Petrology of the tephrite-phonolite suite and cognate xenoliths of the Fortaleza district (Ceará, Brazil)

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Abstract : The alkaline district of Fortaleza (Ceará, Brazil) consists of a number of phonotephritic plugs, domes, and dykes cropping out in the Precambrian basement, aged around 30 Ma.

Chemically and petrographically the rocks range in composition from tephrites and phonolitic tephrites to peralkaline phonolites.

At one locality (Caruru), olivine clinopyroxenite, essexite, and nepheline syenite xenoliths of cognate origin were also found included in phonolites. Whole rock and mineral chemistry variations coherently indicate that the various magmatic bodies of the suite essentially evolved by fractional crystallization.

Mass balance calculations between bulk rocks and constituent minerals show that the evolution from tephrites to phonolitic tephrites and phonolites can be generally accounted for by subtraction of cumulates, which partly correspond to essexites and nepheline syenite xenoliths found in phonolites. Tephrites which are the least fractionated alkaline magmas in the area could, in turn, be derived from parental basanitic melts as suggested by the presence of olivine clinopyroxenite xenoliths that represent the proper fractionated solid complementary to tephritic liquids.

$^{87}Sr/^{86}Sr$ initial ratios (Ro) range from 0.7024-0.7057 suggesting significant crustal contamination processes only for the samples with high isotopic values. The inferred initial Sr ratios of the parental magmas (Ro = 0.7029-0.7036) are remarkably lower than those of southern Brazilian alkaline complexes (Ro = 0.704-0.706) supporting the existence of the Dupal Anomaly in the southern hemisphere mantle.

Key-words : igneous petrology, mineral chemistry, strontium isotopes, tephrite-peralkaline phonolites, cognate xenoliths, Brazil.

Introduction

The origin of phonolite-nepheline syenite magmas has been subjected to various interpretations. These magmas have been considered, in turn, as extreme differentiation products from alkaline basic or trachytic melts (*cf.* Coombs & Wilkinson, 1969 ; Price *et al.*, 1985) ; as produced by liquid immiscibility (*cf.* Ferguson & Currie, 1971) ; or even as partial melting products of basic materials in the lower crust-upper mantle when they were volumetrically predominant with respect to the associated basic rocks (Bailey & Schairer, 1966 ; Bailey, 1987).

In this paper we present data on the tephrite-phonolite suite from the Fortaleza district in northeastern Brazil, with the aim of assessing their genesis and significance in the context of the alkaline magmatism which affected continental Brazil during Cretaceous-Tertiary times. The Fortaleza alkaline district is of particular interest, in this sense, since it represents one of the northernmost alkaline complexes among the Brazilian occurrences, for which only some petrological data are presently available (Vandoros & Oliveira, 1968 ; Rao & Sial, 1972 ; Passos & Gomes, 1979 ; Guimarães *et al.*, 1982 ; Sial, 1987). Hence results from this study may also provide an opportunity to examine the compositional variations among different alkaline rock associations, and eventually to assess regional variations. This work is part of an extensive Brazilian-Italian research project aimed at a systematic petrological study of alkaline magmatism in continental Brazil.

Geological setting

The Fortaleza alkaline district consists of a number of phonotephritic plugs, smooth domes and NE-SW dykes occurring within a radius of 50 km from the city of Fortaleza (Fig. 1). With
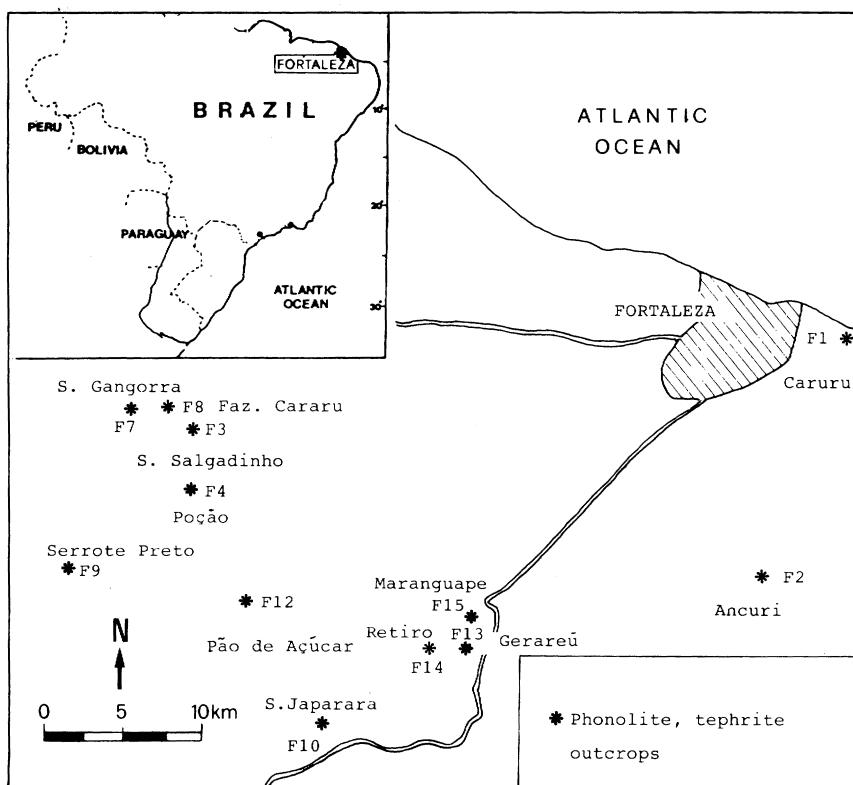

Fig. 1. Locality map of phonolite, tephrite outcrops (asterisks and sampling numbers) of the Fortaleza district, northeastern Brazil.

the exception of Ancuri and Caruru occurrences, cropping out in the Phanerozoic sedimentary cover, the alkaline rocks cut the Precambrian crystalline basement.

Chemically, alkaline rocks range in composition from tephrites and phonotephrites to peralkaline phonolites. The most complete lithological range occurs at Serrote Japarara and Caruru, which show phonotephritic to peralkaline phonolitic compositions. At Caruru, olivine clinopyroxenite, essexite and nepheline syenite xenoliths of cognate origin were also found within the phonolitic dome.

For several occurrences K/Ar and Rb/Sr data give ages around 30 Ma (Cordani, 1970 ; Teixeira et al., 1978). More recently Guimarães (1982) provided a Rb/Sr reference isochron of 30.2 ± 2.2 Ma for samples from Ancuri, Caruru, Japarara and Salgadinho outcrops. This age appears to correspond to the fourth volcano-tectonic phase of the Gondwana continents, which could have induced phonolitic activity in South Africa (Marsh, 1975) as well as in the Fortaleza district in northeastern Brazil, as the result of an important change in position of the rotation poles and spreading rates of the South American and African plates (Sadowsky, 1987).

Fortaleza alkaline magmatism seems to be related to the activation of tectonic lineaments in an ENE-WSW direction, extending from the continent into the ocean as far as the volcanic Archipelago of Fernando de Noronha (Almeida, 1983 ; Almeida et al., 1988).

Classification and petrography

Major and trace element analyses and CIPW norms of the Fortaleza alkaline rocks are reported in Table 1. The distribution of all samples analyzed in the R1-R2 diagram of De La Roche et al. (1980) (Fig. 2), as well as their modal characteristics, have been used for classification purposes.

Most of the hypoabyssal rocks plot in the fields of tephrite, phonotephrite and phonolite ; the differentiation index (D.I.) ranges from 38.5 to 96.5. Phonolites exhibit a definite peralkaline character with agpaitic index A.I. > 1 and normative Ac and Ns. The agpaitic index varies from 1.18 to 1.02, showing the lowest value in those samples which are most

severely affected by alteration of alkali feldspar into clay minerals. Arrows in Fig. 2 indicate a generalized trend of liquids, given by non-cumulitic rocks, according to their chemical composition and textural characteristics. A great number of phonolitic samples depart from the liquid line towards trachy-phonolite compositions, owing to variable amounts of modal cumulus alkali feldspar.

The xenoliths occurring in the Caruru phonolite (F1) consist of one olivine clinopyroxenite (D.I. = 16), essexites (D.I. = 43-46) and nepheline syenites (D.I. = 77-91) (Fig. 2). Texture, bulk rock and mineral chemistry indicate that the essexite and the Ne-syenites can represent cognate cumulitic products related to distinct stages of the tephrite-phonolite evolution (see later).

The tephrite-phonolite suite

a) Tephrites

Tephrites, which are chemically the least differentiated rocks (D.I. = 38 ; mg = 0.55, with Fe_2O_3/FeO = 0.20) are petrographically characterized by a fine grained holocrystalline porphyritic texture, where rare phenocrysts and microphenocrysts of colorless, slightly zoned Ti-salitic clinopyroxenes occur. The groundmass is composed of small rods of brown kaersutitic amphibole, clinopyroxene, and small laths of andesinic plagioclase and interstitial anorthoclase. The scarce nepheline is a late crystallization interstitial phase, whereas widespread Ti-magnetite and apatite are early crystallized minerals.

Small cavities are filled by chlorite, epidote and calcite. Primary calcite, appearing as large interstitial crystals, may be occasionally observed.

b) Phonolitic tephrites

Although petrographically similar to tephrites, their more differentiated character (D.I. = 40-50 ; mg = 0.50-0.45) is modally expressed by lesser content of mafic phases. Textural variations concern the nearly-aphyric vs. porphyritic character of these rocks, also with respect to their mineralogy. Clinopyroxene phenocrysts are of Ti-salitic composition, with hour-glass zoning in the largest crystals ; not

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Table 1. Major, trace element analyses and CIPW norms of Fortaleza alkaline rocks.

	F1S-N Ol-Cp	F10I-D Tph	F13A-D Ph-Tph	F15A-D Ph-Tph	F15-D Ph-Tph	F1R-N Ex	1H-N Ex	F1G-N Ex	F10H-D Ph-Tph	F1L-N Ne-Sy	F1F-N Ne-Sy	F1H-1-N Ne-Sy	F1T-N Ne-Sy	F1C P-Ph	F1Q P-Ph
SiO_2	43.84	45.53	42.51	41.66	41.98	43.69	43.09	46.34	47.16	53.50	54.32	56.85	55.82	55.91	56.39
TiO_2	1.16	3.16	2.90	3.35	3.34	1.67	1.62	0.79	3.50	0.86	0.17	0.16	0.18	0.43	0.42
Al_2O_3	8.45	13.63	14.37	13.82	13.76	16.26	17.14	15.94	15.32	17.31	21.54	19.88	22.13	20.75	21.00
Fe_2O_3	5.03	3.45	4.32	5.05	5.04	5.37	6.08	4.24	3.96	2.60	0.92	0.53	0.53	1.10	0.86
FeO	9.19	7.16	7.72	8.07	8.10	5.87	5.99	5.57	6.91	3.33	0.79	0.44	0.57	1.12	1.29
MnO	0.22	0.15	0.21	0.23	0.23	0.23	0.30	0.18	0.16	0.22	0.13	0.07	0.07	0.12	0.11
MgO	14.01	6.10	5.63	5.71	5.77	5.33	4.98	5.65	4.01	2.64	0.26	0.40	0.11	0.29	0.23
CaO	13.40	10.00	7.72	8.36	8.27	8.22	7.26	9.32	7.51	2.82	1.19	1.65	0.54	1.47	1.45
Na_2O	2.11	3.69	3.57	4.45	4.68	5.19	4.65	6.14	4.08	7.02	9.37	7.20	9.04	9.84	10.00
K_2O	1.03	2.37	2.70	2.17	2.16	2.53	3.14	2.01	3.50	5.79	4.79	7.10	5.75	6.19	5.66
P_2O_5	0.03	0.74	1.28	1.51	1.45	0.20	0.25	0.19	1.03	0.05	0.13	0.02	0.05	0.09	0.09
L.O.I.	1.53	4.01	7.06	5.61	5.20	5.43	5.50	3.64	3.19	3.86	6.40	5.71	5.21	2.69	2.50
Total	100.00	99.99	99.99	99.99	99.98	99.99	100.00	100.01	100.33	100.00	100.01	100.01	100.00	100.00	100.00
V	337	260	210	214	210	176	177	131	231	138	15	11	12	27	25
Cr	653	85	76	n.d.	n.d.	116	117	107	n.d.	123	n.d.	n.d.	n.d.	4	n.d.
Ni	111	41	57	34	32	14	18	12	7	27	10	10	10	13	10
Rb	67	50	83	155	155	222	319	114	100	240	269	268	257	240	224
Sr	147	887	1190	1390	1370	384	344	398	1470	275	113	475	183	408	435
Ba	168	864	1190	1480	941	207	222	169	1180	666	191	618	171	541	566
Zr	36	264	518	598	599	156	253	167	318	293	544	488	1450	725	777
Nb	n.d.	78	136	151	152	23	34	24	98	62	294	57	270	146	147
Y	23	25	41	46	50	27	39	19	26	71	16	17	10	18	21
La	8.06	42.6	100	110	115	38	40.3	14.9	66	71.0	41	51	67	81.5	86
Ce	27.2	90.0	203	215	229	73	82.3	29.7	107	136	90	71	107	119	104
Nd	19.0	42.9	84.0	--	95.8	--	28.7	12.5	--	47.5	--	--	--	27.2	--
Sm	4.98	8.89	14.8	--	17.1	--	6.54	3.13	--	10.4	--	--	--	4.13	--
Eu	1.10	2.78	4.08	--	4.84	--	1.47	1.29	--	2.10	--	--	--	1.15	--
Gd	4.80	7.57	11.4	--	13.3	--	6.34	3.12	--	8.70	--	--	--	3.26	--
Dy	4.46	5.32	7.95	--	9.53	--	5.91	3.03	--	8.84	--	--	--	2.65	--
Er	2.07	2.12	3.49	--	4.09	--	3.33	1.74	--	5.30	--	--	--	1.66	--
Yb	1.77	1.58	2.96	--	3.45	--	3.51	1.83	--	6.27	--	--	--	2.05	--
Lu	0.23	0.21	0.37	--	0.42	--	0.52	0.25	--	0.81	--	--	--	0.29	--
C	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00
Or	6.09	14.00	15.95	12.82	12.76	14.95	18.55	11.88	20.68	34.21	28.30	41.95	33.98	36.58	33.45
Ab	0.45	16.51	18.13	16.91	16.90	10.49	9.90	12.15	23.27	21.65	33.97	28.52	32.93	23.06	27.66
An	10.54	13.63	15.21	11.33	10.16	13.60	16.62	10.00	13.15	0.00	2.57	0.96	2.35	0.00	0.00
Ne	9.43	7.97	6.54	11.24	12.30	18.11	15.95	21.55	6.10	19.04	24.55	17.55	23.60	26.66	26.46
Ac	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.29	0.00	0.00	0.00	3.18	2.49
Ns	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.72	1.23
Di	34.86	19.11	8.57	12.18	12.83	16.37	11.18	20.78	10.40	7.50	1.10	2.15	0.00	1.56	1.24
Ed	9.77	5.88	3.31	4.14	4.38	4.31	3.03	7.41	3.57	3.59	0.96	0.44	0.00	2.95	3.53
Di	44.63	24.99	11.88	16.31	17.21	20.69	14.21	28.18	13.98	11.09	2.06	2.59	0.00	4.51	4.77
Wo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.60	0.00	0.58	0.44
Fo	13.13	4.44	7.04	6.01	5.90	3.98	5.06	3.11	3.62	2.17	0.10	0.00	0.19	0.00	0.00
Fa	4.65	1.72	3.44	2.58	2.54	1.33	1.73	1.40	1.57	1.31	0.11	0.00	0.34	0.00	0.00
Ol	17.77	6.16	10.48	8.59	8.45	5.31	6.79	4.51	5.19	3.48	0.21	0.00	0.53	0.00	0.00
Mt	7.29	5.00	6.26	7.32	7.31	7.79	8.82	6.15	5.74	2.62	1.33	0.77	0.77	0.00	0.00
Il	2.20	6.00	5.51	6.36	6.34	3.17	3.08	1.50	6.65	1.63	0.32	0.30	0.34	0.82	0.80
Ap	0.07	1.75	3.03	3.58	3.43	0.47	0.59	0.45	2.44	0.12	0.31	0.05	0.12	0.21	0.21
D.I.	15.96	38.48	40.63	40.97	41.96	43.55	44.41	45.59	50.05	77.20	86.82	88.03	90.51	91.20	91.28
S.I.	44.66	26.79	23.52	22.44	22.41	21.94	20.05	23.93	17.85	12.35	1.61	2.55	0.69	1.56	1.27
A.I.	0.54	0.63	0.61	0.70	0.73	0.69	0.64	0.77	0.69	1.03	0.96	0.98	0.95	1.10	1.08

