin from crustal and mantle-derived magmas. A binary diagram using Sr isotope ratios also demonstrates that the genesis of the charnockites probably included both magma mixing and fractional crystallization processes.

Key words: Charnockites, anhydrous magma, geochronology, isotope geology, SE Brazil.

Introduction

Hydrous and anhydrous magmatic rock associations with different degrees of preservation of their primary igneous characteristics have received much attention (e.g., Hubbard and Whitley, 1979; Petersen, 1980; Kaiyi et al., 1985; Campos Neto et al., 1988; Janasi, 1992; Kilpatrick and Ellis, 1992; Jordt-Evangelista, 1996; Percival and Mortensen, 2002). Many plutons in which charnockitic rocks are associated with those containing a primary hydrous or hybrid assemblage occur in the central part of Espírito Santo State, SE Brazil (Pedrosa Soares and Wiedemann-Leonardos, 2000). The Varzea Alegre Igneous Complex (VAIC) is a typical example of the late- to post-tectonic Brasiliano magmatism in this region. The pluton is sub-circular with a gabbroic centre surrounded by diorite and granite, and an irregular charnockitic outer ring. The charnockites have orthopyroxene, feldspar and quartz as the primary mineral assemblage. In this article we present new TIMS U-Pb data for single zircon crystals, and Rb-Sr and Sm-Nd whole-rock data for the charnockitic rocks which establish their crystallization age, and reveal a complex origin from mixtures of crust- and mantle-derived magmas.

Geological Setting

The Neoproterozoic Araçuaí–Ribeira belt is part of the Brasiliano-Pan-African orogenic system which among others, also includes the West Congo, Kaoko, Dom

Feliciano, Damara and Gariep belts (Pedrosa Soares et al., 2001). The structural trend in the northern part of the Araçuaí belt is NS, but at its southern boundary the structures inflect to NE-NNE, and south of 21°S the name of the belt changes, by convention, to Ribeira belt (Pedrosa Soares and Wiedemann-Leonardos, 2000; Fig. 1). The geology of Espírito Santo State links the northern part of the Ribeira belt to the Araçuaí belt (Pedrosa Soares and Wiedemann-Leonardos, 2000).

Plutons are an important part of the geological framework of these belts, as is evident from magnetometric surveys (Bosum, 1973) and remote sensing (Meneses and Paradella, 1978). At a late- to post-orogenic stage of the Brasiliano cycle, between 535 and 490 Ma, several complexly-zoned plutons representative of the post-collisional magmatism intruded high-grade amphibolite to granulite facies gneisses (Wiedemann et al., 2002). The VAIC has an outcrop area of 150 km^2 and is located to the northwest of Vitória City (Fig. 1). It belongs to the youngest I-type (G5) suite of plutons and comprises metaluminous, high-K calc-alkaline, orthopyroxene-gabbro to granite, formed in the lower continental crust with an important mantle contribution, implying in P/T conditions of ca. 6 to 7 kbar and 760 to 900°C (Pedrosa Soares and Wiedemann-Leonardos, 2000; Mendes et al., 1999). Its geology, petrography and geochemistry were presented and discussed by Mendes et al. (1997; 1999) and Medeiros et al. (2001). A brief synopsis of these features is provided in the next two sections.

