Geochimica Brasiliensis, **1**(1):41-51, 1987

THE TERTIARY ALKALINE PROVINCE OF FORTALEZA, STATE OF CEARÁ, BRAZIL: OXYGEN ISOTOPES AND REE-GEOCHEMISTRY*

A.N. Sial

* Partially supported by the Brazilian National Council for Scientific and Technological Development (CNPq)
Department of Geology, Center of Technology, Federal University of Pernambuco, Recife, PE

ABSTRACT

The Tertiary volcanic alkaline suite, next to Fortaleza, State of Ceará, Northeast Brazil, is composed of phonolites, trachytes, nepheline syenites, limburgites, ankaramites and essexites. Necks, plugs and dikes, that intruded Precambrian rocks, are the main form of intrusion, constituting the Pão-de-Açúcar, Salgadinho, Japarara, Ancuri, Gangorra, Poção, Serrote Preto, and Caruaru hills. Nodules of alkali syenite, fourchite, spinel or garnet-bearing layred rock, and albite and ilmenite discrete nodules, are common. Zoned aegirine, soda-augite kaersutite, sanidine, ±plagioclase, zoned nepheline, ±sodalite, and zircon are the main phase components of the phonolites and trachytes, besides secondary phases as zeolites which fill vugs.

The nepheline-normative salic rocks are extremely alkali-enriched with Na_2O up to 11.5% and NaO_2/K_2O from 0.81 to 2.03. $\delta^{18}0$ in the Pão-de-Açúcar, Caruru, Ancuri, Serrote Preto and Salgadinho bodies varies from +5.39 to +10.20 $permil_{SMOW}$. Fourchite inclusions in the Caruru dome show $\delta^{18}0$ value (+8.59 $permil_{SMOW}$) lower than the host phonolite (+9.01 and +9.96 $permil_{SMOW}$) supporting the hypothesis of a fourchitic parental magma for the phonolites. The Ancuri hill exhibits +8.78 $permil_{SMOW}$ and a fine-grained nepheline syenite inclusion at Caruru shows $\delta^{18}0$ of +9.54 permil, similar to the core of the Serrote Preto (+9.14 $permil_{SMOW}$) suggesting that at the Caruru dome phonolite gives way to a syenite to the depth. The gray alkali trachytes, in the outermost portion of the Serrote Preto, exhibits a $\delta^{18}0$ value of +7.49 $permil_{SMOW}$ and values even lower were recorded in the bluish aphyric trachyte of the Salgadinho (+6.79 $permil_{SMOW}$, in contrast with the brownish porphyritic trachyte in this neck which exhibits +10.20 $permil_{SMOW}$) and Pão-de-Açúcar necks (+5.39 $permil_{SMOW}$, a value lower than the one estimated for the Earth's mantle). These 0-isotopes ratios resulted from the interaction with meteoric water or indicate a parental magma other than a fourchitic one.

The salic rocks display high LREE fractionation, moderate HREE (Ce_N/Yb_N varies from 9.02 to 21.83), and moderate negative Eu anomaly (Eu/Eu* varies from 0.53 to 0.95) indicating sanidine was fractionated out of the liquid, which is compatible with the low Ba and Sr contents. The aphyric and porphyritic alkali trachytes in the Salgadinho neck differ in their REE signature. The aphyric trachyte shows a concave HREE pattern, with a minimum at the Dy, suggesting that amphibole was fractionated out of the liquid or retained in the source in the mantle (kaersutite is seen as pheno-and xenocryst). Similar concavity is observed in the HREE pattern in the Pão-de-Açucar and Caruru hills. The Serrote Preto and Caruru HREE patterns exhibit a minimum at the Er, explained by garnet fractionation or its retention in the source. Phonolites derived from a fourchitic magma, while ankaramites and limburgites crystallized from a magma formed by a small degree of melting in the mantle.

RESUMO

A suite alcalina, Terciária, próxima à Fortaleza, é composta de fonolitos, traquitos, nefelina sienitos, limburgitos, ankaramitos e essexitos, que intrudem rochas Precambrianas. Nódulos de álcali sienito, furchito, rocha acamada com espinélio e/ou granada, além de xenocristais de albita e ilmenita, são comuns.

Extremamente enriquecidas em álcalis (Na_2O alcança 11,5% e Na_2O/K_2O varia de 0,81 a 2,03), rochas sálicas mostram $\delta\,0^{18}$ de +5,39 a 10,20 $permil_{SMOW}$. Inclusões de furchito no Caruru exibem $\delta\,0^{18}$ (+8,59 $permil_{SMOW}$) inferior ao do fonolito hospedeiro (+9,01 a +9,96 $permil_{SMOW}$). O fonolito do Ancuri exibe +8,78 $permil_{SMOW}$ e uma inclusão de nefelina sienito, no Caruru, +9,54 $permil_{SMOW}$, semelhante ao núcleo do Serrote Preto (+9,14 $permil_{SMOW}$) sugerindo a existência de idêntico núcleo no Caruru. Álcali traquito azulado no bordo do Serrote Preto exibe +7,49 $permil_{SMOW}$ e valores mais baixos foram registrados em traquito afírico do Pico do Salgadinho (+6,79 $permil_{SMOW}$, em contraste com traquito porfirítico, amarronado, que exibe +10,20 $permil_{SMOW}$) e no Pão-de-Açúcar (+5,39 $permil_{SMOW}$, inferior ao do Manto). Estes valores resultaram talvez da interação com água meteórica.

