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Geology, Petrology and Magmatic Evolution of the Felsic Alkaline Rocks of the Vitória Island, São Paulo State, Brazil

Geologia, Petrologia e Evolução Magmática das Rochas Alcalinas Félsicas da Ilha de Vitória, São Paulo, Brasil

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Abstract

This paper presents geological, petrographic, geochemical characteristics and radiometric ages for the felsic alkaline rocks of the Vitória Island Intrusive Complex, São Paulo State, Brazil, and discusses its geochemical evolutionary processes. This intrusive body is about 3 km in diameter and the emerged island areas correspond to its northeastern border. The main intrusion is constituted by nepheline syenite at the central zone, nepheline-bearing syenite at the outer zone, syenite at the border, and quartz syenite at the contact zone with alkali feldspar represented by orthoclase. Clinopyroxene vary from hedenbergite, soda-augite to aegirine-augite, and some crystals have resorption shape and amphibole reaction rim. They are intruded by phonolite, trachyte and lamprophyre dykes. Based on the intrusion relation, the dykes are subdivided into two generations: the first one encompass a radial system and the second a parallel system with NE-SW orientation and sinistral displacement. The alkaline rocks vary from silica undersaturated to oversaturated, show peralkaline to peraluminous compositions and belong to the potassic series. The K-Ar ages for amphibole of the nepheline-bearing syenite and syenite are 89.58 ± 3.18 Ma and 84.35 ± 3.92 Ma, respectively. The rocks are strongly fractionated with high differentiation index (DI) of 88.15 in average, indicating mafic minerals fractionation. $K_2O/(K_2O+Na_2O)$ ratios are low, in average 0.51, in accordance to crystallization of pseudo leucite and potassic feldspar the last observed in thin sections.
Keywords: Vitória Island; Nepheline Syenite; Syenite; Fractional Crystallization

Resumo

Este trabalho apresenta as características geológicas, petrográficas e geoquímicas das rochas alcalinas do Complexo Intrusivo da Ilha de Vitória, SP, bem como as datações radiométricas, e discute processos da evolução geoquímica do magma. O corpo intrusivo tem em torno de 3 km de diâmetro e as áreas emersas das ilhas correspondem à borda nordeste do corpo intrusivo. A intrusão principal é constituída por nefelina sienito na parte central, sienito com nefelina na parte externa, sienito na borda e sienito com quartzo na zona de contato cujo feldspato alcalino é o ortoclásio. O clinopiroxênio tem composição variando de hedenbergita, soda-augita a aegirina-augita e, alguns cristais apresentam-se reabsorvidos e bordas de reação de anfibólio. Essas rochas são intrudidas por diques de fonolito, traquito e lamprófiro. Conforme a relação intrusiva, os diques são subdivididos em duas gerações. A primeira geração forma um sistema radial e, a segunda, um sistema paralelo com orientação NE-SW e deslocamento sinistral. As rochas alcalinas variam de subsaturadas a supersaturadas em sílica, são peralcalinas a peraluminosas e pertencem à série potássica. As idades K-Ar para anfibólio do álcali sienito com nefelina e do álcali sienito são, respectivamente, 89.58 ± 3.18 Ma e 84.35 ± 3.92 Ma. As rochas são fortemente fracionadas e o índice de diferenciação é alto, em média 88.15, indicando fracionamento de minerais máficos. A proporção $K_2O/(K_2O+Na_2O)$ é baixa, em média 0.51, sugerindo possível cristalização de leucita e feldspato potássico, como observado nas lâminas petrográficas.
Palavras-chave: Ilha de Vitória; Nefelina Sienito; Sienito; Cristalização Fracionada

1 Introduction

In the coastal region of southeast Brazil, Cretaceous to Early Cenozoic felsic alkaline intrusive bodies represent an expressive magmatic event called Serra do Mar Magmatic Province (Figure 1). They are constituted mainly of nepheline syenite, syenite, phonolite and trachyte with local occurrences of subvolcanic breccia and lamprophyre dykes.

The alkaline intrusive bodies form three magmatic alignments: A) Poços de Caldas - Cabo Frio with ESE-NEW trend; B) Mendanha - Morro de São João with ENE-SWS trend; C) Monte de Trigo - Vitória Island with ENE-SWS trend. The former two alignments were proposed in a very close region and nowadays, only the Poços de Caldas - Cabo Frio Alignment (Almeida, 1976; Sadowski & Dias Neto, 1981; Thomáz-Filho & Rodrigues, 1999) has been cited in the literature.

Herz (1977) and Thomáz-Filho & Rodrigues (1999) interpreted that the Poços de Caldas - Cabo Frio Alignment would continue to the Vitória-Trindade Chain, forming a single hot-spot track. However, the absolute motion of the South America Plate is NW to NNW (O'Connor & Roex, 1992; Steinberger, 2000), which is widely different from the alkaline rock trends, about E-W. Therefore, it is not considered as resulted from hotspot tracks (Skolotnev *et al.*, 2010) although recent works present evidences of possible mantle plume contribution to their genesis (Santos, 2013, 2016; Bongiolo *et al.*, 2015; Pires *et al.*, 2016). Although both magmatic chains have parallel layout, they are separated from each other about 380 km (Motoki *et al.*, 2012 a), and do not form a single continuous chain (Sichel *et al.*, 2012). In addition, felsic alkaline rocks, such as nepheline syenite, constitute the Poços de Caldas-Cabo Frio whereas the Vitória–Trindade is mainly composed by ultramafic rocks such as basanite and nephelinite, possibly influenced by crustal thickness and chemical composition variation (continental and oceanic crusts environments).