D.I. = Differentiation Index $(Q+Or+Ab+Lc+Ne+Ks+Ac+Ns)$; S.I. = Solidification Index $(MgO*100/(MgO+Fe_2O_3+FeO+Na_2O+K_2O)$; A.I. = Agpaitic Index $(Na_2O+K_2O/Al_2O_3$, mol). Rock name abbreviations : Ol-Cp = olivine clinopyroxenite, Tph = tephrite, Ph-Tph = phonolitic tephrite, P-Ph = peralkaline phonolite, Ne-Sy = nepheline syenite, -D = Dyke, -N = nodule included, n.d. = not detected. Major and trace element analyses carried out by XRF, FeO by titration, L.O.I. by gravimetric method and REE by ICP. Precision and accuracy for trace elements is better than 10%.

uncommonly, these are completely pseudomorphosed by low temperature phases such as chlorite, epidote, and finely-grained opaques.

Clinopyroxenes of the groundmass are usually needle-like of small rods, with the same composition as phenocrysts.

Numerous microphenocrysts of Ti-magnetite and brown amphibole may also be observed. These latter displays a quite inhomogeneous distribution being abundant (*e.g.* F10H) or scarce (*e.g.* F13A) in different samples.

The groundmass is composed of the same mafic phases, and by plagioclase microlites of andesinic composition and alkali feldspar. Small amounts of idiomorphic sphene and apatite and interstitial nepheline are also present.

It is worthnoting the occurrence of primary calcite patches and ocelli rimmed by amphibole

Table 1. (continued).

	F9B P-Ph	F14D P-Ph	F8A P-Ph	F14B P-Ph	F1B P-Ph	F14A P-Ph	F1A P-Ph	F2D-D P-Ph	F12I P-Ph	F14C P-Ph	F9D P-Ph	F3B P-Ph	F9G P-Ph	F3E P-Ph	F3C P-Ph
SiO₂	61.61	55.96	5'.53	56.23	57.09	56.93	57.06	57.30	58.20	56.94	59.09	60.95	59.56	60.49	60.89
TiO₂	0.34	0.18	0.18	0.20	0.34	0.20	0.33	0.29	0.38	0.18	0.16	0.33	0.16	0.34	0.32
Al₂O₃	18.72	19.92	19.93	20.21	20.97	20.09	21.02	20.82	20.27	20.20	19.21	19.49	19.33	19.50	19.31
Fe₂O₃	1.50	2.18	1.52	2.08	1.37	2.03	1.42	1.63	1.63	2.14	2.00	1.41	2.05	1.55	1.30
FeO	1.39	0.46	0.66	0.63	0.79	0.69	0.68	0.86	0.85	0.50	0.82	0.81	0.79	0.82	0.85
MnO	0.20	0.26	0.31	0.25	0.16	0.25	0.16	0.31	0.15	0.26	0.25	0.23	0.25	0.22	0.22
MgO	0.21	0.03	0.01	0.04	0.09	0.05	0.09	0.11	0.20	0.02	0.04	0.09	0.02	0.10	0.09
CaO	1.34	0.51	0.82	0.54	1.20	0.56	0.97	0.67	1.20	0.52	0.64	1.05	0.63	1.05	1.06
Na₂O	9.10	10.67	9.78	11.41	9.79	11.15	9.97	10.04	9.77	11.08	10.41	8.29	9.67	8.83	8.74
K₂O	3.83	4.35	5.08	4.27	5.70	4.52	5.66	5.33	5.90	4.52	4.73	5.99	4.86	5.79	5.97
P₂O₅	0.06	0.00	0.02	0.00	0.07	0.01	0.06	0.03	0.09	0.01	0.02	0.04	0.02	0.04	0.04
L.O.I.	1.71	5.46	4.15	4.14	2.63	3.52	2.59	2.61	1.35	3.63	2.62	1.32	2.64	1.27	1.22
Total	100.01	99.98	99.99	100.00	100.00	99.99	100.01	100.00	99.99	100.00	99.99	100.00	99.98	100.00	100.01
V	5	11	7	12	15	15	16	13	23	13	4	12	5	12	12
Cr	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	5	7	5	4	9	6	8	7	9	9	5	6	7	7	8
Rb	197	420	278	428	295	433	295	400	211	440	303	224	305	229	223
Sr	48	6	41	12	264	13	267	20	227	10	9	70	8	69	74
Ba	96	24	80	37	338	29	364	35	326	40	42	135	30	145	167
Zr	946	2720	1720	2540	999	2640	1060	1490	985	2510	1460	1080	1500	1060	1020
Nb	238	300	267	289	229	290	224	348	188	278	362	256	381	255	245
Y	38	37	35	34	21	31	24	33	26	37	54	41	56	40	38
La	122	168	171	144	94.2	169	93	133	113	160	142	142	142	230	137
Ce	219	183	227	188	136	190	141	184	144	182	266	234	251	236	219
Nd	71.6	--	--	--	27.2	25.0	--	--	--	--	--	--	--	--	--
Sm	10.8	--	--	--	4.15	3.50	--	--	--	--	--	--	--	--	--
Eu	1.68	--	--	--	0.69	0.62	--	--	--	--	--	--	--	--	--
Gd	7.70	--	--	--	3.28	3.19	--	--	--	--	--	--	--	--	--
Dy	6.59	--	--	--	2.86	3.24	--	--	--	--	--	--	--	...	--
Er	3.43	--	--	--	1.99	2.81	--	--	--	--	--	--	--	--	--
Yb	3.64	--	--	--	2.67	4.74	--	--	--	--	--	--	--	--	--
Lu	0.46	--	--	--	0.41	0.70	--	--	--	--	--	--	--	--	--
Or	22.63	25.70	30.02	25.23	33.68	26.71	33.45	31.50	34.86	26.71	27.95	35.40	28.72	34.21	35.28
Ab	57.69	35.98	36.76	35.14	30.27	35.66	30.14	32.70	30.82	35.77	41.32	42.65	42.82	40.14	40.73
Ne	9.36	22.90	20.30	24.40	24.84	23.03	25.17	24.22	21.99	23.28	16.88	13.14	16.01	15.13	13.74
Ac	1.79	6.31	4.40	6.02	3.96	5.87	4.11	4.72	4.72	6.19	5.79	2.86	5.93	4.48	3.76
Ns	0.00	1.14	0.82	2.22	0.51	2.21	0.72	0.51	1.37	1.86	2.10	0.00	0.63	0.36	0.84
Di	1.13	0.16	0.05	0.19	0.48	0.22	0.48	0.43	1.07	0.11	0.17	0.48	0.09	0.54	0.48
Ed	3.08	1.94	2.80	2.17	2.23	2.17	1.88	2.30	2.28	2.08	2.52	1.92	2.57	2.54	2.71
Di	4.20	2.10	2.86	2.36	2.72	2.39	2.37	2.73	3.35	2.18	2.69	2.40	2.66	3.08	3.19
Wo	0.57	0.06	0.30	0.00	0.58	0.00	0.70	0.00	0.60	0.02	0.00	0.91	0.00	0.59	0.56
Fo	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.05	0.00	0.00	0.01	0.00	0.01	0.00	0.00
Fa	0.00	0.00	0.00	0.11	0.00	0.19	0.00	0.35	0.00	0.00	0.28	0.00	0.22	0.00	0.00
Ol	0.00	0.00	0.00	0.11	0.00	0.21	0.00	0.40	0.00	0.00	0.30	0.00	0.23	0.00	0.00
Mt	1.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.61	0.00	0.00	0.00
Il	0.65	0.34	0.34	0.38	0.65	0.38	0.63	0.55	0.72	0.34	0.30	0.63	0.30	0.65	0.61
Ap	0.14	0.00	0.05	0.00	0.17	0.02	0.14	0.07	0.21	0.02	0.05	0.09	0.05	0.09	0.09
D.I.	91.47	92.02	92.30	93.01	93.27	93.48	93.59	93.64	93.76	93.80	94.04	94.04	94.11	94.33	94.34
S.I.	1.31	0.17	0.06	0.22	0.51	0.27	0.50	0.61	1.09	0.11	0.22	0.54	0.12	0.59	0.53
A.I.	1.02	1.12	1.08	1.16	1.06	1.16	1.07	1.07	1.11	1.14	1.16	1.03	1.10	1.07	1.08

shells. This may be related to silicate and carbonate incipient liquid immiscibility as response of relatively high CO_2-H_2O fluid activity. Secondary calcite commonly fills cavities.

c) Peralkaline phonolites

Peralkaline phonolites (D.I. = 91-96) range in texture from essentially aphyric varieties with few sparsely distributed microphenocrysts, through weak-to-medium porphyritic, to highly porphyritic types. The latter type is characterized by cumulitic alkali feldspar phenocrysts, sometimes showing glomeroporphyric texture. The aphyric phonolites represent highly evolved liquid compositions.

The intratelluric assemblage is constituted by clinopyroxene and alkali feldspar, and sometimes by brown amphibole, often surrounded by a rim of opaque grains. The irregular occurrence of the amphibole, generally associated with significant amounts of sphene and magnetite, suggests local increase of P_{H_2O}. Apatite and sphene are always present.

Phenocryst and microphenocryst clinopyroxenes are generally zoned with weakly coloured salitic and Fe-salitic cores and deep green acmitic rims similar to the clinopyroxene rods of the groundmass. In the more differentiated rocks, clinopyroxenes are dark green, and show quenching textures (idiomorphic skeletal crystals, sometimes with swallow tail appearance).

Table 1. (continued).

