Geochemistry of highly-undersaturated ocean island basalt suites from the South Atlantic Ocean: Fernando de Noronha and Trindade islands

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Abstract. The volcanic rocks of the South Atlantic Ocean islands of Fernando de Noronha and Trindade comprise a diverse magmatic series ranging from nephelinites and basanites to phonolites and, on Fernando de Noronha, trachytes. All rock types are highly silica undersaturated (with the exception of Fernando de Noronha trachytes), and have high abundances of incompatible trace elements and strongly LREE (light rare earth element)-enriched REE patterns. Crystal fractionation of parental basanitic magmas produced evolved phonolites and trachytes which display severe trace-element fractionation, even among trace elements (Nb, Ta, Zr, Hf) which normally behave highly incompatibly during crystallisation of alkaline magmas. Moderately to highly evolved compositions develop strongly MREE (middle REE)-depleted REE patterns, and become increasingly depleted in elements such as Nb and, in particular, Ta. Ratios of Nb/Ta and Zr/Hf are highly fractionated in phonolites (60–65, 64–77 respectively in Fernando de Noronha phonolites) compared to ratios in basanites (14, 45 respectively). The compatibility of Nb, Ta, and the REE, and the strong fractionation of Nb/Ta and Zr/Hf ratios and the MREE, during crystallisation from basanite to phonolite are attributable to the crystallisation of small amounts (<5%) of sphene. Trace-element behaviour is relatively insensitive to the major phenocryst phases, and is controlled by minor phases in highly undersaturated alkaline suites. Incompatible trace-element ratios (e.g. La/Nb, Th/Ta) in nephelinites and basanites from Fernando de Noronha and Trindade are generally comparable with those in basaltic and hawaiitic OIB (ocean island basalt) lavas from other South Atlantic islands, but are distinct from those of Gough and Tristan da Cunha OIB. The mantle source for the highly undersaturated volcanism on Fernando de Noronha and Trindade is similar in trace-element characteristics to the "typical" OIB source which produces alkaline lavas with significant relative enrichment in Nb and Ta compared to other trace elements (as expressed by low La/Nb, Ba/Nb and Th/Ta ratios). The highly undersaturated nature of the magmas and the slight fractionation of some incompatible-element ratios (elevated Ba/Nb, Ba/Rb, Ba/Th etc.) is consistent with a smaller degree of melting of a "typical" OIB source, but with residual phlogopite in the source to account for significant K depletion and LIL-element fractionation.

Introduction

Considerable chemical diversity exists among ocean-island basalt (OIB) suites, which range from tholeiitic (e.g. Hawaii) through transitional or mildly alkaline (e.g. Ascension, St. Helena, Gough, Tristan da Cunha) to highly alkaline (e.g. Cape Verde Islands). The marked heterogeneity in radiogenic isotope ratios and incompatible trace-element ratios evident among OIB (e.g. White 1985; Weaver et al. 1987) is not apparently correlated with degree of silica undersaturation. While the location and identity of the source regions of OIB magmas is still conjectural, the evolved trachytes and phonolites found on ocean islands are simply related to the mafic volcanics (basalts, basanites, nephelinites) by extensive low pressure crystal fractionation (Zielinski and Frey 1970; Zielinski 1975; Harris 1983; le Roex 1985; Garcia et al. 1986). Phonolites occur widely as the end-products of fractionation in highly undersaturated volcanic suites in both oceanic and continental intra-plate settings (Irving and Price 1981; Canary Islands [Wolff 1984]; Kaula, Hawaii [Garcia et al. 1986]; Ross Island, Antarctica [Sun and Hanson 1976; Kyle 1981]; East African Rift [Price et al. 1985]; Namibia [Marsh 1987]; Massif Central [Chauvel and Jahn 1984; Downes 1984]; Laacher See [Worner et al. 1984a, b]), and often display marked trace-element fractionation relative to less evolved compositions. There have, however, been relatively few comprehensive trace-element studies of this aspect of ocean-island volcanism.