The Intrusive Complex of the Vitória Island is situated at the easternmost part of Monte de Trigo - Vitória Island felsic alkaline rock alignment (Motoki, 1986). The rocks of this alignment have some differences from those of the Poços de Caldas-Cabo Frio one. The intrusive ages of the former range from 80 to 90 Ma, which are slightly older than the latter (55 to 72 Ma, according to Sonoki & Garda, 1988; Motoki *et al.*, 2010; 2012 b). Vent-filling subvolcanic pyroclastic bodies are common in the latter (Motoki & Sichel, 2006; Motoki *et al.*, 2008 b; c; Sichel *et al.*, 2008) but it does not occur in the former.

The aforementioned intrusive bodies present gradual transition from silica-oversaturated rocks to

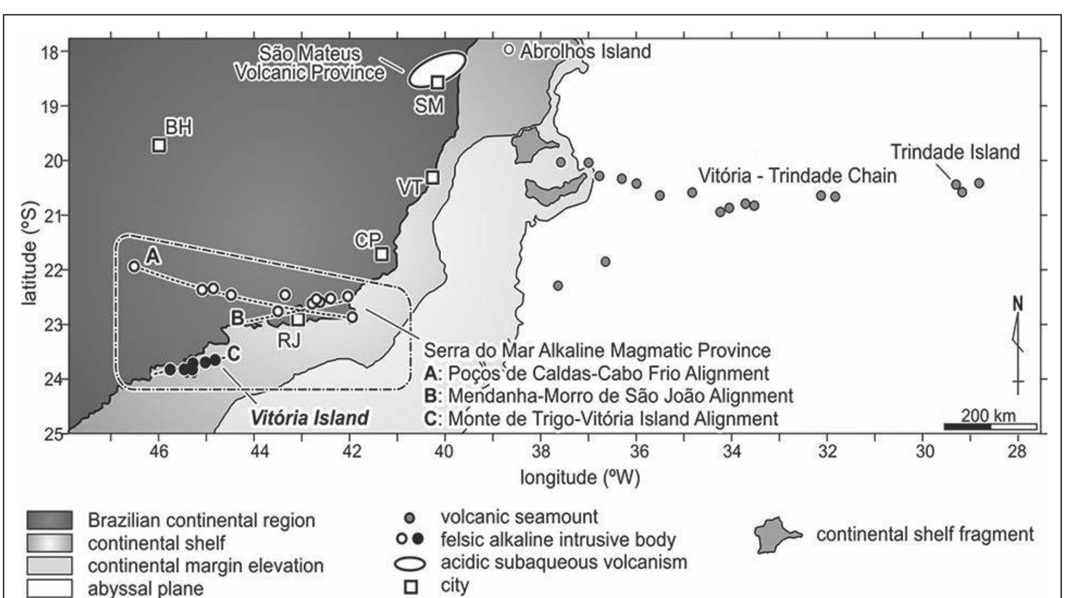

Figure 1 Alkaline magmatic rocks alignments of Southeastern Brazil, after Motoki *et al.* (2012 a). RJ - Rio de Janeiro; CP - Campos; BH - Belo Horizonte; VT - Vitória; SM - São Mateus.

undersaturated in the same intrusive body, hypothetically crossing over the thermal divide, which is a controversy subject.

Bonin (1990) stated that during magma ascent and solidification, water content from wall rocks may play an important role in the melt changing its composition, moving from undersaturated to over-saturated alkaline melts. Higher initial Sr isotopic ratio is also related to crustal contamination in Evisa Complex in Corsica where crossing over thermal divide is related to a set of magmatic changes beyond F-rich fluids migration (Bonin, 1990).

According to literature, magma can cross over thermal divide under some conditions such as continental crust assimilation/contamination, water and fluids content (F, Cl, CO_2, for example). Motoki (1986) showed, for analyzed rocks from Vitória Island, high chlorine, carbonate and fluor contents and high water content, compared to North Nyasa Alkaline Province of Malawi (Eby *et al*., 1998). Water-rich fluids are less effective in REE fluid-melt partition coefficient. Observing the REE content in analyzed rocks we can state that water played an important role in the evolution of undersaturated to oversaturated rock.

This paper presents geological, petrographic, geochemical characteristics and radiometric ages of the Vitória Island felsic alkaline intrusive body, located at São Paulo state, Brazil.

2 Geologic Setting

The Archipelago of Vitória Island is situated at 23°45'S and 45°01'W, about 35 km to the south of Ubatuba city and 35 km to the east of Ilha Bela city, at the North Coast of the São Paulo State, Brazil. It consists of the main island and two small islets: Vitória Island, Pescador Island and Cabras Island (Figure 2). They are composed mainly by syenitic rocks (Figure 3A). The nepheline syenite and nepheline-bearing syenite occur in the southwestern portion of the body. The quartz-bearing syenite showing strongly deformed host rock enclaves is observed locally at the northeastern domain, in the border of the intrusion. The ring-like shape of the structure indicates that the main intrusive body has semi-circular form. Similar structure is observed also in Tanguá (Motoki *et al*., 2010) and Cabo Frio Island (Motoki *et al*., 2012 b) intrusive bodies of the Poços de Caldas-Cabo Frio Alignment. The grain size is homogenous, about 4 mm, but at the contact zone it becomes smaller, about 3 mm. The nepheline-bearing rocks are grey in colour, but syenite and quartz syenite are dark blue changing into dark green due to oxidation.

The main syenitic body is cut by numerous dykes of phonolite and trachyte composition (Figure 2). According to the intrusive relation, they are divided into two generations: 1) The first generation of dykes forms a radial system (Figure 3B); 2) The second-generation constitutes a parallel system (Figure 3C). The center of the radial dykes corresponds approximately to the main syenitic body, suggesting the intrusion WAS caused by hydraulic tensile fracturing (e.g. Hubbert & Willis, 1957; Nicolas & Jackson, 1982; Motoki & Sichel, 2008). The parallel dykes have NE-SW orientation. They show 'en-echelon' pattern and sinistral strike-slip displacement, reforcing a hydraulic shear fracturing mechanism (e.g. Phillips, 1974; Motoki *et al*., 2008c; 2009). Some dykes of lamprophyre composition were also observed (Figure 3D).