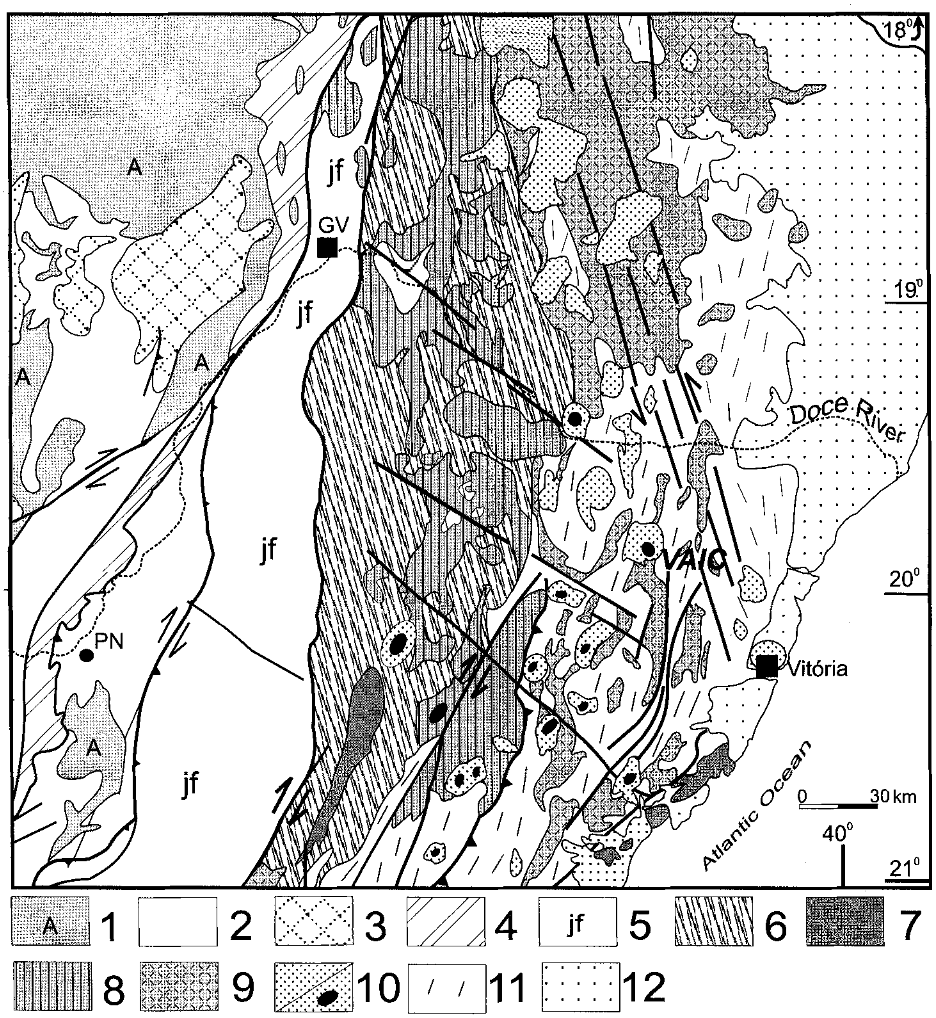

Fig. 1. Geological map of the northern Ribeira/southern Araçuaí Belt and cratonic surroundings (modified from Pinto et al., 1998 and Pedrosa Soares and Wiedemann-Leonardos, 2000). 1–Archean metasedimentary rocks; 2–TTG complexes, with greenstone belt remnants and metasedimentary units; Late Paleoproterozoic and Mesoproterozoic: 3–Paleoproterozoic Borrachudos granitoid suite; 4–Salinas Formation metavolcanic-sedimentary unit (correlated to Dom Silvério Group); 5–Juiz de Fora Complex; 6–Rio Doce Group; 7–Granulite facies domain of Paraíba do Sul Complex. Late Neoproterozoic to Cambrian granitoid suites: 8–I-type G3-I; 9–S-type G3-S and G2 suite. Late Cambrian to Ordovician granitoid suites: 10–I-type G5 (black dots in plutons with mafic cores). 11–High-amphibolite facies domain of Paraíba do Sul Complex; 12–Phanerozoic covers. VAIC–Várzea Alegre Igneous Complex. Cities: GV–Governador Valadares, PN–Ponte Nova, V–Vitória.

Geology of the VAIC

The pluton is inversely zoned from gabbro at the eroded centre to diorite, quartz diorite, monzodiorite and megaporphyritic granite at the border. The gabbro/diorite and megaporphyritic granite are intermingled along contacts, locally generating hybrid quartzdiorite to quartzmonzodiorite. Surrounding this core is a large ring of charnockitic lithotypes including opdalite, jotunite, orthopyroxene-quartz diorite and quartz mangerite (Medeiros et al., 2000; Fig. 2).

The charnockitic rocks are dark green and megaporphyritic. They are foliated at the contact with the host rocks, and become weakly foliated to isotropic inwards. The observed contacts are sharp and parallel to the regional foliation which, together with the foliation in the charnockites, dips inward towards the center of the intrusion. The contacts between the outer ring and the inner core are rarely seen, but where they are visible are also intermingled.

Petrography and Geochemistry of the Charnockitic Rocks

The charnockites essentially consist of plagioclase $An_{65-40}Ab_{32-57}$, perthitic orthoclase $Or_{89-69}Ab_{11-31}$, orthopyroxene $Wo_{1.6-2.5}En_{41.2-30.4}Fs_{57.0-67.4}$, quartz, biotite and

