GEOCHEMICAL EVOLUTION OF THE FELSIC ALKALINE ROCKS OF TANGUÁ AND RIO BONITO INTRUSIVE BODIES, STATE OF RIO DE JANEIRO, BRAZIL

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ABSTRACT – This article presents chemical composition and magmatic evolution processes for the felsic alkaline rocks of Tanguá and Rio Bonito intrusive complex rock bodies, State of Rio de Janeiro, Brazil, and shows also the preliminary Rb-Sr age for Tanguá intrusive body. Most of the analysed rocks are undersaturated in silica with moderate (Na+K)/Al and high $K_2O/(Na_2O+K_2O)$ ratios, being classified to be potassic nepheline syenite. The variation diagrams strongly affirm the crystallisation of titanite, ilmenite, apatite, and clinopyroxene or amphibole and moderately nepheline and sodic alkaline feldspar. The geochemical evolution of the nepheline syenite magma occurs in three stages: $K_2O/(Na_2O+K_2O)$ reduction by leucita fractionation; The same by potash feldspar; Compositional transition from silica undersaturated to oversaturated field crossing over the thermal divide by means of assimilation of country rock of the continental crust. The fractionation crystallisation took place under the H_2O pressure of about 0.7kb, which corresponds to a depth of 3km. The crustal assimilation is relevant in the Soarinho body, moderate in the Tanguá and Rio Bonito complexes.. To cross over the thermal divide, super-reheating of the nepheline syenite magma or injection of fluid-rich magma is required. The preliminary Rb-Sr dating for the rocks of Tanguá body shows the intrusive age of 66.8Ma with the Sr initial ratio of 0.7062.
Keywords: nepheline syenite, fractionation crystallization, crustal assimilation, Tanguá, Rio Bonito.

RESUMO – *Motoki, A., Sichel, S.E., Vargas, T., Aires, J.R., Iwanuch, W., Mello, S.L.M., Motoki, K.F., Balmant, A., Gonçalves, J. Evolução geoquímica das rochas alcalinas félsicas dos corpos intrusivos de Tanguá e Rio Bonito, RJ.* Este artigo apresenta a composição química e a evolução magmática para as rochas alcalinas félsicas de complexos intrusivos de Tanguá e Rio Bonito, RJ, junto com a idade Rb-Sr preliminar do corpo Tanguá. A maioria das rochas é subsaturada em sílica com proporção moderada de (Na+K)/Al e alta taxa de $K_2O/(Na_2O+K_2O)$, sendo classificada como nefelina sienito potássica. Os diagramas de variação afirmam fortemente a cristalização de titanita, ilmenita apatita, e clinopiroxênio ou anfibólio e, moderadamente nefelina e feldspato alcalino sódico. A evolução geoquímica do magma nefelina sienítico ocorreu em três etapas: Redução da $K_2O/(Na_2O+K_2O)$ por fracionamento de leucita; A mesma por fracionamento de feldspato potássico; Transformação composicional de subsaturado para supersaturado em sílica cruzando a barreira térmica por meio de assimilação da rocha encaixante da crosta continental. A cristalização fracionada ocorreu sob a pressão de H_2O de aproximadamente de 0.7 kb, que corresponde a uma profundidade de 3 km. A assimilação crustal é relevante no corpo Soarinho, moderada nos complexos Tanguá e Rio Bonito. Para cruzar a barreira térmica, é necessário super-reaquecimento do magma nefelina sienítico ou injeção do novo magma rico em fluidos. A datação preliminar pelo método Rb-Sr para rochas do complexo Tanguá apresenta a idade intrusiva de 66.8 Ma com a razão inicial de Sr de 0.7062.
Palavras-chave: nefelina sienito, cristalização fracionada, assimilação crustal, Tanguá, Rio Bonito.

INTRODUCTION

In the State of Rio de Janeiro, Brazil, there are ten felsic alkaline intrusive bodies of the Cretaceous to the early Cenozoic (Lima, 1976; Valença, 1980; Sonoki & Garda, 1988), constituting the eastern part of the Poços de Caldas - Cabo Frio alkaline rock alignment (Figure 1; Thomáz Filho & Rodrigues, 1999; Riccomini et al., 2004). They are constituted mainly by nepheline syenite with eventual presence of alkaline syenite, trachyte, phonolite, and vent-filling welded tuff breccia (Motoki et al., 2007a; Sichel et al., 2008). Some of them form non-metallic ore deposits of special quality construction material (Petrakis et al., 2010).

Nepheline syenite, alkaline syenite, and quartz syenite are scarce in world occurrences and their magma evolution processes are little studied, especially in case the coexistence of silica oversaturated and undersaturated rocks. The State of Rio de Janeiro is abundant in such alkaline rocks offering an excellent field for the researchers. The complex intrusive rock bodies of Tanguá and Rio Bonito are present in the central part of the State of Rio de Janeiro.

This article presents chemical analyses of the above-mentioned felsic alkaline rocks, and shows preliminary Rb-Sr radiometric age of Tanguá intrusive body. Based on these data, the authors discuss evolution process for the nepheline syenitic magmas.

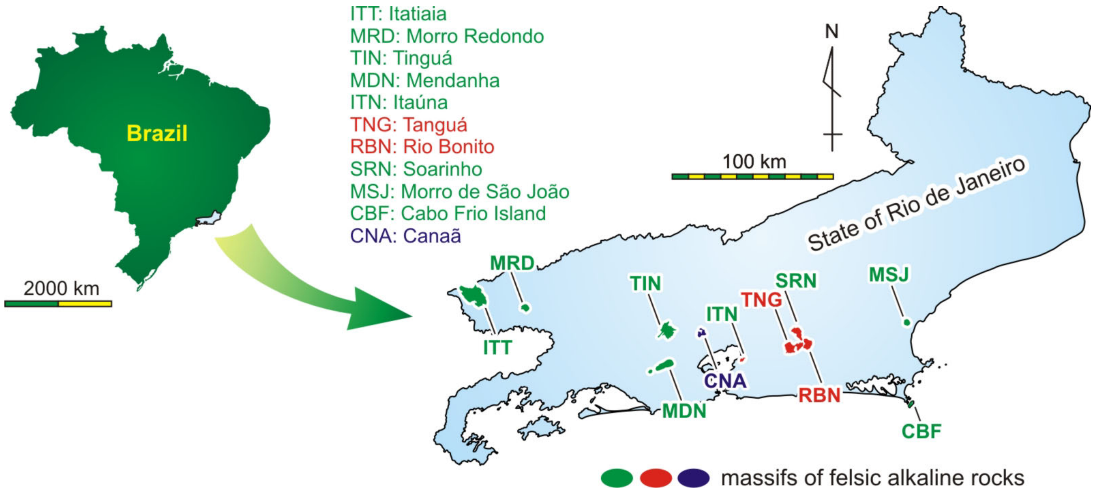

FIGURE 1. Felsic alkaline intrusive rock bodies of the State of Rio de Janeiro, Brazil. The Canaã body is exceptionally made up of nepheline syenite gneiss of the Cambrian to Ordovician and the other ones are of the Early Cenozoic.

REGIONAL GEOLOGY

Tanguá and Rio Bonito felsic alkaline intrusive rock bodies are present at coordinates respectively of 22º42’S, 42º45’W and 22º40’S, 42º37’. They are about 55km to the east-northeast of Rio de Janeiro City (Figure 1). They are intrusive into the metamorphic basement of the Costeira Unit of the Oriental Terrane, with metamorphic age of about 530Ma (Valladares et al., 2008, Motoki & Orihashi, unpublished data). The northern border of Tanguá and Rio Bonito bodies is in contact with muscovite-rich garnet gneiss. These metamorphic rocks are cut by tectonic breccia zones of the late stage of Pan-African continental collision event.

The metamorphic basement is intruded by early Cretaceous mafic dyke swarms (Stewart et al., 1996) that correspond to a part of feeder dykes of the continental flood basalt of Paraná Province (Motoki & Sichel, 2008; Motoki et al., 2009a).

The basement and the mafic dykes are intruded by Early Cenozoic nepheline syenite and alkaline syenite intrusive bodies, such as: Itatiaia (Brotzu et al., 1997), Morro Redondo (Brotzu et al., 1989), Tinguá, Mendanha (Motoki et al., 2007b), Itaúna (Motoki et al., 2008b), Tanguá, Soarinho, Rio Bonito (Valença 1980), Cabo Frio Island (Sichel et al., 2008), and Morro de São João (Brotzu et al., 2007). The syenitic intrusions are cut by the dykes of phonolite, trachyte, and lamprophyre (Motoki & Sichel, 2008; Motoki et al. 2008a).

The above-mentioned alkaline intrusive bodies were emplaced at a depth of 3 to 4km (Motoki & Sichel, 2006; Motoki et al., 2007a). Because of the regional uplift and consequent denudation that took place in the Cenozoic (Ferrari, 2001), the subvolcanic structure is now exposed on the Earth's surface (Motoki et al., 2008c). During the regional uplift, differential erosion occurred highlighting the intrusive bodies forming morphological elevations with relative height of 300 to 900 m (Figure 2), called "alkaline massifs".

The high erosive resistance of nepheline syenite under tropical climate is controversial to the weathering vulnerability of the constituent minerals. This fact is interpreted to be due to the clay-rich impermeable regolith that prevents surface water percolation into the rock body, the phenomenon called weathering passivity (Motoki et al., 2008d).

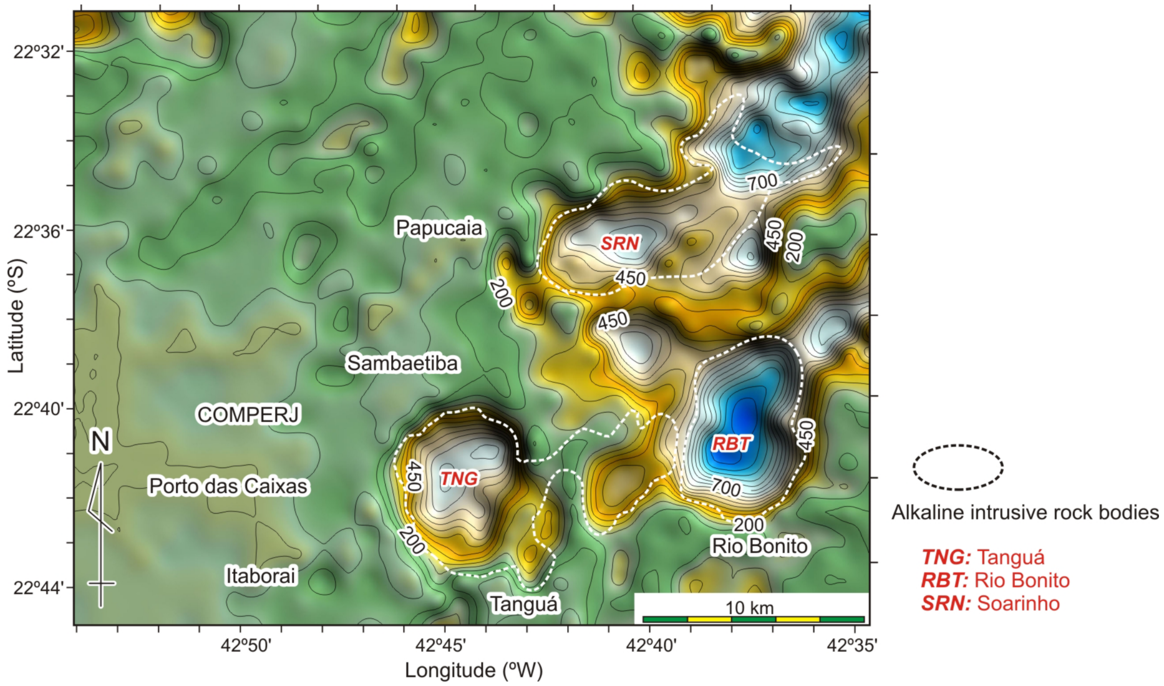

FIGURE 2. Summit level map based on the mesh with interval of 1 km after the method of Motoki et al. (2008c; 2009b) that highlights fundamental morphologic relief of Tanguá (*TNG*), Rio Bonito (*RBT*), and Soarinho (*SRN*) alkaline intrusive bodies. The distribution area of felsic alkaline rocks is modified from Valença (1980).