3 Petrographic Characteristics

The syenitic rocks are composed mainly of alkali feldspar (~80-90% in mode), nepheline (<11%), clinopyroxene, amphibole, and biotite. Some rare samples contain small amount of quartz (<3%). The accessory minerals are magnetite, ilmenite, apatite and analcime. Orthoclase is xenomorphic characterised by interlocking perthite (Figure 4A). The nepheline-bearing rocks sometimes show antiperthite patches. The nepheline is xenomorphic and often altered into analcime and cancrinite (Figure 4B). The modal content is generally lower than 10 vol. %. Only in a small area in the inner portion of the main body nepheline syenite occurs. The outer domain of the body is constituted by nepheline-bearing syenite, so-called pulaskite. The border zone is made up of syenite without nepheline and quartz. At the contact zone, there is alkaline syenite with small amount of xenomorphic quartz, so-called nordmarkite.

The syenitic rocks are leucocratic with mafic minerals content less than 10%. The clinopyroxene is green to light yellow in colour, with extinction angle of about 45°, suggesting an augite composition. Some crystals have resorption shape and amphibole reaction rim (Figure 4C). Similar characteristics are also observed in clinopyroxene from Cabo Frio

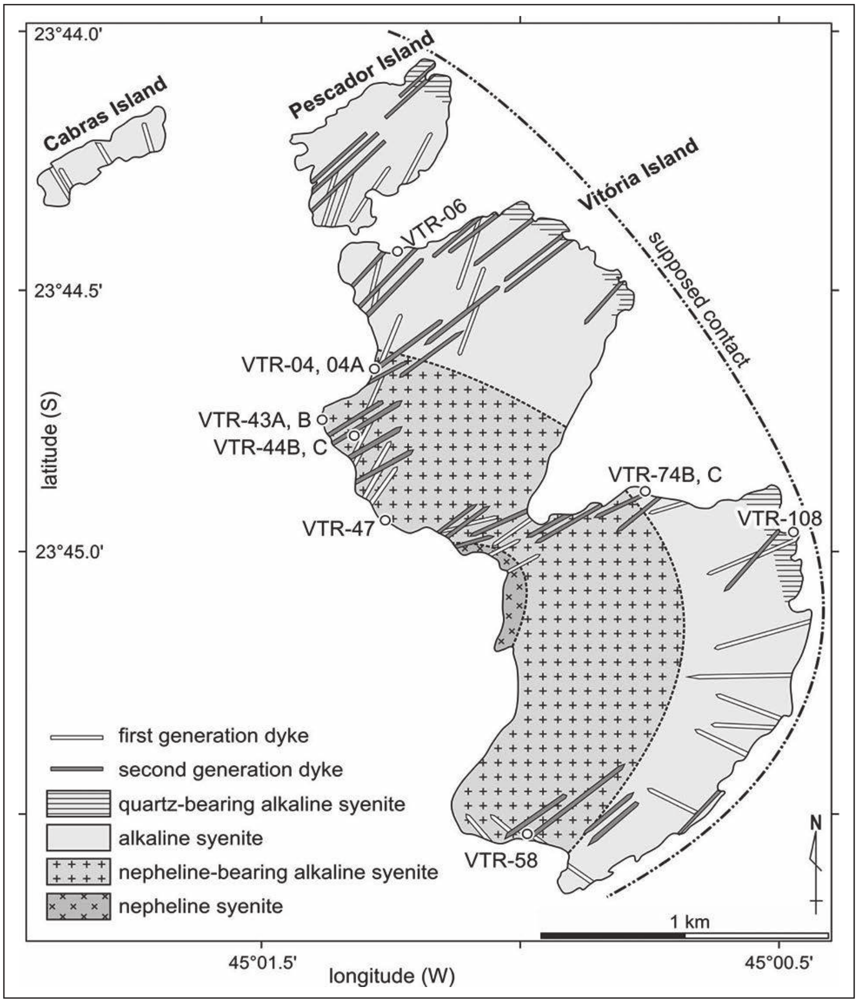

Figure 2 Geologic map of the Vitória Island Intrusive Complex (Motoki, 1986; Woolley, 1987). VTR represent locations where rock samples were collected in the Vitória Island.