As rochas sálicas exibem alto fracionamento de T.R. leves, moderado fracionamento de T.R. pesados (Ce_N/Yb_N varia de 9,02 a 21,83), e moderada anomalia de Eu (Eu/Eu* varia de 0,53 a 0,95), indicativo de fracionamento de sanidina, compatível com baixos teores de Sr e Ba. Os álcali traquitos, afírico e porfirítico, em Salgadinho diferem em suas assinaturas de T.R.. O traquito afírico mostra padrão de T.R. pesados côncavo, com mínimo no Dy, sugerindo fracionamento de anfibólio, ou sua retenção na fonte (kaersutita está presente como feno- e xenocristais). Semelhante concavidade no padrão de T.R. pesados é observada no Pão-de-Açúcar e Ancuri. O Serrote Preto e o Caruru exibem um mínimo no Er, compatível com fracionamento de granada ou sua retenção na fonte. Fonolitos derivaram de uma magma furchítico, enquanto ankaramitos e limburgitos cristalizaram de um magma resultante de uma baixa fusão parcial do Manto.

INTRODUCTION

In the vicinity of Fortaleza, State of Ceará (Fig. 1), a volcanic, predominantly salic, alkaline province, Tertiary in age, is known since along ago (Almeida, 1955; Vandoros & Oliveira, 1968;

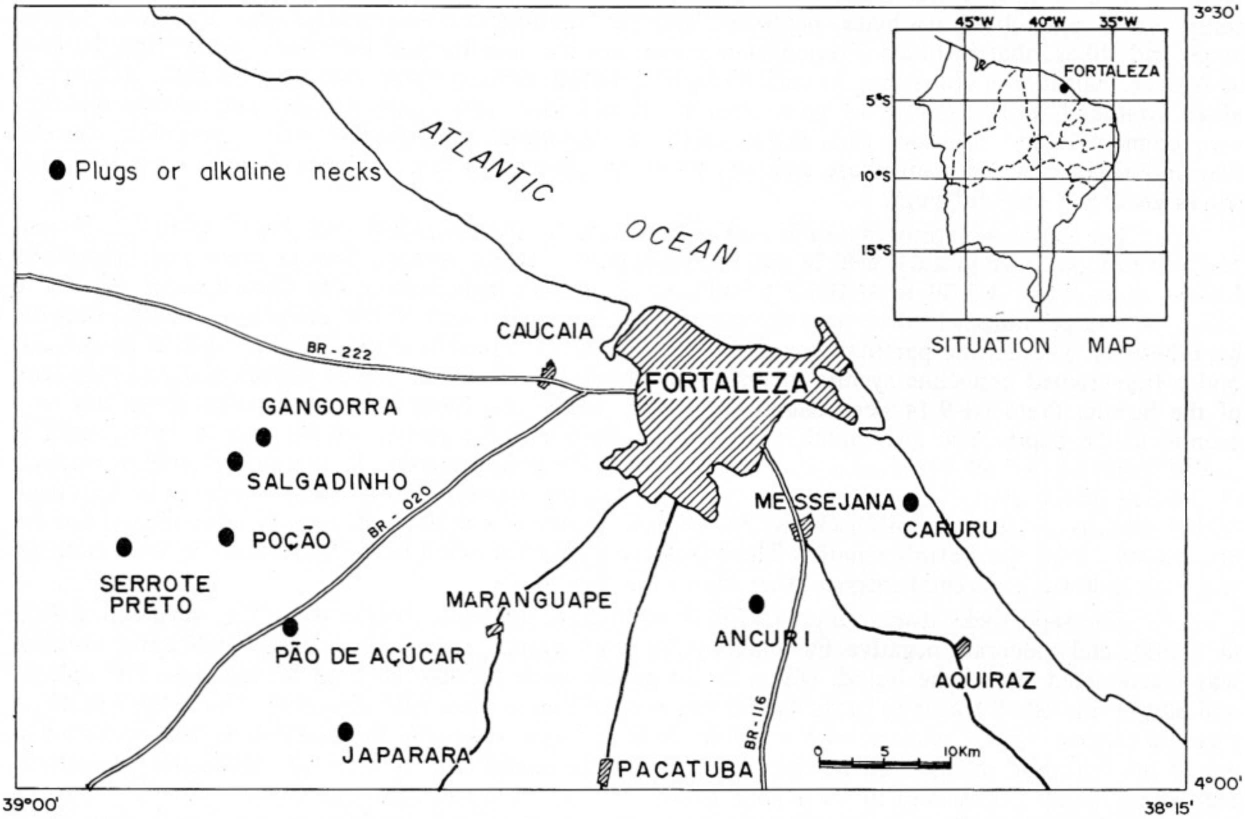

Figure 1 — Situation map with location of the main plugs and necks, according to Guimarães *et al.* (1982).

