 PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY,
ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on Environment, Archaeometry and Cultural Heritage

Petrological, geochemical and Sr-Nd isotopic features of alkaline rocks from the Arraial do Cabo Frio peninsula (southeastern Brazil)

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Submitted, March 2002 - Accepted, July 2002

ABSTRACT. — The alkaline activity in the Cabo Frio region is made up mainly of intermediate and felsic differentiate rocks emplaced about 55 Ma ago into the crystalline basement as sills, plugs and dykes. Two magma suites can be distinguished: (a) a strongly silica-undersaturated tephriphonolite to phonolite serie; (b) a weakly silica-undersaturated to saturated trachyandesite-trachyte series. Petrography, mineral chemistry, whole-rock chemistry trends and isotopic data strongly support a genetic link among the lithotypes of each suites consistent with fractional crystallization processes dominated by the observed phases. The same data, however appear to exclude a link between the two groups of rocks, supporting a petrogenesis by prolonged differentiation processes starting from two distinct parental magma with a slight difference in the SiO₂ saturation. The scarce basanites and trachybasalts reported in the same area could represent the most probable compositions for the parental magmas of the two suites. The initial ⁸⁷Sr/⁸⁶Sr (0.70401-0.70458) and ¹⁴³Nd/¹⁴⁴Nd (0.51239-0.51247) isotopic ratios and the significant potassic component indicate derivation of these rocks from an enriched lithospheric mantle source.

RIASSUNTO. — I prodotti dell'attività alcalina della regione di Cabo Frio sono rappresentati da un

insieme di rocce con chimismo variabile da intermedio a sialico, con età intorno a 55 Ma. Si tratta di filoni, *sill* e *plug*. Questi prodotti appartengono a due serie magmatiche: una fortemente sottosatura (tefrifonolite-fonolite) e l'altra da debolmente sottosatura a satura (trachiandesite-trachite). I dati petrografici, il chimismo dei minerali e quello delle rocce totali, nonché i dati isotopici suggeriscono un legame genetico fra i litotipi di ciascuna delle due serie. Il processo dominante è stato individuato nella cristallizzazione frazionata delle fasi osservate in sezione sottile. Sulla base degli studi condotti, viene esclusa una relazione tra i due gruppi di rocce, mentre viene proposta la presenza di due distinti magmi parentali caratterizzati da leggere differenze di saturazione in silice. Le rare basaniti e trachibasalti rinvenute possono rappresentare le composizioni più probabili dei magmi parentali delle due serie di rocce. Il valore iniziale dei rapporti isotopici ⁸⁷Sr/⁸⁶Sr (0,70401-0,70458) e ¹⁴³Nd/¹⁴⁴Nd (0,51239-0,51247) indicano la derivazione di queste rocce da una sorgente mantellica litosferica arricchita.

KEY WORDS: *alkaline magmas, magmatic evolution, Arraial do Arraial do Cabo Frio, Brazil.*

INTRODUCTION

Southern Brazil has been the site of alkaline magmatism since Early Cretaceous times. The

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earliest intrusions are represented by the complexes of Anitapolis, Jiquiã, Jacupiranga and Pariquera Açu, (131-135 Myr; Amaral *et al.*, 1978, Morbidelli *et al.*, 2000) nearly coeval to the eruption of the Paran -Etendeka continental flood basalts (133-132 Myr; Renne *et al.*, 1992, Turner *et al.*, 1994). The magmatism continued until Eocene with a peak at about 85-90 Myr and it is mainly distributed in the Brasilia and Ribeira Proterozoic mobile belts around the southern border of the S o Francisco craton (Morbidelli *et al.*, 1995).

Along the Brasilia fold belt (Alto Parana ba Igneous Province) the magmatic activity shows a broad range of alkaline rocks, including carbonatites, kimberlites, lamprophyres, lamproites, syenites and the voluminous extrusive kamafugites of the Mata da Corda formation (Gibson *et al.*, 1995).

The alkaline magmas emplaced as intrusions and dyke swarm into the Ribeira mobile belt belong to the Serra do Mar igneous province (Thompson *et al.*, 1998), that extends for 500 Km along the southeastern Brazilian coastline. The intrusive alkaline activity of the Serra do Mar Province is mainly represented by potassic syenites, nepheline syenites and alkali syenite but subordinate granites and qz-syenites also occur. Mafic compositions are also widespread and mostly form dyke swarms. The mafic rocks are alkali basalts, basanites and melanephelinites and more rarer leucites and minettes with potassic and sodic affinity and large variation in the SiO₂-saturation.

Detailed assessment of published K/Ar dates (Sonoki and Garda, 1988, Thompson *et al.*, 1998) indicate that the Serra do Mar magmatism was emplaced between 80 and 55 Ma with a progressive diminution of the radiometric age going eastwards.

The alkaline magmatism emplaced along the Rio-Santos coastline is currently matter of debate. This magmatic activity has been related both to reactivation of lithospheric fractures, due either to passive continental margin extension occurred in Brazil after the opening of the Atlantic Ocean (Ulbrich and Gomes, 1981; Morbidelli *et al.*, 1995; Brotzu *et al.*,

1997) and to the track of the Trindade mantle plume (Thompson *et al.*, 1998).

This study deals with the youngest and easternmost products of the Cretaceous-Eocene Brazilian alkaline magmatism on land occurring in the Arraial do Cabo Frio peninsula, in order to investigate their genesis and evolution. In this area alkaline rocks characterized by variable SiO₂-saturation coexist. The close association of SiO₂-undersaturated to SiO₂-critically saturated and SiO₂-oversaturated felsic alkaline rocks and their petrogenetic relationships are of crucial interest in the petrology of the alkaline rocks. Thus the alkaline rock occurrences from Arraial do Cabo Frio peninsula offers an insight into the genetic relationships of phonolitic and trachytic magma series within a passive margin tectonic setting.

GEOLOGICAL SETTING

The Arraial do Cabo Frio peninsula is located at the eastern end of the Rio de Janeiro coastline (Fig. 1). In this area the alkaline magmatism, described in detail by Lima (1976) and then investigated by Ara jo *et al.*, (1995), Thompson *et al.*, (1998) and by Bennio *et al.*, (2000), is mainly represented by small intrusions of nepheline-syenites and quartz-syenites and by a widespread dyke swarms dominated by trachytes and phonolites with minor occurrences of basanites and trachybasalts. The selected radiometric ages of alkaline rocks (K/Ar, Thompson *et al.*, 1998) range from 53.8 to 55.5 Ma and thus the Arraial do Cabo Frio magmatism represents the younger activity reported for the alkaline province of southern Brazil. In addition to alkaline rocks, tholeiitic dykes, emplaced about 55 Ma ago and with geochemical imprint of E-MORB magmas, have been recently studied (Bennio *et al.*, submitted).

Dykes intrude the late Precambrian metamorphic basement mainly formed by gneisses, migmatites and amphibolites of the

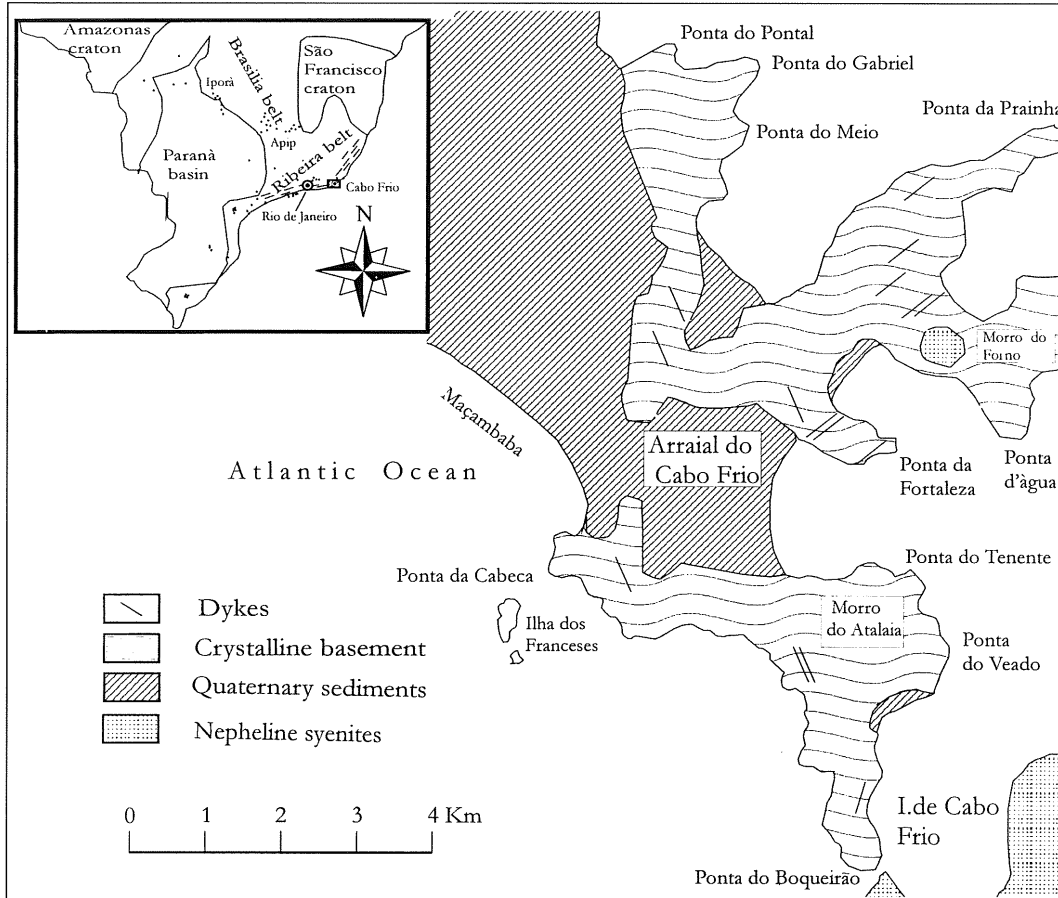


Fig. 1 – Sketch map of the Arraial do Cabo Frio area, with location of the dykes sampled. Inset: general view of SE Brazil.