LITHOLOGIC AND PETROGRAPHIC CHARACTERISTICS

Tanguá and Rio Bonito intrusive complexes are constituted mainly by gross-grained nepheline syenite of light grey macroscopic colour (Photo 1A). This rock is made up of alkaline feldspar, nepheline, and amphibole with magnetite, titanite, and apatite as accessory minerals (Photo 2A). Nepheline grains are commonly of pinkish or brown colour because of Fe^{3+}. Under the thin sections, the amphibole grains have low aspect ratio, generally 2 to 3. Some few grains have clinopyroxene core. This observation suggests that the amphibole is pseudomorph originated from clinopyroxene. The titanite is notably abundant and in some cases it is recognised by naked-eye observation, but zircon is absent. Some samples show signal of metasomatic or hydrothermal alteration.

Alkaline syenite without nepheline is found along the border of the Tanguá body (Photo 2B). This rock is dark grey in macroscopic colour and composed of alkaline feldspar, nepheline, amphibole, and biotite, with accessory minerals of magnetite, titanite, and apatite. The alkaline feldspar phenocrysts of 2 to 3 cm are commonly found (Photo 1B). The dark macroscopic colour is due to grey alkaline feldspar and the genesis of this colour is still unknown. Some of them are of porphyritic texture with alkaline feldspar phenocrysts of 1 to 2 mm. Similar alkaline syenite is known in the intrusive bodies of the Vitória Island and Búzios Island, State of São Paulo, Brazil (Motoki, 1986).

At the occidental border of Tanguá body, there is a local occurrence of pseudoleucite syenite of crystal-supported texture (Photo 1C; Valença & Edgar, 1979). The pseudoleucite crystals have diameter of 5 to 10 cm. Along the southern border of the same body, a strong hydrothermal zone is present where two fluorite mines take place (Souza et al., 2008). One of them is still in active mining. In the eastern border of the same body, volcanic breccia is found (Photo 1D; 2C). The clasts are semi-rounded and the size is widely variable,

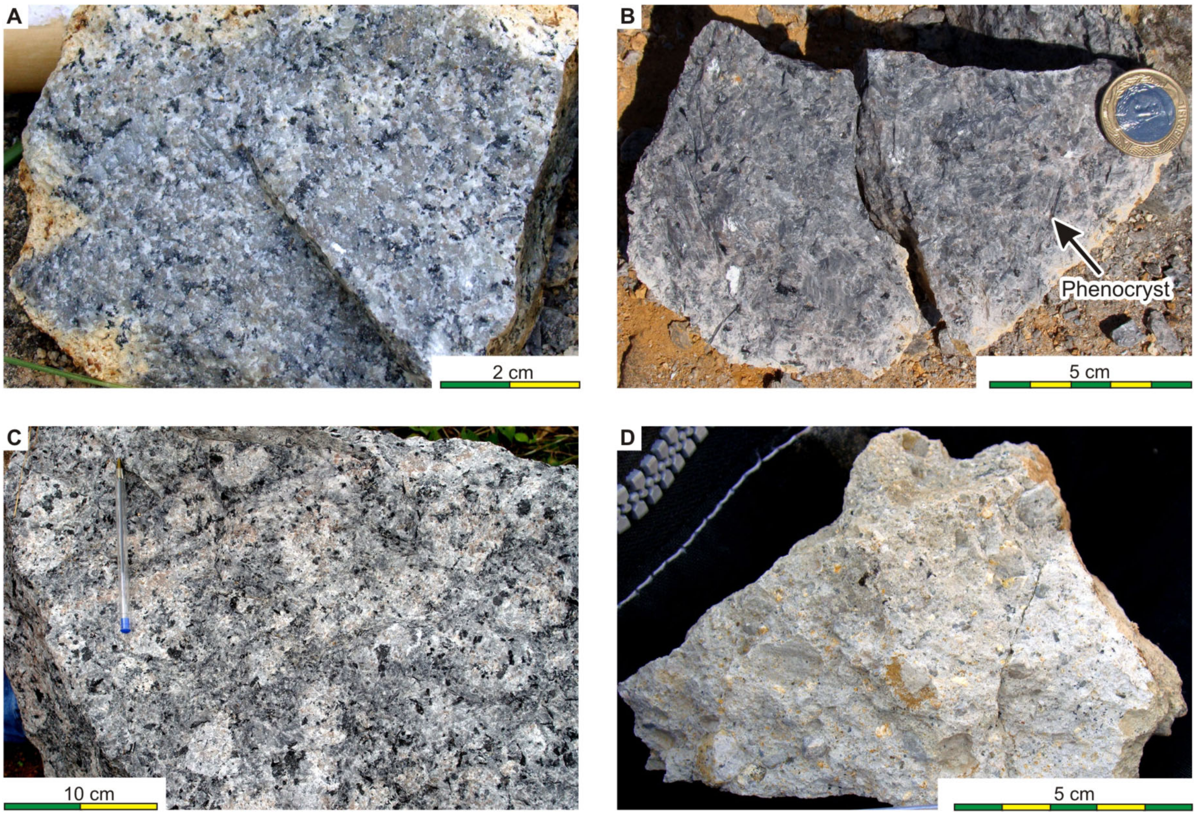

PHOTO 1. Macroscopic view of the felsic alkaline rocks of Tanguá intrusive complex, State of Rio de Janeiro, Brazil: **A)** Nepheline syenite; **B)** Alkaline syenite; **C)** Pseudoleucite nepheline syenite; **D)** Subvolcanic vent-filling breccia.

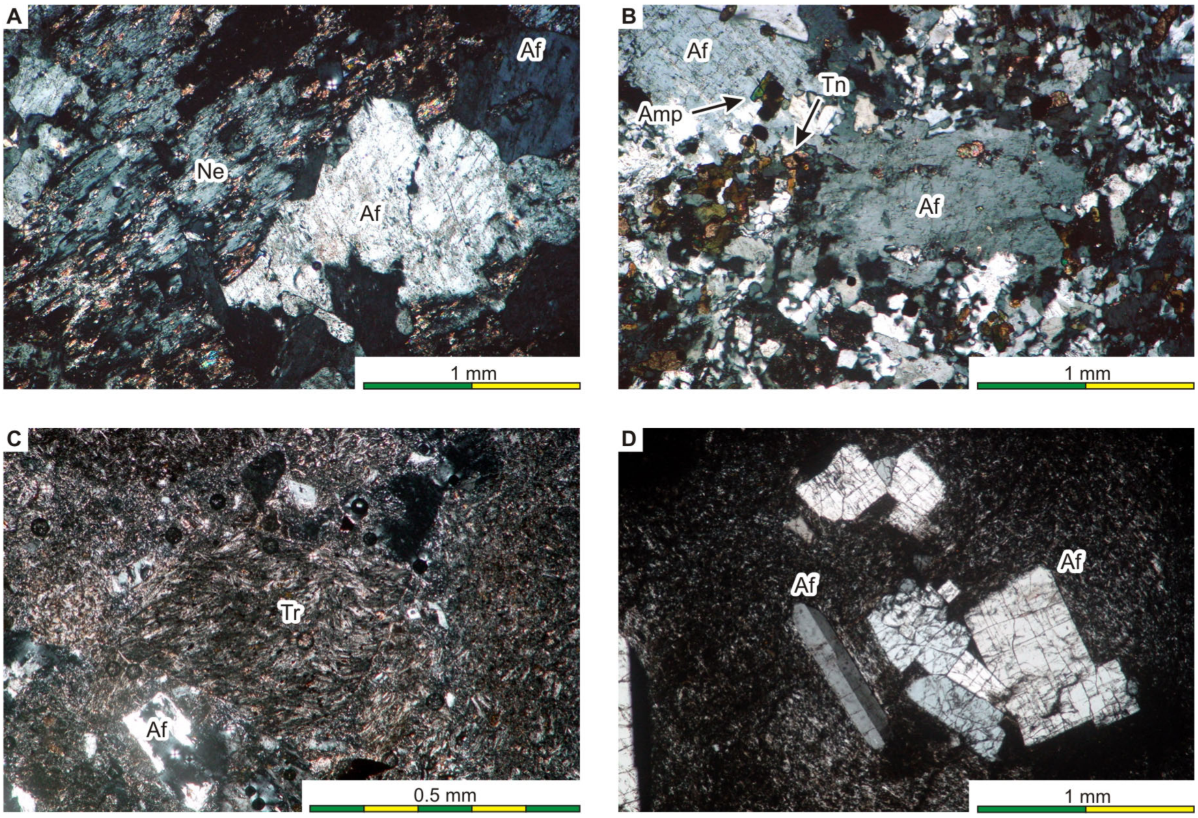

PHOTO 2. Photomicrography in cross nicol for the samples of the Tanguá alkaline intrusive body, Tanguá Municipal District, State of Rio de Janeiro, Brazil: **A)** Nepheline syenite; **B)** Alkaline syenite; **C)** Vent breccia; **D)** Phonolite. The symbols are: Af, alkaline feldspar; Ne, nepheline; Amp, amphibole; Tn, titanite; Tr, trachyte clast.

ranging from millimetres to major than 1 m. The texture is clast-matrix supported and massive, without notable layering. These characteristics are of vent-filling tuff breccia (Motoki et al., 2007c; 2008c). The phonolite (Photo 2D) takes occur either as the dykes intruding into the syenitic bodies or as tabular xenoliths captured by nepheline syenite magma.

The rocks of the Rio Bonito intrusion show similar characteristics of the Tanguá body. The Soarinho complex is characterised by absence of nepheline. Certain samples at the north-west border, close to the Papucaia Village, contain quartz (Valença, 1980).

CHEMICAL ANALYSES

The chemical analyses have been performed at geochemical laboratory of the Geosol™ S.A., Belo Horizonte, State of Minas Gerais, Brazil, using X-ray fluorescence for main and minor elements and mass spectrometer for trace elements. The Rb-Sr datings have been done at the Carnegie Institute, Washington.