	F10E P-Ph	F9A P-Ph	F2C P-Ph	F3D P-Ph	F2A P-Ph	F8B P-Ph	F2B P-Ph	F9E P-Ph	F3A P-Ph	F9C P-Ph	F1E P-Ph	F4A P-Ph	F9F P-Ph	F9H P-Ph	F7A P-Ph
SiO_2	60.21	59.83	57.31	60.46	57.41	58.90	57.46	59.47	60.79	59.97	57.89	58.54	59.94	59.56	58.25
TiO_2	0.16	0.16	0.26	0.32	0.25	0.14	0.26	0.15	0.33	0.18	0.22	0.31	0.17	0.15	0.18
Al_2O_3	20.21	19.31	20.76	19.47	20.60	20.35	20.67	19.33	19.49	19.21	20.61	20.44	19.26	19.40	20.07
Fe_2O_3	0.67	2.02	1.68	1.50	2.05	1.43	2.14	2.12	1.56	1.84	1.58	1.56	2.01	2.23	2.22
FeO	1.16	0.77	0.71	0.81	0.38	0.60	0.31	0.67	0.75	1.08	0.70	0.70	0.92	0.69	0.48
MnO	0.24	0.25	0.29	0.23	0.29	0.28	0.28	0.26	0.23	0.27	0.23	0.19	0.26	0.27	0.30
MgO	0.04	0.00	0.05	0.07	0.04	0.02	0.04	0.00	0.10	0.01	0.14	0.10	0.00	0.00	0.01
CaO	0.79	0.68	0.53	1.03	0.47	0.80	0.48	0.59	1.05	0.64	0.63	0.78	0.65	0.60	0.61
Na_2O	9.63	9.87	10.70	8.96	10.09	10.23	9.97	10.27	8.82	10.42	11.12	10.49	10.37	10.26	11.13
K_2O	5.45	4.82	5.14	5.89	5.25	5.22	5.22	4.70	5.84	4.74	5.00	5.25	4.77	4.75	4.74
P_2O_5	0.02	0.02	0.04	0.04	0.04	0.01	0.03	0.02	0.04	0.03	0.02	0.05	0.02	0.02	0.02
L.O.I.	1.43	2.27	2.52	1.23	3.12	2.02	3.14	2.42	1.00	1.63	1.85	1.60	1.62	2.07	1.97
Total	100.01	100.00	99.99	100.01	99.99	100.00	100.00	100.00	100.00	100.02	99.99	100.01	99.99	100.00	99.98
V	8	n.d.	11	9	11	9	10	n.d.	9	n.d.	10	15	5	6	6
Cr	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	7	8	8	8	7	7	6	4	6	4	7	8	4	8	5
Rb	215	308	389	230	403	292	395	313	226	313	287	252	320	327	319
Sr	20	8	17	64	11	15	12	5	71	8	18	185	6	6	14
Ba	64	49	31	129	19	52	44	34	136	43	36	225	41	36	50
Zr	1020	1490	1500	1080	1700	1500	1610	1560	1040	1690	1650	1340	1660	1690	2020
Nb	198	382	344	258	358	238	357	395	250	426	257	248	413	433	458
Y	28	56	26	42	35	34	28	59	38	64	31	30	60	65	69
La	124	131	128	135	131	154	129	139	137	163	146	125	151	155	173
Ce	185	252	171	236	189	209	177	253	247	296	192	177	259	293	323
Nd	--	--	28.2	--	--	37.6	--	--	66.7	83.4	32.7	--	--	--	--
Sm	--	--	3.90	--	--	5.12	--	--	9.58	13.3	4.77	--	--	--	--
Eu	--	--	0.60	--	--	0.83	--	--	1.73	1.19	0.90	--	--	--	--
Gd	--	--	3.23	--	--	4.31	--	--	6.98	10.0	4.02	--	--	--	--
Dy	--	--	3.15	--	--	3.97	--	--	5.91	9.78	3.73	--	--	--	--
Er	--	--	2.48	--	--	3.08	--	--	3.44	5.68	2.73	--	--	--	--
Yb	--	--	3.73	--	--	4.35	--	--	3.74	6.31	3.83	--	--	--	--
Lu	--	--	0.53	--	--	0.63	--	--	0.50	0.77	0.58	--	--	--	--
Or	32.20	28.48	30.37	34.80	31.02	30.85	30.85	27.77	34.51	28.01	29.55	31.02	28.19	28.07	28.01
Ab	41.56	43.24	33.37	39.37	33.94	37.59	34.31	42.56	40.55	43.40	34.60	35.78	42.83	42.01	36.78
Ne	17.36	15.84	24.27	15.16	23.18	20.60	23.27	16.63	14.73	15.72	23.60	21.74	16.08	16.97	21.70
Ac	1.94	5.84	4.86	4.34	5.93	4.14	6.19	6.13	4.51	5.32	4.57	4.51	5.82	6.45	6.42
Ns	1.32	1.02	1.60	0.82	0.45	1.46	0.02	1.55	0.41	2.26	2.50	1.80	2.01	1.43	2.34
Di	0.16	0.00	0.19	0.38	0.21	0.11	0.21	0.00	0.54	0.03	0.59	0.54	0.00	0.00	0.05
Ed	3.20	2.89	1.89	2.61	1.55	2.62	1.24	2.49	2.37	2.62	1.99	2.12	2.76	2.54	2.15
Di	3.36	2.89	2.08	2.98	1.76	2.72	1.46	2.49	2.91	2.65	2.58	2.66	2.76	2.54	2.20
Wo	0.00	0.00	0.00	0.60	0.02	0.35	0.22	0.00	0.67	0.00	0.00	0.20	0.00	0.00	0.17
Fo	0.02	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.00
Fa	0.47	0.06	0.31	0.00	0.00	0.00	0.00	0.11	0.00	0.61	0.22	0.00	0.33	0.13	0.00
Ol	0.49	0.06	0.34	0.00	0.00	0.00	0.00	0.11	0.00	0.62	0.28	0.00	0.33	0.13	0.00
Il	0.30	0.30	0.49	0.61	0.47	0.27	0.49	0.28	0.63	0.34	0.42	0.59	0.32	0.28	0.34
Ap	0.05	0.05	0.09	0.09	0.09	0.02	0.07	0.05	0.09	0.07	0.05	0.12	0.05	0.05	0.05
D.I.	94.39	94.43	94.46	94.50	94.52	94.62	94.63	94.65	94.71	94.71	94.82	94.85	94.92	94.93	95.25
S.I.	0.24	0.00	0.27	0.41	0.22	0.11	0.23	0.00	0.59	0.06	0.76	0.55	0.00	0.00	0.05
A.I.	1.08	1.11	1.12	1.08	1.05	1.10	1.07	1.14	1.07	1.16	1.15	1.12	1.15	1.14	1.17

Alkali feldspar is always present as lath shaped phenocrysts, generally zoned and often perthitic.

Nepheline occurs as idiomorphic, phenocrysts in the most differentiated and most porphyritic lavas, its occurrence being restricted to the groundmass in the subaphyric and less evolved types.

The groundmass of all peralkaline phonolites is microcrystalline, often oriented, and composed of the same minerals as those of the intratelluric assemblage.

Additional minerals are interstitial analcite and rare rutile. In the subaphyric textural types, patches of varying crystallinity may be observed, possibly indicating local fluid activity variations.

Alteration products occur as incipient clayey transformations of feldspar, or as widespread replacement of nepheline by calcite, zeolite and cancrinite patches.

Many phonolitic rocks contain xenocrysts and small xenoliths not in equilibrium with the host magma. They are represented by : 1) salitic clinopyroxenes embayed and rimmed by opaque grains ; 2) partially resorbed amphiboles jacketed by an overgrowth of opaques and green clinopyroxene rods ; 3) rare olivine xenocrysts ; 4) olivine pyroxenite inclusions and 5) rare nepheline syenite small inclusions. Generally speaking, at the highest degree of differentiation, peralkaline phonolites show a tendency to include dismembered portions of less differentiated rock types and xenocrysts : such

Table 1. (continued).

	F7B P-Ph	F10F P-Ph	F10B P-Ph	F12G P-Ph	F10L P-Ph	F10D P-Ph	F12A P-Ph	F12F P-Ph	F10A P-Ph	F4B P-Ph	F12E P-Ph	F12H P-Ph	F12D P-Ph	F10G P-Ph	F12C P-Ph
SiO$_2$	58.39	60.28	59.89	57.91	60.43	59.86	57.96	58.09	60.21	61.03	58.19	58.30	57.91	60.25	58.26
TiO$_2$	0.18	0.17	0.16	0.21	0.16	0.14	0.19	0.20	0.17	0.21	0.19	0.19	0.19	0.13	0.22
Al$_2$O$_3$	20.00	20.13	20.19	20.88	20.16	20.40	20.79	20.65	20.23	19.28	20.77	20.92	20.86	20.38	20.89
Fe$_2$O$_3$	2.28	1.34	1.61	1.85	1.37	1.42	1.72	1.78	1.48	1.83	1.56	1.48	1.72	1.33	1.56
FeO	0.53	0.59	0.32	0.39	0.55	0.45	0.38	0.43	0.45	0.45	0.49	0.62	0.42	0.55	0.50
MnO	0.30	0.23	0.23	0.23	0.23	0.23	0.22	0.24	0.22	0.37	0.20	0.22	0.23	0.24	0.19
MgO	0.02	0.03	0.05	0.09	0.03	0.01	0.03	0.03	0.02	0.05	0.04	0.01	0.05	0.02	0.06
CaO	0.64	0.81	0.81	0.56	0.81	0.76	0.48	0.54	0.80	0.60	0.53	0.47	0.48	0.77	0.61
Na$_2$O	11.18	9.60	9.66	11.31	9.62	9.94	11.27	11.29	9.67	9.77	11.40	11.38	11.68	10.23	11.27
K$_2$O	4.80	5.52	5.34	4.69	5.47	5.36	4.89	4.96	5.51	5.20	5.03	4.86	4.74	5.27	5.19
P$_2$O$_5$	0.02	0.02	0.01	0.03	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.03
L.O.I.	1.64	1.29	1.74	1.85	1.14	1.40	2.06	1.77	1.22	1.20	1.58	1.51	1.72	0.81	1.21
Total	99.98	100.01	100.00	100.00	99.99	99.98	100.01	100.00	100.00	100.00	100.00	99.98	100.02	99.99	99.99
V	n.d.	9	7	12	7	9	10	10	9	8	10	13	9	9	10
Cr	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	6	5	8	9	9	6	6	7	8	7	6	9	4	8	8
Rb	324	211	214	291	215	225	289	287	215	301	274	291	303	228	264
Sr	10	26	20	45	22	19	15	12	29	n.d.	13	20	29	23	51
Ba	57	62	88	86	70	65	61	54	92	44	43	53	75	62	89
Zr	2070	998	1030	1680	1020	1070	1560	1690	1020	1730	1400	1680	1730	1090	1250
Nb	470	201	194	266	197	196	249	264	196	386	222	266	272	196	206
Y	65	27	27	35	27	26	34	34	27	51	28	35	35	25	25
La	161	134	129	139	134	131	132	137	132	193	113	127	225	126	119
Ce	292	195	168	188	188	174	164	183	183	308	161	191	178	174	161
Nd	90.0	--	--	--	--	--	--	--	--	66.6	--	--	--	27.2	30.0
Sm	14.0	--	--	--	--	--	--	--	--	9.23	--	--	--	3.58	4.42
Eu	1.36	--	--	--	--	--	--	--	--	1.00	--	--	--	0.68	0.84
Gd	10.4	--	--	--	--	--	--	--	--	7.06	--	--	--	3.07	3.70
Dy	10.2	--	--	--	--	--	--	--	-	6.85	--	--	--	2.79	3.22
Er	5.96	--	--	--	--	--	--	--	--	4.65	--	--	--	2.41	2.33
Yb	6.47	--	--	--	--	--	--	--	--	5.79	--	--	--	3.49	3.13
Lu	0.80	--	--	--	--	--	--	--	--	0.79	--	--	--	0.50	0.44
Or	28.36	32.62	31.55	27.71	32.32	31.67	28.90	29.31	32.56	30.73	29.72	28.72	28.01	31.14	30.67
Ab	36.31	40.48	40.42	36.10	41.06	39.78	35.70	35.23	40.11	44.33	35.05	36.60	35.52	40.61	34.04
Ne	21.58	17.51	18.25	24.48	17.43	19.13	23.84	23.49	18.02	14.02	23.71	23.81	24.59	18.89	24.11
Ac	6.60	3.88	4.66	5.35	3.96	4.11	4.98	5.15	4.28	5.29	4.51	4.28	4.98	3.85	4.51
Ns	2.55	0.94	0.54	1.94	0.85	1.01	2.33	2.58	0.83	1.50	2.91	2.53	2.86	1.56	2.72
Di	0.11	0.16	0.27	0.48	0.16	0.05	0.16	0.16	0.11	0.27	0.21	0.04	0.27	0.11	0.32
Ed	2.32	2.31	1.41	1.50	2.21	1.92	1.49	1.70	1.80	2.20	1.80	1.91	1.66	2.33	1.71
Di	2.43	2.47	1.68	1.98	2.37	1.98	1.65	1.86	1.90	2.46	2.02	1.96	1.93	2.44	2.03
Wo	0.13	0.45	0.82	0.12	0.50	0.62	0.15	0.18	0.70	0.04	0.08	0.00	0.02	0.42	0.21
Fo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00
Ol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.00
Il	0.34	0.32	0.30	0.40	0.30	0.27	0.36	0.38	0.32	0.40	0.36	0.36	0.36	0.25	0.42
Ap	0.05	0.05	0.02	0.07	0.05	0.02	0.05	0.05	0.05	0.02	0.05	0.05	0.05	0.02	0.07
D.I.	95.40	95.43	95.43	95.59	95.63	95.70	95.74	95.76	95.81	95.88	95.91	95.94	95.95	96.05	96.06
S.I.	0.11	0.18	0.29	0.49	0.18	0.06	0.16	0.16	0.12	0.29	0.22	0.05	0.27	0.11	0.32
A.I.	1.18	1.08	1.07	1.13	1.08	1.09	1.15	1.16	1.08	1.13	1.16	1.15	1.17	1.11	1.16

a feature conforms well with the genetic relationships between the various rock types.

Primary calcite, although less frequent than in phonolitic tephrites and nepheline syenites (see below), is also sporadically present as large interstitial crystals or rare ocelli with alkali feldspar, or with clinopyroxene plus magnetite.

Cognate xenoliths

a) Olivine clinopyroxenites

They constitute small, centimetric nodules with mesocumulitic texture and are composed of prevalent zoned salitic clinopyroxene, un-

zoned olivine, magnetite and interstitial phlogopite.

b) Essexites

These rocks show meso- to ortho-cumulitic texture. They consist of a medium-coarse grained, slightly heterocrystalline assemblage of colorless Ti-salitic clinopyroxene, plagioclase, alkali feldspar, nepheline and Ti-magnetite, together with brown poikilitic amphibole. The compositions of these minerals are comparable to those of tephrites. Noteworthy is the presence of a large number of haüyne crystals, almost black in colour due to the high density of minute inclusions. Analcite is a minor interstitial phase, and phlogopite associated with

Table 1. (continued).