Riberia mobile belt and are structurally linked to the ENE to EW transcurrent fault system developed at the end of the orogenic Brasiliano Cycle and reactivated during the Mesozoic Gondwana break-up.

ANALYTICAL PROCEDURES

Whole-rock major and trace elements were performed at the Earth Science Departement, Federico II University, Naples, using pressed powder pellets, a PW 1400 XRF spectrometer. Precision is better than 3% relative for major elements, and better than 10% for the trace

elements. Na₂O and MgO have been determined by Atomic Absorption Spectrophotometry, FeO by titration and L.O.I. by standard gravimetric techniques (Naples). Mineral compositions were obtained at Earth Science Departmen, La Sapienza University, Rome, using a CAMECA SX50. REE were determined with Inductively Coupled Plasma-Mass Spectrometry at CRPG, Nancy, France following the methods described by Govindarju and Mevelle (1987).

Sr-and Nd isotope analyses were performed at the “Centro Interdipartimentale di Servizio di Analisi Geomineralogiche”, Naples. Samples were prepared for measurements as

follows: 0.3 g of powder were dissolved with high purity HF-HNO₃-HCl mixtures. Sr and Nd were extracted by conventional ion-exchange chromatographic techniques. The total blank was ca. 6 ng Sr and 4 ng Nd. Measurements were made using a VG354 double-collector thermal ionization mass spectrometer running in peak jumping mode, by normalizing to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ and $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$ for mass fractionation effects. The quoted error is twice the standard deviation of the mean (2sigma) and is $\pm 1 \cdot 10^{-5}$. Repeated analyses of NBS-987 Sr standard yielded a mean value of $^{87}\text{Sr}/^{86}\text{Sr} = 0.71027 \pm 0.00001$ (N = 50) and the La Jolla Nd standard a mean value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.51183 \pm 0.00001$ (N = 26).

PETROGRAPHY AND CLASSIFICATION

Twenty samples of alkaline rocks have been sampled along the coastline of Arrial do Cabo Frio Peninsula (Fig. 1).

On the basis of the mineralogy and whole-rock chemistry two main groups have been recognized: a strongly alkaline group (tephriphonolites and phonolites), with normative nepheline ranging from 12.9 to 30.4%, and a weakly alkaline group (trachyandesite and trachyte) ranging from silica undersaturated (ne-normative = 2.8%) to quartz-normative rocks (Tab. 1,4,5). The felsic rocks define two discrete fields in the Total Alkali Silica diagram (Le Bas et al., 1986; Fig. 2).

STRONGLY ALKALINE SUITE (SAS)

Tephriphonolites

Tephriphonolites rocks are porphyritic in texture with alkali feldspar, amphibole, pyroxene, and scarce plagioclase (An₅₇₋₃₈) and biotite phenocrysts. The coarse-grained groundmass mainly consists of alkali feldspar and nepheline and minor amounts amphibole, clinopyroxene and biotite microlites. Accessory

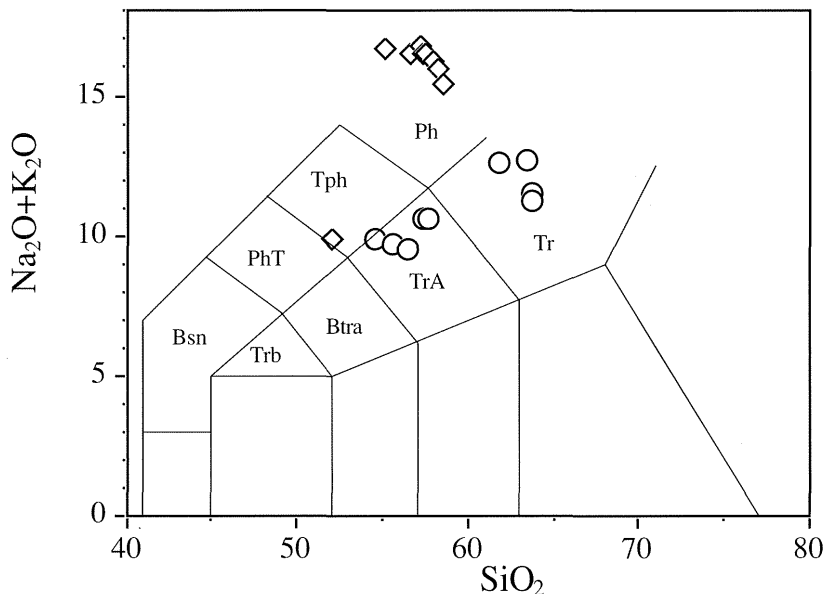


Fig. 2 – Total alkali-silica diagram (Le Bas *et al.*, 1986) for the dykes of the Arrial do Cabo Frio area. Circles: weakly alkaline suites; diamonds: strongly alkaline suites. Bsn = basanite; PhT = phonotephrite; Tph = tephriphonolite; Ph = phonolite; Trb = trachybasalt; Btra = basaltic trachyandesite; TrA = trachyandesite; Tr = trachyte.

minerals include apatite, magnetite ($ulv_{0.30mol\%}$) and scarce sphene while calcite and analcime, growing on nepheline grains, represent the main secondary minerals.

Early to late-crystallized K-feldspars range in composition from Or_{83} to Or_{62} . Zoned clinopyroxenes display an evolutionary trend from salite to fe-salite ($Ca_{49-47}Mg_{40-29}Fe_{11-24}$). Yellow-brown cores of amphiboles are kaersutitic grading towards mg-hastingsitic rims (nomenclature according to Leake 1978). Euhedral mica phenocrysts are strongly zoned with phlogopitic cores ($Mg\# 0.76$) and, sometimes, mg-biotitic rims ($Mg\# 0.46$).

Phonolites

Phonolitic rocks are porphyritic in texture with mostly sanidine and nepheline phenocrysts, together with subordinate pyroxene, amphibole, biotite, nosean, magnetite ($ulv_{0.28-0.33mol\%}$), apatite and sphene. The phenocrystic assemblage is set in a coarse to fine-grained groundmass made up of the some phases. Two samples display rounded olivine (Fo_{81}) xenocrysts.

K-feldspars show large compositional variations ($Or_{61-91}Ab_{38-8}An_1$), with zoning trends evolving towards Na-poor composition. Pale green to green clinopyroxenes mainly plot in the Fe-salite field ($Ca_{47-45}Mg_{32-20}Fe_{21-35}$) and display a slight Na increase if compared to those occurring in the tephriphonolitic rocks. Both amphiboles and biotites display chemical compositions very similar to those recognized in the tephriphonolitic rocks. The nepheline composition is uniform ($Ne_{75}Ks_{20}Qz_5$).

Nepheline syenites

Nepheline-syenites have hypidiomorphic textures and medium grain size. They are made up of perthitic K-feldspar ($Or_{62-67}Ab_{37-32}An_{1-0}$) and subhedral to euhedral nepheline ($Ne_{71}Ks_{22}Qz_7$). Pyroxenes ($Ca_{47-46}Mg_{32-17}Fe_{21-37}$) with sometimes amphibole rims complete the paragenesis. Magnetite ($ulv_{0.23-0.12 mol\%}$) apatite and large sphene grains are the main accessory phases.

WEAKLY ALKALINE SUITE (WAS)

Trachyandesites

Trachyandesitic rocks are more or less porphyritic, with sanidine, plagioclase (An_{49-45}), amphibole, magnetite ($ulv_{0.31-0.33 mol\%}$), biotite ($Mg\# 0.57$) and clinopyroxene phenocrysts. The groundmass is essentially dominated by alkali feldspar with minor mafic phases (amphibole and magnetite).

Core to rim and/or groundmass relationships clearly indicate Ab increase ($Or_{94-70}Ab_{5-30}An_{1-0}$) in the late sanidine.

Brown-green amphiboles are hastingsites with a narrow compositional range ($Mg\# 0.45-0.43$).

Trachytes

Trachytic rocks contain sanidine phenocrysts and rare amphibole, magnetite and biotite in a sanidine rich groundmass.