The X-ray fluorescence cannot determine individual contents of Fe^{2+} and Fe^{3+}, but individual values of Fe^{2+} and Fe^{3+} are necessary for the CIPW Norm calculation. In cases of basaltic rocks, the Fe^{3+}/Fe_{total} ratio is estimated as 0.15 to 0.20. However, geochemical analyses data by atomic absorption for the other felsic alkaline rocks indicate that the Fe^{3+}/Fe_{total} is higher because clinopyroxene has acmite component. The Figure 3 shows that the Fe^{3+}/Fe_{total} ratio (mol) rise up in function of (Na+K)/Al (mol). These felsic alkaline rocks of the Tanguá and Rio Bonito have average molecular proportion of (Na+K)/Al about 0.9, and therefore the Figure 3 suggests Fe^{3+}/Fe_{total} (mol) in a range of 0.3 to 0.4. The authors adopt Fe^{3+}/Fe_{total} (mol) to be 0.35 for the CPIW Norm calculation in this article.

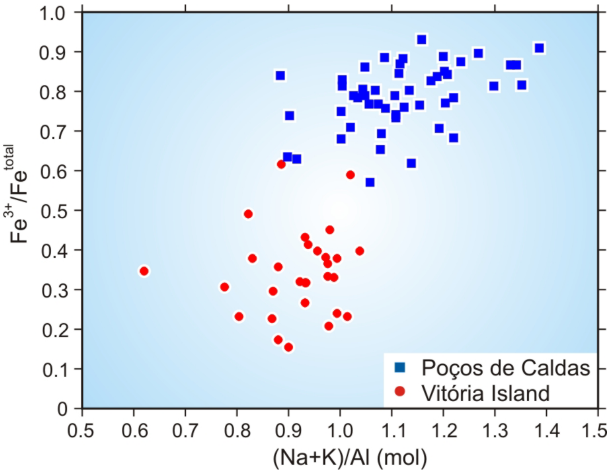

FIGURE 3. Relation between Fe^{3+}/Fe_{total} (mol) and of (Na+K)/Al (mol) for the syenitic rocks of alkaline intrusive complex of Poços de Caldas (Ulbrich, 1984) and of the Vitória Island (Motoki, 1986).

MAJOR ELEMENTS

The Table 1, and 2 present the results of chemical analyses for major and minor elements respectively of the Tanguá and Rio Bonito intrusive complexes. The Figure 4 demonstrates the igneous rock classification diagram of Na_2O+K_2O vs. SiO_2 according to Le Bas et al. (1986). For the purpose of comparison, the geochemical data of Valença (1980) also are shown.

The average SiO_2 for the rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna bodies are, respectively, 58.87, 58.41, 60.08, and 55.12 wt%, being equivalent to andesite. Although, these rocks have relatively low silica contents they are highly felsic. The average differentiation index (D.I., Thornton & Tuttle, 1960) for Tanguá, Rio Bonito, Soarinho, and Itaúna bodies are, respectively, 91.73, 90.90, 86.19, and 86.90wt%.

According to the geochemical classification of Le Bas et al. (1986), most of the samples fall on the phonolite field, being classified to be phonolite or nepheline syenite. The contents of Na_2O and K_2O are high, and the average Na_2O values for the Tanguá, Rio Bonito, Soarinho, and Itaúna bodies are, respectively, 5.04, 5.15, 5.02, and 6.87 wt%, and K_2O values are, respectively, 8.55, 8.33, 5.43, and 7.74 w%. Most of the rocks have Na_2O+K_2O higher than 12 wt%.

Because of high alkali and low SiO_2 contents, the rocks are highly undersaturated. The average Norm nepheline of Tanguá and Rio Bonito bodies are 8.55 and 9.91. Most of the samples of the Soarinho body, adjacent intrusion of the Tanguá and Rio Bonito (Figure 2), have normative quartz, in average of 2.36 wt% (Valença, 1980).

The Na_2O vs. K_2O diagram presents that the most of the analysed rocks fall on the potassic to the ultrapotassic field (Figure 5). The average ratio of $K_2O/(Na_2O+K_2O)$ for Tanguá, Rio Bonito, Soarinho, and Itaúna bodies are, respectively, 0.63, 0.62, 0.52, and 0.53. The K_2O and Na_2O contents show general negative correlation.

The Al_2O_3 content is in general high. The average values for Tanguá, Rio Bonito, Soarinho, and Itaúna bodies are, respectively, 19.67, 19.86, 15.74, and 20.27 wt%. On the alkali-alumina diagram, a half of the samples are classified to be peralkaline and the other to be subalkaline-subaluminous (Figure 6).

On the other hand, the rocks of Soarinho body are more subalkaline and low K_2O and Na_2O contents in comparison with the other intrusive bodies. In addition, most of them are oversaturated in silica, with Norm quartz (Valença, 1980). They are less alkaline and have intermediate characteristics between nepheline syenite and granite.

TABLE 1. Main and trace elements for the felsic alkaline rocks of the Tanguá Alkaline Intrusive Complex Rock Body, State of Rio de Janeiro, Brazil. The sample names with * are of phonolite or trachyte and the others are of nepheline syenite and alkaline syenite. The magma differentiation index (D.I.) refers to the sum of all CIPW Norm minerals (Thornton & Tuttle, 1960). The Silica Saturation Index (SSI) is proposed by the authors in this paper: SSI=1000*(SiO_2/60.0835-Al_2O_3/101.9601-5*(Na_2O/61.9785+K_2O/94.1956)-CaO/56.077-MgO/40.304-MnO/70.937-FeO/71.844+2*Fe_2O_3/159.687).

	1A-TG*	1D-TG*	1F-TG*	2-TG	2A-TG	5-TG	6A-TG	6C-TG
SiO_2	60.50	60.52	59.66	55.57	56.13	55.84	55.35	59.03
TiO_2	0.46	0.71	0.57	0.94	0.95	1.12	0.33	0.78
Al_2O_3	18.80	17.82	19.16	20.33	20.25	20.74	21.41	20.52
FeO^*	1.35	2.41	2.25	2.56	2.57	2.89	2.02	2.48
MnO	0.18	0.22	0.19	0.13	0.13	0.11	0.24	0.19
MgO	0.40	0.42	0.32	0.63	0.64	1.04	0.24	0.47
CaO	1.70	1.15	1.80	2.18	2.20	2.91	1.35	1.67
Na_2O	4.40	4.04	5.04	5.04	6.04	3.15	7.59	6.54
K_2O	7.90	7.63	8.15	9.39	5.43	11.40	7.80	8.34
P_2O_5	0.07	0.06	0.04	0.15	0.14	0.23	0.00	0.07
Total	95.81	95.08	97.27	97.02	94.58	99.54	96.40	100.19
Cr	12.3	8.9	22.0	21.6	8.1	5.0	10.0	5.4
Ni	3.4	3.5	15.3	16.3	4.2	17.8	13.8	15.9
V	15.5	17.9	14.9	31.6	29.9	40.6	16.7	29.2
Rb	169.5	157.9	153.4	264.3	263.6	259.1	207.3	164.0
Sr	210.4	62.0	170.5	1394.8	1384.9	1422.5	28.2	360.9
Ba	101.5	36.5	33.0	264.3	258.4	242.9	56.5	56.6
Zr	402.3	350.5	347.0	359.4	446.8	97.4	1106.4	725.5
Y	31.6	33.6	29.2	33.3	32.5	32.7	33.0	35.4
Nb	129.8	152.8	130.6	127.0	120.9	55.1	258.3	227.1
Th	6.4	4.7	8.7	8.4	5.8	0.5	29.4	16.8
U	2.7	3.2	2.5				7.5	4.0
Cu	5.7	3.9	4.3	7.0	6.1	8.1	2.2	3.9
Pb	15.0	16.4	14.0	10.7	10.5	6.9	21.3	16.3
Zn	100.7	128.2	72.4	69.2	70.1	53.5	117.8	68.3
Sn	2.1	3.4	2.5	3.1	1.9	2.7	3.2	3.2
S	245	8889	133	656	661	1270	608	275
Mg(%)	34.6	23.7	20.2	30.5	30.7	39.1	17.5	25.2
D.I.	92.3	89.9	91.6	89.1	89.2	90.6	90.1	92.3
SSI	6	66	-79	-235	-96	-211	-353	-234
$K_2O/(Na_2O+K_2O)$	0.64	0.65	0.62	0.65	0.47	0.78	0.51	0.56

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Table 1 - continues...

	8A-TG	8B-TG	8C-TG	8E-TG	9-TG	10A-TG	10B-TG	11B-TG
SiO_2	58.60	60.48	63.57	59.47	60.50	60.11	58.63	57.90
TiO_2	0.93	0.65	0.63	1.03	1.10	1.13	1.42	0.90
Al_2O_3	19.00	21.63	19.35	20.00	18.50	19.25	19.37	18.60
FeO^*	2.97	2.47	2.55	3.13	2.62	2.83	3.24	2.41
MnO	0.14	0.22	0.26	0.17	0.17	0.18	0.15	0.14
MgO	0.56	0.44	0.38	0.69	0.45	0.69	0.80	0.35
CaO	1.90	1.62	0.96	2.07	1.60	1.93	2.64	2.10
Na_2O	3.90	7.15	5.70	3.86	6.60	4.99	4.35	2.30
K_2O	9.50	8.57	8.07	9.89	6.70	8.54	9.18	10.30
P_2O_5	0.15	0.07	0.06	0.17	0.09	0.13	0.18	0.09
Total	97.77	103.39	101.63	100.60	98.43	99.89	100.09	95.19
Cr		9.1	11.8	5.9		2.0	4.3	
Ni		16.5	17.2	17.9		17.2	17.6	
V		24.8	8.9	34.2		36.7	38.7	
Rb	204.0	191.0	254.7	254.5	123.0	135.5	146.5	181.0
Sr	1116.0	420.2	21.3	1098.3	24.0	127.2	127.9	1643.0
Ba	131.0	100.4	97.0	178.7	20.0		3.3	191.0
Zr	641.0	1135.0	609.0	616.3	496.0	395.8	589.7	567.0
Y	35.0	37.6	64.1	39.7	97.0	73.7	78.7	30.0
Nb	137.0	231.2	234.9	155.3	191.0	188.0	199.6	181.0
Th	7.0	23.3	18.1	16.3	9.0	4.3	14.1	5.0
U	10.0	5.6	4.6	2.0	10.0	2.3	4.3	10.0
Cu		5.4	4.1	8.6		3.6	3.5	
Pb		19.2	14.2	14.3		12.9	14.2	
Zn		78.5	79.6	32.3		87.0	92.8	
Sn		3.2	6.3	4.4		4.2	4.4	
S		427	213	915		313	1448	
Mg#(%)	25.2	24.1	21.0	28.2	23.5	30.3	30.6	20.6
D.I.	90.9	95.6	96.4	93.7	90.1	91.9	90.2	90.2
SSI	-80	-282	-53	-99	-102	-96	-117	2
$K_2O/(Na_2O+K_2O)$	0.71	0.55	0.59	0.72	0.50	0.63	0.68	0.82