Cordani, 1970; Rao & Sial, 1972; Braga *et al.*, 1977; Guimarães, 1982, and Guimarães *et al.*, 1982). Although the Caruru hill, nearby Messejana village, was petrographically described in 1968 (Vandoros & Oliveira, 1968) and the Ancuri hill in 1972 (Rao & Sial, 1972), the other occurrences were discovered only in 1977 (Braga *et al.*, 1977) after detailed geological mapping when several necks, plugs and domes were identified.

Vandoros & Oliveira (1968) related the Caruru phonolite to the Remédios Fm. phonolites, in the Fernando de Noronha Archipelago. Almeida (1955), however, was the first one to point a possible relationship between magmatic activity in the Fernando de Noronha Archipelago and the one around Fortaleza. This was later reinforced by Cordani (1979) who stressed the similarity between these two provinces. Rao & Sial (1972) described the petrography of the Caruru and Ancuri hills, the nodules found in the first one, and attempted through a statistical approach a comparison between the Fernando de Noronha phonolites and those in this province. Gorini (1977) studying the tectonic fabric of the equatorial Atlantic and the adjoining continental margins regarded the Caruru phonolite as the westernmost extension of the conspicuous east-west Fernando de Noronha ridge.

Braga *et al.* (1977) preparing the Fortaleza and São Luiz do Curu map sheets provided a brief petrographic description of six necks of salic alkaline rocks, including phonolites and alkali trachytes (Serrote Preto, Pão-de-Açúcar, Salgadinho, Japarara, Caruru and Ancuri). The Salgadinho neck and the Poção and Gangorra plugs were studied in details by Passos & Gomes (1978).

Besides all studies referred to above, Guimarães *et al.* (1982) discussed the petrography, major element and mineral chemistry of the rocks in this province, concluding that phonolites formed by differentiation of a parental fourchitic magma, while limburgites and ankaramites as narrow dikes only, crystallized from a mafic magma formed by a small degree of partial fusion in the mantle. A similar model has been previously proposed by Stormer & Whitney (1978) for the phonolites and related rocks of the Fernando de Noronha Archipelago.

GEOCHRONOLOGY

Issler *et al.* (1977) anticipated an age of 34 ± 2 m.y. through the Rb-Sr reference isochron method, for this province as a whole. An initial $^{87}Sr/^{86}Sr$ ratio of 0.7032 ± 0.0002 was then found. Previous geochronological study (Vandoros & Oliveira, 1968) through the K-Ar method revealed a 26.6±0.8 m.y. w.r. age and a 28.6±0.9 m.y. feldspar age for the phonolite at the Caruru hill. A detailed geochronological work is still necessary to investigate possible variations in the initial $^{87}Sr/^{86}Sr$ ratios within the province or any age trend which may exist.

PETROGRAPHY AND FORM OF OCCURRENCE

In this alkaline province salic volcanic rocks predominate forming domes (Caruru), necks (Pão-de-Açúcar, Salgadinho, Japarara), plugs (Ancuri and Poção) and narrow dikes. The Gangorra and Serrote Preto hills have been partially eroded down and their caotic appearance do not allow precising the structures well. Possibly, Gangorra is a conic structure and the Serrote Preto, a ring-structure. Dikes of limburgite, ankaramites and alkali gabbro are also recorded at this province.

These bodies intruded the Precambrian terrain using SW-NE trending fractures or according to the main metamorphic foliation of the basement. The dikes, however, do not show a preferential orientation. Columnar structures, slightly inclined, are present in almost all necks, with the exception of the Pão-de-Açúcar, where they are predominantly vertical. The Caruru hill approaches a domal shape and is partially covered by recent sediments at their borders, that preclude a direct observation of the nature of the contact. The Serrote Preto hill have its borders composed of fine-grained, aphyric trachyte, while its core is mostly composed of a slightly coarse, weathered gray to brown syenite which resembles nodules found at Caruru dome. This intrusion has an elliptical shape and is probably concentric. The summit of the Japarara hill is practically inacessible but its topography suggests it is a neck, similar to the Salgadinho one, the most expressive body in this province.

Petrographically, the necks are made up of phonolites and trachytoid phonolites, while the salic dikes are mostly trachytes. The phonolites usually have euhedral nepheline phenocrysts, aegirine-augite phenocrysts and sanidine, in a groundmass essentially composed of the same minerals, besides sodalite in a few samples. In some nepheline crystals albite exsolution was observed, mainly next to the rims. Well-developed kaersutite crystals are observed at the Caruru dome, Salgadinho and Japarara necks, as well as elongate crystals in the groundmass. This phase either derived from the mantle as a xenocryst or crystallized from a parental magma. Crystals exhibiting reaction rims are not in equilibrium with the liquid, and are probably xenocrysts. Small crystals in the groundmass, however, probably crystallized from the phonolitic liquid. The pyroxenes are usually aegirine-augite, sometimes with aegirine cores. Aegirine phenocrysts were only observed at Pão-de-Açúcar neck. Pyroxenes are usually zoned and form aggregates in the groundmass or deep green, elongate crystals. Microprobe studies (Guimarães *et al.*, 1982) indicate that these pyroxenes belong to the diopside-hedenbergite-acmite series with a fractionation trend from soda-augite to aegirine. Besides, it was verified that the pyroxene of the Salgadinho neck is essentially soda-augite and at Pão-de-Açúcar neck, aegirine. Normal and reverse zoning have been detected which implies in the assumption that oxygen fugacity varies from body to body. Amphiboles are kaersutite and ferro-kaersutite, reflecting a rather low oxygen fugacity.