Sanidine have a large chemical variation ($Or_{94-70}Ab_{5-30}An_{1-0}$) and show a clear tendency towards Ab enrichment.

Yellow-reddish Ti-Fe biotites ($Ti < 0.5$ atom formula unit; Rock 1982) show narrow compositional variations with $Mg\#$ ranging from 0.57 to 0.45.

Amphiboles phenocrysts are katophoritic in composition ($Mg\# 0.50-0.41$); some grains reach richteritic composition in the rims.

MAJOR AND TRACE ELEMENT DISTRIBUTION

The SAS and WAS rock-types can be easily distinguished in several variation diagrams using MgO as differentiation index. At comparable MgO values the samples of SAS group have higher contents of Al_2O_3 , Na_2O , CaO and Rb and lower SiO_2 , FeOtot and Ba, respect to WAS ones.

Both groups display negative correlation between MgO and SiO_2 , Al_2O_3 , Na_2O , K_2O , Rb, Zr, Nb, Y, La and Ce; opposite trends are shown by TiO_2 , FeO, CaO, P_2O_5 , Sc, V, Sr and Ba. It to be noted that the WAS suite have Sr

and Zr almost constant, while K_2O and Ba concentrations firstly increase and then suddenly decrease (Tab. 1, Fig. 3).

Mantle-normalized incompatible trace element patterns of trachyandesitic and tephriphonolitic rocks mainly differ for the pronounced Ba negative anomaly occurring in the latter. Phonolites show pronounced Ba, Sr, P and Ti negative anomalies coupled with Zr

positive anomaly. Trachytes show flat normalized abundances from Rb to Ce followed by pronounced Sr, P and Ti negative anomalies (Tab. 1, Fig. 4).

All the selected alkaline rocks from Arraial do Cabo Frio peninsula have chondrite-normalized patterns showing, on the whole, LREE enrichment with respect to HREE (La_n/Sm_n 58-12).

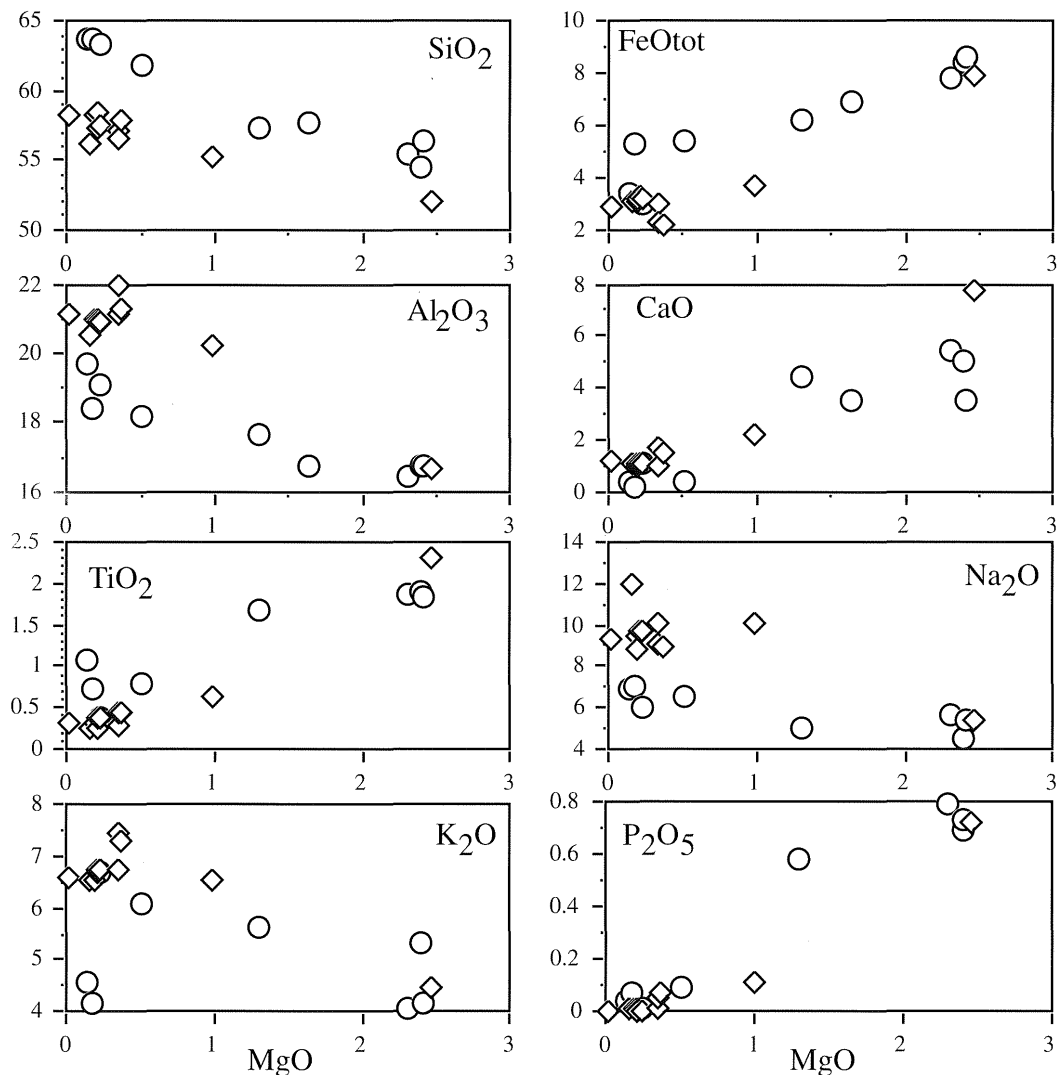


Fig. 3 – Variation in contents of major and trace elements with MgO. Symbols in fig. 2.

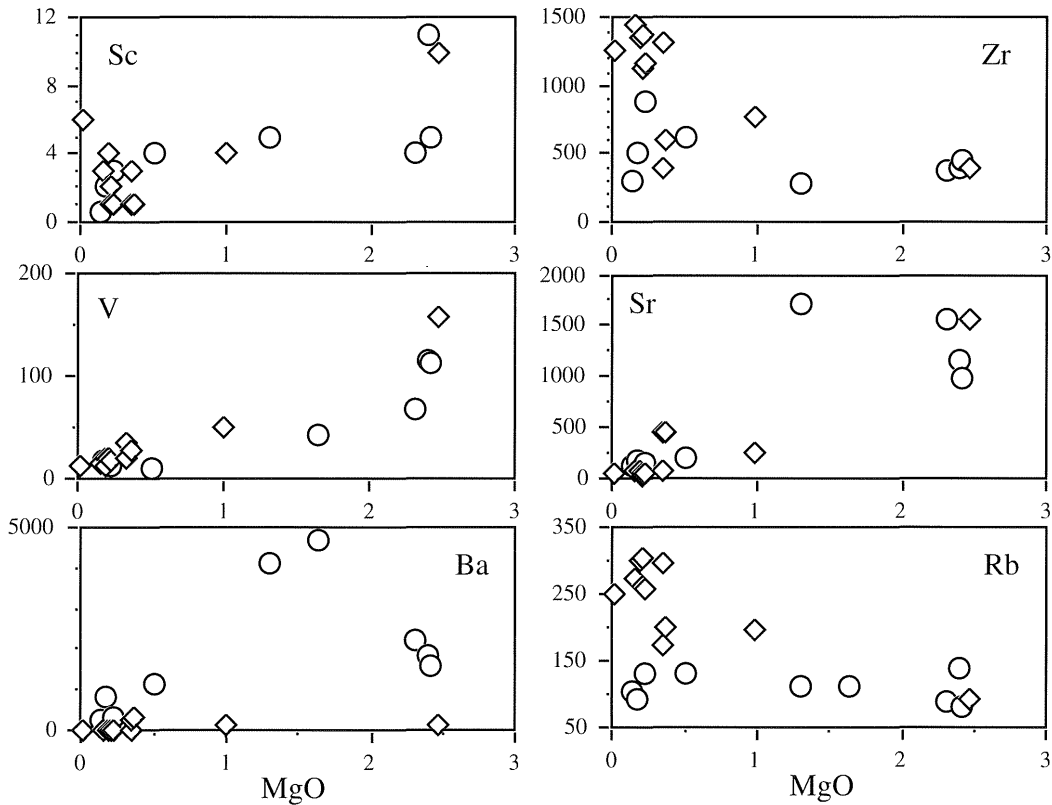


Fig. 3 – Variation in contents of major and trace elements with MgO. Symbols in fig. 2.

Within the SAS suite, phonolitic and nepheline syenite samples (F61 and F43 samples) exhibit strong and variable MREE depletion respect to tephriphonolitic rocks (F14 sample). The trachytic sample (F15) show a lower MREE depletion than phonolitic rocks (Tab. 2, Fig. 5).

STRONTIUM AND NEODYMIUM ISOTOPES

Strontium and neodymium isotope measurements were performed on fresh samples, (i.e. without secondary minerals). Initial ratios have been calculated to 55 Ma.

The SAS and WAS rocks show a restricted

range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ($\text{Sr}_0 = 0.70401\text{--}0.70458$) and ϵNd (-3.48 to -1.91) (Tab. 3, Fig. 6). It to be remarked that two suites cannot be divided on isotopic basis.