	F12M P-Ph	F10C P-Ph	F12L P-Ph	F12B P-Ph
SiO_2	58.40	60.04	58.36	58.46
TiO_2	0.19	0.14	0.19	0.18
Al_2O_3	20.66	20.38	20.86	21.20
Fe_2O_3	1.58	1.62	1.77	1.39
FeO	0.48	0.30	0.32	0.39
MnO	0.20	0.24	0.22	0.16
MgO	0.05	0.02	0.02	0.03
CaO	0.54	0.78	0.50	0.47
Na_2O	11.48	10.06	11.21	11.18
K_2O	5.07	5.31	4.97	5.11
P_2O_5	0.02	0.02	0.02	0.02
L.O.I.	1.32	1.10	1.57	1.40
Total	99.99	100.01	100.01	99.99
V	10	9	9	9
Cr	n.d.	n.d.	n.d.	n.d.
Ni	6	5	9	8
Rb	273	225	289	255
Sr	15	15	13	25
Ba	48	65	58	76
Zr	1410	1090	1600	1080
Nb	228	198	249	181
Y	29	28	32	24
La	127	129	135	97
Ce	167	171	176	135
Or	29.96	31.38	29.37	30.20
Ab	35.12	40.01	36.02	35.83
Ne	23.25	19.10	23.62	24.25
Ac	4.57	4.69	5.12	4.02
Ns	3.24	1.06	2.19	2.20
Di	0.27	0.11	0.11	0.16
Ed	1.77	1.44	1.28	1.35
Di	2.04	1.55	1.39	1.51
Wo	0.09	0.82	0.32	0.20
Il	0.36	0.27	0.36	0.34
Ap	0.05	0.05	0.05	0.05
D.I.	96.14	96.23	96.32	96.49
S.I.	0.27	0.12	0.11	0.17
A.I.	1.18	1.09	1.14	1.13

magnetite in irregular patches has also been found.

c) Nepheline syenites

These xenoliths represent ortho-cumulitic rocks. Texturally, they are xenomorphic and sub-equigranular, and are composed of pre-dominant alkali feldspar and nepheline, subordinate light green clinopyroxene, and light brown amphibole, these last two phases occurring both in large poikilitic crystals and in smaller idiomorphic rods. Abundant sphene and magnetite are early crystallized phases. Phlogopite, rutile, and interstitial analcite have also been observed.

A great number of ocelli of primary calcite, associated with alkali feldspar ± nepheline ± acmitic clinopyroxene and generally rimmed by clinopyroxenes with the same composition, characterize these rocks ; where ocelli are absent, a large amount of primary interstitial calcite crystals occur.

Mineral chemistry

a) Feldspars

Alkali feldspar represents the most abundant feldspar in the alkaline suite of Fortaleza, plagioclase occurring in significant amounts only in the least differentiated rocks (tephrite, phonotephrites and cumulitic essexites). Table 2 and Fig. 3 show representative analyses and compositional variations of these phases.

Alkali feldspar from tephrites and phonotephrites ranges from sanidine to anorthoclase (Or_{42-28}), and coexists with plagioclase (An_{22-31}). Alkali feldspar from peralkaline phonolites is essentially sanidine, generally zoned with sodium enrichment from phenocrysts cores (Or_{72-45}) to rims (Or_{52-36}) to groundmass microlites, which are quite variable in composition (Or_{16-87}). Microlites of pure albite occur in the groundmass, generally coexisting with K-sanidine, as lowest temperature feldspar phases (*cf.* Ghiorso, 1984).

Consistently, feldspar compositions of the tephrite-phonolite suite plot along solvus boundaries of progressively lower temperature (Fig. 3). In nepheline syenite cumulates, alkali feldspar is always orthoclase, mostly in the range Or_{58-59}, sometimes with a K-rich core (Or_{88}). Plagioclase from essexite cumulitic xenoliths is almost unzoned, with composition around An_{47-49}.

b) Feldspathoids

Nepheline occurs almost everywhere except in the least differentiated rocks, where it is either absent, or present as scarce interstitial phase. Its abundance markedly increases in relation to the degree of differentiation, and it does not display significant compositional variations. Normative quartz contents are relatively low and compositions lie in the solid solution range investigated by Hamilton (1961), which would suggest crystallization temperatures between 1068° and 775°C (Table 3). Analcite, generally, shows a rather homogeneous composition (Table 3).

c) Clinopyroxene, amphibole, and phlogopite

Clinopyroxene shows a wide compositional variation from salite through Fe-salite to aegi-

Fig. 2. R1 (4Si-11(Na+K)-2(Fe+Ti)) - R2 (6Ca+2Mg+Al) classificative diagram (after De La Roche *et al.*, 1980) for the Fortaleza alkaline rocks. Arrows denote liquid line of descent of the tephrite-phonolite trend. Also plotted cognate xenoliths of olivine clinopyroxenite, essexite and nepheline syenite, included in the Caruru phonolite.

rine-augite to acmite, from tephrites to the most differentiated peralkaline phonolites. Such a variation consists of a general and gradual increase in hedenbergitic and then acmitic molecules. This also holds for clinopyroxene compositional variations from essexite to nepheline syenite xenoliths (Table 4 and Fig. 4 and 5). A similar clinopyroxene compositional trend is found from core to rim of phenocrysts and from microphenocrysts to groundmass. Clinopyroxenes from carbonate ocelli in nepheline syenites (*e.g.* sample 1L-N) are remarkably Na-rich, slightly Ca- and extremely Al_2O_3-poor with respect to those of the host lavas. They show the same compositional range of clinopyroxenes of the most differentiated peralkaline phonolites.

Amphibole (Table 5) occurs sporadically and is generally associated with relatively high amount of magnetite and sphene. It does not reveal significant zoning. Its composition varies from kaersutite (tephrites) to Fe-kaersutite (peralkaline phonolites). Amphibole from essexites is ferroan pargasitic hornblende, while that from nepheline syenite xenoliths has richterite composition (nomenclature after Leake, 1978). Phlogopite with rather constant composition has been observed in essexites and nepheline syenites (Table 5).

d) Fe-Ti-oxides

Ti-magnetite is by far the most abundant opaque phase in the Fortaleza alkaline suite. Its compositional variation is rather narrow, with a significant increase of ulvo-spinel (Fe_2TiO_4 up to 43%) and jacobsite moleculae ($MnFe_2O_4$ 8-12%) only in peralkaline phonolites (Table 5).

Petrogenesis

Compositional characteristics and petrographical, and mineralogical variations suggest that the rock suite from tephrites to peralkaline

Table 2. Representative microprobe analyses of feldspars from Fortaleza alkaline rocks (atomic proportions based on 32 oxygens per formula unit).

	F10I-D Tph			F13A-D Ph-Tph				F1H-1N Ne-Sy			F1G-N Ex			F9B P-Ph	
	g	g	g	g	g	g	g	Ac	Ar	Bc	Ac	Bc	Br	Apc	Apr
SiO_2	65.82	63.94	65.06	59.23	59.37	60.13	60.84	64.93	65.28	64.69	55.67	55.67	56.26	66.31	66.28
TiO_2	0.02	0.04	0.00	0.18	0.24	0.29	0.15	0.05	0.03	0.01	0.01	0.00	0.00	0.03	0.04
Al_2O_3	19.98	20.60	20.36	24.87	24.77	24.51	23.69	19.21	18.82	18.80	27.63	27.74	28.10	19.57	19.50
Fe_2O_3	0.60	1.59	0.28	0.34	0.47	0.40	0.33	0.12	0.31	0.06	0.03	0.03	0.03	0.19	0.22
MnO	0.04	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.02	0.00	0.03	0.02	0.02	0.02	0.00
MgO	0.04	0.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.56	1.09	1.25	6.21	5.72	4.58	4.42	0.41	0.23	0.17	9.30	9.85	9.71	0.08	0.02
Na_2O	8.16	7.08	6.22	7.18	7.26	7.02	7.38	4.58	4.78	1.36	5.86	5.74	5.86	6.53	7.54
K_2O	4.77	5.40	7.13	1.11	1.42	2.79	2.33	10.03	9.88	14.96	0.48	0.43	0.46	7.68	6.20
Total	99.99	100.24	100.30	99.13	99.25	99.73	99.15	99.34	99.35	100.05	99.01	99.48	100.44	100.41	99.80
Si	11.7462	11.4714	11.6737	10.6836	10.7039	10.8114	10.9659	11.8517	11.9082	11.9149	10.1099	10.0749	10.0790	11.8672	11.8739
Ti	0.0027	0.0054	0.0000	0.0244	0.0325	0.0392	0.0203	0.0069	0.0041	0.0014	0.0014	0.0000	0.0000	0.0040	0.0054
Al	4.2021	4.3555	4.3053	5.2867	5.2630	5.1936	5.0321	4.1323	4.0459	4.0808	5.9134	5.9164	5.9327	4.1275	4.1169
Fe^{3+}	0.0806	0.2146	0.0378	0.0461	0.0638	0.0541	0.0448	0.0165	0.0426	0.0083	0.0041	0.0041	0.0040	0.0256	0.0297
Mn	0.0060	0.0015	0.0000	0.0015	0.0000	0.0015	0.0015	0.0015	0.0031	0.0000	0.0046	0.0031	0.0030	0.0030	0.0000
Mg	0.0106	0.1310	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ca	0.1071	0.2095	0.2403	1.2000	1.1048	0.8822	0.8535	0.0802	0.0449	0.0335	1.8094	1.9098	1.8636	0.0153	0.0038
Na	2.8232	2.4625	2.1637	2.5108	2.5376	2.4470	2.5788	1.5788	1.6904	0.4856	2.0632	2.0139	2.0353	2.2656	2.6187
K	1.0858	1.2358	1.6319	0.2554	0.3266	0.6399	0.5357	2.3353	2.2990	3.5148	0.1112	0.0993	0.1051	1.7532	1.4168
Total	20.0643	20.0873	20.0526	20.0086	20.0322	20.0690	20.0326	20.0451	20.0382	20.0393	20.0171	20.0214	20.0228	20.0616	20.0652
Abwt%	69.04	61.62	52.13	61.92	62.56	60.24	63 63	40.46	38.73	11.42	50.31	48.58	49.35	54.69	63.46
Anwt%	2.78	5.56	6.14	31.40	28.90	23.04	22 34	1.14	2.03	0.84	46.81	48.88	47.94	0.39	0.10
Orwt%	28.18	32.82	41.73	6.68	8.55	16.72	14 03	58.40	59.24	87.74	2.88	2.54	2.71	44.92	36.44

	F1B P-Ph			F3B P-Ph		F2C P-Ph							F10G P-Ph		
	Apr	g	Apc	Apc	g	Apc	Bpc	Bpr	g	g	Apc	g	Apc	g	\g
SiO_2	65.76	65.72	65.05	66.42	65.85	65.83	65.63	66.72	65.83	68.37	64.91	64.67	65.61	67.93	65.83
TiO_2	0.00	0.08	0.02	0.02	0.06	0.00	0.03	0.00	0.00	0.00	0.01	0.00	0.01	0.06	0.02
Al_2O_3	19.25	19.24	19.74	19.24	19.02	18.89	18.63	19.00	18.88	19.55	19.10	18.53	19.33	19.44	19.03
Fe_2O_3	0.14	0.44	0.12	0.14	0.36	0.14	0.11	0.12	0.19	0.24	0.32	0.38	0.21	0.16	0.33
MnO	0.00	0.03	0.00	0.03	0.00	0.02	0.01	0.00	0.00	0.03	0.00	0.02	0.01	0.01	0.03
MgO	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	0.23	0.15	0.57	0.32	0.34	0.05	0.07	0.06	0.11	0.00	0.03	0.01	0.48	0.03	0.20
Na_2O	5.35	4.81	6.11	5.89	5.99	4.35	3.33	5.73	4.46	11.48	3.21	1.54	4.62	9.88	5.56
K_2O	9.20	9.93	7.64	8.41	8.08	10.73	12.24	8.87	10.53	0.29	12.40	14.79	10.10	2.73	8.82
Total	99.93	100.40	99.26	100.47	99.70	100.01	100.05	100.50	100.00	99.97	99.99	99.94	100.37	100.24	99.82
Si	11.8883	11.8648	11.7883	11.9085	11.8955	11.9459	11.9681	11.9651	11.9415	11.9604	11.8674	11.9291	11.8560	11.9533	11.9043
Ti	0.0000	0.0109	0.0027	0.0027	0.0082	0.0000	0.0041	0.0000	0.0000	0.0013	0.0027	0.0000	0.0014	0.0079	0.0027
Al	4.1013	4.0935	4.2158	4.0653	4.0492	4.0398	4.0037	4.0155	4.0361	4.0305	4.1153	4.0282	4.1165	4.0314	4.0556
Fe^{3+}	0.0190	0.0598	0.0164	0.0189	0.0489	0.0191	0.0151	0.0162	0.0259	0.0316	0.0440	0.0527	0.0286	0.0212	0.0449
Mn	0.0000	0.0046	0.0000	0.0046	0.0000	0.0031	0.0015	0.0000	0.0000	0.0044	0.0000	0.0031	0.0015	0.0015	0.0046
Mg	0.0000	0.0000	0.0027	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ca	0.0445	0.0290	0.1107	0.0615	0.0658	0.0097	0.0137	0.0115	0.0214	0.0000	0.0059	0.0020	0.0929	0.0057	0.0387
Na	1.8751	1.6835	2.1466	2.0473	2.0978	1.5304	1.1773	1.9922	1.5685	3.8934	1.1378	0.5507	1.6185	3.3705	1.9492
K	2.1216	2.2868	1.7661	1.9234	1.8619	2.4837	2.8472	2.0291	2.4365	0.0647	2.8918	3.4800	3.3281	0.6128	2.0345
Total	20.0498	20.0328	20.0492	20.0321	20.0272	20.0317	20.0306	20.0296	20.0300	19.9863	20.0650	20.0458	20.0434	20.0041	20.0346
Abwt%	44.92	40.65	51.87	49.28	50.62	36.64	27.94	47.91	37.55	98.27	27.00	12.97	38.64	83.70	46.97
Anwt%	1.13	0.74	2.84	1.57	1.68	0.25	0.34	0.29	0.54	0.00	0.15	0.05	2.35	0.15	0.99
Orwt%	53.95	58.61	45.29	49.15	47.69	63.12	71.72	51.80	61.91	1.73	72.85	86.98	59.00	16.15	52.04

Abbreviations : A, B = different crystals, p = phenocryst, g = groundmass, c = core, r = rim. Analyses carried out with SEMQ-ARL instrument using natural silicate and oxides as standards. Rock name abbreviations as in Table 1.

phonolites evolved essentially by shallow fractional crystallization processes, leaving behind cumulates which were sometimes sampled as inclusions by phonotephritic lavas. Moreover, the existence of olivine clinopyroxenite cumulate xenoliths suggests that the least differentiated tephritic magmas could, in turn, have been fractionated products of basanitic melts apparently not yet found in the area. In fact addition of about 30% of olivine clinopyroxenite (sample F1S-N) to the tephrite F10I-D gives rise to a basanitic composition which could be considered
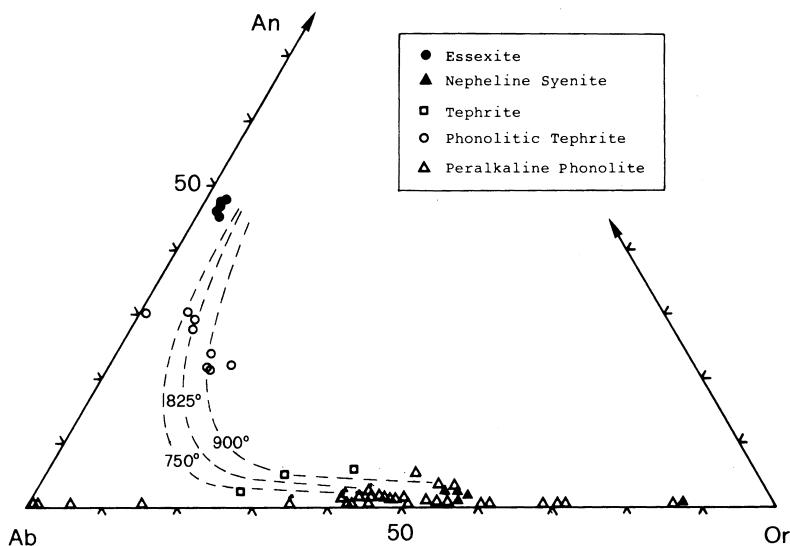
Fig. 3. Feldspar composition of Fortaleza alkaline rocks in the Ab-Or-An diagram (mol%). The extent of solvus for 900°, 825° and 750°C is indicated by dashed lines (after Ghiorso, 1984).