Nodules of a dark rock identified as fourchite by Rao & Sial (1972) suggest that the parental magma had probably a fourchitic composition and its differentiation gave rise to phonolites and alkali trachytes. The presence of syenitic nodules imply, perhaps, that the fourchitic magma passed through an intermediate syenitic stage in its crystallization.

GEOCHEMISTRY

Major elements

From the chemical viewpoint, this province is characterized by high alkali values, especially Na_2O. A few representative analyses with their respective CIPW, extracted from Guimarães (1982), are shown in Table 1. Although this is a continental province, salic rocks are as Na_2O-enriched as the Atlantic islands (e.g. Trindade in the South Atlantic; and Cape Verte and Gorringe bank, southwest of Portugal, in the North Atlantic). These rocks are predominantly peralkalic, with agpaitic index above 1.0. Values of Na_2O up to 11.5 percent were recorded and Na_2O/K_2O varies from 0.81 to 2.03, Na_2O usually greater than K_2O. They are all nepheline-normative rocks except for one sample at the Ancuri plug. Guimarães *et al.* (1982) found high F in almost every sample analysed, and high Cl too, except in the fourchite nodules at Caruru. Opposite behavior was observed for Ba and Sr which are much higher in the fourchite (Guimarães, 1982) than in the salic rocks, suggesting an important K-feldspar fractionation in the generation of the phonolites starting from the fourchitic composition.

Oxygen isotopes

Isotopic technique and standards — All oxygen extractions were performed by reaction with fluorine in the Department of Geology of the University of Georgia, in Athens, United States. Isotopic analyses were made using a VG Micromass 602 C double collecting mass spectrometer. Routine intercomparisons of samples with Rose quartz standard were made, the standard being +8.45 permil relative to SMOW (standard mean ocean water; Craig, 1961). The results of 0-isotopes are presented in the notation δ in parts permil (permil, $^0/_{00}$), and the δ value is defined as:

$$\delta\ (^0/_{00}) = \frac{R\ (\text{sample}) - R\ (\text{standard})}{R\ (\text{standard})} \times 1000$$

where $R = {}^{18}O/{}^{16}O$

Table 1 — Representative chemical analyses of volcanic rocks from the alkaline province near Fortaleza, Ceará (Guimarães, 1982).

Major elements

	Salgadinho		Caruru		Pão-de-Açúcar		Ancuri		S. Preto
Oxides	SA-04	SA-20	CA-18	CA-16	PA-04	PA-10	AN-12	AN-02	SP-11
SiO_2	56.60	60.70	54.00	57.10	55.70	56.60	56.20	59.50	57.40
TiO_2	0.35	0.41	0.36	0.48	0.22	0.21	0.28	0.23	0.17
Al_2O_3	19.30	19.90	21.00	21.00	20.90	20.90	21.20	22.30	18.70
Fe_2O_3	1.30	2.10	0.75	1.50	1.50	1.30	1.90	1.60	1.70
FeO	1.43	1.14	1.93	1.07	1.07	1.29	1.43	0.50	3.28
MnO	0.17	0.13	0.24	0.01	0.08	0.08	0.11	0.07	0.27
MgO	0.13	0.29	0.14	0.46	0.06	0.07	0.06	0.07	0.06
CaO	1.10	1.40	0.94	1.60	0.55	0.52	0.49	0.52	0.78
Na_2O	9.11	5.60	9.98	8.20	11.25	11.49	10.44	6.03	8.77
K_2O	6.13	6.86	5.92	6.74	5.61	5.66	5.74	5.73	5.54
P_2O_5	0.06	0.07	0.08	0.10	0.05	0.05	0.05	0.05	<0.05
CO_2	0.17	0.13	0.23	0.20	0.13	0.17	0.20	0.30	0.12
H_2O+	2.64	0.21	4.00	2.04	2.47	1.10	1.67	2.31	2.53
H_2O-	0.30	0.12	0.24	0.46	0.23	0.13	0.23	0.50	0.01
S	0.03	0.03	0.03	0.02	0.01	0.01	0.01	0.03	0.02
Total	98.82	99.09	99.84	100.98	99.83	99.58	100.01	99.74	99.40
CIPW norms									
Q								1.93	
C		1.53						5.81	
Or	36.74	40.86	35.29	39.48	33.28	33.71	34.33	34.17	33.53
Ab	30.20	46.28	22.82	28.09	26.11	27.65	27.13	51.43	35.49
An		5.60		0.58				1.20	
Ne	19.44		28.66	22.06	27.33	26.51	27.25		17.03
Hl	0.26	0.34	0.42		0.44	0.45	0.35	0.02	0.22
Ac	3.82		2.19		4.36	3.80	5.54		5.04
Ns	1.56		1.20		2.83	3.52	0.86		0.56
Wo(Di)	1.58		1.55	1.32	0.96	0.91	0.35		1.35
En(Di)	0.22		0.17	1.14	0.09	0.08	0.03		0.04
Fs(Di)	1.51		1.55		0.98	0.93	0.37		1.48
En(Hy)		0.73						0.18	
Fs(Hy)									
Fo	0.05		0.07		0.03	0.04	0.05		0.05
Fa	0.33		0.71		0.30	0.49	0.78		1.89
Mt		2.83		2.01				1.08	
Il	0.68	0.79	0.69	0.91	0.42	0.41	0.54	0.45	0.34
Ap	0.15	0.17	0.20	0.24	0.12	0.12	0.12	0.12	0.13