Isotopic data of SAS and WAS rocks completely overlap those reported by Thompson *et al.*, (1998) for coeval basanites and trachybasalts sampled in the Arraial do Cabo Frio peninsula ($\text{Sr}_0 = 0.70403\text{--}0.70460$ and $\epsilon\text{Nd} = -3.51$ to -1.96) and plot within the field defined by the Late Cretaceous mafic alkaline dykes and the alkaline complexes outcropping in the Serra do Mar region and along São Paulo-Rio de Janeiro coastline ($\text{Sr}_0 = 0.70394\text{--}0.70523$ and $\epsilon\text{Nd} = -3.52$ to 2.42 ; Brotzu *et al.*, 1989, 1992, 1997, Valente, 1997, Piccirillo, pers. comm.).

TABLE I

Major and trace element analyses (recalculated on anhydrous basis) of representative rocks of Arraial do Cabo Frio. Major elements in wt%, trace elements in parts per million.

Group	SAS	SAS	SAS	SAS	SAS	SAS	SAS	SAS	SAS	SAS	SAS	WAS
Lithotype	Tph	Ph	Ph	Ph	Ph	Ph	Ne-sy	Ph	Ph	Ph	Ph	TrA
Sample	F14	F21	F43	F63b	F63	F51	F61	F57	F62	F4	F40	F11
SiO ₂	52.10	55.18	56.11	57.38	57.52	57.22	56.65	58.22	57.89	58.28	58.52	54.62
TiO ₂	2.29	0.63	0.27	0.38	0.37	0.30	0.45	0.31	0.43	0.31	0.26	1.88
Al ₂ O ₃	16.68	20.26	20.50	20.89	20.87	21.16	21.97	20.95	21.27	21.15	21.00	16.78
FeO	5.26	1.25	0.65	0.43	0.85	0.83	1.31	0.75	1.42	1.34	0.66	4.28
Fe ₂ O ₃	2.62	2.46	2.44	2.84	2.33	2.11	0.94	2.37	0.75	1.50	2.57	4.18
MnO	0.22	0.22	0.26	0.29	0.28	0.24	0.13	0.24	0.15	0.30	0.30	0.22
MgO	2.47	0.99	0.15	0.21	0.23	0.34	0.34	0.19	0.36	0.01	0.20	2.40
CaO	7.78	2.24	1.09	1.10	1.06	1.02	1.69	1.02	1.46	1.17	1.05	5.02
Na ₂ O	5.36	10.11	12.00	9.75	9.75	10.04	9.04	9.43	8.93	9.35	8.76	4.58
K ₂ O	4.49	6.54	6.51	6.73	6.74	6.73	7.43	6.51	7.27	6.59	6.67	5.35
P ₂ O ₅	0.72	0.11	0.01	0.00	0.00	0.01	0.05	0.01	0.07	0.00	0.01	0.69
LOI	5.81	4.35	2.53	1.50	1.36	4.05	1.78	2.98	2.29	4.46	0.90	3.47
Sc	10	4	3	1	1	1	3	4	1	6	2	11
V	159	51	15	20	18	19	34	20	27	12	13	115
Zn	126	108	139	143	129	125	59	138	68	133	148	251
Rb	92	197	274	261	258	295	173	298	200	250	303	139
Sr	1550	252	62	43	40	67	442	64	442	55	18	1168
Y	40	36	46	44	42	37	25	42	27	42	43	39
Zr	391	764	1447	1137	1171	1316	392	1348	607	1258	1378	396
Nb	199	302	337	411	410	328	192	336	225	170	280	96
Ba	131	166	29	22	33	33	271	31	339	36	15	1814
La	121	163	178	189	182	138	101	154	95	147	150	98
Ce	215	231	199	262	253	179	151	191	156	248	197	160
Nd	77	45	28	38	40	29	30	32	31	65	31	66
qz	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
cor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
or	26.51	38.66	38.47	39.78	39.81	39.79	43.92	38.47	42.94	38.96	39.41	31.55
ab	21.60	11.60	15.13	19.96	20.77	19.54	15.43	24.73	21.19	25.37	30.24	33.69
an	8.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.40
ne	12.87	30.44	29.30	27.10	26.59	28.08	30.43	25.34	25.87	25.31	22.03	2.70
di	20.99	8.45	3.12	2.44	4.00	4.22	5.43	3.52	5.79	4.76	1.13	8.72
hy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ol	0.01	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.09	0.00	0.00	2.51
mt	3.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.30	6.05
il	4.36	1.20	0.52	0.72	0.69	0.57	0.85	0.59	0.81	0.58	0.49	3.57
ap	1.71	0.26	0.03	0.01	0.01	0.03	0.12	0.03	0.16	0.00	0.02	1.64
ac	0.00	7.12	7.07	8.21	6.74	6.09	2.71	6.85	2.18	4.34	2.83	0.00
hm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Tph = tephriphonolite; Ph = phonolite; Ne-sy = nepheline syenite; TrA = trachyandesite; Tr = trachyte.

TABLE 1: *Continued*

Group Lithotype Sample	WAS TrA F20	WAS TrA F12	WAS TrA F3	WAS Tr F15	WAS Tr F8	WAS Tr F63a	WAS Tr F36
SiO ₂	55.52	56.44	57.34	61.83	63.79	63.40	63.68
TiO ₂	1.86	1.83	1.68	0.78	0.73	0.38	1.09
Al ₂ O ₃	16.41	16.75	17.67	18.20	18.44	19.12	19.69
FeO	3.18	3.50	5.14	0.67	0.41	2.26	0.31
Fe ₂ O ₃	4.60	5.12	1.04	4.72	4.88	0.72	3.03
MnO	0.23	0.16	0.24	0.24	0.02	0.08	0.06
MgO	2.31	2.41	1.30	0.51	0.17	0.23	0.13
CaO	5.40	3.52	4.39	0.39	0.22	1.13	0.42
Na ₂ O	5.64	5.38	5.00	6.50	7.10	6.01	6.96
K ₂ O	4.06	4.17	5.61	6.08	4.18	6.67	4.59
P ₂ O ₅	0.79	0.73	0.58	0.09	0.07	0.01	0.04
LOI	3.70	1.60	7.74	1.46	1.45	0.00	1.32
Sc	4	5	5	4	2	3	0.5
V	68	113	44	11	18	12	14
Zn	138	188	118	119	113	50	99
Rb	86	81	111	130	91	130	105
Sr	1547	970	1715	204	161	148	117
Y	39	33	20	48	47	49	28
Zr	370	440	278	621	509	875	297
Nb	120	101	345	182	142	239	220
Ba	2231	1575	4115	1147	853	328	237
La	121	90	101	144	164	165	105
Ce	226	186	171	238	309	299	211
Nd	86	64	66	82	123	85	57
qz	0.00	0.86	0.00	0.00	5.96	0.00	4.65
cor	0.00	0.00	0.00	0.00	2.00	0.00	2.60
or	23.97	24.65	27.29	33.13	24.70	39.41	27.12
ab	42.60	45.52	46.06	37.04	60.07	50.10	58.89
an	7.48	9.23	5.04	9.21	0.66	5.49	1.82
ne	2.78	0.00	2.64	2.85	0.00	0.41	0.00
di	11.03	2.68	7.35	7.43	0.00	0.05	0.00
hy	0.00	4.76	0.00	0.00	0.42	0.00	0.32
ol	0.45	0.00	3.27	4.29	0.00	2.76	0.00
mt	5.62	6.50	3.50	1.51	0.00	1.04	0.00
il	3.53	3.47	3.42	3.19	0.90	0.72	0.78
ap	1.87	1.74	1.26	1.37	0.16	0.01	0.10
ac	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hm	0.73	0.64	0.00	0.00	4.88	0.00	3.03

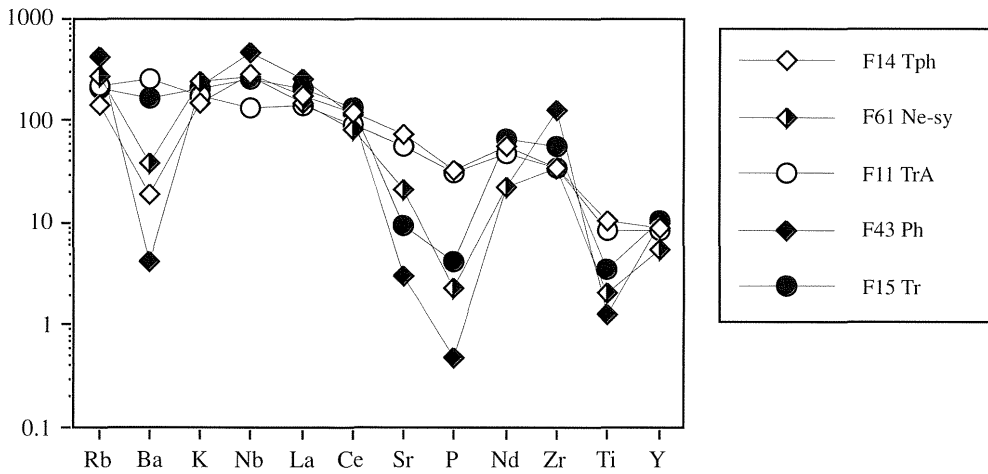


Fig. 4 – Mantle normalized incompatible element diagram of representative Arraial do Cabo Frio rocks. Normalization values after Sun and McDonough (1989).