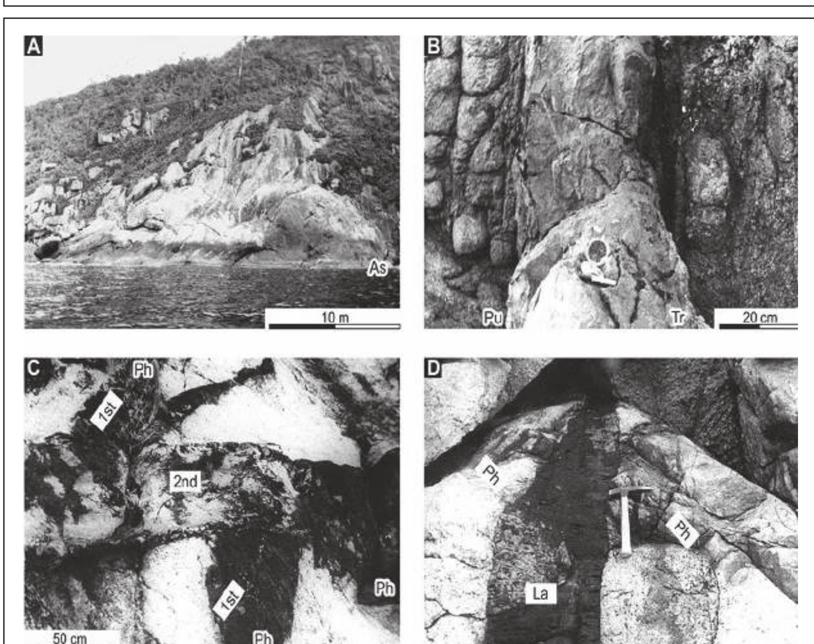

Figure 3 Alkaline rocks of the Vitória Island Intrusive Complex, São Paulo state, Brazil: A) Alkaline syenite (As), VTR-108 (Figure 2); B) Trachyte dyke with strong deuteric alteration (Pu - pulaskite), (Tr - trachyte), VTR-43B; C) Second generation phonolite dyke (2nd, VTR-74B) cutting first generation one (1st, VTR-74A); D) Second generation lamprophyre dyke (La, VTR-44C) cutting first generation phonolite dyke(Ph, VTR-44B). As - syenite; Pu - nepheline--bearing syenite (pulaskite); Tr - trachyte; Ph - phonolite; La - lamprophyre.

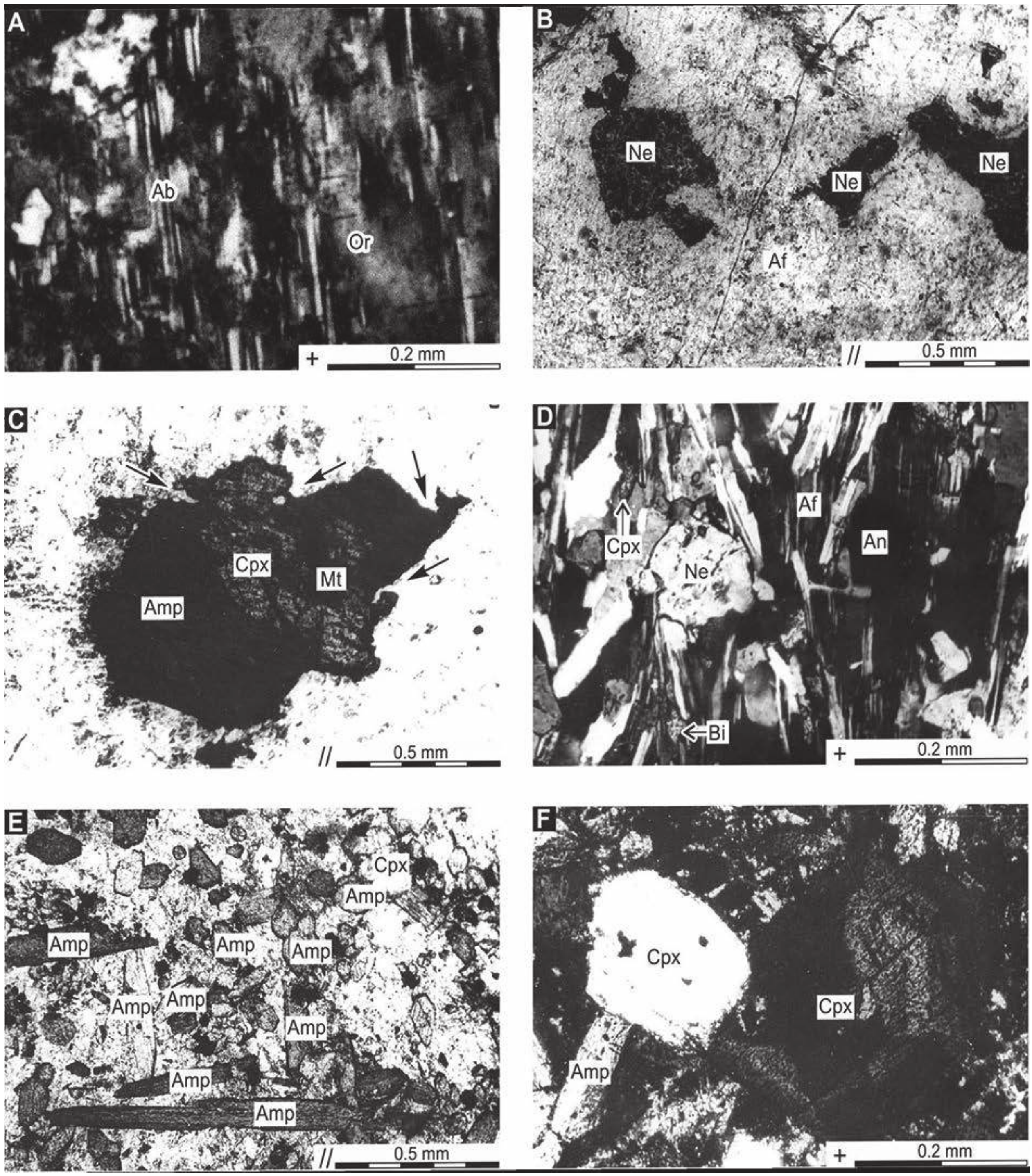

Figure 4 Microscopic aspects of the alkaline rocks of the Vitória Island body: A) Interlocking perthite of quartz-bearing syenite, VIT-06 (Figure 2); B) Nepheline coloured by methylene blue, VTR-43A; C) Reaction rim of amphibole around clinopyroxene crystal, VTR-04A; D) Trachytic texture; E) Cumulate texture of lamprophyre with kaersutite (Amp), VTR-58; F) Titano-augite (Cpx) of the lamprophyre, VTR-58. Ab - sodic lamellae of the perthite; Or - Orthoclase; Ne - nepheline; Cpx - clinopyroxene; Amp - amphibole; Mt - magnetite; An - analcime; Bi - biotite. Af – alkali feldspar.