Whole rock (w.r.) oxygen isotopes — Analyses of w.r. oxygen isotopes were performed in 10 samples from 5 of the occurrences of alkalic rocks in this province (Caruru, Serrote Preto, Ancuri, Salgadinho, and Pão-de-Açúcar). Results are found in Table 2.

Only few papers dealing with 0-isotopes in alkaline rocks are available and even those (e.g. Foland & Friedman, 1977; Pankhurst *et al.*, 1976) do not bother with details, but just use this technique to reinforce conclusions obtained from other sources.

A large variation in $\delta^{18}0$ (from 5.39 to 10.20 permil) similar to what is observed in Red Hill, New Hampshire, United States (Foland & Friedman, 1977) was recorded. As the lowest value encountered is even below the one estimated for the Earth's mantle, much likely it underwent a secondary overprint, a common phenomenon in volcanic rocks, usually susceptible to interaction with meteoric water. Unfortunately, it was not possible to have the mineral components separated to analysing for $^{18}O/^{16}O$ which would allow evaluating the primariety of the w.r. $\delta^{18}O$ as well as using mineral pairs, supposedly in isotopic equilibrium, for geothermometry. Another problem encountered is that of obtaining a systematic sampling since most of the time these bodies show a chaotic aspect, and samples have little positional value.

In the Caruru dome, 4 samples were analysed, two of the phonolite and two of the autoliths, one of them petrographically similar to the core of the Serrote Preto (pink, fine-grained nepheline syenite) and the other one is a fourchite. In these rocks there is only a small $\delta^{18}O$ variation (1.37 permil). The fourchite shows a $\delta^{18}O$ value of +8.59 permil, lower than the host phonolite, and in agreement with the hypothesis of a fourchitic parental magma for the phonolites, as proposed by Guimarães *et al.* (1982). Similar differentiation scheme was proposed for the alkaline suite of Fernando de Noronha Archipelago (Stormer & Whitney, 1978).

The fine-grained nepheline syenite inclusion in the Caruru dome exhibits $\delta^{18}O$ of +9.54 permil, similar to the rock in the core of Serrote Preto (+9.14 permil) and leads to the assumption that below the present level of exposure at the Caruru hill, there is a syenitic body, as it happens at the Serrote Preto hill.

The Morro do Ancuri phonolite (sample AN-06) exhibited $\delta^{18}O$ value (+ 8.78 permil) lower than the Caruru phonolites, but slightly higher than the fourchitic nodules at the Caruru dome. This comes to support that $\delta^{18}O$ is a rather primary value, or if any further modification ever took place, it was just trivial.

Two samples of the Serrote Preto were analysed and yielded distinct values. The fine-grained syenite collected at the core exhibits a $\delta^{18}O$ value within the variation found for the phonolites in this province, but the alkali trachyte yielded a much lower (+7.49) permil). $\delta^{18}O$ value even lower (+6.79 permil) was found in the alkali trachyte of the Salgadinho neck. Low values like this may have resulted from a later modification of the isotopic composition of these rocks by interaction with meteoric water, or indicate they derived from a parental magma, other than the fourchite one, which generated the phonolites (alkali basaltic magma?). The sample S-2 (brownish porphyritic trachyte), also from the Salgadinho neck, exhibited a much higher $\delta^{18}O$ value (+10.2 permil) by its turn. Unlikely these two rocks in the Salgadinho neck derived from a single magma, regarding that their composition do not depart very much from each other, but their $\delta^{18}O$ differ from almost 4.0 permil. A possible explanation is that one of them, the brownish trachyte (S-2), has undergone a deep modification in its original isotopic composition. The degree of alteration of this rock, more evident than in the aphyric alkali trachyte in contact with it, apparently seems to support such an idea.

The phonolite of the Pão-de-Açúcar neck (sample PA-04) exhibited a much lower $\delta^{18}O$ value (+5.39 permil) in relation to the other phonolites in the province (Caruru and Ancuri). Such a value is even lower than the one estimated for the Earth's mantle (around +6 permil) suggesting it is not primary and has suffered a post-extrusion modification. However, it is difficult to admit in the same magmatic province samples having $\delta^{18}O$ increased while other ones had this value lowered, especially if they show about the same miner-

Table 2 — Whole-rock oxygen isotope analyses for some of the volcanic rocks in the Tertiary province of Fortaleza, Ceará.