TABLE 2
REE contents of selected
Arrial do Cabo Frio rocks.

Group Litotype Sample	SAS Tph F14	SAS Ph F61	SAS Ph F43	WAS Tr F15
La	130.88	101.09	178.43	144.82
Ce	220.00	150.54	198.72	238.32
Pr	23.47	11.96	12.90	26.86
Nd	82.91	29.90	27.81	81.52
Sm	12.09	3.53	3.06	12.13
Eu	3.60	0.86	0.66	2.75
Gd	9.15	3.28	2.48	8.36
Tb	1.15	0.39	0.40	1.22
Dy	5.87	2.10	2.66	6.47
Ho	1.06	0.41	0.61	1.18
Er	2.95	1.42	2.27	3.64
Tm	0.38	0.22	0.42	0.49
Yb	2.62	1.55	3.72	3.44
Lu	0.38	0.24	0.62	0.53
La _n /Yb _n	49.9	65.2	48.0	42.1
La _n /Sm _n	10.8	28.7	58.3	11.9

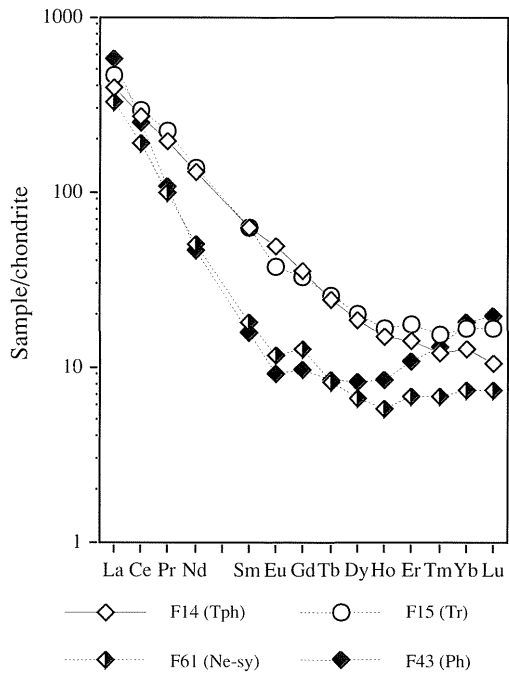


Fig. 5 – Chondrite-normalized rare earth elements diagrams for representative Arraial do Cabo Frio rocks. Normalization values after Boynton (1984).

TABLE 3
Sr-Nd isotopic data recalculated at 55 Ma of Arraial do Cabo Frio rocks.

Group	sample	$^{87}\text{Sr}/^{86}\text{Sr}$	Rb ppm	Sr ppm	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_0$ (55Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	Sm	Nd	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_0$ (55Ma)
SAS	F43	0.71431	274	62	12.69	0.70439	0.51240	3.06	27.81	0.07	0.51240
SAS	F14	0.70453	92	1550	0.17	0.70440	0.51250	12.09	77.07	0.09	0.51246
SAS	F61	0.70516	173	442	1.13	0.70428	0.51250	3.53	29.90	0.07	0.51245
SAS	F63	0.71888	258	40	18.79	0.70420	0.51250	3.60	40.00	0.05	0.51247
WAS	F63a	0.70600	130	148	2.55	0.70401	0.51240	3.02	85.00	0.02	0.51239
WAS	F11	0.70485	139	1168	0.34	0.70458	0.51249	11.20	66.00	0.10	0.51245
WAS	F15	0.70580	130	204	0.17	0.70437	0.51243	12.13	81.52	0.09	0.51240

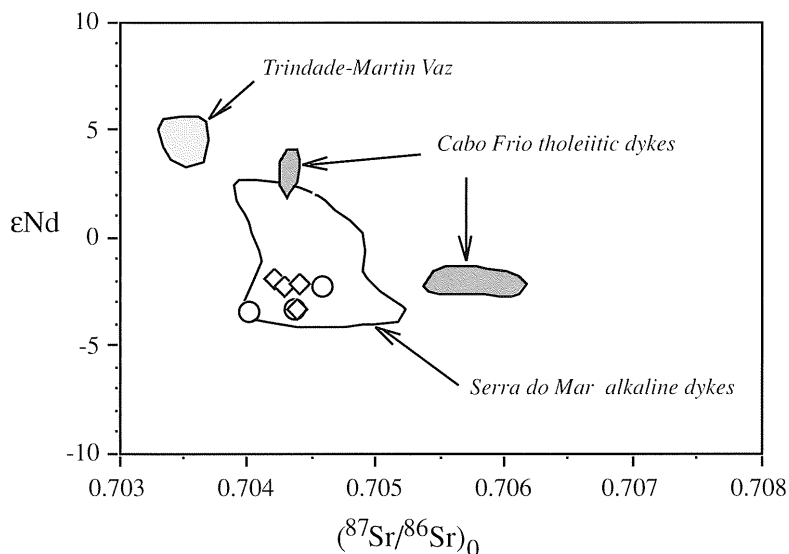


Fig. 6 – $(^{87}\text{Sr}/^{86}\text{Sr})_0$ vs ϵNd diagram for the Arraial do Cabo Frio alkaline rocks recalculated at 55 Ma. Fields of Trindade-Martin Vaz rocks (Marques *et al.*, 1999), Serra do Mar mafic alkaline rocks (Thompson *et al.*, 1998) and Arraial do Cabo Frio tholeiitic dykes (Bennio *et al.*, in press), are also shown.

Strong and significative differences are instead observed with the isotopic composition of the Trindade-Martin Vaz present day hot spot related magmas ($\text{Sr}_0=0.70339\text{-}0.70360$ and ϵNd 3.63-5.24; Marques *et al.*, 1999; Siebel *et al.*, 2000) and the Late Cretaceous Arraial do Cabo Frio tholeiitic dykes ($\text{Sr}_0=0.70434\text{-}0.70613$ and $\epsilon\text{Nd}=-2.2$ to $+3.8$; Bennio *et al.*, in press).

DISCUSSION

Low pressure evolution and genetic relationships of Arraial do Cabo Frio alkaline dykes

Compositional variations and textural relationships of essential minerals suggest a genetic linkage between rock types forming the two magma suites.

Pyroxenes from the SAS suite display a trends of evolution from salite towards Fe-salites with a moderate Na_2O enrichment as,

generally, observed in miaskitic magmas (Tab. 4, Fig. 7). Similar trends have been observed in the pyroxenes of Morro Redondo (Brotzu *et al.*, 1989) and Morro São João (Bennio, 2000, 2001) complexes. Evolutionary trends characterized by strong Na-enrichment have been observed in the pyroxenes of the Passa Quatro and Itatiaia intrusions (Brotzu *et al.*, 1992, 1997).

Micas from the two suite can be distinct on the basis of their chemical compositions showing strong differences in the Ti content. The overall compositional range of Arraial do Cabo Frio brown micas overlap those observed for the Passa Quatro (Brotzu *et al.*, 1992), Itatiaia (Brotzu *et al.*, 1997) and Morro São João (Bennio, 2000, 2001) analogues (Table 4, Fig. 8).

Amphibole from SAS rocks are represented by kaersutites and mg-hastingsites, having, somewhat lower SiO_2 and MnO and higher Al_2O_3 , CaO and K_2O than the amphiboles of the WAS rocks mostly represented by hastingsite and katophorite varieties (Tab.4).

TABLE 4

Representative analyses of mafic minerals of Arraial do Cabo Frio rocks.