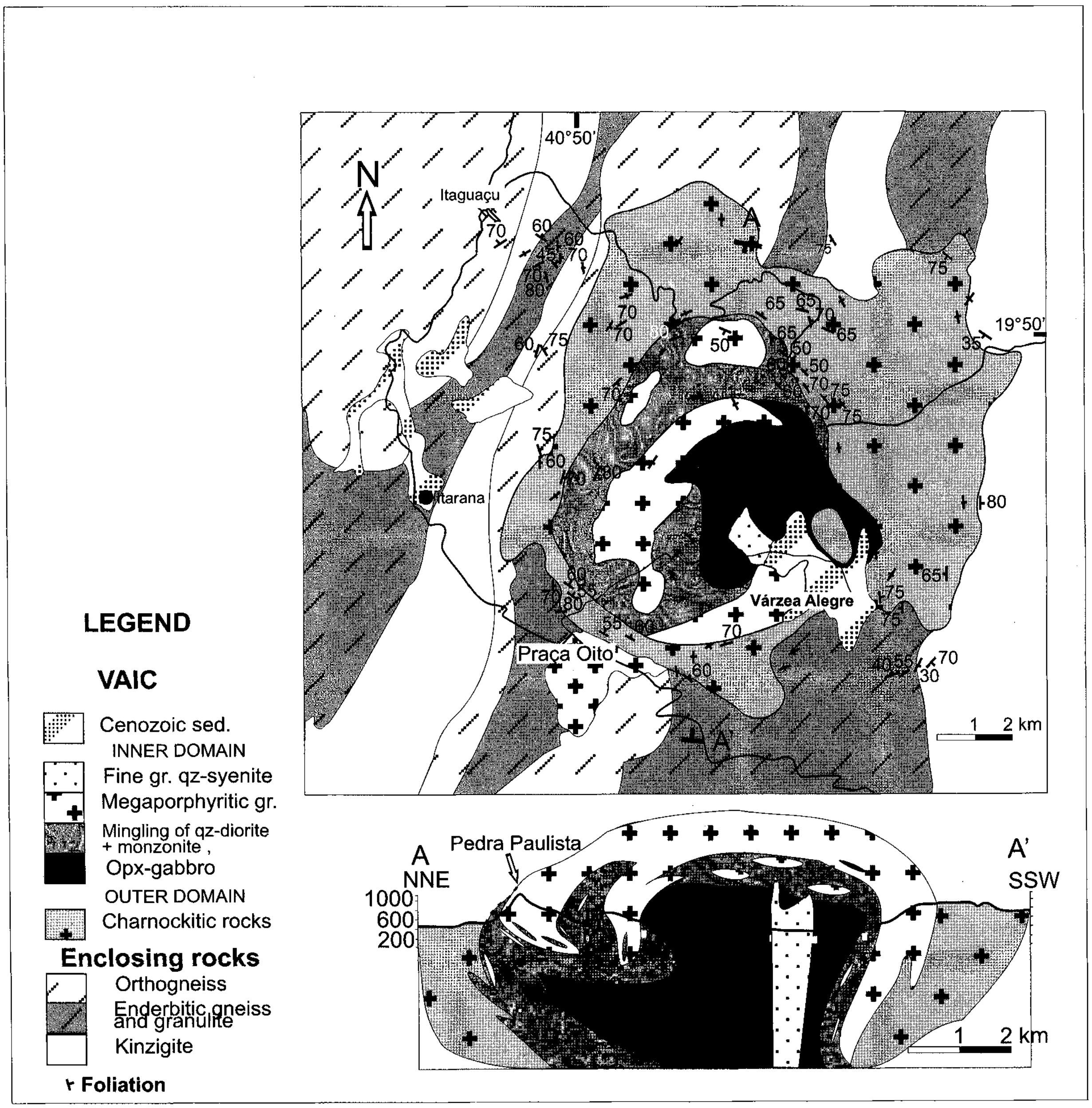

Fig. 2. Geological map of the Várzea Alegre Igneous Complex. Geology of the VAIC from Medeiros et al. (2000) and Tuller (1993).

Mg-hastingsitic hornblende to magnesian hastingsite (Mendes et al., 1999). Accessory minerals are ilmenite, magnetite, pyrite, apatite, zircon and rare allanite and hematite. Porphyritic texture is characterized by plagioclase and alkali feldspar megacrysts up to 6 cm long, set in a medium- to coarse-grained matrix that becomes fine-grained and partially recrystallized where it is compressed against the megacrysts. Bent biotite grains and deformed twin lamellae in feldspar are features developed during weak ductile deformation. Orthopyroxene is partially replaced by biotite, amphibole and opaque oxide minerals, and alters to chlorite and iddingsite. Alkali feldspar replaces plagioclase. The density of perthite lamellae varies, and mesoperthite is locally present. Ilmenite has discrete hematite exsolution lamellae, and is locally intergrown with or being replaced by magnetite. Apatite and zircon occur as inclusions in the principal phases such as feldspars, quartz and biotite, or as small crystals usually associated with the mafic minerals.

Representative analyses of charnockitic rocks from the VAIC are given in table 1. A complete listing can be found in Mendes et al. (1997), or can be obtained on request from the first author. Silica contents range from 54 to 65 wt.%, and the rocks are chemically classified as quartz monzodiorite, quartz monzonite, granodiorite and granite

Table 1. Whole-rock representative geochemical analysis of the VAIC charnockitic rocks.