Table 3. Representative microprobe analyses of nepheline (ne) and analcite (anc) from Fortaleza alkaline rocks (atomic proportions based on 32 and 6 oxygens per formula unit respectively).

	F1G-N Ex	F1L-N Ne-Sy	F1H-1N Ne-Sy	F1F-N Ne-Sy		F3B P-Ph	F12C P-Ph			F1B P-Ph	F2C P-Ph	F10G P-Ph
	anc	anc	anc	anc	ne	ne	anc	ne Ac	ne Ar	ne	ne	ne
SiO2	51,61	50,16	50,54	50,75	43,93	44,95	54,51	44,48	45,19	45,13	44,82	45,84
TiO2	0,00	0,01	0,04	0,03	0,02	0,00	0,00	0,02	0,03	0,04	0,01	0,00
Al2O3	24,90	27,98	28,47	25,86	33,76	31,54	23,86	33,20	32,26	31,61	32,51	30,79
Fe2O3	0,19	0,15	0,02	0,14	0,38	0,80	0,13	0,46	1,17	1,34	0,41	1,80
MnO	0,03	0,00	0,03	0,01	0,02	0,00	0,00	0,00	0,01	0,07	0,02	0,21
MgO	0,13	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,03	0,00	0,00
CaO	0,47	0,03	0,24	0,00	0,29	0,05	0,00	0,01	0,01	0,27	0,00	0,09
Na2O	13,65	14,56	12,99	14,70	17,00	16,63	13,15	16,74	16,60	16,92	16,21	15,74
K2O	0,13	0,02	0,26	0,11	4,40	4,64	0,09	5,28	5,22	4,13	5,02	4,98
P2O5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Tot	91,11	92,91	92,60	91,60	99,80	98,60	91,74	100,20	100,50	99,54	99,00	99,45
Si	1,918	1,834	1,843	1,883	8,387	8,681	1,993	8,483	8,597	8,641	8,613	8,792
Ti	0,000	0,000	0,001	0,001	0,003	0,000	0,000	0,003	0,004	0,006	0,001	0,000
Al	1,090	1,206	1,224	1,131	7,596	7,180	1,028	7,462	7,232	7,133	7,363	6,960
Fe3+	0,005	0,004	0,001	0,004	0,055	0,116	0,004	0,066	0,167	0,193	0,060	0,260
Fe2+	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Mn	0,001	0,000	0,001	0,000	0,003	0,000	0,000	0,000	0,002	0,011	0,003	0,034
Mg	0,007	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,009	0,000	0,000
Ca	0,019	0,001	0,009	0,000	0,059	0,010	0,010	0,002	0,002	0,055	0,000	0,019
Na	0,983	1,032	0,918	1,057	6,293	6,227	0,932	6,191	6,124	6,281	6,039	5,854
K	0,006	0,001	0,012	0,005	1,072	1,142	0,004	1,285	1,268	1,009	1,230	1,217
P	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Tot	4,030	4,078	4,009	4,081	23,468	23,357	3,960	23,491	23,396	23,337	23,309	23,136

Abbreviations : A, B = different crystals, p = phenocryst, g = groundmass, c = core, r = rim. Rock name abbreviations as in Table 1.

an appropriate parental magma of mantle origin. Parental basanitic melts similar to those inferred for the Fortaleza suite appear to represent a widespread magma type, found in many Brazilian alkaline complexes (e.g. Jacupiranga, Juquiá, Morro Redondo, Piratini ; Beccaluva et al., 1990 ; Brotzu et al., 1989 ; Barbieri et al., 1987). On the whole, they closely correspond

Table 4. Representative microprobe analyses of clinopyroxene from Fortaleza alkaline rocks (atomic proportions based on 6 oxygens per formula unit).

| | F10I-D | F10I-D | F13A-D | F13A-D | F1E-N | F1E-N | F1E-N | F1G-N | F1G-N | F1G-N | F1G-N | F1L-N | F1L-N | F1F-N | F1F-N | F9B |
| | Tph | Tph | Ph-Tph | Ph-Tph | Ex | Ex | Ex | Ex | Ex | Ex | Ex | Ne-Sy | Ne-Sy | Ne-Sy | Ne-Sy | P-Ph |
	pc	g	g	g	Ac	Ar	Bc	Ac	Ar	Bc	Br	Ac	Ar	Ac	Bc	Ar
SiO_2	48.57	46.06	49.75	44.81	52.63	52.77	52.85	51.34	51.50	51.05	52.42	52.03	52.22	48.48	51.50	51.44
TiO_2	2.25	3.40	1.80	3.94	0.25	0.32	0.18	0.27	0.19	0.12	0.04	0.81	0.79	0.80	0.95	0.42
Al_2O_3	5.00	7.14	3.61	8.06	2.41	2.45	1.25	2.75	0.79	1.22	1.60	0.28	0.25	2.74	1.29	1.23
FeO	5.73	7.58	7.34	8.92	9.60	9.47	9.56	10.15	14.99	11.93	27.67	15.50	14.95	14.79	10.24	17.18
MnO	0.09	0.13	0.23	0.21	0.17	0.14	0.24	0.14	0.37	0.15	0.43	0.86	0.89	2.19	1.90	1.93
MgO	14.15	12.75	14.43	11.26	13.38	13.33	12.28	12.78	8.79	11.24	1.35	8.26	8.78	7.60	11.25	5.60
CaO	22.68	22.10	22.43	22.03	20.22	20.92	21.02	22.18	21.02	22.71	2.72	16.89	17.83	21.37	21.61	20.69
Na_2O	0.38	0.57	0.41	0.62	0.90	0.69	1.61	0.55	1.91	0.99	10.99	4.33	3.70	1.55	1.68	1.24
Cr_2O_3	0.32	0.00	0.00	0.00	0.02	0.02	0.05	0.03	0.03	0.01	-0.00	0.05	0.07	0.00	0.00	0.00
Total	99.17	99.73	100.00	99.85	99.58	100.11	99.04	100.19	99.59	99.42	97.22	99.01	99.48	99.52	100.42	99.73
Si	1.8090	1.7176	1.8424	1.6832	1.9640	1.9622	1.9825	1.9141	1.9662	1.9364	2.0097	1.9776	1.9794	1.8653	1.9214	2.0099
Ti	0.0630	0.0953	0.0501	0.1113	0.0070	0.0089	0.0051	0.0076	0.0055	0.0034	0.0012	0.0232	0.0225	0.0231	0.0267	0.0123
Al	0.2195	0.3138	0.1576	0.3568	0.1060	0.1074	0.0553	0.1208	0.0355	0.0545	0.0723	0.0125	0.0112	0.1242	0.0567	0.0566
Fe^{3+}	0.0545	0.1014	0.0861	0.0989	0.0162	0.0000	0.0850	0.0748	0.1616	0.1202	0.7429	0.2835	0.2358	0.2297	0.1782	0.0124
Fe^{2+}	0.1240	0.1350	0.1412	0.1812	0.2833	0.2944	0.2149	0.2416	0.3170	0.2582	0.1443	0.2091	0.2380	0.2461	0.1413	0.5489
Mn	0.0028	0.0041	0.0072	0.0067	0.0054	0.0044	0.0076	0.0044	0.0120	0.0048	0.0140	0.0277	0.0286	0.0714	0.0600	0.0639
Mg	0.7855	0.7087	0.7965	0.6304	0.7442	0.7388	0.6866	0.7101	0.5002	0.6355	0.0771	0.4679	0.4960	0.4358	0.6256	0.3261
Ca	0.9050	0.8829	0.8899	0.8865	0.8084	0.8334	0.8447	0.8859	0.8598	0.9229	0.1117	0.6878	0.7240	0.8809	0.8638	0.8661
Na	0.0274	0.0412	0.0294	0.0452	0.0651	0.0497	0.1171	0.0398	0.1414	0.0728	0.8169	0.3191	0.2719	0.1156	0.1215	0.0939
Cr	0.0094	0.0000	0.0000	0.0000	0.0006	0.0006	0.0015	0.0009	0.0009	0.0003	0.0000	0.0015	0.0021	0.0000	0.0000	0.0000
Total	4.0000	4.0000	4.0004	4.0002	4.0002	3.9998	4.0001	4.0000	4.0000	4.0090	3.9900	4.0100	4.0095	3.9923	3.9952	3.9902
Al^{IV}	0.1910	0.2824	0.1576	0.3168	0.0360	0.0378	0.0175	0.0859	0.0338	0.0545	--	0.0125	0.0112	0.1242	0.0567	--
Al^{VI}	0.0284	0.0314	0.0000	0.0400	0.0700	0.0695	0.0377	0.0349	0.0018	0.0000	0.0723	0.0000	0.0000	0.0000	0.0000	0.0566
Ca	48.34	48.19	46.32	49.14	43.51	44.54	45.93	46.21	46.46	47.53	10.25	41.03	42.03	47.25	46.21	47.65
Mg	41.96	38.68	41.46	34.94	40.06	39.48	37.33	37.04	27.03	32.72	7.07	27.91	28.79	23.38	33.47	17.94
Fe^b	9.68	13.12	12.20	15.90	16.41	15.97	16.72	16.73	26.50	19.73	82.67	31.04	29.16	29.35	20.30	34.39
Na	2.83	4.34	2.85	4.92	6.20	4.79	11.77	3.85	14.26	7.14	83.50	32.28	27.23	11.76	12.09	9.87
Mg	81.24	74.66	77.25	68.72	70.93	71.19	69.06	68.87	50.48	62.38	7.88	47.34	49.67	44.33	62.24	34.28
Fe^c	15.91	20.99	19.89	26.35	22.85	24.00	19.15	27.26	35.24	30.47	8.60	20.36	23.08	43.90	25.66	55.84