Group	Sample	Lithotype	Mineral		SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Cr ₂ O ₃	Sum	Mg#	Ca	Fe*	Mg	Ulvösp
SAS	F14	Tph	amph	c	38.50	4.52	14.13	11.88	0.25	12.31	12.4	1.99	2.13			98.09	0.64				
SAS	F14	Tph	amph	r	38.53	2.90	14.35	13.57	0.34	11.70	12.05	1.96	2.30			97.70	0.60				
WAS	F11	TrA	amph	r	38.13	1.57	12.67	21.65	1.42	6.99	0.11	2.67	1.79			97.76	0.43				
WAS	F11	TrA	amph	c	46.27	1.61	5.14	18.9	3.16	8.35	5.8	6.03	1.25			96.55	0.50				
SAS	F14	Tph	mica	c	35.49	5.53	15.54	10.07	0.10	17.77	0.11	0.57	8.99	0.37		94.53	0.76				
SAS	F14	Tph	mica	r	33.90	5.23	14.34	19.74	1.73	10.07	0.09	0.44	9.29	0.24		95.06	0.46				
WAS	F11	TrA	mica	c	35.71	7.63	14.40	15.89	0.38	12.24	0.07	0.60	8.73	0.34		95.99	0.57				
WAS	F15	Tr	mica	c	35.70	7.92	13.29	17.33	0.36	10.86	0.00	0.81	8.23	1.23		95.73	0.52				
WAS	F15	Tr	mica	r	34.95	7.80	12.88	19.79	0.41	9.14	0.00	0.84	8.10	0.96		94.87	0.45				
SAS	F14	Tph	cpx	c	48.65	1.61	4.81	6.43	0.07	13.80	23.60	0.40			0.07	99.44	0.79	49.3	10.6	40.1	
SAS	F14	Tph	cpx	r	40.84	4.82	10.18	9.48	0.08	10.19	22.77	0.57			0.00	98.92	0.66	51.3	16.8	31.9	
SAS	F14	Tph	cpx	gm	49.83	1.12	2.87	12.34	1.32	9.67	21.42	1.45			0.00	100.00	0.56	47.0	23.4	29.5	
SAS	F43	Ph	cpx	c	48.81	1.69	4.26	11.42	1.00	10.44	21.82	1.45			0.05	100.94	0.60	47.4	21.1	31.5	
SAS	F43	Ph	cpx	r	50.83	0.46	1.70	13.79	1.47	9.06	21.07	1.69			0.00	100.07	0.51	46.2	26.2	27.7	
SAS	F62	Ph	cpx	gm	49.05	0.72	2.55	18.12	1.92	6.24	20.08	2.19			0.08	100.96	0.36	45.2	35.3	19.5	
SAS	F61	Ne-sy	cpx	c	49.78	0.97	3.17	11.23	0.84	10.72	22.06	1.18			0.04	100.00	0.61	47.6	20.3	32.1	
SAS	F61	Ne-sy	cpx	gm	49.55	0.49	1.93	18.24	2.88	5.39	19.32	2.60			0.00	100.40	0.31	44.6	38.1	17.3	
SAS	F21	Ph	ol	c	39.92			18.05	0.35	43.30	0.38					102.01	0.81				
SAS	F21	Ph	ol	r	39.84			18.35	0.54	42.48	0.46					101.66	0.80				
SAS	F14	Tph	mt	gm		11.52	6.66	74.1	1.72	2.10					0.07	96.15					30.0
SAS	F43	Ph	mt	c		11.12	1.25	80.2	3.22	0.18					0.00	95.96					33.0
SAS	F62	Ph	mt	c		8.17	0.8	84.9	3.31	0.00					0.18	97.32					28.0
SAS	F61	Ne-sy	mt	gm		2.50	0.38	90.6	1.91	0.11					0.07	95.56					12.0
SAS	F61	Ne-sy	mt	c		5.45	0.33	85.6	4.4	0.00					0.00	95.82					23.0
WAS	F11	TrA	mt	c		13.8	5.15	73.6	0.14	0.09					0.00	92.76					33.0
WAS	F11	TrA	mt	gm		10.7	2.54	76.6	0.00	0.00					0.00	89.86					31.0

c = core; r = rim; gm = groundmass. Mg# = Mg/(Mg+Fe+Mn); Fe* = Fe+Mn. End member mol%; amph = amphibole; cpx = clinopyroxene; ol = olivine; mt = magnetite.

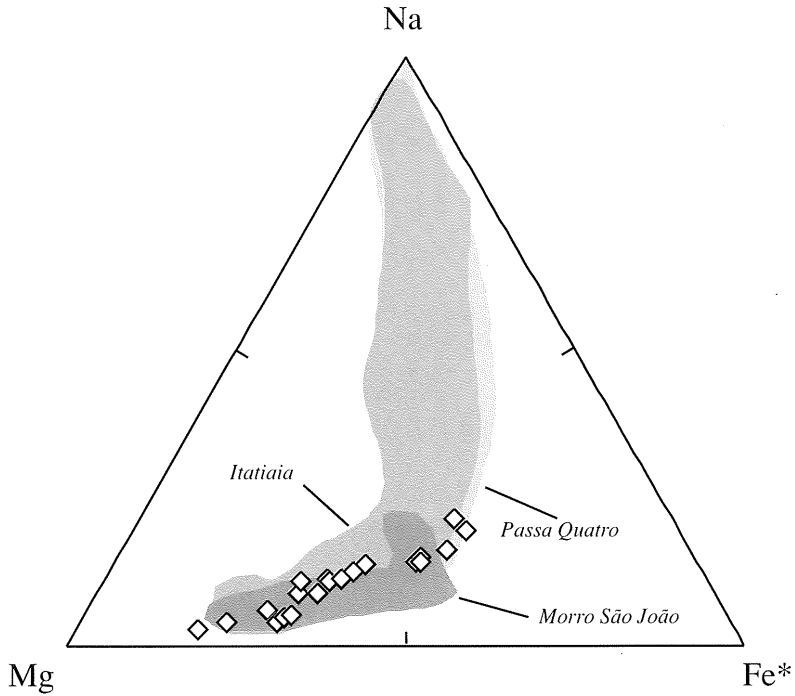


Fig. 7 – Pyroxene compositions plotted in the Na-Mg-Fe* (Fe*=Fe+Mn-Na) diagram (a.f.u.). The fields indicate the pyroxene trends of the Passa Quatro (Brotzu *et al.*, 1992), Itatiaia (Brotzu *et al.*, 1997) and Morro São João (Bennio, 2000, 2001) alkaline complexes for comparison. Symbols in fig. 2.

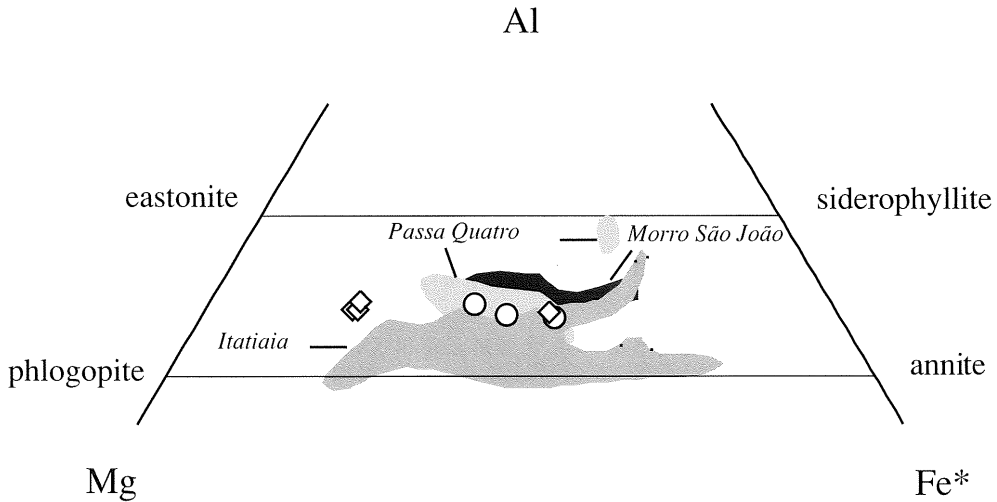


Fig. 8 – Brown mica compositions of the Arraial do Cabo Frio rocks. The shaded fields indicate mica compositions of the Passa Quatro (Brotzu *et al.*, 1992), Itatiaia (Brotzu *et al.*, 1997) and Morro São João (Bennio, 2000, 2001) complexes. Symbols in fig. 2.

TABLE 5
Representative analyses of felsic minerals of Cabo Frio rocks.