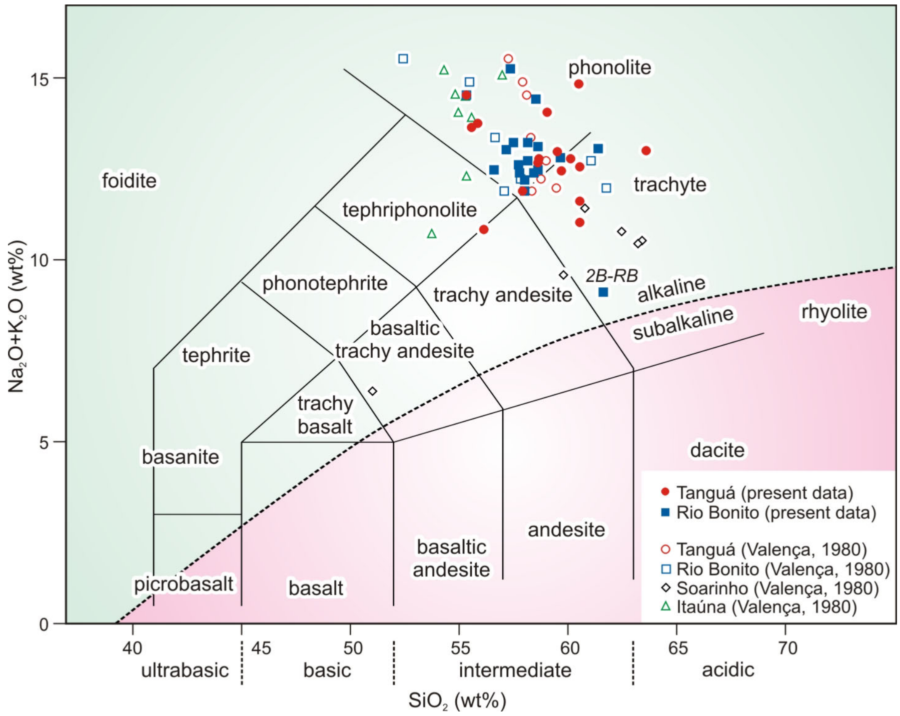

FIGURE 4. Chemical composition of the alkaline rocks of the intrusive complex of Tanguá, Rio Bonito, Soarinho, and Itaúna, State of Rio de Janeiro, Brazil, of the present work and those of Valença (1980) on the classification diagram of Na_2O+K_2O vs. SiO_2 (Le Bas et al., 1986).

TABLE 2. Main and trace elements for the felsic alkaline rocks of the Rio Bonito Alkaline Intrusive Complex Rock Body, State of Rio de Janeiro, Brazil. The sample names with * are of phonolite or trachyte and the others are of nepheline syenite and alkaline syenite. The D.I. and the SSI are the same of the Table 1.

	2D-RB*	2E-RB*	7-RB*	11A-RB*	1-RB	2A-RB	2B-RB	2H-RB	3A-RB
SiO_2	57.48	58.12	57.70	58.00	58.43	56.58	61.59	58.11	57.17
TiO_2	1.03	1.20	1.20	1.40	1.03	1.16	1.08	0.99	1.08
Al_2O_3	20.10	19.06	19.44	18.50	19.39	19.26	17.71	19.83	19.23
FeO^*	1.97	1.90	2.18	2.16	2.11	2.20	3.11	1.95	2.00
MnO	0.19	0.15	0.15	0.14	0.14	0.17	0.09	0.26	0.20
MgO	0.71	0.74	0.92	0.83	0.96	0.93	2.09	0.63	0.64
CaO	2.28	2.23	2.53	2.70	2.46	2.89	2.54	2.30	2.13
Na_2O	5.47	5.52	4.81	4.20	4.26	5.03	3.80	5.45	5.32
K_2O	8.54	7.96	8.55	8.40	8.86	8.19	5.86	8.54	8.48
P_2O_5	0.20	0.17	0.27	0.32	0.30	0.28	0.41	0.13	0.18
Total	99.14	98.19	99.06	97.95	99.20	98.01	100.14	99.35	97.63
Cr	1.2	1.3	7.0	1.2	7.2	8.2	20.2	5.7	18.5
Ni	1.7	1.3	16.1	1.9	15.1	16.1	36.3	16.6	16.9
V	47.5	49.9	31.9	52.7	35.5	32.4	123.9	28.2	32.8
Rb	142.8	116.8	111.6	113.4	100.2	115.7	313.6	143.9	143.2
Sr	1752.6	11539.6	1686.7	2077.9	2278.1	1639.3	340.5	566.9	1021.0
Ba	209.3	224.2	289.1	379.8	518.0	297.7	769.9	12.5	137.4
Zr	375.8	349.3	252.9	463.2	95.6	302.8	170.3	611.9	399.2
Y	53.4	34.4	34.7	39.4	22.5	35.9	17.3	58.5	54.7
Nb	207.6	101.0	97.2	97.2	49.6	102.9	13.4	276.8	228.6
Th	11.6	8.6	6.3	9.4	0.0	6.6	5.8	18.2	14.4
U	2.8	2.1	0.0	2.5			3.3	3.2	
Cu			7.8		9.4	6.9	82.3	5.1	5.4
Pb	11.0	8.5	10.5	8.2	9.7	11.9	41.6	14.8	14.1
Zn	92.6	83.4	81.6	82.6	80.1	91.8	193.3	116.7	97.2
Sn	4.0		4.0		2.8	3.2	9.2	4.6	3.3
S	1028		282		404	359	1564	579	600
Mg#(%)	29.5	31.1	32.8	30.8	34.6	32.9	43.8	27.3	27.0
D.I.	90.2	88.7	89.3	88.2	90.6	87.0	86.7	90.0	88.3
SSI	-196	-145	-141	-68	-102	-164	129	-181	-172
$K_2O/(Na_2O+K_2O)$	0.61	0.59	0.64	0.67	0.68	0.62	0.61	0.61	0.61

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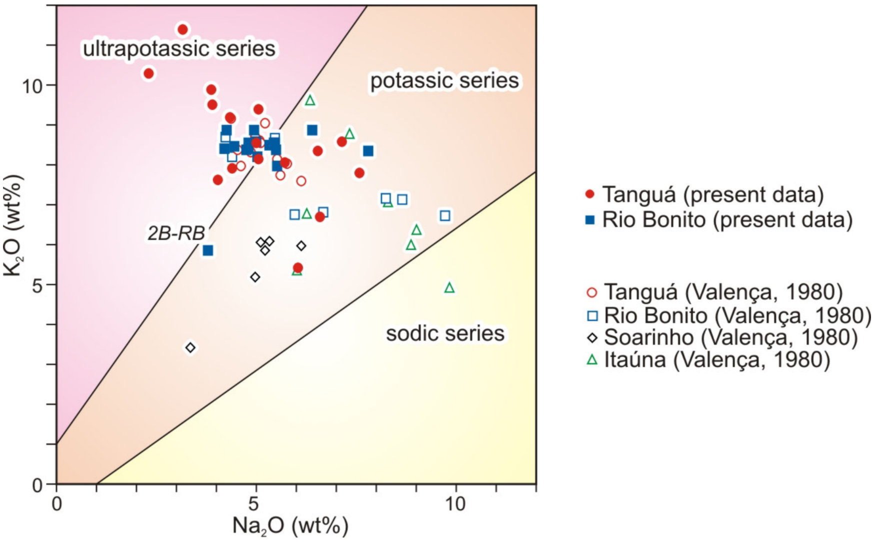

FIGURE 5. The alkaline rocks of the intrusive complex of Tanguá, Rio Bonito, Soarinho, and Itaúna, plotted on the Na_2O vs. K_2O diagram (Middlemost, 1975). The symbols are the same of the Figure 4.

Table 2 - continues...

	3C-RB	9A-RB	9B-RB	10-RB	10B-RB	12A-RB	12B-RB	12C-RB
SiO_2	57.78	57.33	58.49	61.35	58.58	58.60	59.61	57.99
TiO_2	1.30	0.60	0.73	0.93	1.10	1.00	1.06	1.32
Al_2O_3	19.11	23.77	21.84	21.49	20.34	18.90	20.07	19.64
FeO^*	3.73	1.82	2.29	2.72	3.28	3.15	3.13	3.69
MnO	0.18	0.12	0.16	0.16	0.21	0.14	0.16	0.17
MgO	1.03	0.35	0.47	0.74	0.76	0.65	0.08	1.05
CaO	2.76	1.53	1.64	2.51	2.51	2.40	2.43	2.87
Na_2O	4.76	7.81	6.41	4.95	5.50	4.80	5.00	4.44
K_2O	8.37	8.34	8.86	8.87	8.39	8.40	8.57	8.47
P_2O_5	0.32	0.07	0.07	0.20	0.23	0.22	0.23	0.32
Total	99.49	101.81	101.05	104.02	101.03	98.38	100.46	100.10
Cr	21.2	681.0	10.0	11.6	9.7		10.4	4.3
Ni	17.0	14.4	14.6	17.3	17.4		16.4	17.2
V	34.1	18.3	23.2	29.5	33.0		22.2	34.6
Rb	109.8	137.4	141.4	119.0	127.8	113.0	119.3	108.1
Sr	1659.6	442.7	480.0	3622.1	1883.3	1369.0	1156.4	1790.9
Ba	317.8	48.3	28.9	434.5	211.0	65.0	101.0	285.8
Zr	279.8	349.1	365.7	80.5	300.6	532.0	393.7	216.5
Y	39.2	25.5	32.0	37.6	49.1	34.0	31.5	37.8
Nb	110.8	180.5	212.2	133.6	190.3	107.0	104.4	100.6
Th	5.3	22.4	17.3	5.1	12.3	5.0	6.0	5.2
U		3.3	2.9			10.0	0.0	0.0
Cu	7.9	3.0	4.0	12.1	8.2		6.9	8.1
Pb	10.0	11.9	12.0	9.4	11.9		11.6	9.3
Zn	96.9	55.6	68.6	76.4	95.8		81.3	97.6
Sn	3.3	3.7	3.3	4.7	3.4		3.1	4.3
S	419	204	584	366	1595		1140	372
Mg#(%)	33.0	25.6	26.7	32.7	29.2	26.9	4.4	33.7
D.I.	88.4	97.2	95.0	97.6	91.5	89.3	93.2	90.1
SSI	-131	-389	-272	-125	-180	-105	-110	-114
$K_2O/(Na_2O+K_2O)$	0.64	0.52	0.58	0.64	0.60	0.64	0.63	0.66

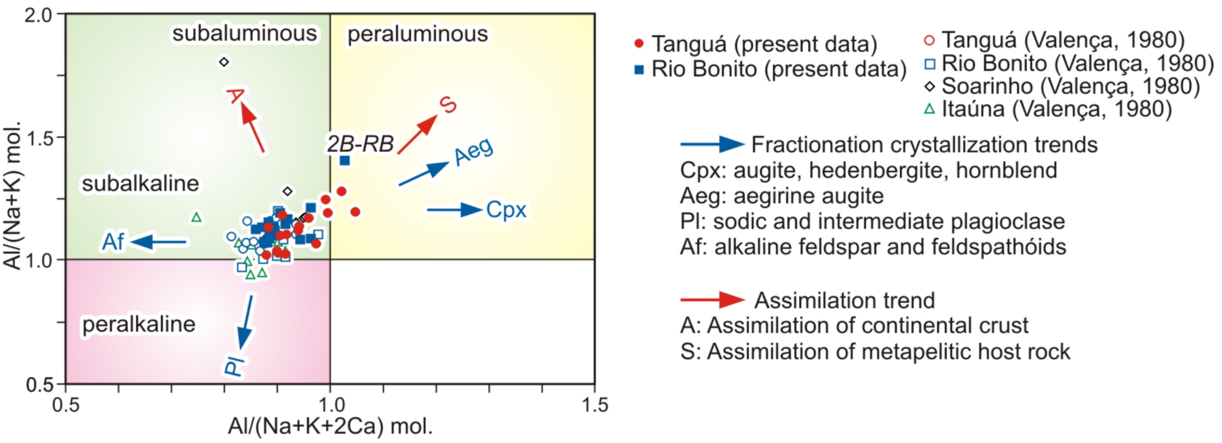

FIGURE 6. Relation between alkali and alumina for the alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna intrusive complex on the diagram of Al/(Na+K) vs. Al/(Na+K+2Ca) of Shand (1943). The symbols are the same of the Figure 4.