Volcanic rocks from South Atlantic Ocean islands display considerable geochemical diversity, both between- and within-island, comparable to that displayed

worldwide by OIB suites. Ascension and Bouvet islands are typified by mildly alkaline basalt to comendite sequences (Harris 1983; le Roux and Erlank 1982), have similar trace-element characteristics (Weaver et al. 1987), and are comparable isotopically to the majority of OIB (e.g. White 1985). Saint Helena, Gough and Tristan da Cunha islands are typified by moderately alkaline basalt to trachyte sequences (Baker 1969; le Roux 1985; Baker et al. 1964). The trace-element characteristics of St. Helena OIB are generally similar to those of Ascension and Bouvet (Weaver et al. 1987) in spite of significant isotopic differences (highly radiogenic Pb in St. Helena OIB; Sun 1980; White 1985). The volcanics of Gough and Tristan da Cunha have trace-element (Weaver et al. 1987) and Pb, Sr and Nd isotopic characteristics (Sun 1980; White 1985) distinct from those of other South Atlantic Ocean islands.

Fernando de Noronha and Trindade islands differ from other South Atlantic Ocean islands in that they are characterised by highly silica-undersaturated volcanism (Almeida 1955, 1961). Rock types range from nepheline basalt to phonolite, with trachyte developed on Fernando de Noronha. Only limited geochemical data are available for these islands. Almeida (1955) gave major element analysis for a limited number of Fernando de Noronha samples ranging from basanite to phonolite, and Gerlach et al. (1987) reported trace element data for mafic rocks. Sun (1980) and Gerlach et al. (1987) presented isotopic data for Fernado de Noronha. Gerlach et al. (1987) identified small differences in isotopic composition between older alkaline rocks and younger, more highly undersaturated, rocks, the former having more radiogenic Sr and less radiogenic Nd ($^{87}Sr/^{86}Sr =$ 0.70457–0.70485; $^{143}Nd/^{144}Nd = 0.51271$–0.51281) than the latter ($^{87}Sr/^{86}Sr = 0.70365$–0.70418; $^{143}Nd/^{144}Nd =$ 0.51277–0.51290). Ratios of $^{206}Pb/^{204}Pb$ are somewhat higher in the highly undersaturated rocks, the total range in $^{206}Pb/^{204}Pb$ ratios being only from 19.1 to 19.6 (Sun 1980; Gerlach et al. 1987). Much more sparse data are available for Trindade; Almeida (1961) gave a limited number of whole-rock major element analyses, and Oversby (1971) reported $^{206}Pb/^{204}Pb$ ratios of 19.0–19.2 for Trindade samples.

In this paper, the magnitude and causes of trace-element fractionation during crystallisation of these highly undersaturated magmas are investigated, and the relationship of the mantle source for Fernando de Noronha and Trindade magmas to those for other South Atlantic suites is assessed.

## Geology and petrology of Fernando de Noronha and Trindade

The geology and petrography of the igneous rocks of both Fernando de Noronha and Trindade has been described by Almeida (1955, 1961), and the petrography of some of the Fernando de Noronha samples discussed here has been described by Smith and Burri (1933), and that of some of the Trindade samples by Prior (1900). Only brief relevant background information is given.

Fernando de Noronha

The archipelago of Fernando de Noronha lies 345 km from the Brazilian coastline at approximately 3° 50′ S, 32° 25′ W (Fig. 1). The archipelago rises some 4200 m above the surrounding ocean floor, and forms part of a chain of seamounts (the Fernando de Noronha Ridge) extending eastwards from the Brazilian mainland. The main island of Fernando de Noronha has an area of 16.9 km² with a maximum elevation of 320 m above sea level, and is composed of late Miocene–Pliocene volcanics. A simplified geological map of Fernando de Noronha (Fig. 1) is after Almeida (1955) who distinguished three periods of volcanic activity. The Remedios Formation comprises plugs and domes of phonolite, alkali trachyte, and alkali basalt and highly compositionally variable dykes emplaced into pyroclastic tuffs (Almeida 1955), and ranging from 8–11.8 Ma old (Cordani 1967). The phonolites contain variable proportions of alkali feldspar, nepheline and sodalite and occasional sodic pyroxene and amphibole as phenocryst phases. The trachytes are only sparsely porphyritic, containing phenocrysts of alkali feldspar and traces of plagioclase (andesine) mantled by alkali feldspar, with microphenocrysts of aegerine-augite, magnetite, sphene, sodalite and amphibole. Above the Remedios Formation, and separated by a substantial erosional break, is the Quixaba Formation which is dominated by nepheline basalt flows (termed ankaratrites by Almeida) with minor nephelinite dykes, tuffs and breccias, and ranges from 1.7–3.0 Ma old (Cordani 1967). The nepheline basalts contain olivine and minor titanaugite, biotite and magnetite as phenocryst phases, while more mafic nepheline basalts contain mellite in the groundmass. The Sao Jose Formation comprises a single basanite flow on the islet of Sao Jose, and represents the youngest (undated) volcanic activity on the island.