	VA42	VA164	HR29	VA262	VA244	VA125	VA16	MP161	MP128	VA90	VA264	VA261	MP718	MP173
SiO_2	64.90	64.00	62.40	62.39	61.82	61.00	61.00	60.70	59.90	59.00	57.43	53.99	54.40	53.10
TiO_2	0.94	0.78	1.40	0.89	1.37	1.10	1.30	1.10	1.00	1.50	1.58	1.97	1.90	1.90
Al_2O_3	15.10	16.10	15.30	16.14	14.84	16.10	16.10	17.50	17.20	15.10	15.89	16.58	17.10	16.20
Fe_2O_3	5.57	5.45	7.38	6.45	7.93	6.75	7.08	6.46	7.81	9.30	9.52	11.28	11.20	9.60
MnO	0.11	0.08	0.17	0.15	0.13	0.10	0.12	0.11	0.11	0.14	0.16	0.18	0.18	0.15
MgO	0.99	1.00	1.60	1.02	1.98	2.60	1.70	0.99	1.00	1.80	2.29	2.76	1.80	3.70
Cao	3.60	4.80	3.80	3.64	3.58	3.90	4.50	4.60	4.40	5.00	4.99	6.22	6.60	7.90
Na_2O	3.50	3.50	3.00	3.21	3.01	3.20	3.50	3.50	3.50	3.50	3.39	3.28	3.00	3.20
K_2O	3.60	3.40	3.70	4.14	3.72	3.60	3.10	3.90	4.10	3.40	2.84	2.02	2.40	2.30
P_2O_5	0.42	0.39	0.49	0.39	0.50	0.53	0.44	0.42	0.41	0.66	0.73	0.95	0.86	0.77
LOI	1.40	0.70	0.17	0.63	0.31	0.90	1.20	0.12	0.31	0.60	0.29	0.21	0.35	0.68
Total	100.13	100.20	99.41	99.05	99.19	99.78	100.04	99.40	99.74	100.00	99.11	99.44	99.79	99.50
V	35	31	178	43	88	67	57	122	182	125	106	121	160	216
Zn	101	98	105	102	117	126	130	65	31	134	135	169	58	85
Rb	79	82	110	84	87	91	72	79	110	64	62	36	38	67
Ba	2246	2593	2060	2588	2101	3043	2594	3010	3400	2727	2154	1746	2030	1070
Sr	428	458	510	475	437	518	534	650	531	579	581	677	760	890
Ga	20	23	30	19	19	23	22	—	—	21	21	21	30	28
Nb	36.2	28	50	29.5	33.8	33.2	33.4	30	40	35.2	38.6	46	64	26
Hf	22.3	17.1	—	22	22	22.9	21.8	—	—	18.3	20.5	23	—	—
Zr	819	642	1000	840	767	915	860	940	1000	724	828	1084	1760	600
Y	29	26	50	34	32	32	32	18	25	36	36	36	70	54
XMg	0.26	0.27	0.30	0.24	0.33	0.43	0.32	0.23	0.20	0.28	0.32	0.33	0.24	0.43
K/Rb	378.1	344	279.1	408.9	354.8	328.2	357.2	409.6	309.3	440.8	380	465.6	524	284.8
Rb/Sr	0.18	0.18	0.22	0.18	0.20	0.18	0.13	0.12	0.21	0.11	0.11	0.05	0.05	0.07
La	—	—	111.30	56.18	100.90	—	—	50.07	49.41	—	67.15	70.38	71.36	—
Ce	—	—	190.70	126.90	212.80	—	—	89.96	96.47	—	153.00	159.70	140.10	—
Nd	—	—	88.61	57.67	93.94	—	—	48.98	58.44	—	79.22	82.61	84.96	—
Sm	—	—	12.10	10.50	15.28	—	—	8.10	10.90	—	14.10	14.08	13.60	—
Eu	—	—	3.19	3.54	3.26	—	—	3.80	4.09	—	3.73	3.46	4.32	—
Gd	—	—	8.43	7.21	9.69	—	—	6.15	8.02	—	9.75	9.67	10.19	—
Dy	—	—	4.23	5.04	5.91	—	—	3.80	4.95	—	6.95	6.77	6.16	—
Ho	—	—	0.78	0.94	1.06	—	—	0.66	0.93	—	1.32	1.27	1.15	—
Er	—	—	1.57	2.21	2.24	—	—	1.60	2.52	—	3.20	3.03	2.74	—
Yb	—	—	1.03	1.48	1.33	—	—	1.38	1.91	—	2.28	2.14	2.19	—
Lu	—	—	0.13	0.19	0.15	—	—	0.18	0.26	—	0.27	0.29	0.28	—
REE tot	—	—	422.07	271.86	446.56	—	—	214.68	237.90	—	340.97	353.40	337.05	—
Ce/YbN	—	—	47.90	22.18	41.39	—	—	16.86	13.06	—	17.36	19.30	16.55	—
Eu/Eu*N	—	—	0.92	1.18	0.77	—	—	1.58	1.28	—	0.92	0.86	1.08	—