Island Intrusive Body (Araújo, 1995; Motoki *et al.*, 2012 b). The amphibole is brown to brownish/red suggesting that the composition must be close to barkevikite. Some idiomorphic crystals present short prismatic shape suggesting that they are pseudomorph after clinopyroxene. The rocks present biotite in brown to yellow-brownish colour besides idiomorphic magnetite and ilmenite crystals with ca. 0.3 mm in size and some grains showing resorption. Euhedral apatite with size from 0.1 to 0.5 mm is scattered all over the matrix.

The fine-grained felsic rocks are characterized by well-developed trachytic texture showing microcrystalline groundmass and alkali feldspar microlites (Figure 4D). However, the central part of the dykes has a width of up to 1 m being composed of rocks with interstitial texture and alkali feldspar framework. The clinopyroxene phenocrysts are strongly green with extinction angle of ca. 20° suggesting they are aegirine-augite. Phenocrysts of alkali feldspar, amphibole, and biotite are also observed.

The lamprophyre is composed by titano-augite and long prismatic kaersutite crystals (Figures 4E, F).

4 Geochemical Classification of the Alkaline Rocks

The whole-rock chemical analyses of the Vitória Island samples have been performed at the Geochemical Laboratory of the GeoSol™ S.A., Belo Horizonte, Minas Gerais State, Brazil, using ICP atomic emission (ICP-AES) and atomic absorption spectrometry (AAS) according to the methodology described in Hoffman (1992). The results are presented in Table 1.

Figure 5 shows the geochemical classification of the rocks on SiO_2 vs. Na_2O+K_2O diagram based

	Syenite						
wt%	VTR-6	VTR-26	VTR-31	VTR-37	VTR-78	VTR-80	VTR-81A
SiO_2	60.60	62.00	61.80	60.60	59.40	60.70	60.40
TiO_2	0.70	0.84	0.75	0.71	0.70	0.61	0.88
Al_2O_3	17.6	17.4	17.1	17.5	18.1	18.9	17.0
Fe_2O_3	1.92	1.90	1.80	2.20	2.50	2.60	2.60
FeO	3.21	3.85	3.85	3.21	3.21	2.42	3.56
MnO	0.17	0.15	0.14	0.15	0.16	0.13	0.28
MgO	0.66	0.83	0.66	0.65	0.72	0.63	0.64
CaO	2.00	2.40	2.10	2.20	2.30	2.00	2.40
Na_2O	5.90	4.40	4.90	6.40	6.30	5.30	6.20
K_2O	6.90	5.80	6.30	6.00	6.10	6.30	5.60
P_2O_5	0.22	0.21	0.23	0.20	0.23	0.15	0.26
Total	99.88	99.78	99.63	99.82	99.72	99.74	99.82
ppm							
Cr	<2	<2	<2	<2	<2	<2	<2
Ni	12	12	12	11	<5	20	11
V	<5	17	40	<5	20	84	<5
Rb	77	72	77	79	90	115	114
Sr	100	296	188	370	300	400	300
Ba	1150	2300	1520	1800	2100	3100	1800
Zr	104	110	280	350	444	204	264
Y	<10	15	25	36	28	42	50
Nb	<20	32	64	73	70	82	94
Th	<30	<30	<30	<30	<30	<30	<30
U	<30	<30	<30	<30	<30	<30	<30
Cu	<5	<5	<5	<5	<5	<5	<5
Pb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	<200	<200	<200	<200	<200	<200	<200
Sn	<5	<5	<5	<5	<5	<5	<5
S	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mg#	0.20	0.15	0.21	0.21	0.24	0.22	0.22
D.I.	89.30	89.99	88.04	88.73	85.34	89.77	85.02
K/NaK	0.61	0.61	0.68	0.65	0.62	0.69	0.60
NK/A	0.98	0.78	0.87	0.97	0.94	0.82	0.96

Table 1 Continues

	Syenite				Pulaskite		
% peso	VTR-85	VTR-87	VTR-88	VTR-108	VTR-04	VTR-43A	VTR-110
SiO_2	61.60	60.40	60.30	61.10	59.30	60.70	58.70
TiO_2	0.66	0.80	0.71	0.78	0.74	0.71	0.70
Al_2O_3	17.90	16.60	16.80	17.90	18.10	18.60	17.30
Fe_2O_3	1.40	2.40	2.10	1.20	1.50	0.80	2.50
FeO	2.71	3.28	4.06	3.71	3.71	3.42	3.71
MnO	0.15	0.24	0.20	0.18	0.13	0.20	0.21
MgO	0.65	0.70	0.85	0.67	0.86	0.85	0.82
CaO	2.00	1.80	2.10	2.30	2.30	2.20	2.50
Na_2O	6.00	5.60	5.40	5.50	6.30	5.80	6.30
K_2O	6.30	7.40	6.30	6.00	6.00	6.30	6.30
P_2O_5	0.13	0.20	0.15	0.25	0.19	0.18	0.27
Total	99.50	99.42	98.97	99.59	99.13	99.76	99.31
ppm							
Cr	<2	<2	<2	<2	<2	<2	<2
Ni	<5	8	9	17	16	<5	14
V	7	27	50	32	<5	<5	<5
Rb	98	86	113	101	97	103	98
Sr	370	106	77	280	250	406	320
Ba	2800	1100	4700	2560	1500	2400	2540
Zr	104	200	380	120	365	246	290
Y	20	19	46	20	30	24	50
Nb	58	38	72	34	88	70	86
Th	<30	<30	<30	<30	<30	<30	<30
U	<30	<30	<30	<30	<30	<30	<30
Cu	<5	8	<5	<5	<5	<5	<5
Pb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	<200	<200	<200	<200	<200	<200	<200
Sn	<5	<5	<5	<5	<5	<5	<5
S	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mg#	0.23	0.19	0.20	0.20	0.23	0.27	0.20
D.I.	89.43	84.25	85.56	88.43	86.51	89.72	83.80
K/NaK	0.51	0.57	0.54	0.52	0.49	0.52	0.50
NK/A	0.93	1.04	0.93	0.87	0.93	0.88	0.99