Trindade

The island of Trindade lies 1140 km east of the Brazilian coast at approximately 20° 30′ S, 29° 20′ W (Fig. 1). The island rises 5000 m above the surrounding ocean floor, and, together with the island of Martin Vaz, lies on a continuation of a chain of seamounts (the Columbia seamounts) that extend from the Brazilian mainland. Trindade has an area of only 6 km² and a maximum elevation of 600 m above sea level, and represents the deeply eroded remnants of a major volcanic edifice. A simplified geological map of Trindade (Fig. 1) is after Almeida (1961) who recognised five periods of volcanic activity on Trindade. The Trindade Complex comprises nephelinitic and phonolitic pyroclastics intruded by numerous, compositionally diverse, dykes and domes (including phonolite), and forms the major part of the central and western portions of the island. The overlying Desejado Sequence forms a central plateau and consists of a succession of phonolite and nephelinite flows intercalated with compositionally equivalent pyroclastics, and intruded by phonolite domes. The phonolites may contain phenocrysts of alkali feldspar (sanidine-anorthoclase cryptoperthite) and microphenocrysts of sodic augite, amphibole, nosean, sphene, apatite and biotite. The nephelinites are generally aphanitic, but may contain large phenocrysts of augite, biotite and some nepheline, with nepheline, analcite and sodalite in the groundmass. The Morro Vermelho formation comprises a sequence of analcite-bearing nepheline basalt (ankaratrite) flows and pyroclastics in excess of 200 m thick in the eastern half of the island. These basalts contain olivine phenocrysts set in a groundmass of titanaugite, magnetite, nepheline, apatite, biotite and analcite. The Valado Formation consists of very limited exposure of tannbuschite flows, pyroclastics and tuffs in the north central part of the island. The most recent volcanics recognised on the island are nepheline basalt lavas and tuffs erupted from the Paredo Hill volcano, and are dominantly exposed at the eastern end of the island. These lavas are petrographically indistinguishable from those of the Morro Vermelho Formation.
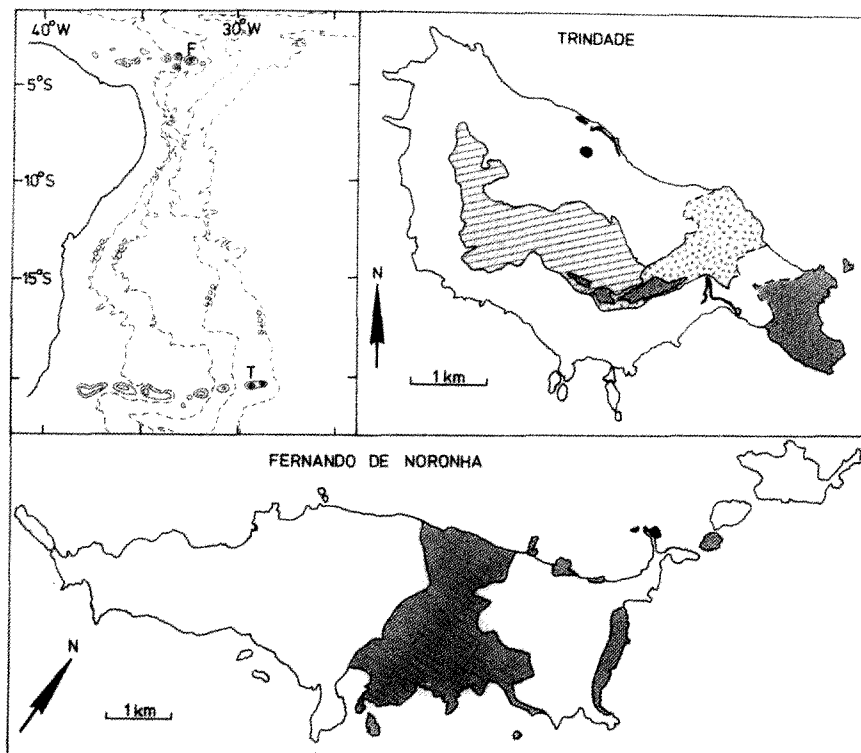
Fig. 1. Generalised geological maps of Fernando de Noronha and Trindade islands after Almeida (1955; 1961). Only the main volcanic units identified on the islands are shown. Fernando de Noronha; *cross hatched* – Remedios Formation; *blank* – Quixaba Formation; *black* – Sao Jose Formation. Trindade; *blank* – Trindade complex; *lined* – Desejado sequence; *dashed* – Morro Vermelho Formation; *black* – Valado Formation; *cross hatched* – Paredao Hill volcano. *Upper left inset* shows location of Fernando de Noronha (*F*) and Trindade (*T*) islands in the South Atlantic Ocean