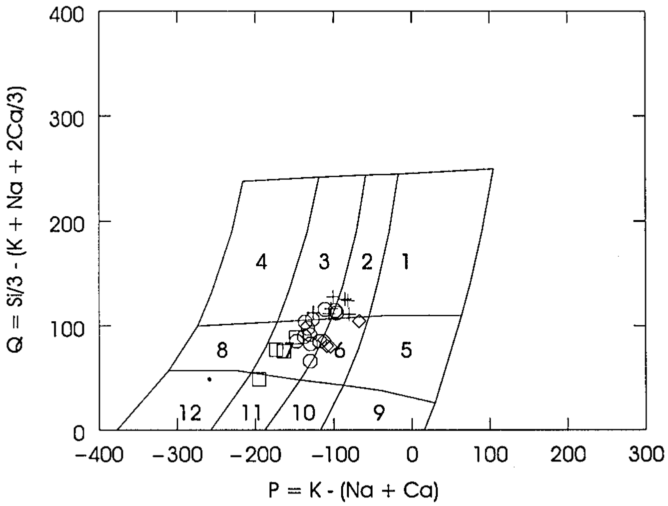

Fig. 3. Q vs. P classification diagram from Debon and Le Fort (1983) for the VAIC charnockitic rocks. Fields: 1–granite; 2–adamellite; 3–granodiorite; 4–tonalite; 5–quartzsyenite; 6–quartzmonzonite; 7–quartzmonzodiorite; 8–quartzdiorite; 9–syenite; 10–monzonite; 11– monzogabbro; 12–gabbro.

(Fig. 3). The charnockitic rocks are metaluminous and have a high-K calc-alkaline character. They have high Ti, P, Zr, Ba and REE contents, moderately high K and Fe contents, and low Mg, Al and V contents when compared to typical calc-alkaline granitoids (Mendes et al., 1997). Trends in Harker diagrams are coherent, and demonstrate the calc-alkaline nature of the rocks (Fig. 4). Ti, Fe, Mg, Ca, P, Sr and V behave as compatible elements, while Na, K, Rb and Ba are incompatible. Very high Al, Ca, Sr, Ba and K contents found in some samples were associated with a possible feldspar accumulation by Mendes et al. (1997). Microprobe analyses of feldspars containing high K, Ba and Sr concentrations are given in Mendes et al. (1999). Many of the geochemical features may be attributed to a hybrid origin from mantle-derived magmas and crustal melts, and fractional crystallization combined with magma mixing has been suggested as the cause of differentiation of the charnockitic suite (Mendes et al., 1997).

Geochronology and Isotope Geology

U-Pb data ages from non-abraded zircons, for rocks of the charnockitic ring were obtained by isotope dilution/TIMS at the Laboratory of Geochronology of the University of Brasília. The analytical procedures were those presented by Laux et al. (2004). Four single grain zircons were selected and the results are given in table 2. A concordia age of 498.6±4.9 Ma was obtained for the zircon grains (Fig. 5).

Rb-Sr and Sm-Nd whole-rock data were obtained for eleven and six samples, respectively, at the Geochronological Research Centre of the Institute of Geosciences, University of São Paulo. The Rb-Sr methodology is described in Kawashita (1972) and the Sm-Nd analyses followed the description presented by Sato et al. (1995). The results are shown in tables 3 and 4 and a model age of 500 Ma was used to calculate initial isotope compositions.

High strontium isotopic ratios $(^{87}Sr/^{86}Sr)_i$ and ε_{Sr}(550 Ma), ranging from 0.7087 to 0.7116 and 68.89 to 110.80, respectively, were preliminarily interpreted by Medeiros et al. (2000) as a result of crustal component participation. Additionally, the 1/Sr vs. $(^{87}Sr/^{86}Sr)i$ graph (Fig. 6A) shows that two arrays can be distinguished. One, parallel to the x axis, can be attributed to fractional crystallization from a single magma. An isochron age of 500±12 Ma with $(^{87}Sr/^{86}Sr)i$ = 0.70855 is obtained for these rocks (Fig. 6B). The other steeply inclined array could be produced by magma mixing between a less radiogenic, perhaps enriched mantle-derived magma, and more radiogenic, crustally derived magma.

Comparing the samples analyzed for Sm-Nd (Table 4) with those plotted in the diagram of figure 6A, it is clear that they belong to the fractional crystallization group. Four of them show considerable ε_{Nd}(500) variation from −13.97 to −15.59 (samples VA-90, 125, 261 and 257). Whereas these values indicate strong crustal influence, the range should not be associated only with a simple

Table 2. U-Pb in zircon analytical results of the VAIC charnockitic rocks. (1) Total U and Pb concentrations corrected for analytical blank; (2) not corrected for blank or non-radiogenic Pb; (3) radiogenic Pb corrected for blank and initial Pb/U corrected for blank; (4) ages given in Ma using decay constants recommended by Steiger and Jäger (1977).