Group	Sample	Lithotype	Mineral		SiO ₂	Al ₂ O ₃	FeO	CaO	Na ₂ O	K ₂ O	BaO	SrO	Sum	An	Ab	Or	Ne	Ks	Qz
SAS	F14	Tph	pl	c	54.13	28.38	0.35	10.85	4.34	0.25	0.00	0.88	99.18	57.1	41.3	1.6			
SAS	F14	Tph	pl	c	58.81	25.99	0.07	7.61	7.24	0.14	0.00	0.00	99.86	61.4	37.8	0.8			
WAS	F11	TrA	pl	c	54.80	27.16	0.45	9.86	5.54	0.63	0.17	0.17	98.78	47.8	48.6	3.6			
WAS	F11	TrA	pl	c	54.30	27.99	0.43	10.57	5.10	0.56	0.09	0.49	99.53	51.7	45.1	3.3			
SAS	F14	Tph	kf	c	66.11	19.13	0.18	0.26	1.71	14.13	0.03	0.00	101.55	1.3	15.3	83.4			
SAS	F14	Tph	kf	gm	65.60	18.88	0.25	0.45	4.25	10.99	0.02	0.00	100.45	2.1	36.2	61.6			
SAS	F43	Ph	kf	c	66.50	19.09	0.25	0.23	4.32	10.32	0.09	0.00	100.80	1.1	37.8	61.1			
SAS	F43	Ph	kf	r	66.40	18.84	0.17	0.16	3.35	11.28	0.05	0.00	100.25	0.8	30.8	68.4			
SAS	F62	Ph	kf	c	66.41	18.79	0.19	0.17	1.71	13.98	0.00	0.00	101.25	0.8	30.8	68.4			
SAS	F62	Ph	kf	gm	65.10	18.60	0.19	0.26	0.84	15.74	0.02	0.00	100.75	1.3	7.4	91.3			
SAS	F61	Ne-sy	kf	c	67.00	19.01	0.23	0.28	3.95	10.07	0.11	0.00	100.65	1.5	36.8	61.7			
SAS	F61	Ne-sy	kf	r	66.79	18.92	0.22	0.11	3.62	11.39	0.06	0.00	101.12	0.5	32.4	67.1			
WAS	F11	TrA	kf	c	63.55	19.58	0.21	0.20	0.56	16.73	0.00	0.00	100.83	0.8	4.8	94.4			
WAS	F11	TrA	kf	gm	65.59	18.47	0.09	0.01	3.31	11.64	0.00	0.00	99.11	0.1	30.2	69.8			
WAS	F3	Tr	kf	c	66.04	18.71	0.04	0.22	3.43	10.14	0.00	0.00	98.58	1.2	33.6	65.3			
WAS	F3	Tr	kf	gm	68.45	19.43	0.04	0.02	11.70	0.20	0.00	0.00	99.84	0.1	98.9	1.0			
SAS	F14	Tph	neph	c	44.09	32.74	0.45	0.76	16.89	5.79			100.72				75.8	20.0	4.2
SAS	F14	Tph	neph	r	43.50	32.32	0.56	1.55	16.02	5.96			99.91				75.0	20.8	4.2
SAS	F43	Ph	neph	r	43.70	32.29	0.59	0.73	14.32	6.16			97.78				70.9	22.3	6.8
SAS	F43	Ph	neph	c	45.36	32.87	0.55	0.53	14.30	5.78			99.38				69.8	20.7	9.5
SAS	F62	Ph	neph	c	44.01	33.39	0.56	0.20	15.50	6.33			99.98				72.8	21.8	5.4
SAS	F62	Ph	neph	r	43.94	33.64	0.46	0.10	14.90	6.66			99.70				70.5	23.1	6.4
SAS	F61	Ne-sy	neph	c	43.78	33.19	0.55	0.37	15.65	5.89			99.43				74.4	20.5	5.1
SAS	F61	Ne-sy	neph	r	44.22	32.54	0.63	0.43	15.22	5.82			98.86				73.1	20.5	6.5

c = core; r = rim; gm = groundmass; Pl = plagioclase; kf = alkali feldspar; neph = nepheline. End members in mol%.

Petrographical features, major and trace element variations and isotopic ratios clearly suggest that fractional crystallization processes under closed-system conditions can be able to produce the different compositions observed in the two groups of rocks occurring in the Arraial do Cabo Frio alkaline dyke swarms. Mass balance calculations for both groups were performed in order to model the transition from the least to the most differentiated rocks. The results (Tab.6) for the SAS indicate that the phonolites could be produced by 25% fractionation of solid phases consisting of clinopyroxene (23.08%), plagioclase (29.85%), alkali feldspar (32.13%), amphibole (3.43%), apatite (2.46%), Ti-magnetite (1.77%) and sphene (2.46%) starting from phonotephritic compositions. For the WAS the most differentiated trachytes could be produced by 55% fractionation of plagioclase (23.86%), alkali feldspar (24.32%), amphibole (18.49%) and apatite (3.51%) starting from trachyandesitic compositions. The above results are in good agreement with phenocrystic assemblages and, particularly, with different plagioclase/alkaline feldspar ratios observed in the two rock suites and with the abundance of sphene observed in the SAS rocks. In addition, sphene fractionation in the SAS suite is coherent with the difference observed in the REE pattern of the most evolved lithotype of the two groups. The MREE depletion in the phonolites and nepheline-syenites can be related, in fact, to the sphene fractionation that preferentially remove MREE. Mass balance models have been further tested through trace element using published mineral-liquid partition coefficients determined for alkaline assemblages and the Rayleigh fractionation equation (Tab.6). The results confirm that the compositional variations in the two series can be reported to different liquid lines of descent.

More complex are the genetic relationships between the two groups of rocks. Although coexisting series with large variation in SiO_2 -saturation have been reported in many worldwide magmatic provinces, their genesis is

still a matter of debate. Discussions have focused on the constraints placed by phase equilibria in the Petrogeny's Residua System, in which evolved magmas may fractionate towards either the granite minimum, producing oversaturated magma types or towards the phonolite minimum, producing undersaturated magmas. The Arraial do Cabo Frio rocks plot in the Petrogeny's Residua System near trachytic and phonolitic minima, respectively (Fig. 9). The SAS rocks follow a trend very close to fractionation curves. This distribution indicate that the rocks of WAS group cannot be formed starting from any SAS sample and vice-versa. It follows that in terms of crystal fractionation, the Arraial do Cabo Frio rocks may require different parental magma characterized by difference in the SiO_2 saturation.

Foland *et al.*, (1993) have proposed that combined assimilation and fractional crystallization process (AFC) is the most likely process able to straddle the thermal divide in the Petrogeny's Residua System producing saturated and oversaturated magmas starting by felsic undersaturated magmas.

In contrast to the Foland's model many authors (e.g. Wilson *et al.*, 1995; Panter *et al.*, 1997 and Brotzu *et al.*, 1997) in order to explain the genesis of coexisting alkaline magma series invoked distinct basaltic parental magmas with slight differences in the SiO_2 -saturation.

The overall geochemical and isotopic feature of the Arraial do Cabo Frio alkaline dykes rule out significative AFC processes. Trachyandesites and tephriphonolites have trace element concentrations, also in that more sensible to crustal contamination (e.g. Rb, Nb), strictly comparable and very similar initial isotopic ratios [$(\text{Sr}_0 = 0.70458-0.70440$ and $\text{Nd}_0 = 0.51245-0.51246$, respectively)]. Therefore, crustal contamination was negligible in the petrogenesis of the WAS and thus a common parental magma for both the WAS and SAS rocks of Arraial do Cabo Frio rocks cannot be reasonably suggested.

Mafic to felsic alkaline dykes of the Arraial

TABLE 6
Mass balance results on Arraial do Cabo Frio samples.

		Kf	Pl	Amph	Cpx	Ti-mt	Ap	Sph	F	ΣR^2
SAS group	F14-F21	32.13	29.85	3.43	23.08	7.3	2.46	1.77	0.25	0.09
WAS group	F11-F15	24.32	23.86	18.49	21.12	8.69	3.51		0.55	0.82
		Y	La	Ce	Nd	Nb	Ba			
SAS group	C*	40	131	215	77	199	131			
	G*obs	36	163	231	45	302	166			
	G*calc	46	189	284	56	660	166			
	D	0.90	0.68	0.82	1.28	0.13	0.83			
WAS group	C*	39	98	160	66	96	1814			
	G*obs	48	144	238	82	182	1147			
	G*calc	48	144	238	82	169	1188			
	D	0.63	0.344	0.32	0.61	0.03	1.72			

D = bulk partition coefficients calculated using Rayleigh fractionation law and concentrations of the elements.

C* = initial values for trace elements; G*obs = observed values for trace elements; G*calc = calculated values for trace elements.

Kd data are from Kyle *et al.*, (1981), Irving and Price (1981) and Ricci (2000).

Kf = K-feldspar; Pl = plagioclase; Amph = amphibole; Cpx = clinopyroxene; Ti-mt = Ti-magnetite; Ap = apatite; Sph = sphene.

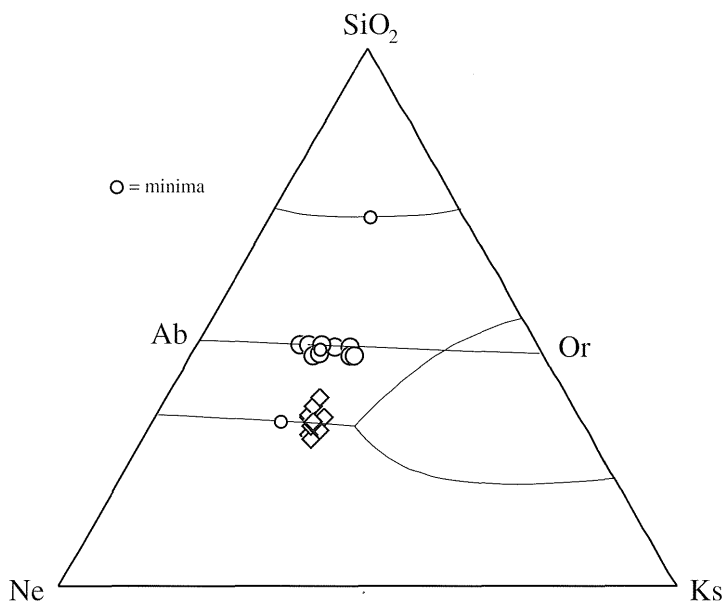


Fig. 9 – The Arraial do Cabo Frio rocks as plotted in the Ne-Ks-SiO₂ system (after Hamilton and MacKenzie, 1965). Symbols in fig. 2.

do Cabo Frio peninsula have composition, serial affinity and isotopic feature similar to those emplaced westward in the Serra do Mar region (Thompson *et al.*, 1998, Valente, 1997). Therefore, the studied alkaline dykes could be regarded as the younger and eastern extension of the Serra do Mar dyke swarms. In addition, a full compositional and isotopic overlap between dykes and the intrusive complexes of the Serra do Mar igneous province exist. It is important to remark that undersaturated and oversaturated syenites coexist in some plutonic complexes (e.g., Soarinho, Valença, 1980; Itatiaia, Brotzu *et al.*, 1997). Late Cretaceous mafic alkaline dykes, together with felsic differentiated, show large variation in the SiO_2 saturation degree. This feature is evident in the R_1 - R_2 diagram (Fig. 10) where all the

compositions of alkaline dykes sampling are plotted. Therefore, it is likely that some more mafic compositions could represent suitable parental magmas of the Arraial do Cabo Frio trachyandesites and phonotephrites. It is strongly supported by olivine xenocrysts (Fo_{81}) recognized in phonolitic rocks.