MINOR ELEMENTS

According to the previous explanations, the behaviours of in major elements have some differences in each intrusive body. However, those of minor elements are similar in those alkaline complexes.

The Figure 7 shows the projections of the above-mentioned rocks on the classification diagram for granitic rocks (Pearce et al., 1984; Pearce, 1996) indicating geotectonic conditions for each type of magma. The contents of Y, Rb, and Nb suggest that the magmas were generated in intraplate environments. The Nb vs. Y and Rb vs. Y+Nb diagrams also present the same tendency.

The Ba contents are low in comparison with the nepheline syenite and alkaline syenite the intrusive complexes of the other regions, such as the Vitória Island (Motoki, 1986). The average values for the Tanguá, Rio Bonito, Soarinho, and Itaúna bodies are respectively 118, 255, 998, and 436ppm. On the other hand the Sr contents are highly variable, respectively 601, 2077, 703, and 1096ppm.

Ba and Sr present positive correlation (Figure 8A). On the Ba-Sr-Rb triangular diagram (Bouseily & Sokkary, 1975), most of the alkaline rock fall on the normal and abnormal granite fields, and some of them, on the highly differentiated rock field (Figure 8B).

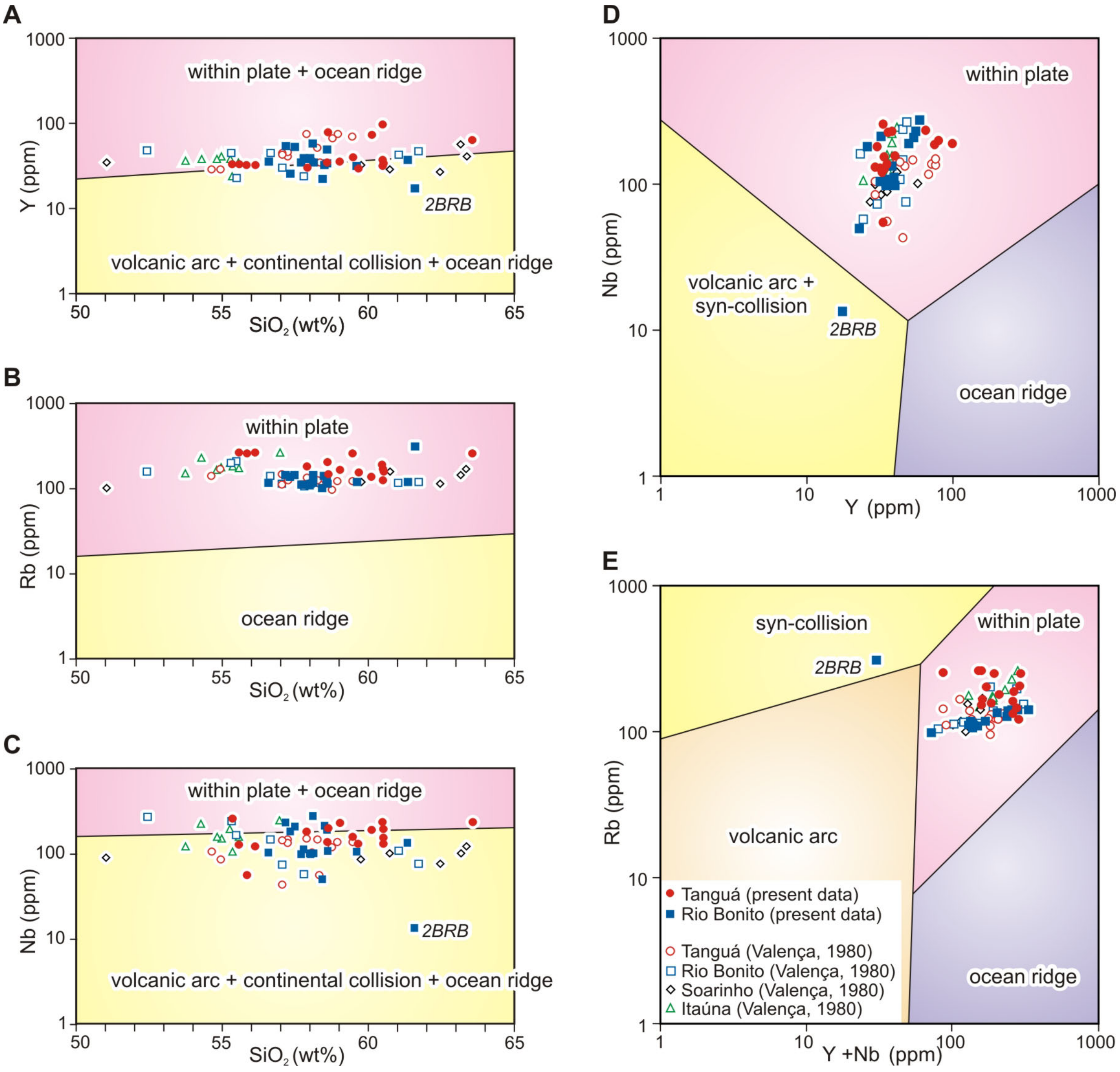

FIGURE 7. The alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna intrusive complexes, State of Rio de Janeiro, Brazil plotted on the classification diagram of Pearce et al. (1984) and Pearce (1996): **A)** Y vs. SiO_2; **B)** Rb vs. SiO_2; **C)** Nb vs. SiO_2; **D)** Nb vs. Y; **E)** Rb vs. Y+Nb. The symbols are the same of the Figure 4.

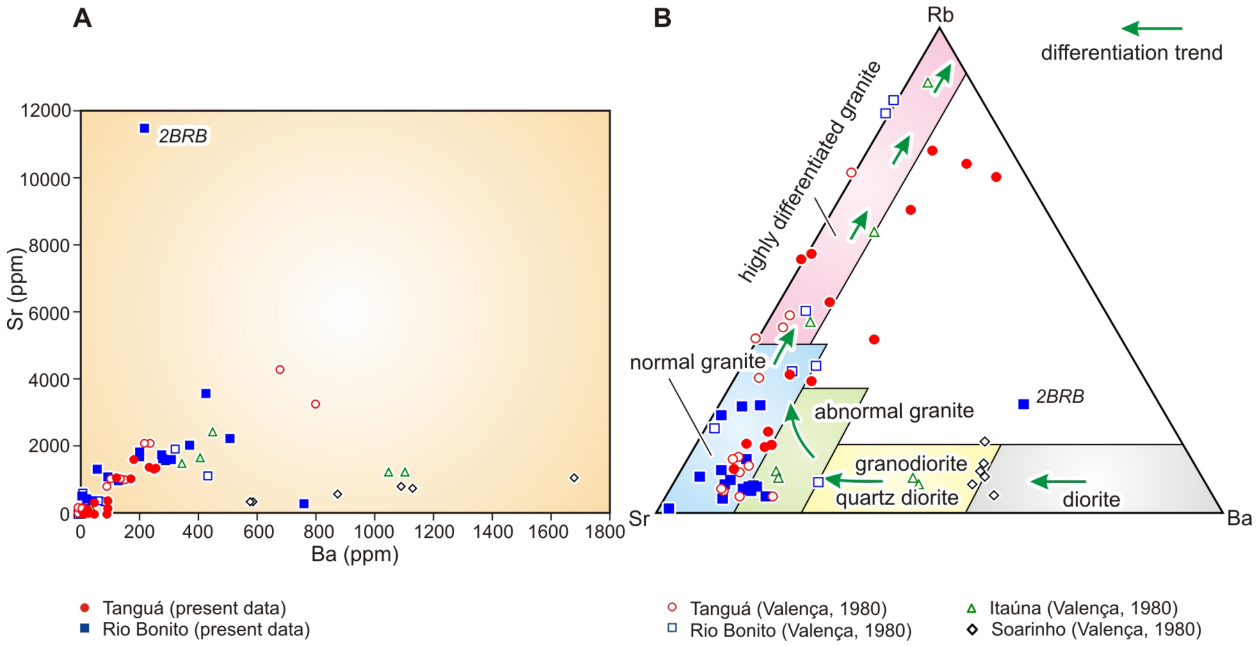

FIGURE 8. Ba-Sr relation for the alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna, intrusive complex, State of Rio de Janeiro, Brazil, based on the data of the present work and Valença (1980): **A)** Sr vs. Ba diagram; **B)** Ba-Sr-Rb triangular diagram (Bouseily & Sokkary, 1975). The symbols are same of the Figure 4.

FRACTIONATION CRYSTALLISATION

The SiO_2 contents of the above-mentioned felsic alkaline rocks are distributed in a relatively wide range, from 54.73 to 61.59 wt% according to the present data and from 53.75 to 63.36t% to the data of Valença (1980). The variation corresponds to the range from basaltic to dacitic andesite.

The SiO_2 variation like this is generally due to fractionation crystallization of the magma. However, the data projected on the Na_2O+K_2O vs. SiO_2 diagram demonstrate negative correlation (Figure 4). The geochemical data on some Harker diagrams show dispersion and the R^2 for the FeO*, MgO, and K_2O are low, respectively, 0.0334, 0.0142, and 0.0025 (Figure 9A, B, C). Therefore, the conventional fractionation crystallization observed in the calc-alkaline rocks, characterized by the elevation of SiO_2 and $K_2O/(K_2O+Na_2O)$ and the reduction of MgO and FeO, is not expressive for the nepheline syenitic rocks.

On the other hand, CaO shows relatively good negative correlation to SiO_2, with the R^2 of 0.119 (Figure 9D). The combinations of FeO*-CaO and MgO-CaO also present good correlation with respective R^2 of 0.7369 and 0.6972 (Figure 10A, B). The above-mentioned pairs suggest the fractionation of clinopyroxene and/or amphibole. Both of the minerals are recognized under the microscope (Photo 2B).

The TiO_2 content demonstrates a high positive correlation to CaO and FeO* with respective R^2 of 0.7826 and 0.5783 (Figure 10C, D). This fact strongly suggests the fractionation of ilmenite and titanite. These minerals are found commonly in felsic alkaline rocks as accessory minerals. The P_2O_5 has a high correlation to CaO with the R^2 of 0.7629, suggesting apatite fractionation (Figure 10E).

The positive correlation between Na_2O and Al_2O_3 is moderately high, with the R^2 of 0.4579 (Figure 10F), pointing out nepheline and/or sodic alkaline feldspar fractionation. The positive correlation is found also between K_2O and Al_2O_3, suggesting fractionation of leucite and/or potassic alkaline feldspar. However, it is not so relevant with R^2 of 0.0866 (Figure 10G),

The correlation between CaO and Al_2O_3 is not expressive with the R^2 of 0.1946 (Figure 10H). Therefore, in spite of the expressive fractionation of alkaline feldspar, the plagioclase fractionation was limited. It is believed that the CaO was used mainly for the crystallization of clinopyroxene and/or amphibole and little for plagioclase.