	Concentrations (1)			Observed (2)		Atomic Ratios (3)					Ages (Ma) (4)		
Fraction/ number of grains	Weight (mg)	U (ppm)	Pb (ppm)	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{235}U$	Error (%)	$^{206}Pb/^{238}U$	Error (%)	$^{207}Pb/^{206}Pb$	Error (%)	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
VA04E/3	0.039	92	9	184	0.639223	2.69	0.080905	2.52	0.057302	0.87	501	501	503
VA04C/3	0.029	119	14	125	0.651021	2.92	0.082104	2.33	0.057508	1.65	508	509	511
VA043/1	0.055	112	10	328	0.627122	1.65	0.079221	1.47	0.057412	0.71	491	494	507

Analyzed zircons are pale rose, clean, long and prismatic.

Table 3. Rb-Sr isotopic analyses of the VAIC charnockitic rocks.

Sample	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	Error	$^{87}Sr/^{86}Sr$	Error	$(^{87}Sr/^{86}Sr)i$	ε (0)	ε (0.5 Ga)
VA-04	55.25	610.87	0.2618	0.0037	0.71074	0.00011	0.708875	88.57346	70.51839
VA-257	59.79	665.12	0.2602	0.0037	0.71074	0.00016	0.708886	88.57346	70.68035
VA-249B	54.20	675.20	0.2324	0.0036	0.71026	0.00011	0.708604	81.76011	66.67533
VA-249C	75.61	674.14	0.3262	0.0050	0.71198	0.00012	0.709656	106.1746	81.61543
VA-90	64.00	579.00	0.3199	0.0015	0.71080	0.00002	0.708521	89.42512	65.48923
VA-125	91.00	518.00	0.5085	0.0012	0.71223	0.00001	0.708607	109.7232	66.71384
VA-261	36.00	677.00	0.1539	0.0014	0.70963	0.00001	0.708534	72.81760	65.67343
VV-1751	82.70	591.90	0.4000	0.0100	0.71160	0.00120	0.708750	100.7807	68.74669
VV-1752	41.90	514.30	0.2400	0.0100	0.70980	0.00100	0.708090	75.23066	59.37111
VV-1756	54.90	545.40	0.2900	0.0100	0.71060	0.00070	0.708534	86.58623	65.67498
VV-1759	47.60	552.60	0.2500	0.0100	0.70960	0.00100	0.707819	72.39177	55.51760