| | F9B | F1B | F3B | F3B | F3B | F3B | F2C | F2C | F2C | F9F | F9F | F10G | F10G | F12C | F12C | F12C |
| | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph | P-Ph |
	Apc	Apc	Apr	Apc	g	g	Apc	Apr	Bpr	Apc	Apr	Apc	Apr	g	Ac	Bc
SiO_2	51.42	45.66	49.61	49.08	48.98	50.02	51.65	51.33	51.56	48.94	50.54	47.75	49.44	49.74	50.63	51.13
TiO_2	0.68	2.67	0.76	0.87	0.92	0.73	1.40	1.85	0.90	1.42	2.01	1.15	0.87	0.86	0.52	1.49
Al_2O_3	1.87	5.36	1.69	3.61	2.50	1.90	0.51	0.46	0.59	0.94	0.91	4.52	3.52	0.85	1.56	0.59
FeO	14.28	11.53	16.75	11.50	13.44	18.39	26.01	24.49	26.75	24.54	26.03	12.07	11.13	23.93	16.91	27.33
MnO	1.48	0.68	2.10	1.04	2.47	3.57	1.38	1.51	1.07	2.64	1.70	1.12	1.19	3.09	2.00	1.35
MgO	8.34	10.65	6.50	10.05	7.94	3.79	1.00	1.07	0.82	0.51	0.18	9.44	10.19	1.13	6.29	0.18
CaO	20.52	20.54	20.01	21.48	20.68	17.61	6.08	6.10	5.10	14.20	8.43	21.14	21.57	10.62	16.97	3.95
Na_2O	1.11	1.35	2.24	1.50	1.71	2.92	10.10	10.11	10.64	5.32	8.70	1.43	1.32	7.40	4.03	11.45
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.02	0.00	0.00	0.00	0.01	0.00	0.00
Total	99.70	98.44	99.66	99.18	98.64	98.95	98.13	96.92	97.44	98.53	98.50	98.62	99.23	97.63	98.91	97.47
Si	1.9796	1.7486	1.9200	1.8618	1.8975	1.9733	1.9902	1.9982	1.9920	1.9547	1.9724	1.8282	1.8760	1.9615	1.9461	1.9735
Ti	0.0197	0.0769	0.0221	0.0248	0.0268	0.0217	0.0406	0.0542	0.0261	0.0426	0.0590	0.0331	0.0248	0.0255	0.0150	0.0432
Al	0.0848	0.2419	0.0771	0.1636	0.1141	0.0883	0.0232	0.0211	0.0269	0.0442	0.0419	0.2039	0.1574	0.0395	0.0707	0.0268
Fe^{3+}	0.0000	0.1883	0.2010	0.1735	0.1659	0.1442	0.6699	0.6371	0.7340	0.3704	0.5535	0.1796	0.1383	0.5520	0.3073	0.7959
Fe^{2+}	0.4597	0.1809	0.3411	0.1913	0.2695	0.4625	0.1682	0.1602	0.1302	0.4492	0.2960	0.2068	0.2148	0.2371	0.2362	0.0862
Mn	0.0483	0.0221	0.0688	0.0334	0.0810	0.1193	0.0450	0.0498	0.0350	0.0893	0.0562	0.0363	0.0382	0.1032	0.0651	0.0441
Mg	0.4785	0.6079	0.3749	0.5682	0.4584	0.2228	0.0574	0.0621	0.0472	0.0304	0.0105	0.5387	0.5763	0.0664	0.3604	0.0104
Ca	0.8463	0.8427	0.8297	0.8729	0.8583	0.7443	0.2510	0.2544	0.2111	0.6076	0.3525	0.8671	0.8768	0.4487	0.6988	0.1633
Na	0.0828	0.1002	0.1681	0.1103	0.1284	0.2233	0.7545	0.7630	0.7969	0.4119	0.6582	0.1061	0.0971	0.5657	0.3003	0.8568
Cr	0.0000	0.0000	0.0000	0.0000	0.0000	0.0006	0.0000	0.0000	0.0003	0.0002	0.0000	0.0000	0.0000	0.0003	0.0000	0.0000
Total	3.9998	4.0095	4.0028	3.9999	4.0000	4.0002	4.0000	4.0000	3.9997	4.0010	4.0001	4.0000	3.9999	4.0000	4.0000	4.0003
Al^{IV}	0.0204	0.2419	0.0771	0.1382	0.1025	0.0267	0.0098	0.0018	0.0080	0.0442	0.0276	0.1718	0.1240	0.0385	0.0539	0.0265
Al^{VI}	0.0644	0.0000	0.0000	0.0254	0.0116	0.0616	0.0134	0.0193	0.0188	0.0000	0.0142	0.0322	0.0334	0.0010	0.0168	0.0003
Ca	46.17	45.75	45.69	47.45	46.81	43.96	21.06	21.86	18.23	39.27	27.78	47.42	47.53	31.87	41.90	14.84
Mg	26.10	33.00	20.65	30.89	25.00	13.16	4.81	5.33	4.07	1.96	0.82	29.45	31.24	4.71	21.60	0.94
Fe^b	27.71	21.24	33.64	21.64	28.17	42.87	74.11	72.79	77.68	58.75	71.39	23.11	21.21	63.40	36.49	84.20
Na	8.39	10.03	17.04	11.41	13.17	23.53	80.21	83.92	84.20	43.85	71.84	11.04	10.03	59.00	30.99	91.47
Mg	48.50	60.83	38.03	58.79	47.02	23.48	6.10	6.82	4.98	3.23	1.14	56.02	59.55	6.92	37.18	1.10
Fe^c	43.09	29.13	44.91	29.78	39.79	52.97	13.67	9.24	10.80	52.91	27.00	32.93	30.41	34.06	31.81	7.41

$Fe^b=Fe^{2+}+Fe^{3+}+Mn$ at% ; $Fe^c = Fe^{2+}+Fe^{3+}+Mn-Na$; Fe^{3+}/Fe^{2+} partitioning according to Papike *et al.* (1974). Abbreviations : A, B = different crystals, p = phenocryst, g = groundmass, c = core, r = rim.
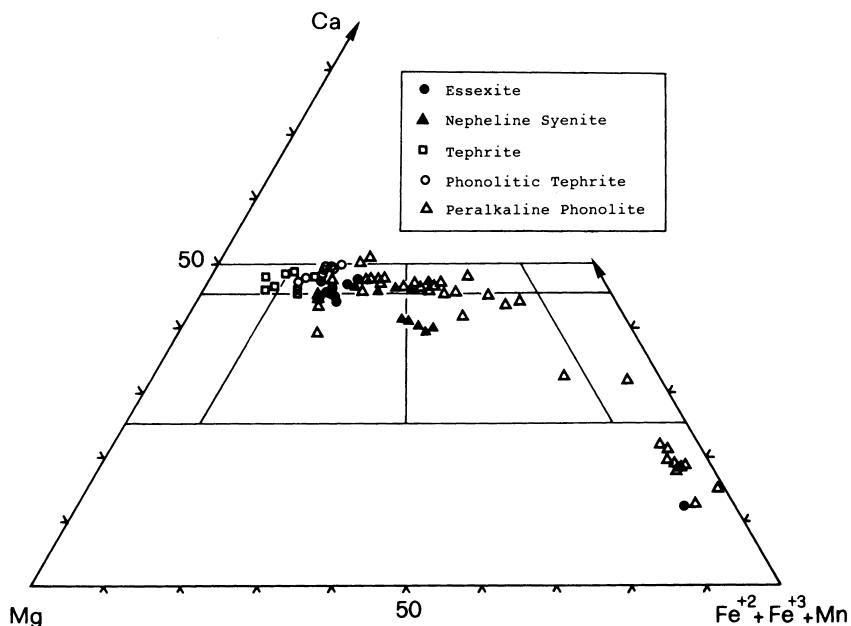
Fig. 4. Pyroxene composition of Fortaleza alkaline rocks in the Ca-Mg-(Fe^{2+}+Fe^{3+}+Mn) diagram (at%).
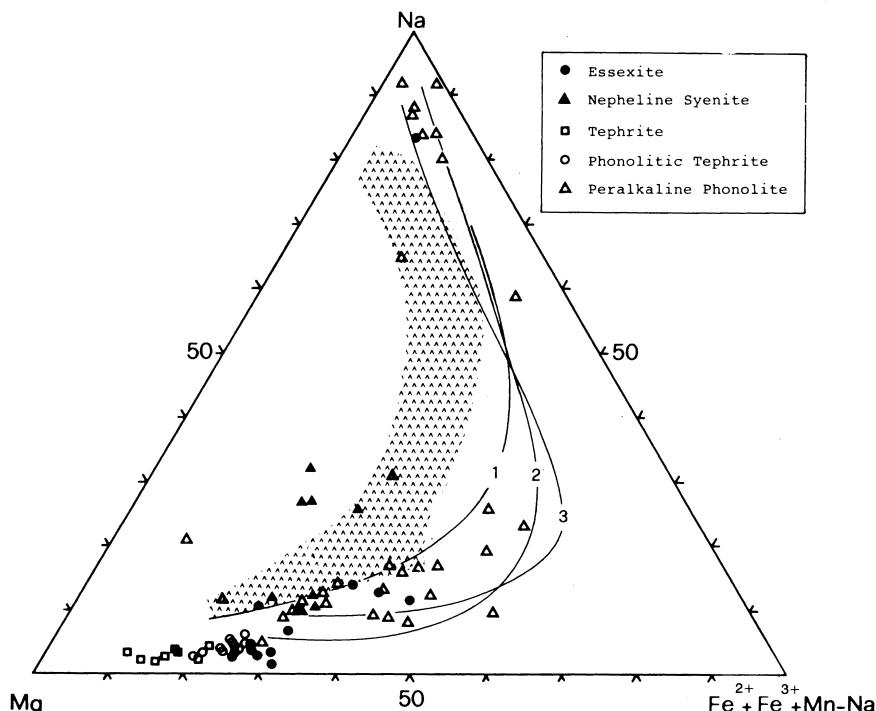

Fig. 5. Pyroxene composition of Fortaleza alkaline rocks in the Na-Mg-(Fe^{2+}+Fe^{3+}+Mn-Na) diagram (at%). Pyroxene compositional trends of other alkaline complexes are also reported for comparison : hachured area, Fen (Andersen, 1988) ; 1, Uganda (Le Bas, 1987) ; 2, Iron Hill (Nash, 1972) ; 3, Piratini, South Brazil (Barbieri et al., 1987).

Table 5. Representative microprobe analyses of amphibole (amph), phlogopite (phl) and magnetite (mt) from Fortaleza alkaline rocks (atomic proportions based on 23, 22, 32 oxygens per formula unit, respectively).

	F10I Teph	F1E-N Ex				F1L-N Ne-Sy				F 9B P-Ph		F 10G P-Ph
	amph	amph	phl	mt	mt	amph	phl	mt	mt	amph	mt	mt
SiO2	37,66	42,85	39,50	0,00	0,00	52,03	40,41	0,00	0,00	36,35	0,00	0,00
TiO2	7,44	1,84	4,29	9,58	9,30	2,24	3,23	7,11	8,19	3,95	15,12	7,86
Al2O3	13,86	12,47	12,40	1,16	0,87	1,23	12,25	0,33	0,37	14,43	0,37	1,76
Fe2O3	0,00	0,00	0,00	48,79	49,25	0,00	0,00	54,85	51,64	0,00	38,82	51,63
FeO	13,44	12,72	10,85	38,24	37,98	12,34	10,19	36,12	36,57	19,89	40,76	34,83
MnO	0,14	0,12	0,21	0,93	0,90	0,81	0,32	1,33	1,38	0,88	3,86	2,50
MgO	10,65	11,97	17,97	0,70	0,63	14,18	19,56	0,58	0,60	6,14	0,04	1,03
CaO	11,54	10,24	0,03	0,00	0,24	5,53	0,00	0,00	0,00	10,49	0,27	0,01
Na2O	2,40	4,08	0,91	0,00	0,00	6,66	0,94	0,00	0,00	2,72	0,00	0,00
K2O	1,36	1,56	9,43	0,00	0,00	1,47	9,95	0,00	0,00	2,34	0,00	0,00
P2O5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
NiO	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Cr2O3	0,00	0,05	0,00	0,00	0,04	0,01	0,02	0,09	0,15	0,00	0,01	0,01
Tot	98,50	97,90	95,60	99,4	99,21	96,50	96,87	100,42	98,9	97,20	99,25	99,62
Si	5,632	6,356	5,780	0,000	0,000	7,718	5,828	0,000	0,000	5,724	0,000	0,000
Ti	0,837	0,205	0,473	2,188	2,134	0,250	0,350	1,622	1,894	0,468	3,468	1,784
Al	2,443	2,181	2,139	0,416	0,312	0,215	2,082	0,120	0,134	2,679	0,132	0,625
Fe3+	0,000	0,000	0,000	11,152	11,306	0,000	0,000	12,517	11,944	0,000	8,908	11,726
Fe2+	1,681	1,578	1,328	9,712	9,690	1,531	1,229	9,161	9,402	2,619	10,394	8,794
Mn	0,018	0,015	0,026	0,240	0,232	0,102	0,039	0,342	0,358	0,117	0,997	0,638
Mg	2,373	2,646	3,918	0,315	0,286	3,134	4,204	0,263	0,277	1,441	0,017	0,462
Ca	1,849	1,627	0,005	0,000	0,078	0,879	0,000	0,000	0,000	1,770	0,087	0,003
Na	0,695	1,173	0,260	0,000	0,000	1,916	0,263	0,000	0,000	0,830	0,000	0,000
K	0,260	0,295	1,760	0,000	0,000	0,278	1,830	0,000	0,000	0,471	0,000	0,000
P	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Ni	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Cr	0,000	0,006	0,000	0,000	0,010	0,001	0,002	0,021	0,036	0,000	0,003	0,002
Tot	15,788	16,081	15,689	24,024	24,048	16,024	15,828	24,045	24,045	16,119	24,007	24,035

Fe^{3+}/Fe^{2+} partitioning in magnetite assumed to give cations = 24. Abbreviations : A, B = different crystals, p = phenocryst, g = groundmass, c = core, r = rim. Rock name abbreviations as in Table 1.

to alkaline basic magmas whose genesis is constrained by experimental petrology (Green, 1973 ; Brey & Green, 1977) to hydrous low-degree partial melting of enriched mantle source at high-pressure (25-30 kbar). The crystallization order of liquidus phases in the whole suite (olivine, clinopyroxene, plagioclase, alkali feldspar, nepheline) is in accordance with the experimental results of the Ne-Ab-Fo-Di system (Kogarko, 1977) : in this system, melts compositionally comparable to the studied rocks, after removal of olivine and clinopyroxene, crystallize along the ternary olivine-clinopyroxene-feldspar cotectic line before falling to the quaternary invariant point where nepheline joins the previous phases. This does not support nephelinite as parental magma which would involve the crystallization of nepheline before that of feldspar.

In the Ne-Ks-Qz system, phonolites and nepheline syenites plot along the thermal through between m-M minimum points for P_{H_2O} = 1 kbar (Fig. 6). The evolutionary trend is characterized by a decrease of Or/Ab ratio toward the minimum M, from the least to the most differentiated phonolites, consistently with sodium enrichment from early- to late-crystallized alkali feldspar. A reversal compositional trend occurs when feldspar crystallization is joined by nepheline in the latest fractionation stages with groundmass K-sanidine and albite in the most evoluted phonolitic liquids, corresponding to the minimum M.

Elemental variations versus differentiation index (Fig. 7) display a general increase of Si, Na, K, Al and decrease of Fe, Ca, and Mg, which are compatible with a general evolution by fractional crystallization processes. However it must be pointed out that the compositional differences among phonolitic tephrites in terms of petrographical (variations in amphibole abundance) and chemical features, prevent these rocks from being considered as strictly comagmatic. Particularly, elements such as P, Ba, Sr, V, Zr, and Nb have distinctly different concentration which are probably related to differences in the parental magmas.