Thompson *et al.*, (1998), in their study of the mafic alkaline dyke swarm of the Serra do Mar province reported Arraial do Cabo Frio dykes of basanitic and trachybasaltic composition with isotopic ratios similar to those of the rocks here analyzed. In addition, Valente (1997) sampled in the late Cretaceous dyke swarm of the Serra do Mar province mafic alkaline rocks ranging from basanites to alkali basalts, together with phonolites and trachytes. The author divided alkaline rocks into two main

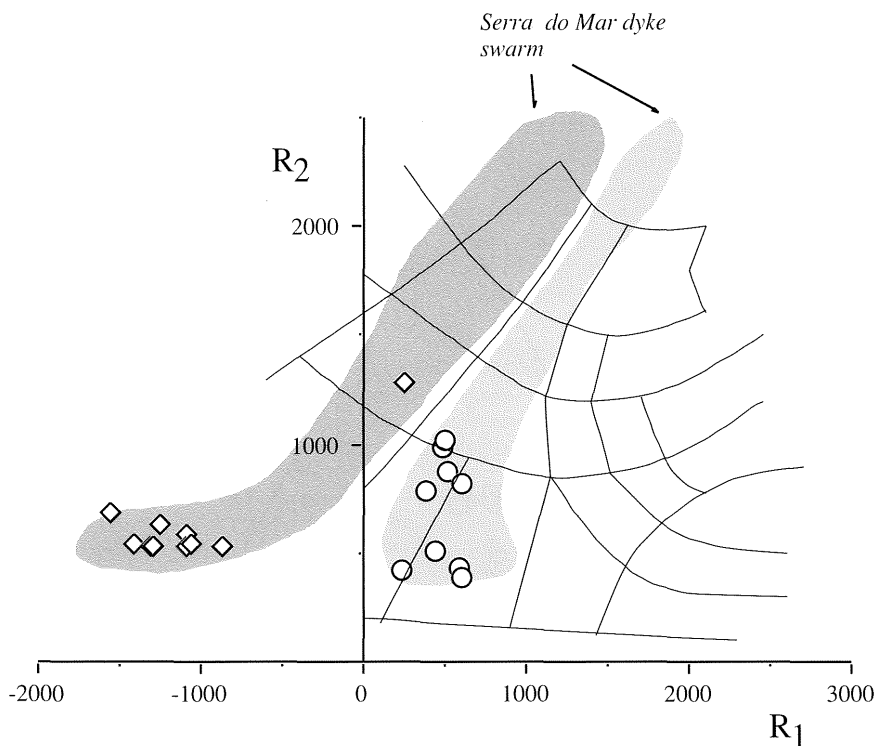


Fig. 10 – R_1 - R_2 diagram for the Serra do Mar alkaline dykes swarm. Symbols in fig. 2. Fields indicate dyke compositions of the Serra do Mar alkaline province. (data from Thompson *et al.*, 1998 and Valente, 1997).

series: a strongly undersaturated suite and a mildly alkaline suite (TAD suite). The latter include undersaturated to saturated basalts, together with trachytes and miaskitic phonolites. Compositional variations and isotopic ratios suggest a genetic link between basanites and tephriphonolites-phonolites and between TAD mafic magmas and trachyandesites-trachytes broadly consistent with fractional crystallization processes under closed-system conditions.

In conclusion, according to geochemical and isotopic data we suggest that the different groups observed among the Arraial do Cabo Frio alkaline dykes are the result of fractional crystallization in a closed system of different mafic parental magmas characterized by slight differences in the SiO₂-saturation producing trachytic residua in the weakly SiO₂ undersaturated group and phonolitic residua in the strongly SiO₂ undersaturated group.

A possible source for the Arraial do Cabo Frio alkaline magmas

Thompson *et al.*, (1998) suggested that the widespread alkaline magmatism of the Serra do Mar province was generated in response to the passage of the Trindade mantle plume below the southeastern part of the São Francisco craton. This hypothesis, appears supported by the distributions of the intrusive complexes and dykes which lie along to the postulated track of the Trindade hot spot at 56 Ma, and by the reasonable radiometric age progression from West to East, consistent with the South American plate shifting over a fixed-site mantle plume.

The new geochemical and isotopic data here report strongly contrasts with the hypothesis of the Trindade hot-spot involvement in the genesis of the Arraial do Cabo Frio alkaline rocks.

The alkaline rocks from Arraial do Cabo Frio, in fact, do not have geochemical analogies with rocks of the Trindade-Martin Vaz island. In this latter respect it is worth noting the different serial affinity, as Arraial do

Cabo Frio rocks have generally potassic affinity while the lavas recently erupted at Trindade-Martin Vaz are mainly sodic (Marques *et al.* 1999). Even more interesting is the different isotopic composition of the Arraial do Cabo Frio alkaline rocks and the present-day volcanics of the Trindade plume which clearly imply that the alkaline activity in the two areas were fed by distinct, unrelated sources. Starting from alkaline melts of the Trindade-Martin Vaz island, wide amounts (up to 30%) of crustal components are required to obtain the isotopic compositions of the Arraial do Cabo Frio alkaline rocks; it does not agree with their overall geochemical patterns.

In addition, Bennio *et al.* (in press) sampled in the Arraial do Cabo Frio dyke swarm broadly coeval tholeiitic basalt with geochemical and isotopic features typical of melts derived by MORB-like sources which excluded the presence of incompatible element-rich components in the asthenospheric mantle of this area.

Thus, on the basis of the data here presented we suggest that the alkaline magmatism in the Arraial do Cabo Frio region, and more generally of the Rio-Santos coastline, could be related to the partial melting of incompatible element enriched lithospheric mantle in response to the passive continental margin extension occurred in southeastern Brazil after the opening of the South Atlantic ocean.

CONCLUSIONS

The alkaline activity in the Arraial do Cabo Frio region is represented by small intrusions and dykes emplaced about 55 Ma ago in the late Precambrian basement with a generally east-west trend. Intermediate to felsic differentiated rocks and mafic rocks are prevailing and subordinate, respectively.

Two main suites of strongly alkaline (tephriphonolite-phonolite) and weakly alkaline (trachyandesite-trachyte) rocks with potassic affinity are apparent.

Trace element and Sr-Nd isotopic

compositions of the least differentiated rocks (tephrifonolites and trachyandesites) preclude a direct link between the two recognized suites, and suggest that each series originated from a distinct mafic parental magma with different degrees of SiO₂ saturation. These different magmas then evolved towards trachytic and phonolitic residua through fractional crystallization processes without any detectable crustal contribution. The basanites and trachybasalts reported by Thompson *et al.*, (1998) in the Arraial do Cabo Frio dyke swarm could be representative of parental magmas of the two suites.

The strong differences in isotopic compositions observed between Trindade and Arraial do Cabo Frio samples seem rule out the involvement of the Trindade mantle plume. On the other hand the Sr₀ and Nd₀ together with the geochemical compositions, support derivation from an enriched lithospheric mantle for the parental magmas of the studied rocks.

The strong compositional and isotopic analogies between the Arraial do Cabo Frio rocks and the other Serra do Mar alkaline occurrences suggest that the parental magmas derived by strictly similar mantle sources and then successively evolved through broadly similar differentiation processes.

The significant difference in isotopic composition between the alkaline and coeval tholeiitic dykes with geochemical fingerprint MORB-like (Bennio *et al.*, in press) indicate involvement of different sources in the genesis of Arraial do Cabo Frio magmas.

In conclusion, we suggest that, at the Arraial do Cabo Frio peninsula, the geodynamic processes related to the opening of the South Atlantic Ocean caused almost at the same time partial melting of asthenospheric and lithospheric mantle which generated respectively tholeiitic and alkaline magma compositions.

ACKNOWLEDGMENTS

This work has been supported by Italian (MIUR, CNR Grants) and Brazilian (FAPESP) agencies.

We thank M. Serracino (CNR, Roma) for the skilled help in microprobe analyses, A. Canzanella and V. Monetti for the help in the XRF procedures and for the technical assistance with Atomic Absorption Spectrophotometry, respectively, and Luigi Franciosi and Rino Ricci for their help in improving the style of manuscript. Very special thanks to P. Comin-Chiaramonti and A. Lo Giudice for their useful comments.

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