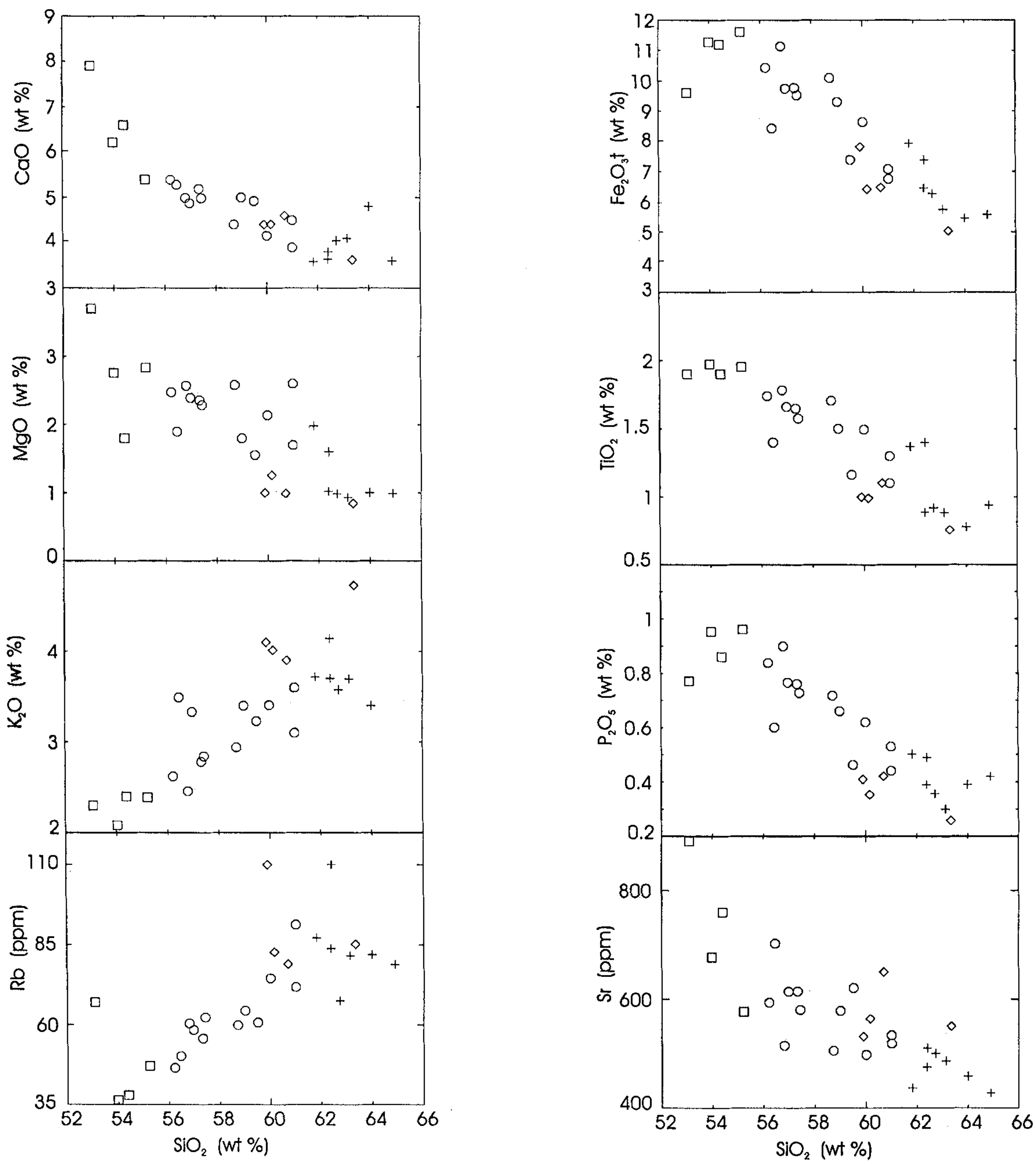

Fig. 4. Harker diagrams of the VAIC charnockitic rocks. Symbols: □ opx-quartz diorite, O jotunite, + opdalite, ◇ quartz mangerite.

Table 4. Sm-Nd isotopic results for the VAIC charnockitic rocks.

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	Error	$^{143}Nd/^{144}Nd$	Error	$(^{143}Nd/^{144}Nd)i$	ε (0)	T_{DM} (Ga)	ε (0,5 Ga)
VA-90	13.786	76.433	0.1091	0.0004	0.511922	0.000016	0.511565	–13.97	1.631	–8.3805
VA-125	12.544	69.351	0.1094	0.0004	0.511897	0.000010	0.511539	–14.45	1.672	–8.8880
VA-261	16.451	89.933	0.1106	0.0004	0.511839	0.000010	0.511477	–15.59	1.779	–10.098
VA-257	15.694	87.247	0.1088	0.00034	0.511889	0.000037	0.511533	–14.61	1.675	–9.0059
VA-249	12.433	70.400	0.1068	0.00034	0.511971	0.000034	0.511621	–13.01	1.527	–7.2764
VA-04	15.707	95.212	0.0997	0.00032	0.511955	0.000039	0.511628	–13.32	1.455	–7.1347

fractional crystallization process. It could also be obtained by the involvement of a mixed component. However, the samples VA-04 and VA-249 have similar $\varepsilon_{Nd}(500)$ values (–13.01 and –13.32) and Sr isotopic ratios close to that of the fractional crystallization trend shown in figure 6A.

T_{DM} model ages are in the range 1.46–1.78 Ga, with a mean value of 1.63 Ga. Except for the oldest values, these model ages are also found in other granites and host rocks in the region. However, they do not correspond to any known orogeny, magmatic, tectonic or metamorphic event in the region, and probably represent source mixing ages. The average T_{CHUR} value is 1.1 Ga, a model age roughly coincident with the age of the initial continental rifting that preceded the opening of a branch of the Adamastor-Brasilide ocean at around 817 Ma (Pedrosa-Soares et al., 1998, 2001). The T_{CHUR} age may therefore reflect a mantle recharge or mantelic contamination episode accompanying the mantle upwelling leading to rifting.

Discussion and Conclusions

The coincidence with in error of the TIMS-U/Pb and Rb-Sr isochronic data for the charnockitic rocks of the VAIC indicate that their crystallization age is very similar to a Rb-Sr whole-rock isochron age of 508±12 Ma found by Medeiros et al. (2000) for the VAIC megaporphyritic granite. The $(^{87}Sr/^{86}Sr)i$ value of 0.7084 confirms the important crustal contribution to these rocks. An earlier view that the charnockite ring was emplaced well before the inner granites (Medeiros et al., 2000) is now refuted

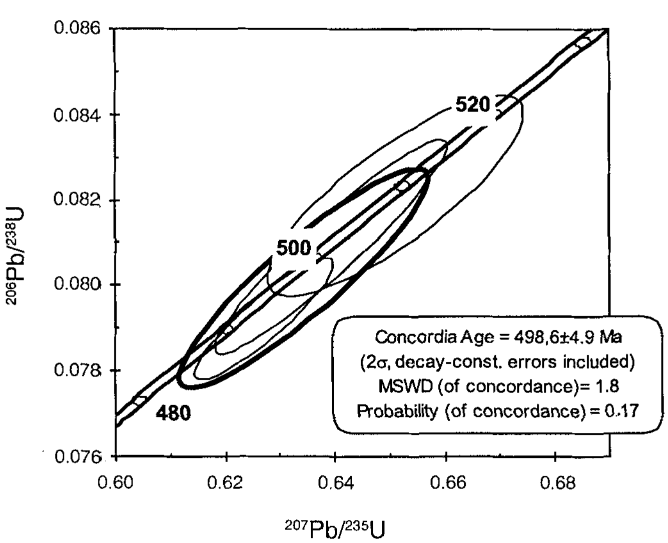

Fig. 5. U-Pb concordia diagram for zircon grains of the VAIC charnockitic rocks.