According to mass balance calculations
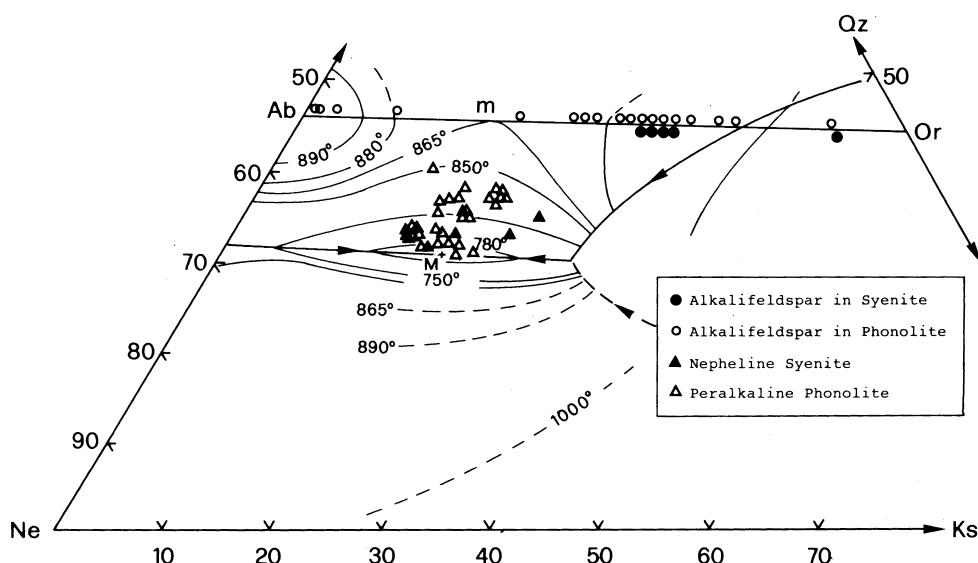
Fig. 6. Plot of whole rock and alkali feldspar compositions of Fortaleza phonolites and nepheline syenites in the Ne-Ks-Qz residual system at $P_{H_2O} = 1$ kbar (Hamilton & McKenzie, 1965).

between host rocks and phenocrysts, the least differentiated tephrites (F10I-D) represented in the suite could have produced phonolitic tephrite magmas by subtraction of salite (22%), andesine (14%), Ti-magnetite (3.0%), olivine (2.7%) and apatite (0.3%), corresponding to an alkaligabbroic mineral assemblage (Table 6).

The least differentiated peralkaline phonolites could, in turn, be derived from phonolitic tephrites by subtraction of a virtual mineral assemblage of essexitic composition (represented among the sampled cognate inclusions). Removal of large amounts of ferromagnesian minerals over a long fractionation interval (liquid fraction from 40.3 to 3.8) is responsible for the appearance of a distinct D.I. gap at this stage. Finally, the most differentiated peralkaline phonolite magmas could be produced from the least differentiated ones by subtraction of a nepheline syenite cumulitic solid, whose composition approaches fairly well those of the nepheline syenite xenoliths.

REE distributions do not contradict the above fractionation scheme, being characterized by generally parallel patterns and more pronounced La/Sm fractionation from tephrites to phonolitic tephrites to peralkaline phonolites (Fig. 8), accompanied by the appearance in the

phonolites of a distinct negative Eu anomaly. Some phonolitic samples, however, appear to be remarkably affected by cumulus enrichment in alkali feldspar phenocrysts (e.g. sample F1C) which is reflected by an overall decrease of total REE and reduction to disappearance of the negative Eu anomaly.

Similar patterns also characterize the essexitic and Ne-syenitic xenoliths. Interestingly, in the cumulitic olivine clinopyroxenite xenolith a significant negative Eu anomaly appears, as already observed in some clinopyroxenes from alkaline rocks (Worner et al., 1983; Henderson, 1984).

In addition, concomitantly with the fractionation of major phases and apatite, a significant removal of intermediate REE-rich phases such as sphene is also required in order to account for the change of intermediate and heavy REE patterns from positively fractionated (Dy/Lu > 1) in phonolitic tephrites, to V-shaped (Dy/Lu < 1) in the most differentiated peralkaline phonolites. Accordingly, Rayleigh fractionation modelling (Shaw, 1970) using REE partition coefficients for phonolites (Worner et al., 1983) shows that subtraction of about 1% sphene and 1.5% apatite from the least differentiated peralkaline phonolite, together with prevalent
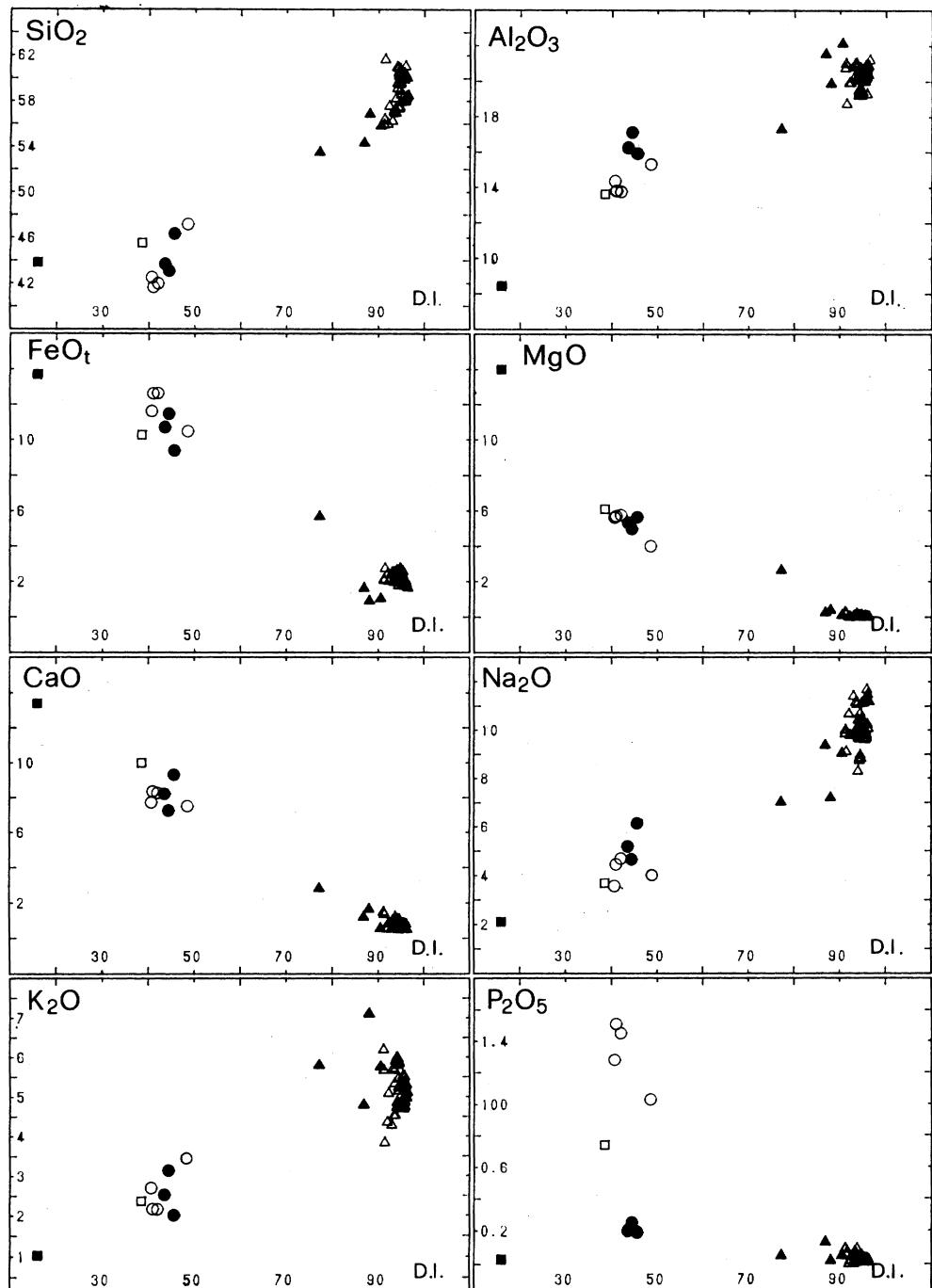
amount of alkali feldspar can produce the V-shaped trend observed in the most differentiated peralkaline phonolites (*e.g.* F14A, F12C, F1B, F2C, F1E). This also results in a general attenuation of the negative Eu anomaly possibly due to the lower Kd_{Eu} for sphene with respect
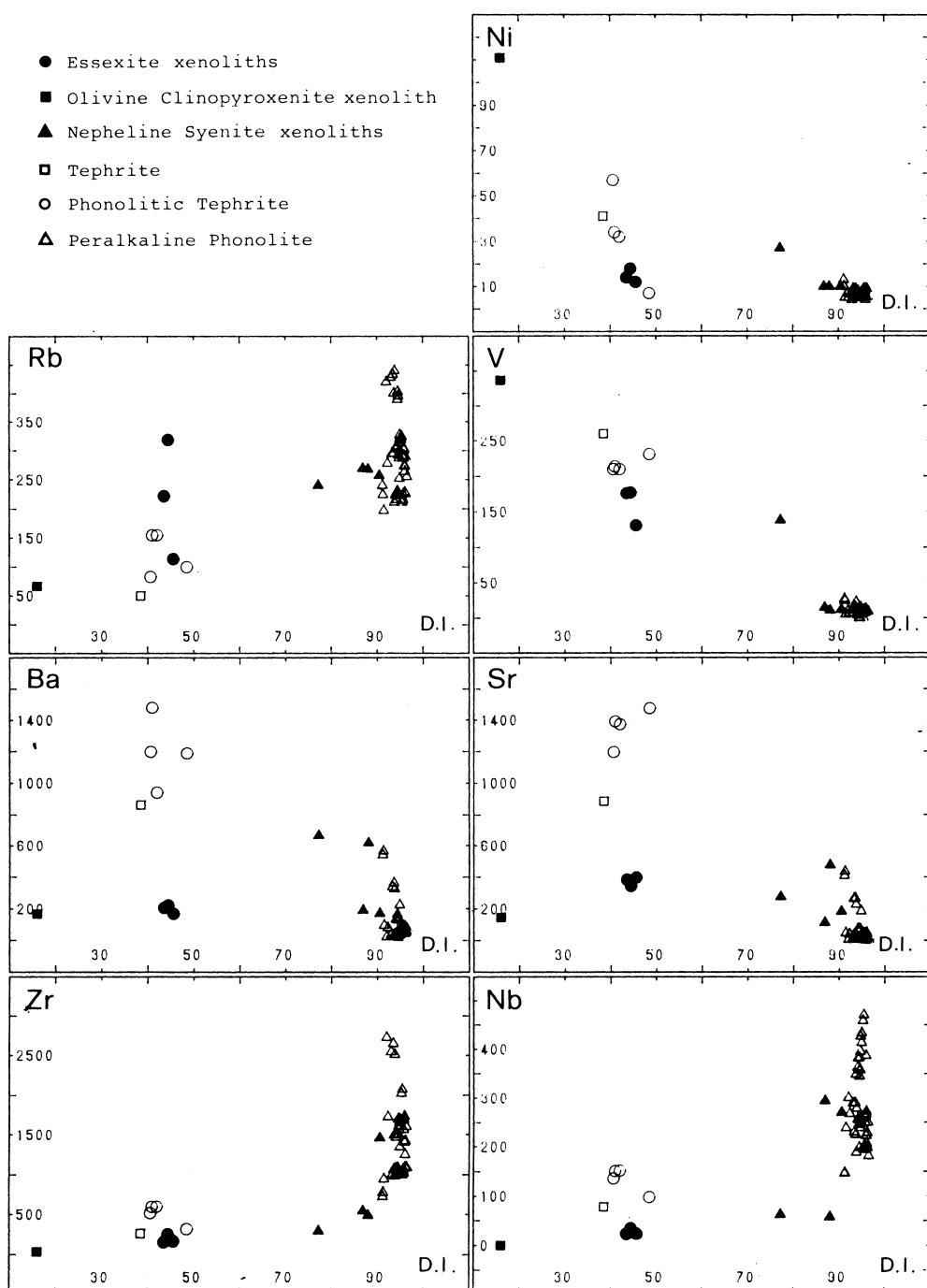
Fig. 7. Major and trace element variations vs differentiation index (D.I. = Q+Or+Ab+Lc+Ne+Ks+Ac+Ns) for Fortaleza alkaline rocks.

Table 6. Least squares mass balance calculations for the Fortaleza magma fractionation based on bulk rock and mineral composition.

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From     BASANITE (calc)    F=100%      Subtracted solid       Corresponding  Cumulates

                         Minerals       Oxides wt%          Ol-Cp  (F1S-N)

SiO2      46.75                         SiO2    44.75            44.52
TiO2       2.66                         TiO2     1.19            1.18
Al2O3     12.53    30%  of Ol-Cp        Al2O3    8.62            8.58
FeOt      11.73                         FeOt    14.00           13.93
MnO        0.18         (F1S-N)         MnO      0.22            0.22
MgO        8.80                         MgO     14.30           14.23
CaO       11.44                         CaO     13.68           13.61
Na2O       3.33                         Na2O     2.15            2.14
K2O        2.04                         K2O      1.06            1.05
P2O5       0.54                         P2O5     0.03            0.03


To/From  TEPHRITE (F10I-D)    F=70%                            Gabbro

SiO2      47.61            ol    2.7    SiO2    45.62
TiO2       3.30            cpx  22.4    TiO2     3.11            (not represented in
Al2O3     14.25            pl   14.0    Al2O3   13.18
FeOt      10.73            mt    3.0    FeOt    10.43           the sampled xenoliths)
MnO        0.16            ap    0.3    MnO      0.21
MgO        6.38                         MgO      9.71
CaO       10.46           r2 = 0.71     CaO     14.29
Na2O       3.86                         Na2O     3.08
K2O        2.48                         K2O      0.11
P2O5       0.77                         P2O5     0.25


To/From PH-TEPHRITE (F10H-D)   F=40.3%                 Ex (F1R-N)     Ex (F1H-N)

SiO2      48.69           cpx  17.8     SiO2    47.61    46.20         45.59
TiO2       3.61           pl   13.6     TiO2     3.93     1.77          1.71
Al2O3     15.82           af   23.4     Al2O3   15.32    17.19        18.14
FeOt      10.81           ne   11.3     FeOt    11.67    11.32        12.12
MnO        0.17           amph   7.8    MnO      0.24     0.24         0.32
MgO        4.14           mt   12.0     MgO      4.54     5.64         5.27
CaO        7.75           sph    2.5    CaO      8.42     8.69         7.68
Na2O       4.34           ap     2.4    Na2O     3.76     5.49         4.92
K2O        3.61                         K2O      3.36     2.68         3.32
P2O5       1.06          r2 = 0.004     P2O5     1.15     0.21         0.26


To/From  P-PHONOLITE (F12I)    F=3.8%             Ne-Sy (F1L-N)   Ne-Sy (F1H-1N)