The low correlation indexes on the Harker diagrams indicate that unlike the cases of calc-alkaline magmas, the SiO_2 elevation by fractionation crystallization is not expressive in the case of nepheline syenite magma. The differentiation index (D.I) and magnesium number (Mg#, Mg/(Mg+Fe) mol) also are not useful indicators of magma differentiation. This phenomenon can be due to very high-grade

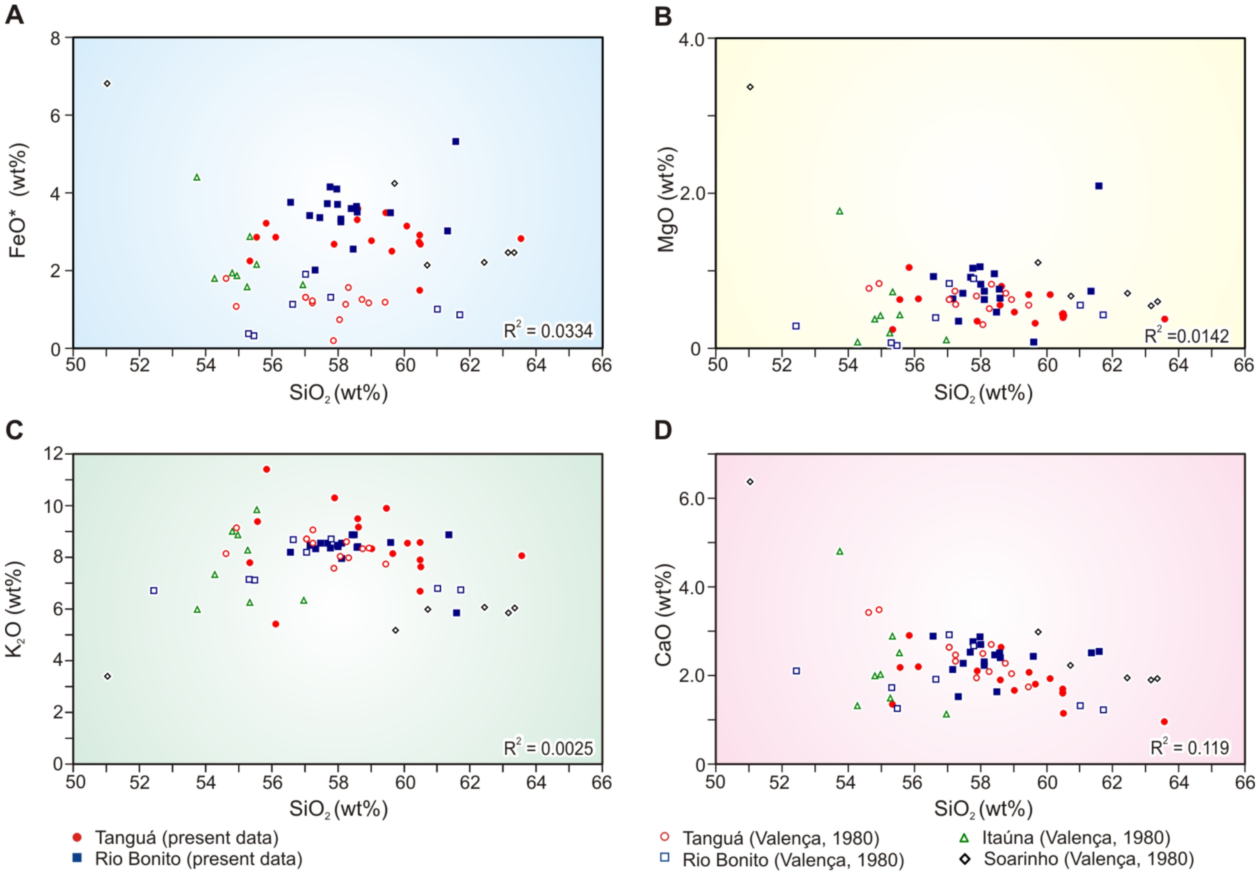

FIGURE 9. Harker diagram for the alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna intrusive complex, State of Rio de Janeiro, Brazil, based on the data of the present work and Valença (1980). The symbols are same of the Figure 4.

fractionation of these nepheline syenite magmas. In fact, the average values of the Mg# for the Tanguá, Rio Bonito, Soarinho, and Itaúna intrusive bodies are, respectively, 26.6, 29.5, 26.0, and 18.2%, and those of D.I. are respectively, 91.7, 90.9, 86.19, and 86.90.

By the way, the terminal system diagram of Q-Ne-Kf (Schairer & Bowen, 1935; Hamilton & Mackenzie, 1960) is useful for the analyses of the magma fractionation process for felsic alkaline rocks. This system has two minimum temperature points: one is on the silica oversaturation field and another, on the silica undersaturation field. On the Figure 11, these points are expressed as *Gr* and *Ns* that represent respectively the compositions of granitic and nepheline syenitic magmas of the minimum temperatures.

The samples of the Tanguá and Rio Bonito intrusive complexes are plotted mainly on the silica undersaturation field along the cotectic curve. The data are concentrated between the dry cotectic curve and that of 1kb of H_2O, corresponding to about 0.7kb of H_2O (Figure 11). This H_2O pressure suggests a depth of about 3km, which fits well the intrusion depth estimation by fission track datings for apatite (Motoki et al., 2007a).

Valença (1980) considered that the nepheline syenite magma of relatively low-grade fractionation is present within the domain of leucite on the Q-Ne-Kf terminal diagram and by means leucite fractionation the remnant magma evolved form K-rich to Na-rich. Ulbrich (1984) presented the similar conclusion based on the studies of the alkaline intrusive complex of the Poços de Caldas, States of Minas Gerais and São Paulo, Brazil. The samples of the Itaúna intrusive complex have high Norm nepheline and low $K_2O/(Na_2O+K_2O)$ wt% ratio, and therefore the rocks are delivered from highly differentiated magma by fractionation crystallization.

It is considered that for the nepheline syenite magma the $K_2O/(Na_2O+K_2O)$ wt% proportion is an efficient and practical parameter as magma differentiation index, rather than SiO_2. The rocks with low $K_2O/(Na_2O+K_2O)$ wt% are originated from highly differentiated nepheline syenite magma and those with high $K_2O/(Na_2O+K_2O)$, relatively primitive one.

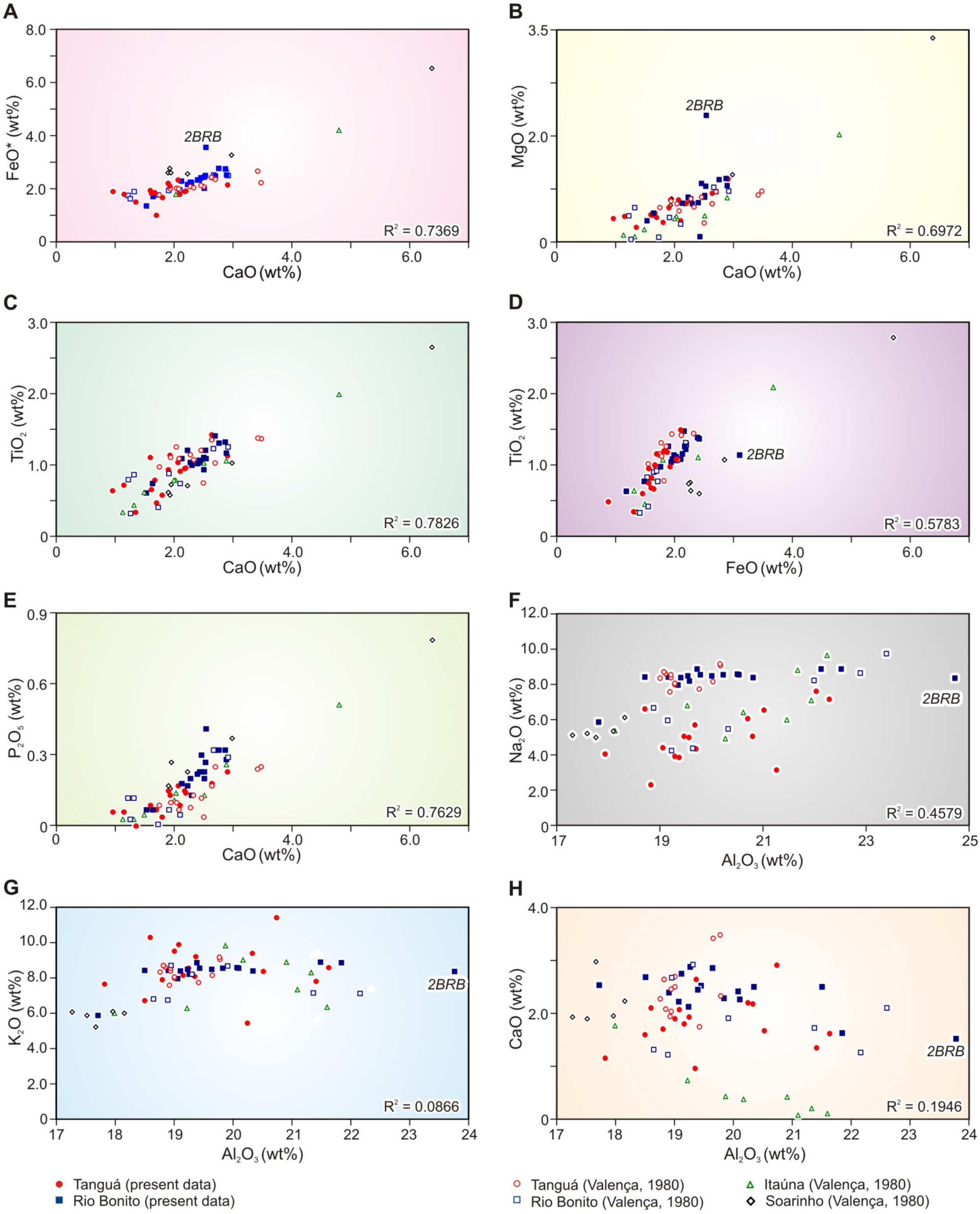

FIGURE 10. Variation diagrams with high correlation index for the alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna, State of Rio de Janeiro, Brazil, based on the data of the present work and Valença (1980). The symbols are same of the Figure 4.

The leucite crystallization reduces $K_2O/(Na_2O+K_2O)$ wt% ratio of the remnant magma. However, only one of the analysed samples is present on the domain in which leucite crystallisation takes place and three of them are on the border of this domain (Figure 11). Most of the samples are along the cotectic line on which the leucite crystallisation does not occur. Therefore, leucite fractionation is not enough to explain the entire magma evolution process from sodic to postassic. For the magmas of the composition along the cotectic curve, the $K_2O/(Na_2O+K_2O)$ rate decreases by means of the fractionation of potash-feldspar. The crystallised feldspar has K:Na ratio of 7:3 to 6:4. In this way, the magma composition can evolve up to the *Ns* point of the Figure 11.