Sample	Rock type	Whole-rock $\delta^{18}O$ (SMOW)	Igneous body
CA-02	Phonolite	+ 9.01	Caruru dome
CA-03	Phonolite	+ 9.96	
CA-06	Fine-grained nepheline syenite inclusion	+ 9.54	
CA-09	Fourchite inclusion	+ 8.59	
AN-06	Phonolite	+ 8.78	Ancuri plug
SP-05	Fine-grained nepheline syenite	+ 9.14	Serrote Preto ring-structure
SP-07	Bluish alkali trachyte	+ 7.49	
S-1	Bluish, aphyric alkali trachyte	+ 6.79	Salgadinho neck
S-2	Porphyritic trachyte	+ 10.20	
PA-04	Phonolite	+ 5.39	Pão-de-Açúcar neck

alogical and major chemical compositions. The fracturing as well as the columnar jointing may have greatly facilitated the rock-meteoric water interaction, resulting in a radical modification of the original isotopic composition.

REE-geochemistry

Rare-earth elements (REE) were analysed in the Department of Geology, Memorial University of Newfoundland (MUN), Canada, by X-ray fluorescence.

Analytical techniques — The analytical method for the REE in this study was a modified version (Fryer, 1977) of the thin film X-ray fluorescence procedure of Eby (1972). The rare-earths have been separated as a group by ion-exchange chromatography and transferred onto the SA-2 ion-exchange papers, previously cut to fit the sample holders. Prior to separation, 50 mg of Tm was added as an internal yield standard holders. All samples were analysed on a Philips PW 1450 X-ray fluorescence spectrometer with a tungsten tube. The analytical error is estimated to be less than 10% for all the elements tabulated. Results for Pr, Tb, Ho and Lu are not reported because its use in correcting for chemical yield. The chondritic values used for normalization are Leedey chondrite data (Masuda *et al.*, 1973) divided by 1.20 (Sun & Hanson, 1976; Taylor & Gorton, 1977) to make these data comparable to average chondrite data.