SiO2      59.10          Na-cpx 0.3     SiO2    58.74    55.52         60.29
TiO2       0.39          af    20.1     TiO2     1.27     0.89          0.17
Al2O3     20.58          ne     2.6     Al2O3   19.43    17.96        21.08
FeOt       2.36          sph    0.7     FeOt     2.61     5.67          0.92
MnO        0.15          mt     0.6     MnO      0.04     0.23          0.07
MgO        0.20          ap     0.7     MgO      0.79     2.74          0.42
CaO        1.22                         CaO      2.52     2.93          1.75
Na2O       9.92          r2 = 0.16      Na2O     4.50     7.29          7.64
K2O        5.99                         K2O      8.85     6.01          7.53
P2O5       0.09                         P2O5     1.25     0.05          0.02


To   P-PHONOLITE  (F14A)     F=2.8%
```

Abbreviations : r^2 = total square residuum, F = % of liquid fraction, ol = olivine, cpx = clinopyroxene, Na-cpx = Na-clinopyroxene, pl = plagioclase, af = alkali feldspar, ne = nepheline, amph = amphibole, mt = magnetite, ap = apatite, sph = sphene. Rock name abbreviations as in Table 1.

to neighbouring REE (Worner *et al.,* 1983).

The sharp decrease in Sr and Ba (Fig. 7) together with high values of the Sm/Eu ratio in the most evolved peralkaline phonolites indicate the predominant role of alkali feldspar fractionation. Rb, Zr, Nb behave as highly residual elements, being strongly enriched in the most differentiated peralkaline phonolites. Significantly, such a Zr enrichment is in agreement with the experimental results indicating that zircon crystallization is prevented by the forma-

tion of soluble alkali-Zr-silicate complexe in strongly alkaline melts (Watson, 1979 ; Linthout, 1984).

A peculiar feature of the nepheline syenite xenoliths is the presence of patches composed of primary calcite + acmitic clinopyroxene + alkali feldspar. This suggests a significant CO_2 enrichment of magmas, that, for advanced fractionation stages, could have approached carbonate-silicate liquid immiscibility conditions. This also supports a derivation of the Fortaleza
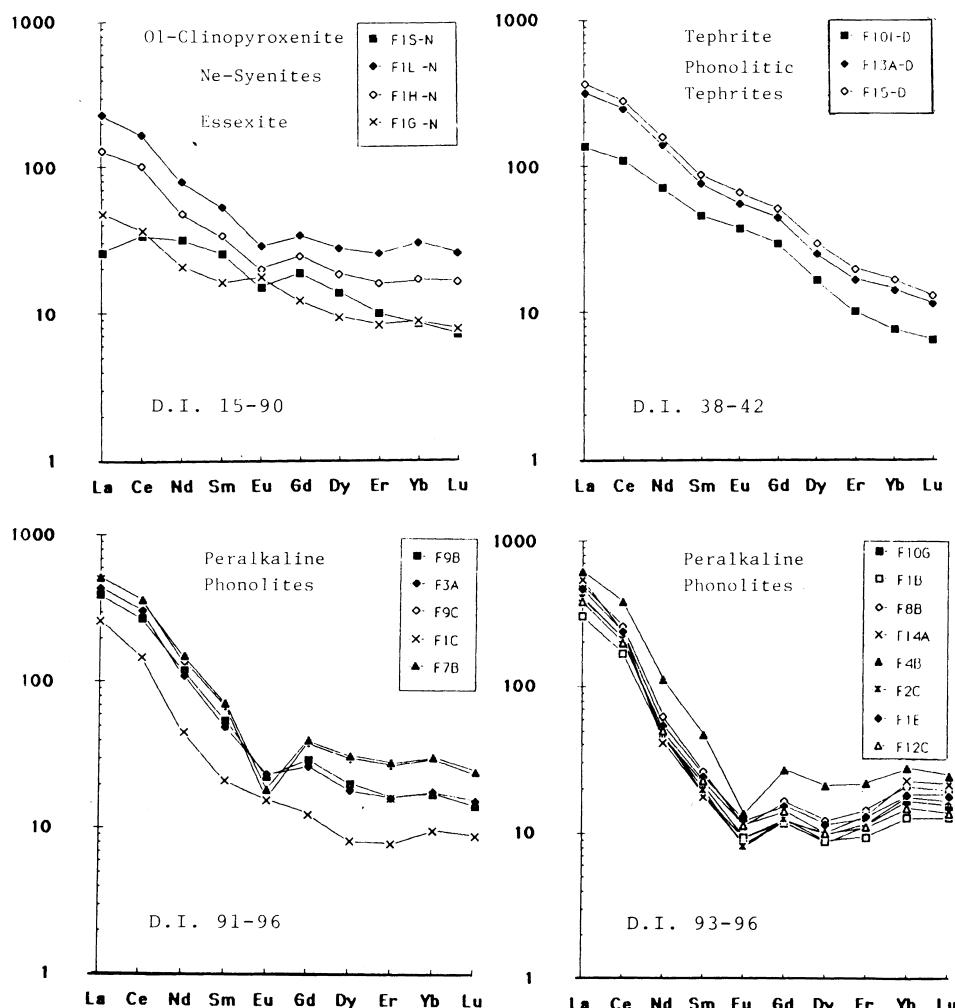
Fig. 8. Chondrite normalized REE patterns for representative Fortaleza alkaline rocks. Sample numbers as referred in Table 1. Also indicated D.I. range.

tephrite-phonolite suite from CO_2-enriched parental melts generated by a low degree of mantle partial melting deep in the sub-continental lithosphere (cf. Wyllie, 1978, 1987).

Strontium isotopes

The initial $^{87}Sr/^{86}Sr$ ratios (Ro) of the Fortaleza alkaline rocks (Table 7) range from 0.7024 to 0.7057, as those of analogous alkaline associations (Bell & Powell, 1970 ; Laughin et al., 1971 ; Rock, 1987), which are believed to be

derived from mantle magmas not significantly affected by crustal contamination (Table 7). Accordingly, crustal contamination processes appear to have played a minor role, and could probably be admitted only for those samples showing higher isotopic ratios. As observed in the diagrams of Fig. 9, some samples with high $^{87}Sr/^{86}Sr$ ratios tend also to be high in Rb and low in Sr, in accordance with their more fractionated nature. The application of an assimilation fractional crystallization model (AFC, cf. De Paolo, 1981), despite of the fact that rocks from different outcrops, obviously do not

Table 7. Strontium isotopic ratios of the Fortaleza alkaline rocks.

	Rb	Sr	$^{87}Sr/^{86}Sr$	±	$^{87}Sr/^{86}Sr_i$ (30 Ma)
Ol–cpx					
F1S–N	67	147	0.70624	3	0.70568
Tph					
F10I–D	50	887	0.70487	3	0.70480
Ph–Tph					
F15–D	155	1373	0.70454	3	0.70440
Ex					
F1G–N	114	398	0.70326	2	0.70291
F1R–N	222	384	0.70431	3	0.70360
Ne–Sy					
F1F–N	269	113	0.70834	3	0.70540
P–Ph					
F1C	240	408	0.70489	3	0.70416
F9B	197	48	0.70978	3	0.70472
F1B	295	264	0.70542	3	0.70404
F7A	319	14	0.73047	5	0.70237

Rock name abbreviations as in Fig. 1. Measurements by VG 54 E micromass spectrometer. Precision expressed as 2 sigma is $\pm 3*10^{-5}$. $^{87}Rb = 1.42*10^{-11}$ y^{-1} ; observed values were corrected taking into account $^{88}Sr/^{86}Sr = 0.1194$. Several determinations of standard NBS 987 SrCO$_3$ gave $^{87}Sr/^{86}Sr = 0.71024 \pm 3$.

belong to the same magmatic system, would indicate only a limited contamination of the order of a few percent of crustal material assimilated by the most differentiated phonolitic magmas. It has to be noted that in the case of Caruru, the application of the AFC model conforms to the observed Sr isotope distribution, since the highest ratios are found in some of the cognate inclusions (olivine clinopyroxenite and nepheline syenite), representing the cumulate solids fractionated in the same magma chamber which fed the associated phonolitic host magmas. The essexitic cognate inclusions reveal the lowest $^{87}Sr/^{86}Sr$ ratios (0.7029-0.7036), representing the least differentiated and uncontaminated magmas of this locality. A very low ratio is also found in the peralkaline phonolite (0.7024 ; sample F7A) from Serrote Gangorra, which is, however, of limited value since it is characterized by extremely high and low Rb and Sr contents, respectively.

As a result, it may be reasonable to assume that the low $^{87}Sr/^{86}Sr$ initial ratios (0.7029-0.7036) of the whole alkaline district represent the isotopic composition of the uncontaminated parental magmas, and, by implication, those of their mantle source. It should be emphasized that these Sr-isotopic ratios in the equatorial region are remarkably lower than those of other alkaline complexes of southern Brazil (Juquiá, 0.7052-0.7080, Beccaluva *et al.*, 1988 ; Morro Redondo, 0.7049-0.7056, Brotzu *et al.*, 1989 ; Piratini, 0.7046-0.7057, Barbieri *et al.*, 1987 ; Tunas, 0.7046-0.7081, Gomes *et al.*, 1987) and of flood basalts from the Paraná Basin (0.7046-0.7062, Piccirillo *et al.*, 1989). Instead, they are comparable with those of alkaline rocks from the Cameron line directly across the Atlantic (0.7027-0.7037, Fitton & Dunlop, 1985).

Thus the data from this work seem to confirm the existence of a worldwide more radiogenic mantle region, on a large geographical scale (Dupal anomaly, Dupré & Allègre, 1983 ; Hart, 1984), in the southern hemisphere.

Conclusions

The alkaline rocks of Fortaleza district range in composition from tephrites to phonolitic tephrites to peralkaline phonolites. At one locality (Caruru) phonolites include cognate xenoliths of olivine clinopyroxenitic, essexitic, and nepheline syenitic composition. Petrographical and whole rock chemical variations, as well as mineral composition trends represent a coherent set of data indicating for the whole suite, although constituted by independent magmatic bodies, a unitary magmatic system essentially evolving by fractional crystallization. Minor and trace elements of tephrites and phonolitic tephrites, which represent the least differentiated magmas of the area, probably reflect slight, but significant variations in the nature of the inferred basanitic parental melts. The basanitic nature of parental magmas is strongly supported by the presence of olivine clinopyroxenite cumulate inclusions in the Caruru phonolites, which represent the proper fractionated solids, complementary to tephritic magmas.

Evolution from tephrites to phonolitic tephrites may be generally accounted for by subtraction of a alkaligabbroic cumulitic assemblage (not represented among the sampled cognate inclusions). The least differentiated peralkaline phonolites could, in turn, be derived from phonolitic tephrites by removal of an essexitic assemblage as that represented in the cognate inclusions. The most differentiated peralkaline phonolitic liquids, corresponding to the mini-
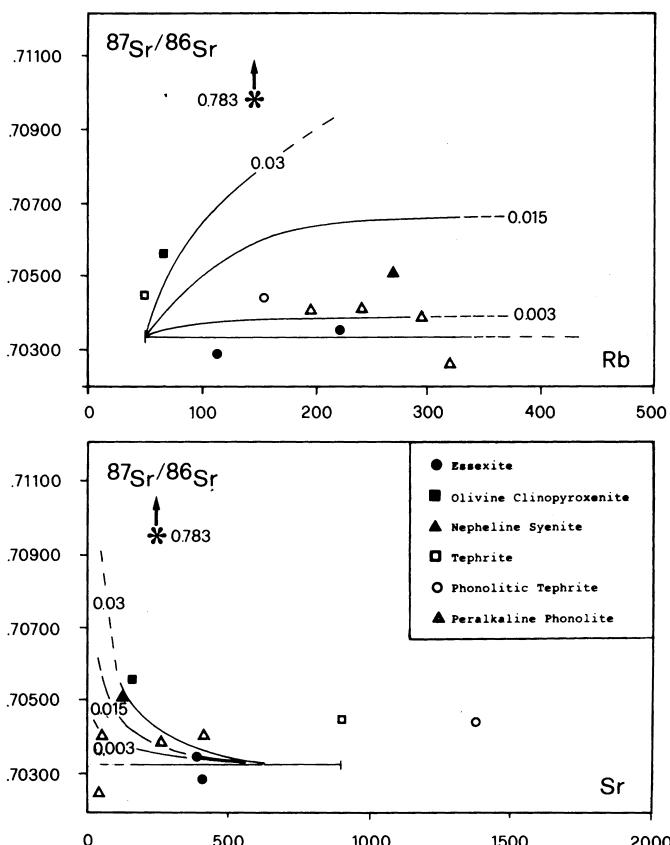
Fig. 9. Initial $^{87}Sr/^{86}Sr$ vs Sr and Rb diagrams for Fortaleza alkaline rocks. The modelled lines represent possible evolutionary path of magmas affected by combined wall rock assimilation and fractional crystallization (DePaolo, 1981). Figures refer to ratio mass of wall rock assimilated/mass of fractionated phases, per time unit. Kd_{Sr} = 2.1, Kd_{Rb} = 0.2, residual liquid fraction F = 0.06. Asterisk represents average composition of Brazilian continental basement (Projeto Radambrasil, 1981) used as contaminant in the calculations. The end of the horizontal bar represents the assumed initial magma composition for the modelling.

mum M in the Ne-Ks-Qz system, could be produced by further removal of nepheline syenite cumulates whose compositions correspond to that of the cognate inclusions.

Variation in REE patterns from tephrites to peralkaline phonolites conforms well to this fractionation scheme, provided that apatite and particularly sphene be fractionated in appropriate amounts in order to fit the V-shaped REE patterns in the most differentiated peralkaline phonolites.

$^{87}Sr/^{86}Sr$ initial ratios, covering a wide range (0.7024-0.7057), suggest significant crustal contamination processes particularly in the most fractionated magmas. The inferred $^{87}Sr/^{86}Sr$ initial ratios of the parental magmas (0.7029-

0.7036) are remarkably lower than those of the other alkaline complexes and of Paraná flood basalt of southern Brazil, supporting the existence of less radiogenic mantle sources in the Atlantic equatorial region compared to the southern hemisphere.

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