Table 1 Continues

	Pulaskite	Nepheline Syenite				Phonolite	
% peso	VTR-111	VTR-25	VTR-45	VTR-60C	VTR-64	VTR-48D	VTR-04B
SiO_2	59.90	60.50	60.50	60.80	59.90	60.50	59.50
TiO_2	0.63	0.33	0.63	0.43	0.44	0.16	0.15
Al_2O_3	17.50	18.90	19.00	19.10	18.70	19.10	18.10
Fe_2O_3	1.80	1.50	1.20	0.70	0.95	2.30	2.60
FeO	3.28	2.71	3.56	3.42	3.28	3.40	2.85
MnO	0.20	0.10	0.10	0.10	0.11	0.16	0.19
MgO	0.65	0.42	0.73	0.55	0.63	0.24	0.77
CaO	2.70	1.30	2.10	1.60	1.90	1.20	1.10
Na_2O	6.70	6.80	5.00	6.10	6.70	5.70	6.70
K_2O	5.80	6.70	6.50	6.60	6.70	6.00	6.20
P_2O_5	0.23	0.11	0.14	0.11	0.14	0.07	<0.05
Total	99.39	99.37	99.46	99.51	99.45	98.83	98.16
ppm							
Cr	<2	<2	<2	<2	<2	<2	8
Ni	<5	<5	<5	<5	<5	13	8
V	<5	<5	<5	<5	<5	<5	87
Rb	110	136	97	143	138	225	250
Sr	456	214	360	240	300	30	31
Ba	2700	1280	2700	1160	1720	64	122
Zr	350	250	290	560	344	350	805

Table 1 Continues

Y	52	19	31	29	25	<10	30
Nb	160	<5	84	98	156	58	81
Th	<30	<30	<30	<30	<30	<30	<30
U	<30	<30	<30	<30	<30	<30	<30
Cu	<5	<5	<5	<5	<5	<5	<5
Pb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	<200	<200	<200	<200	<200	<200	<200
Sn	<5	<5	<5	<5	<5	230	< 5
S	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mg#		0.16	0.22	0.19	0.21	0.07	0.21
D.I.		90.62	90.48	91.42	88.30	90.40	87.96
K/NaK		0.50	0.57	0.52	0.50	0.51	0.48
NK/A		1.03	1.24	1.11	1.02	1.20	1.02

Table 1 Continues

% peso	VTR-74A	VTR-4A	VTR-44B	VTR-54A	VTR-81B	VTR-58
SiO_2	60.10	58.20	58.10	59.70	65.50	44.30
TiO_2	<0.10	<0.10	0.21	0.33	<0.10	3.20
Al_2O_3	18.80	19.70	19.50	18.10	19.10	15.50
Fe_2O_3	3.30	3.20	2.20	1.50	0.14	4.00
FeO	1.85	2.00	3.56	4.28	0.42	6.78
MnO	0.21	0.14	0.15	0.23	<0.01	0.17
MgO	0.38	0.16	0.30	0.60	0.09	5.30
CaO	0.76	1.30	2.00	0.53	0.50	9.80
Na_2O	6.70	8.60	5.90	6.40	7.50	3.60
K_2O	5.20	5.50	6.90	6.90	6.50	3.40
P_2O_5	0.06	<0.05	0.05	0.07	<0.05	0.78
Total	97.36	98.80	98.87	98.64	99.75	96.83
ppm						
Cr	13	7	<2	7	<2	<2
Ni	12	<5	16	7	7	51
V	70	<5	54	70	<5	240
Rb	244	194	157	217	179	70
Sr	46	58	92	47	28	730
Ba	148	38	124	116	116	1200
Zr	1040	640	364	570	320	312
Y	65	40	36	36	< 10	38
Nb	74	<5	<5	122	40	112
Th	<30	<30	<30	<30	<30	<30
U	<30	<30	<30	<30	<30	<30
Cu	10	<5	<5	<5	<5	<5
Pb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	< 200	<200	< 200	<200	<200	< 200
Sn	21	<5	<5	<5	< 5	<5
S	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Mg#	0.12	0.06	0.09	0.16	0.00	0.48
D.I.	90.96	88.35	89.35	88.62	97.09	56.25
K/NaK	0.44	0.39	0.54	0.52	0.46	0.49
NK/A	0.89	1.02	0.88	0.99	1.01	0.62

Table 1 Major and trace elements for the alkaline rock of the Vitória Island Intrusive Complex, São Paulo State, Brazil. Pulaskite corresponds to nepheline-bearing syenite. The Magma Differentiation Index (D.I.) corresponds to sum of the all of Norm felsic minerals (Thornton & Tuttle, 1960). n.a. - not analyzed; n.d. - not detected; NK/A: $(Na+K)/Al_{mol}$. K/NaK: K2O/(K2O+Na2O) wt%.

on Le Bas *et al*. (1986). The coarse-grained rocks fall mainly on the trachyte (syenite) field and the fine-grained ones correspond to the phonolite (nepheline syenite) field. These rocks are less alkaline than ones presented in the Poços de Caldas-Cabo Frio Alignment. The lamprophyre plots in the tephrite field.

In the Na_2O vs. K_2O diagram of Figure 6 almost all felsic rocks are classified in the potassic series. The K_2O+Na_2O is approximately 13 wt.%, which is about 2 wt.% lower than those rocks from Poços de Caldas-Cabo Frio Alignment.

In the alkaline-alumina saturation diagram (Figure 7), the felsic rocks form a linear trend from peralkaline to peraluminous fields. Similar tendency is also observed for the felsic rocks from Poços de Caldas-Cabo Frio Alignment.