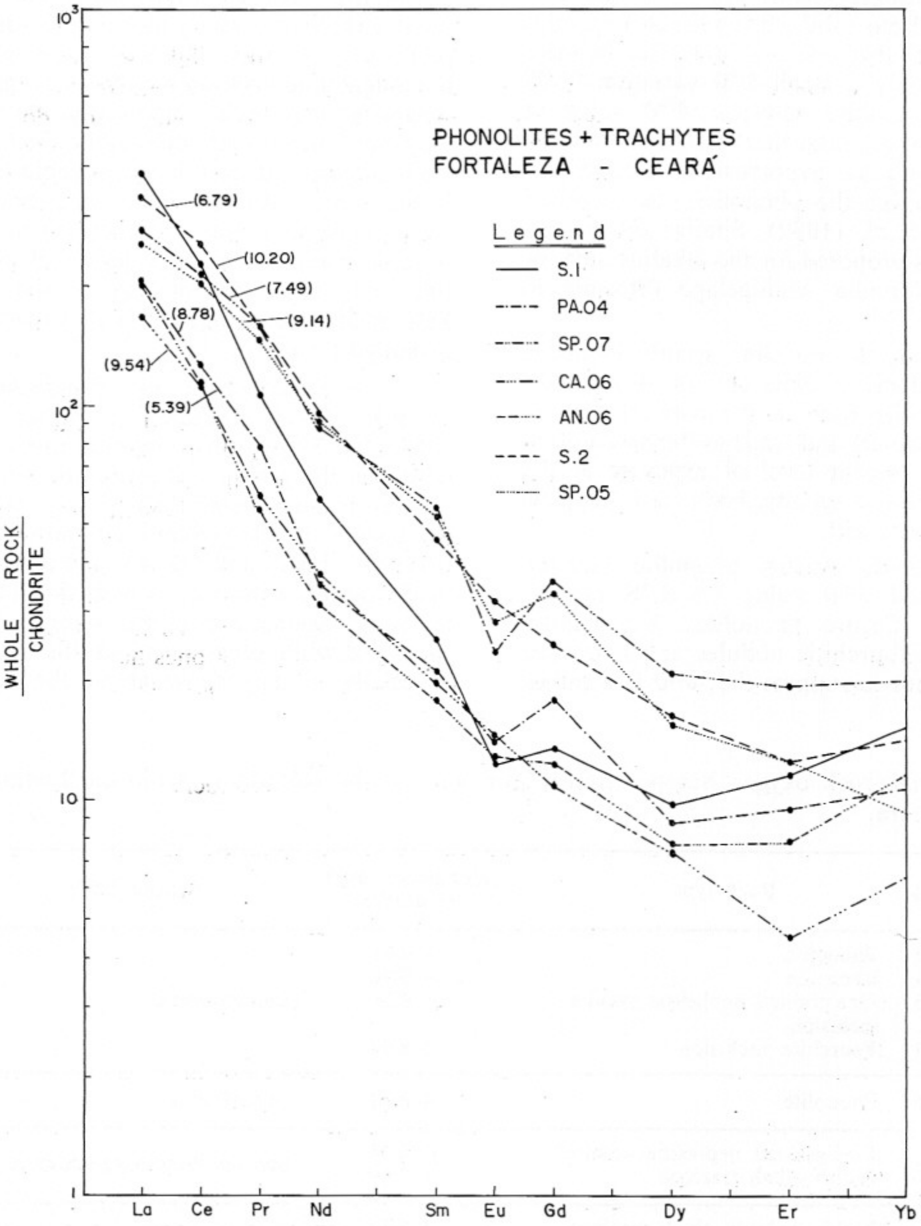

Figure 2 — Chondrite-normalized REE-patterns for seven samples in the alkaline province next to Fortaleza, Ceará. Numbers in parentheses are $\delta^{18}O$ values. S-1 and S-2 are samples from the Salgadinho neck; PA-04 from the Pão-de-Açúcar neck; SP-05 and SP-07 from the Serrote Preto ring-structure; CA-06 from the Caruru dome, and AN-06 from the Ancuri plug.

REE patterns — Seven samples were analysed for REE and results are found in Table 3 and patterns in Figure 2, where it is also plotted the respective $\delta^{18}O$ values. All samples are REE-enriched relative to chondrite abundances. The REE-normalized to chondrite values show high LREE fractionation and moderate HREE fractionation (Ce_N/Yb_N varies from 9.02 to 21.83). All samples except two (S-2 and CA-06) display a moderate negative Eu anomaly (Eu/Eu* varies from 0.53 to 0.73). In samples S-2 (Salgadinho neck) and CA-06 (Caruru dome), Eu/Eu* is of 0.95 and 0.90, respectively.

Samples SP-05 and SP-07 from the Serrote Preto exhibit similar REE signatures, except in the heaviest REE, suggesting in the sample SP-05 a HREE-enriched phase was fractionated out of the liquid (sphene, zircon or apatite). Both revealed negative Eu anomaly and this implies in a feldspar fractionation (probable K-feldspar), or its retention in the source.

The bluish, aphyric (S-1) and the brownish, porphyritic trachyte (S-2) differ in their REE signatures which are not parallel (La_N/Sm_N is of 15.30 for the S-1 and 7.37 for the S-2). The sample S-2 is more HREE-enriched with slightly concave pattern and a minimum at the Er, and lacks Eu anomaly. Sample S-1 displays a concave HREE pattern, with a minimum in the Dy and with a moderate, negative Eu anomaly. The divergences between these patterns suggest that they are not cogenetic and this agrees with the be-

Table 3 — Whole-rock REE analyses (ppm) for salic rocks of the alkaline province of Fortaleza, Ceará, Northeast Brazil.

Rare-earth elements

	AN-06	CA-06	S-1	S-2	SP-05	SP-07	PA-04
La	63.06	53.17	122.77	106.58	80.72	86.58	64.62
Ce	103.50	90.16	186.44	206.38	164.37	177.58	102.15
Nd	19.02	22.32	32.21	56.72	54.33	53.26	21.14
Sm	3.53	3.94	5.02	9.03	10.22	10.92	4.15
Eu	1.00	1.06	0.88	2.29	2.04	1.74	1.03
Gd	3.27	2.81	3.45	6.38	8.60	9.13	4.66
Dy	2.52	2.45	3.23	5.23	5.13	6.80	2.85
Er	1.68	0.95	2.44	2.69	2.69	4.21	2.05
Yb	2.45	1.36	3.23	2.98	1.93	4.14	2.25
ΣREE	200.03	178.25	359.57	398.28	330.03	354.36	204.90
La_N/Sm_N	11.16	8.44	15.30	7.37	4.93	4.95	9.75
Ce_N/Yb_N	10.82	9.02	14.78	17.68	21.83	10.95	11.60
Eu/Eu*	0.91	0.90	0.55	0.95	0.66	0.53	0.73

Eu/Eu* = Eu_N: Eu (interpolation between Sm_N and Gd_N)

Other trace elements

	AN-06	CA-06	S-1	S-2	SP-05	SP-07	PA-04
Pb	21	11	18	18	16	n.d.	25
Th	63	29	42	32	36	56	52
U	24	2	9	2	13	n.d.	17
Rb	403	193	285	194	195	313	281
Sr	14	428	11	97	54	5	11
Y	28	16	34	44	42	67	31
Zr	1413	518	1412	781	875	1450	1407
Nb	373	167	264	257	259	431	259
Zn	177	70	158	118	113	n.d.	153
Cu	8	5	5	2	0	n.d.	5
Ni	0	1	0	0	0	n.d.	0
Ba	26	597	33	171	79	14	18
V	8	26	2	6	2	0	6
Ga	35	23	31	23	24	33	36

havior of the 0-isotopes. The REE signature of sample S-1 is compatible with amphibole fractionation. As kaersutite phenocrysts and xenocrysts are observed in several salic alkaline rocks in this province, this favours the fractionation of this phase or its retention in the source. Although, at least to our knowledge, the behavior of rare-earths in kaersutite is unknown, we assume that it is probably similar to hornblende, that is, HREE-enriched relative to the LREE, with negative Eu anomaly and a maximum at the Dy (Hanson, 1978). The concavity observed in the HREE pattern in the samples S-1, PA-04 and AN-06, with a minimum at the Dy, is likely a consequence of the kaersutite fractionation. On the other hand, in the samples CA-06 (Caruru dome) and SP-07 (Serrote Preto ring-structure), the REE pattern displays a minimum at the Er, and this can be related to garnet fractionation. Garnet bearing xenoliths at Caruru are suggestive of garnet in the source and the presence of this mineral as a residual phase in the partial melting may have been responsible for the observed REE pattern.