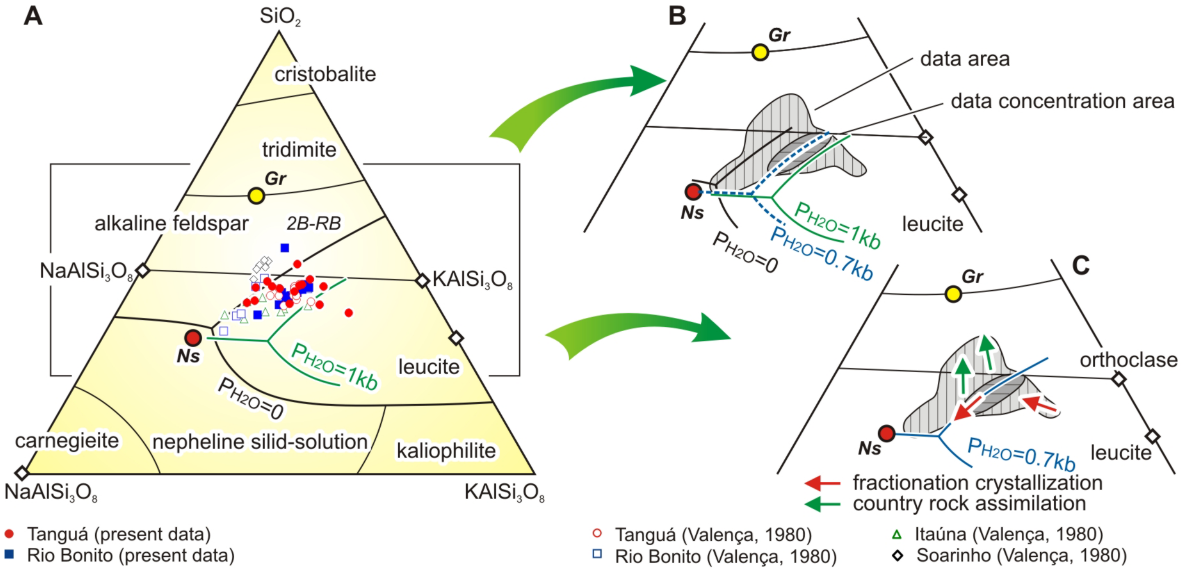

FIGURE 11. Alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna, State of Rio de Janeiro, Brazil based on the data of the present work and Valença (1980): **A)** On the SiO_2-$NeAlSi_3O_8$-$KfAlSi_3O_8$ diagram without H_2O (Schairer & Bowen, 1935) and with 1kb of H_2O (Hamilton & Mackenzie, 1960); **B)** Data concentration area; **C)** Magma evolution trend. The symbols are same of the Figure 4.

CONTINENTAL CRUST ASSIMILATION

The Figure 11A shows that there are some samples which are plotted on the upper side of the cotectic curve, that is, to the silica oversaturated side. The distribution area crosses over the thermal divide which is present between albite and orthoclase (Figure 11B). These compositions are thermodynamically unstable and cannot be explained by simple fractionation crystallisation.

A possible explanation for this phenomenon is the mixture between silica undersaturated and oversaturated compositions. The silica undersaturated composition is represented by the nepheline syenite magma along the cotectic curve. The silica oversaturated composition is represented by the low-temperature magma generated by the partial melting of the continental crust country rocks of the *Gr* point of the Figure 11. Such a mixture takes place by the assimilation of the country rock into the nepheline syenitic magma (Figure 11C).

The country rock of the Tanguá, Rio Bonito, Soarinho, and Itaúna intrusive complexes is granitic orthogneiss and pelitic paragneiss.

Motoki (1986) proposed the diagram of silica saturation vs. (Na+K)/Al (mol) in order to verify the effects of continental crust assimilation by nepheline syenite magma. The above-mentioned paper adopted the value of normative quartz subtracted by normative nepheline as the index that represents the silica saturation.

The authors improve this idea proposing the Silica Saturation Index, SSI, to represent the degree of silica saturation for felsic alkaline rocks, such as nepheline syenite, alkaline syenite, phonolite and trachyte. The interested rocks must have enough high (Na+K)/Al (mol) and all of the Al_2O_3 is used for alkaline feldspar and feldspathoids. The Ca is distributed for clinopyroxene and amphibole, and therefore no plagioclase and biotite are crystallised. Based on this hypothesis, the SSI is calculated by the following equation:

$$SSI=1000*(SiO_2/60.0835-Al_2O_3/101.9601-5*(Na_2O/61.9785+K_2O/94.1956)-CaO/56.077-MgO/40.304-MnO/70.937-FeO/71.844+2*Fe_2O_3/159.687)$$

The above-mentioned formula is apparently complex but this parameter is independent on the Fe^{3+}/Fe^{total} being convenient for XRF analyses data. The CIPW Norm calculation is unnecessary. When the SSI is negative, the magma has chemical potentiality of nepheline crystallization. When this parameter is slightly positive, the magma has no potentiality for nepheline or quartz crystallisation. When it is positive and enough high, the magma has chemical potentiality of quartz crystallisation.

The diagram of the SSI vs. (Na+K)/Al (mol) examines the continental crust assimilation by means of two thermodynamic incompatibilities. The vertical axis treats alkali-silica saturation, which is related to the incompatibility between quartz and nepheline. The horizontal axis shows alkali-alumina saturation, to the incompatibility between aegirine and muscovite.

The continental crust rocks, such as granite, granodiorite, and gneiss of similar composition are subalkaline and oversaturated in silica, and therefore they are plotted on the left-top quadrant of this diagram. On the other hand, typical nepheline syenite is peralkaline and undersaturated in silica, and therefore they are projected on the right-bottom quadrant. If these components are mixed, the data projected form a negative correlation trend, which is form left-top to right-bottom.

The Figure 12 presents the projection of the data of Tanguá, Rio Bonito and Soarinho of the present work and Valença (1980). The distribution area of the Tanguá, Rio Bonito, Soarinho, and Itaúna samples form a linear trend that crosses over the limits of both of the thermodynamic incompatibilities. Such a distribution does not occur by fractionation crystallisation. The convergence is very good with R^2 of 0.5764. Excluding the sample 35 of the Soarinho complex, the R^2 becomes 0.6331, showing clear evidences of the continental crust assimilation. The samples of the Soarinho complex are under strong effects of the country rock contamination. The sample 2B-RB of the Rio Bonito body has high SSI and considered to be the sample with high crust assimilation.

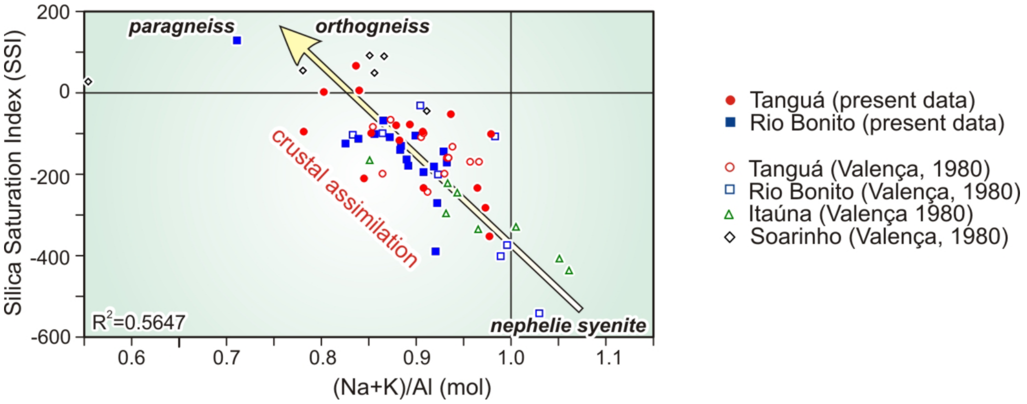

FIGURE 12. The diagram of Silica Saturation Index (SSI) vs. (Na+K)/Al (mol) for the felsic alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna, State of Rio de Janeiro, Brazil, based on the data of the present work and of Valença (1980) in order to examine the effects of the continental crust assimilation into the nepheline syenite magma based on the alkali-silica and alkali-alumina saturation. The arrow shows the continental crust assimilation trend. The symbols are same of the Figure 4.

RB-SR DATING

The authors have performed Rb-Sr datings for five rock samples of the Tanguá intrusive complex and four samples of the Rio Bonito complex. Two of the Tanguá samples are under strong influence of crustal assimilation and unsuitable for the dating. The Rio Bonito samples have similar $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, and therefore it is not possible to trace a comprehensive isochron.

The isochron based on the three samples of Tanguá show a good convergence with R^2 of 0.9738. The age is 66.8Ma and the ($^{87}Sr/^{86}Sr$) initial ratio is 0.7062 (Figure 13, Table 3). However, because of the small number of analysed samples, the age reliability is limited. This age, of preliminary result, is close to the Ar-Ar laser-spot ages of the nepheline syenite intrusion of the Mendanha, State of Rio de Janeiro (Motoki et al., 2007a).

The nepheline syenitic rocks are scarce in zircon and therefore are for U-Pb datings. However, these rocks are abundant in titanite. Therefore, spot datings using LA-ICP-MS are desired in near future.

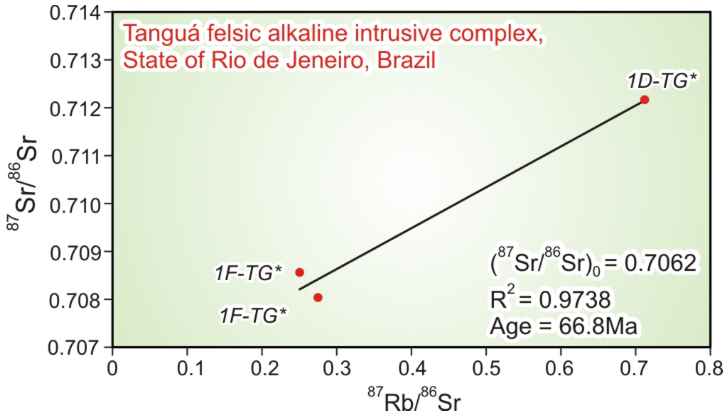

FIGURE 13. Rb-Sr isochron for the felsic alkaline rocks of the Tanguá intrusive complex, State of Rio de Janeiro, Brazil.

TABLE 3. Preliminary Rb-Sr data for the samples of Tanguá and Rio Bonito intrusive complexes, State of Rio de Janeiro, Brazil. Only the three samples of the Tanguá complex provide a comprehensive isochron with the age of 66.8Ma and the Sr initial ratio of 0.7062.

Sample	Rb(ppm)	Sr(ppm)	87Rb/86Sr	87Sr/86Sr
Tanguá				
1C-TG*	151.59	177.14	2.5059	0.7088
1D-TG*	155.96	64.14	7.1199	0.7128
1F-TG*	148.13	157.80	2.7490	0.7082
Rio Bonito				
2D-RB*	126.64	1737.00	0.2135	0.7051
2E-RB*	118.02	1648.50	0.2097	0.7052
7-RB*	113.33	1653.30	0.2007	0.7052
11A-RB*	103.16	1979.00	0.1526	0.7052

DISCUSSION

The above-mentioned data indicate that the geochemical evolution of the nepheline syenite magma took place in the following three stages: 1) $K_2O/(Na_2O+K_2O)$ ratio reduction by the leucita fractionation; 2) The same by the potash feldspar fractionation; 3) SSI elevation by the assimilation of the continental crust country rock.