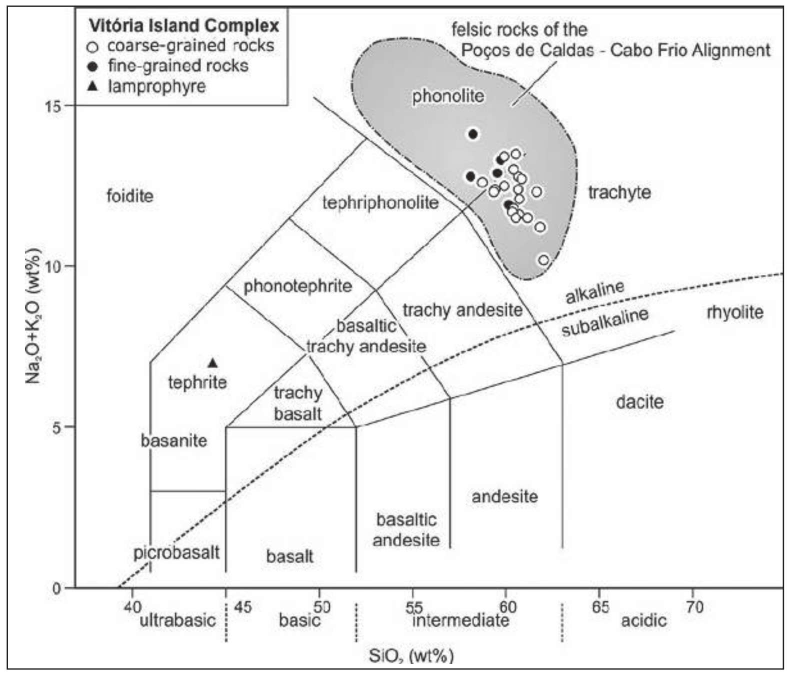

Figure 5 Geochemical classification of alkaline rocks from Vitória Island Intrusive Complex on the Na_2O+K_2O vs. SiO_2 (Le Bas *et al*., 1986). Data from Poços de Caldas-Cabo Frio Alignment are from Valença (1980), Motoki *et al*. (2010; 2012 b), and Sichel *et al*. (2012).

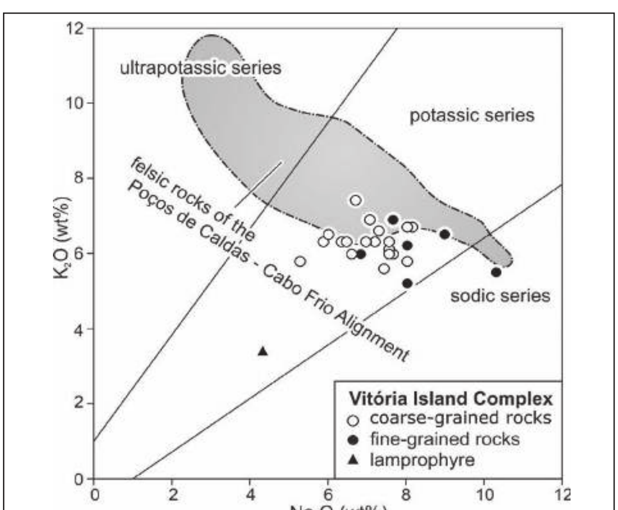

Figure 6 Na_2O vs. K_2O diagram from Middlemost (1975) for alkaline rocks of Vitória Island. Data from Poços de Caldas-Cabo Frio Alignment are as on Figure 5.

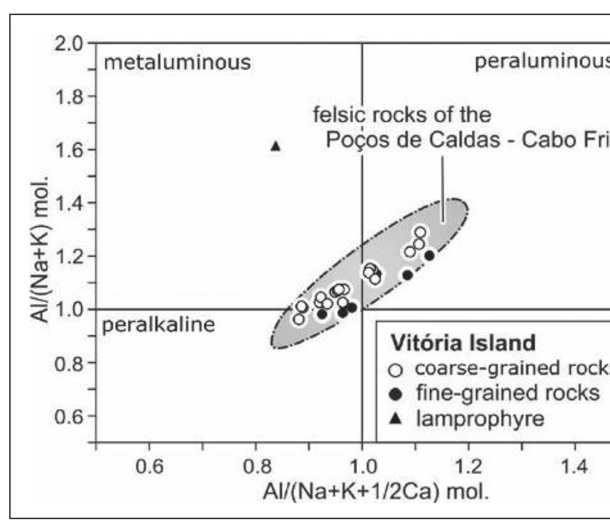

Figure 7 Alkaline-alumina saturation diagram plot from Maniar & Piccoli (1989) for alkaline rocks from Vitória Island Intrusive Body. Data from Poços de Caldas-Cabo Frio as on Figure 5.

5 Radiometric Dating

Four radiometric ages have been performed at the Geochronological Centre of São Paulo University, Brazil: 1) K-Ar in biotite from nepheline-bearing syenite; 2) K-Ar in amphibole from nepheline-bearing syenite; 3) K-Ar in amphibole from syenite; 4) Whole-rock K-Ar dating for phonolite. The quantitative analyses of potassium for K-Ar ages have been performed by frame photometry method and for ^{40}Ar quantification, by mass spectrometer for gas, such as described in Motoki (1986) and results are shown in Table 2. Biotite of nepheline-bearing syenite, sample VTR-4, yielded an age of 80.75 ± 4.54 Ma, with high atmospheric ^{40}Ar, 40.91%. In such case, the apparent age tends to become younger (Dalrymple & Lamphere, 1969). Phonolite sample (VTR-4A) yielded an age of 80.32 ± 1.97 Ma.