In addition to what is observed through the 0-isotopes and the REE-geochemistry, trace elements such as Sr and Ba contents are compatible with the fractionation of plagioclase and K-feldspar from a fourchitic magma (SP-05, SP-07, PA-04 and S-1) during the magma ascent to the surface. Probably, K-feldspar fractionation followed that of plagioclase when the magma passed through a syenite composition in its evolution.

SUMMARY

Four among seven samples analysed in this study exhibit REE-patterns with negative Eu anomaly, compatible with feldspar fractionation from the magma or that it behaved as a residual phase during the partial melting. The very steep slopes of the REE-patterns (Ce_N/Yb_N varies from 9 to 22) also suggest a source already enriched in LREE and such enrichment could have happened prior to melting take place. According to Menzies & Wass (1983) LREE enrichment may be accomplished by veining of the subcontinental mantle with volatite-rich phases like amphibole, apatite and carbonates, which provide the volatile flux necessary to trigger anatexis. The paucity of basic magmas in this province, except for a few narrow dikes (1 m wide), supports a possibility that alkali trachyte magmas rather represent a low degree of partial melting in the mantle, and migration to the surface with little, if any, differentiation. Similar hypothesis has been invoked by Wright (1969) to explain the presence of olivine nodules in trachytes, the absence of a parental mafic magma and the large volume of salic rocks. However, the presence of fourchite nodules in the Caruru dome, seems to imply that at least in part fourchite magma may have acted as the parental magma in this province.

Some samples exhibit REE-patterns compatible with the retention of garnet in the residue of the partial melting in the mantle. Two of them also show evidences for feldspar fractionation and being plagioclase and garnet mutually exclusive in the peridotites in the top of the mantle one can assume that if feldspar was responsible for the negative Eu anomaly observed in the REE patterns, it did not remain in the residue of partial melting, but it was rather fractionated out of the liquid during its ascent to the surface. Judging from the discrete Eu anomalies observed, it is assumed that this fractionation was a modest one unless a high oxygen fugacity precluded Eu to enter in the feldspar structure.

Three samples showed REE signatures compatible with amphibole fractionation (kaersutite). If this was the case, this phase was fractionated along K-feldspar to form syenites at depth, as attested by the presence of syenite inclusions in the Salgadinho neck. Kaersutite may have also been kept in the source in the mantle during the partial melting. The congruent melting of this mineral is able to generate an alkali olivine basaltic magma (Forbes & Starmer, 1974), so this phase may have also contributed to the formation of the parental magma in this province. Limburgite and ankaramite dikes probably formed from independent batch of magma derived straight from the mantle by a low degree of melting.

ACKNOWLEDGEMENTS

The Brazilian National Council for Scientific and Technological Development (CNPq) partially supported the field work and provided me an one-year post-doctoral work in the United States and Canada. I am also thankful to B.J. Fryer, Memorial University of Newfundland (MUN), Canada, for helping me with the REE analyses and Cleve Solomon with the 0-isotopes analyses in Georgia, USA.

REFERENCES

ALMEIDA, F.F.M. (1955) Geologia e petrologia do Arquipélago de Fernando de Noronha. Dept. Nac. Prod. Min. (DNPM), Div. Geol. Min., Monografia 13, Rio de Janeiro, 133p.

BRAGA, A.P.G.; PASSOS, C.A.B.; SOUZA, E.M.; FRANÇA, J.B.; MEDEIROS, M.F.; ANDRADA, V.A. (1977) Projeto Fortaleza (Relatório Final). Dept. Nac. Prod. Min. (DNPM) — Comp. Pesq. Rec. Min. (CPRM), **1**:180p.

CORDANI, U.G. (1970) Idade do vulcanismo no Oceano Atlântico. Bol. Inst. Geoc. Astron. Univ. São Paulo, São Paulo, **1**:9-75.

CRAIG, H. (1961) Standard for reporting concentrations of deuterium and oxygen-18 in natural waters. Science, **133**:1833-1934.

EBY, G.N. (1972) Determination of rare-earth, yttrium and scandium abundances in rocks minerals by ion-exchange X-ray fluorescence.

FOLAND, K.A. & FRIEDMAN, I. (1977) Application of Sr and O isotope relations to the petrogenesis of the alkaline rocks of the Red Hill Complex, New Hampshire, USA. Contr. Min. Petrol., **65**:213-225.