The first stage of the magmatic evolution is the leucite crystallisation, which is indicated by the presence of pseudo leucite at the western border of the Tanguá intrusive complex. Because of the slow magma cooling, the leucite crystals were transformed into pseudo leucite. However, pseudo leucite syenite is rare in the Tanguá body and it is composed mainly by nepheline syenite.

The second stage is the magma fractionation along the cotectic curve, which is characterised by potash feldspar crystallisation. The nepheline syenite sometimes contains alkaline feldspar phenocrysts of 2 to 3cm in size and they can be the potash feldspar in fractionation. In this moment, no EPIM data is available.

The pseudoleucite syenite has biotite of 2 cm in size however without clinopyroxene in the groundmass (Photo 1C). The pseudo leucite crystals are 5 to 10 cm in diameter and constituted by nepheline, potash feldspar, and clinopyroxene without biotite of 2mm in size. The contact with the matrix is not sharp, showing aspects different from the pseudo leucita of the other alkaline intrusive bodies.

The continental crust assimilation is the third stage, which took place by means of partial melting of the country rock. This phenomenon occurred in all of the studied felsic alkaline rock bodies, more expressively in the Soarinho body and less expressively in the Itaúna Body. All of the six samples of the Soarinho complex have strong effects of continental crust assimilation. The proportion of the assimilation origin materials is from 40 to 60 wt%. Three samples of the Rio Bonito complex present from 40 to 60 wt% of crustal assimilation, five samples of Tanguá complex, from 20 to 30 wt%, and two samples of the Itaúna intrusion, from 10 to 20%. The relation between the fractionation crystallization and continental crust assimilation is well represented by the diagram the SSI vs. K_2O/(Na_2O+K_2O) wt% (Figure 14).

In the cases of calc-alkaline magmas, the geochemical evolution by fractionation crystallisation and by continental crust assimilation are of the same sense and it is difficult to distinguish. However, in the cases of felsic alkaline magmas, the geochemical evolution directions by the above-mentioned processes are different. Therefore, some diagrams can distinguish the trends originated from fractionation crystallisation and continental crust assimilation (Figure 15).

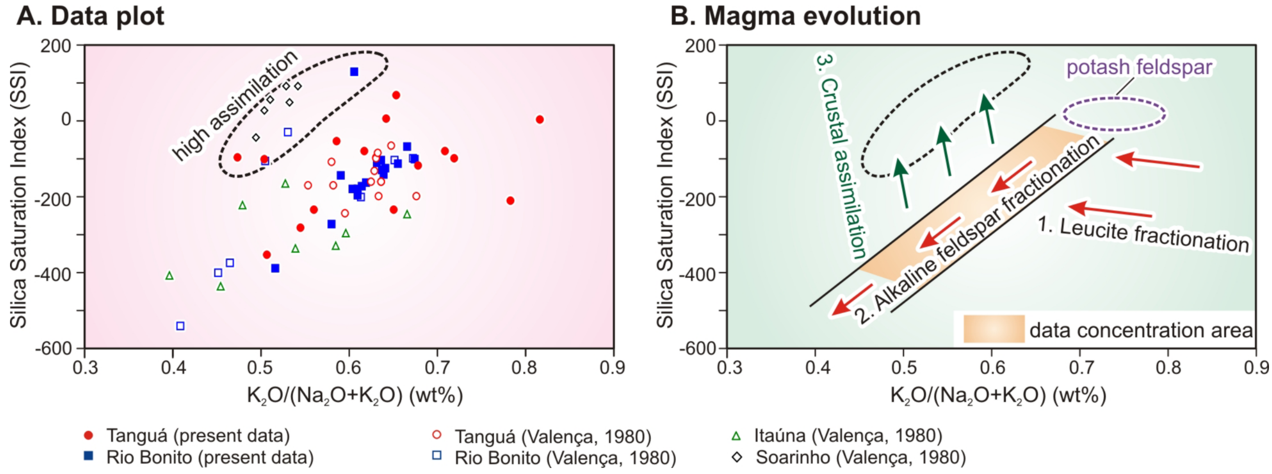

FIGURE 14. Diagram of the Silica Saturation Index (SSI) vs. K_2O/(Na_2O+K_2O) wt% for the felsic alkaline rocks of Tanguá, Rio Bonito, Soarinho, and Itaúna, State of Rio de Janeiro, Brazil, based on the data of the present work and Valença (1980). The symbols are same of the Figure 4.

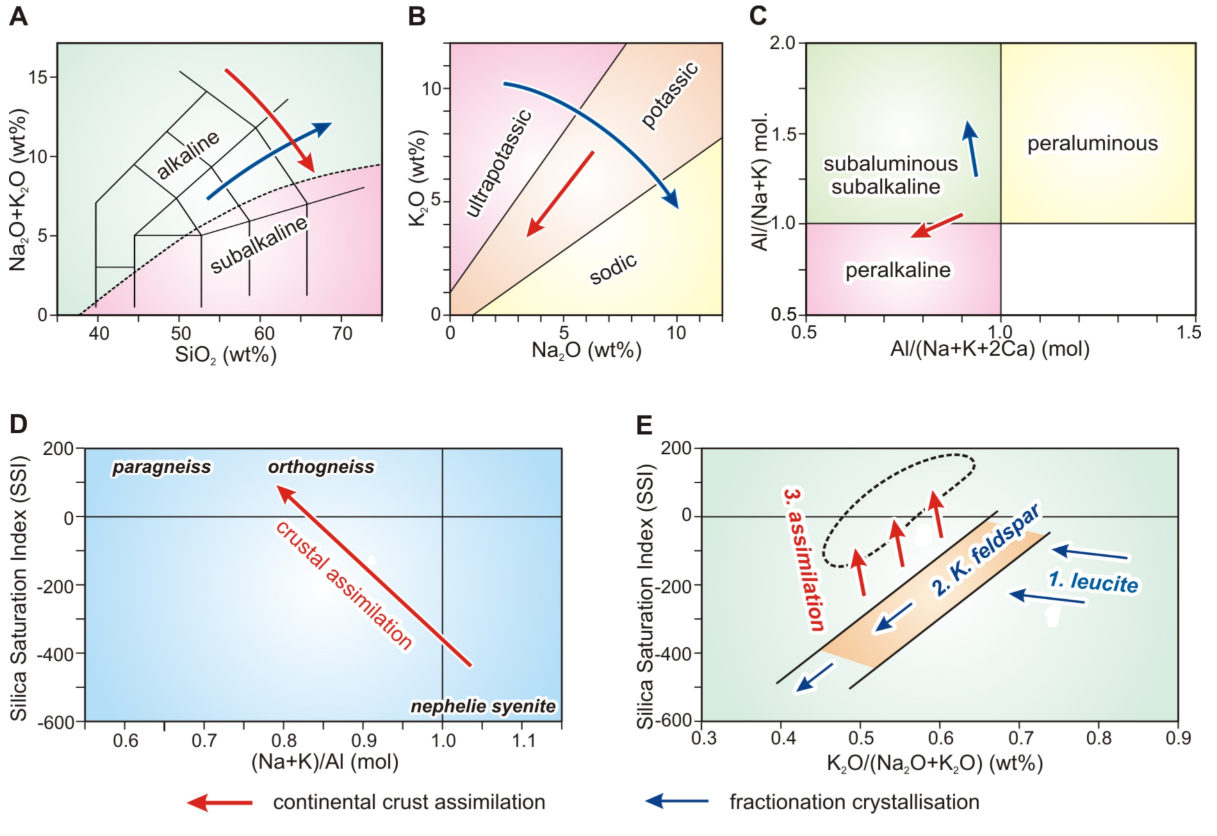

FIGURE 15. Trends of the fractionation crystallization and continental crust assimilation for the nepheline syenite magma on the diagrams: A) Na_2O+K_2O vs. SiO_2, Le Bas et al. (1986); B) K_2O vs. N_2O, Middlemost (1975); C) Al/(Na+K) vs. Al/(Na+K+2Ca), Shand (1943); D) SSI vs. (Na+K)/Al, Motoki (1986); E) SSI vs. K_2O/(Na_2O+K_2O), the proposal of the authors.

The nepheline syenite magma cannot develop form silica undersaturation to the oversaturation field by fractionation crystallisation because of the thermal divide. To cross over the thermal divide some special factors are necessary, such as: 1) Injection of high temperature magma into the nepheline syenite magma chamber causing magma super-reheating of more than 50°C (Motoki, 1986); 2) Injection of fluid-rich magma reducing melting temperature of the host rock.

The intrusive bodies of the Morro do São João and the Cabo Frio Island (Figure 1) contain xenolith-like igneous pyroxenite fragments. The Mendanha (Figure 1) and the Vitória Island (State of São Paulo) intrusive bodies are cut by lamprophyre dykes. If the intrusion of the hot magmas occurred into the liquid-state nepheline syenite magma chamber, the magma super-reheating could take place. The magma super-reheating would cause resorption of pre-crystallised clinopyroxene and opaque minerals. This phenomenon is observed in the syenitic rocks of the Vitória Island (Motoki, 1986).

On the other hand, the injection of fluid-rich new magma should result the transformation of clinopyroxene into amphibole. The samples of the Tanguá intrusive complex frequently contain pseudomorph of amphibole after clinopyroxene. Some of them have remnant core of clinopyroxene.

CONCLUSION

The above-mentioned geochemical data of the felsic alkaline rocks of the Tanguá, Rio Bonito, Soarinho, and Itaúna intrusive complexes lead the authors to the following conclusions:

1. Most of the alkaline rocks are undersaturated in silica and characterised by moderate (Na+K)/Al and high $K_2O/(Na_2O+K_2O)$ ratios. They are classified to be potassic nepheline syenite.
2. The variation diagrams for the main elements indicate strong tendency of titanite, ilmenite, apatite, and clinopyroxene or amphibole crystallization and moderate tendency of sodic alkaline feldspar and nepheline. Plagioclase fractionation is little expressive.
3. The preliminary Rb-Sr dating for three rock samples of the Tanguá intrusive body presents the age of 66.8Ma and the Sr initial ratio of 0.7062.
4. The geochemical evolution of the nepheline syenite magma occur in the following three stages: 1) $K_2O/(Na_2O+K_2O)$ reduction by leucita fractionation; 2) The same by potash feldspar fractionation; 3) Compositional transition from silica undersaturated to oversaturated field crossing over the thermal divide by means of assimilation of the continental crust country rocks.
5. The main phase of the fractionation crystallization occurred under the H_2O pressure of about 0.7kb, which corresponds to a depth of about 3km. The $K\text{-}_2O/(N_2O+K_2O)$ wt% is an efficient and practical parameter to represent the fractionation crystallization degree of the nepheline syenite magma.
6. According to the data of the present work and those of Valença (1980), the continental crust assimilation is relevant in the Soarinho complex, moderate in the Tanguá and Rio Bonito bodies, and less expressive in the Itaúna intrusion. Some of the samples are composed of about 60% of assimilated continental crustal materials. For the continental crust assimilation crossing over the thermal divide, super-reheating of the nepheline syenite magma and/or injection of fluid-rich magma to the nepheline syenite magma chamber are necessary.

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HOMAGE TO THE MEMORY

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