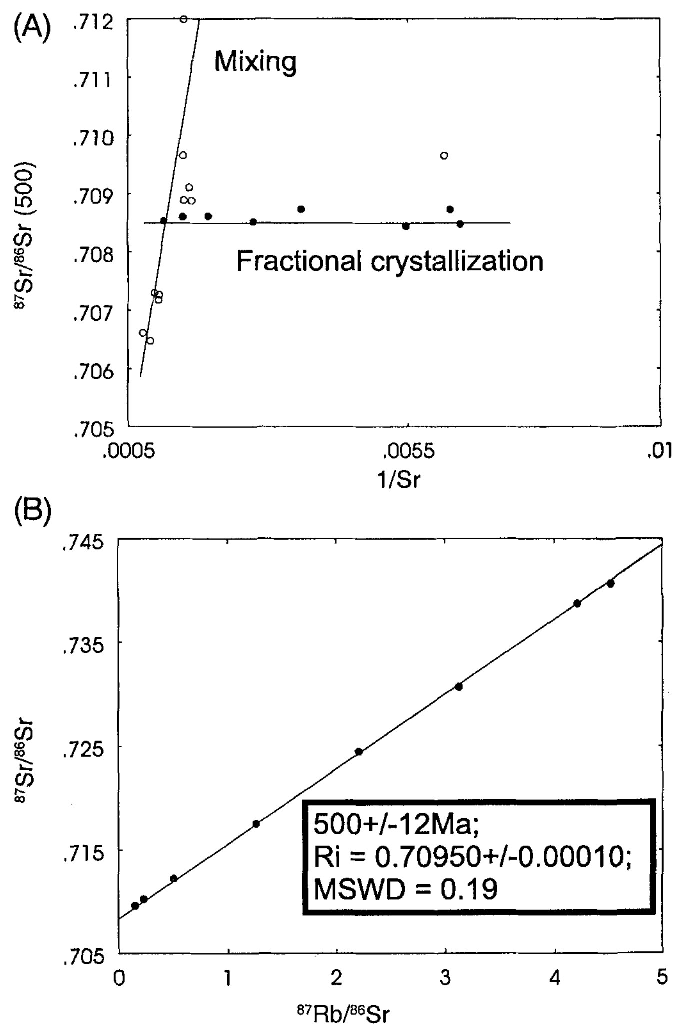

Fig. 6. (A) 1/Sr vs. $^{87}Sr/^{86}Sr$ (500) diagram of the VAIC charnockitic rocks; (B) Rb-Sr whole-rock isochron diagram of the VAIC charnockitic rocks.

by the new ages. The intermingled contact relationships between the core rocks and the charnockitic ring can be explained by penecontemporaneous injection of contrasting magmas in separate pulses over a short time interval.

The ages obtained are similar to those found for other post-tectonic intrusions in the northern Ribeira Belt (Wiedemann et al., 2002), such as Santa Angélica and Mimoso do Sul with conventional U-Pb zircon ages of 513±8 Ma and 480±4 Ma, respectively (Söllner et al., 2000), and Pedra Azul with a Rb-Sr whole-rock isochron age of 536±31 Ma (Platzer, 1997). An almost concordant single zircon from the Aimorés charnockite pluton yielded a U-Pb age of 500 Ma reported by Mello (2000), who also obtained a lower concordia intercept of 498.6±35.6 Ma. The upper concordia intercept is imprecisely defined, but the discordance suggests that these rocks have an older inherited component.

Based on major and trace elements behavior, Mendes et al. (1997) suggested a combination of fractional crystallization and magma mixing processes for the petrogenesis of the VAIC charnockitic suite. The present isotopic data confirm this proposal. The lower radiogenic component of the VAIC may not represent the most primitive magma involved, but has characteristics similar to Brasiliano mafic rocks in the region, such as LIL and HFS element enrichment and high $(^{87}Sr/^{86}Sr)_i$ ratios. These features have been attributed to the presence of an enriched mantle (Ludka et al., 1998; Gimenez Filho et al., 2000). An exclusively crustal origin for the studied charnockites should be viewed with caution, and an important mantle contribution must be considered as an alternative (Mendes et al., 1999).

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