Sample	VTR-04	VTR-04	VTR-74	VTR-04A
Rock	Pulaskite	Pulaskite	Syenite	Phonolite
Mineral	biotite	amphibole	amphibole	whole-rock
K (%)	7.1845	1.5184	1.3963	4.1047
Radiometric ^{40}Ar (ccSTP/g)	2.3322 x 10^{-5}	5.1456 x 10^{-6}	4.6830 x 10^{-6}	1.3096 x 10^{-5}
Atmospheric ^{40}Ar (%)	40.91	18.54	26.56	8.12
age (Ma)	80.75 ± 4.54	89.58 ± 3.18	84.35 ± 3.92	80.32 ± 1.97

Table 2 K-Ar dating data for the Vitória Island alkaline rocks, São Paulo State, Brazil. The pulaskite corresponds to nepheline-bearing syenite.

	Biotite	Amphibole	Alkali Feldspar	Whole-Rock
Sr (ppm)	33.4	23.8	376.9	378.8
Rb (ppm)	323.2	25.5	76.8	73.8
$^{87}Rb/^{86}Sr$	31.48	1.19	0.59	0.56
$^{87}Sr/^{86}Sr$	0.7503	0.7070	0.7062	0.7055

Table 3 Rb-Sr isotope data for minerals and whole-rock from syenite (VTR-108) of the Vitória Island Intrusive Complex, São Paulo state, Brazil.

Amphibole K-Ar ages of nepheline-bearing syenite (VTR-4) and syenite (VTR-74), are, respectively, 89.58 ± 3.18 Ma and 84.35 ± 3.92 Ma. The atmospheric ^{40}Ar contents are lower than that obtained in biotite grains, 18.5% and 26.56%, respectively; therefore, these ages seem to be more accurate. They are similar to the other ages of intrusive complexes of the Monte de Trigo-Vitória Island Alignment (Sonoki & Garda, 1988).

$^{87}Sr/^{86}Sr$ initial ratios have been determined by thermal ionization mass spectrometer (TIMS), according to procedures described in Heilbron et al., (2013) and the results are displayed on Table 3. The $^{87}Sr/^{86}Sr$ initial ratio of 0.7055 indicates mantle origin being comparable to that of EM1. It is similar to those of the Poços de Caldas-Cabo Frio Alignment and also of Tanguá, Cabo Frio Island, Itatiaia and Morro de São João intrusive complexes, which have Sr initial ratios of 0.7062, 0.7049, 0.7049, and 0.7047, respectively (Motoki *et al*., 2010; 2012 b).

6 Fractional Crystallization

The SiO_2 content of the felsic rocks, with exception for syenitic aplite, ranges from 58.10 to 62.20 wt. %. Figure 5 shows that the silica variation could be related to fractional crystallization process, which increases water content while magma ascend to the surface. These felsic alkaline rocks are highly fractionated magmas with low MgO, CaO, and FeO*, with respective mean value of 0.62, 1.88, and 3.28 wt. %, and with high magma differentiation index (D.I. – 88.15, Thornton & Tuttle, 1960).

The main agent of fractional crystallization of this stage are the felsic minerals. Valença (1980) proposed that by means of leucite fractionation in nepheline syenite magma a sodic signature becomes potassic. Ulbrich (1984) confirmed this idea proposing that the felsic alkaline magma becomes peralkaline (agpaitic) from meta-aluminous (miaskitic).

Alkaline rocks of Vitória Island are characterized by relatively low $K_2O/(K_2O+Na_2O)$ wt. %, ranging from 0.39 to 0.57, with mean value of 0.51. These ratios point to advanced fractional crystallization, being comparable to that of Cabo Frio Island (Figure 8), with phonolite samples (VTR-4A and VTR-74A) being the highest fractionated rocks in Vitória alkaline complex. Motoki (1986) presents data for residual system of SiO_2-$NeAlSiO_4$-$KAlSiO_4$, which expresses rock samples plotting close to 1 Kbar minimum suggesting that they represent fractionated liquids.

Figure 8 $K_2O/(K_2O+Na_2O)$ wt% ranges of alkaline rocks from Vitória Island Intrusive Complex, São Paulo State, Brazil, in comparison to those from Poços de Caldas-Cabo Frio Alignment.

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7 Conclusions

Field observations, petrographic descriptions, geochemical features, and radiometric ages lead to the following conclusions:

Vitória Island felsic alkaline intrusive body, São Paulo state, Brazil, is about 3 km in diameter. The main intrusive body is constituted by nepheline syenite in its inner zone, nepheline-bearing syenite in the outer zone, syenite in the border, and quartz-bearing alkaline syenite along the contact zone. The emerged island areas correspond to the northeast border of the intrusive body.

The main body is intruded by phonolite, trachyte, and lamprophyre dykes. According to the field relationship, they are subdivided into two generations. The first-generation dykes form a radial system, indicating intrusion by hydraulic tensile fracturing. The second-generation constitutes a parallel system with NE-SW orientation and sinistral displacement, suggesting intrusion by hydraulic shear fracturing.

The alkali feldspar of the coarse-grained rocks is orthoclase and clinopyroxene composition varies from hedenbergite to aegirine-augite. Some crystals have resorption features and reaction rim of amphibole.

These alkaline rocks belong to the potassic series which compositions vary from silica-undersaturated to oversaturated, and from peralkaline to peraluminous. Geochemically, these rocks correspond to syenite and nepheline syenite.

K-Ar ages in amphibole from the nepheline-bearing syenite and from syenite are 89.58 ± 3.18 Ma and 84.35 ± 3.92 Ma, respectively.

The alkaline rocks are highly fractionated with magma differentiation index of ca. 88.15. The $K_2O/(K_2O+Na_2O)$ wt. % ratios of ca. 0.51 indicates that felsic mineral fractionation played an important role in the magmatic evolution. Other characteristics such as low Ba and Sr contents, low V and Co, low Ba and relatively low Sr (data from this work and Motoki, 1986) represent, respectively, fractionation of feldspar, magnetite and clinopyroxene beyond amphibole due to low MREE content (Motoki, 1986).

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