Samples and analytical technique

The samples used in this study come from the collections of the British Museum (Natural History), and were chosen as far as possible to cover the full compositional range of rock types on each island. Unfortunately, correlation of the samples with the mapped formations of Almeida (1955, 1961) is not always possible, especially for Trindade. Analytical data for the major elements and trace elements Ni, Cr, V, Zn, Rb, Sr, Ba, Th, Zr, Nb, La, Ce, Nd and Y were obtained by X-ray fluorescence (XRF) analysis using a Philips PW1400 automatic spectrometer at the Department of Geology, University of Leicester, and by epithermal neutron activation analysis (ENAA) at Pierre Sue. For XRF analysis rock powders (crushed in agate) were dried overnight at 100° C. Major element concentrations were determined on glass fusion beads made using a lithium tetraborate/lithium metaborate flux (rock: flux ratio 1:5) after pre-ignition of the dried rock powder at 900° C to determine weight loss on ignition (reported in Tables 1, 2 as LOI). Major element calibrations were based on a wide range of international standards, and a Rh anode X-ray tube was used to make the major element determinations. Trace element concentrations were determined on pressed-powder pellets made using an organic binder (Moviol). Determinations of Ni, Zn, Zr, Nb, Rb, Sr, Y and Th were made using a Rh anode X-ray tube with mass absorption corrections applied using the intensity of the Rh Kα Compton scatter peak (Harvey and Atkin 1982). Determinations of Cr, V, Ba, La, Ce and Nd used a W anode X-ray tube, with mass absorption corrections applied using the intensities of the W Lα Rayleigh scatter peak and Fe Kα to cross the Fe-absorption edge after the technique of Nesbitt et al. (1976). Trace element calibrations were based on international standards together with some spiked standards. Data for Cr, Ni, Sc, Co, Cs, Rb, Ba, Zr, La, Ce, Eu, Tb, Hf, Ta, Th and U were determined by ENAA at Pierre Sue by J.-L. Joron. The ENAA technique employed has been described by Chayla et al. (1973) and Jaffrezic et al. (1980). Where the same elements have been determined by both XRF and ENAA, the ENAA data for Th and La are quoted in Tables 1,

2, while the XRF data for Cr, Ni, Rb, Ba, Zr, Ce and Nd are quoted. In addition, REE abundances have been determined for representative samples by instrumental neutron activation analysis (INAA) at the University of Oklahoma, using reactor facilities provided by Georgia Institute of Technology under the Department of Energy reactor sharing program. These data are given in Table 3. The analytical technique employed generally followed that outlined by Potts et al. (1981, 1985).

Geochemistry

A total of twenty two samples from Fernando de Noronha and thirteen samples from Trindade have been analysed for major and trace elements by XRF and ENAA, and selected samples analysed for a more complete range of REE by INAA. Analytical data for selected samples from both islands are given in Tables 1–3. Full analytical data are available upon request.

Effects of alteration on geochemistry

Subaerial alteration of volcanic rocks in tropical environments may result in significant mobility of major and trace elements, and Gunn and Watkins (1976) recognised substantial secondary redistribution of alkalies within Fernando de Noronha lava flows. Among analysed nepheline basalts from Fernando de Noronha, one sample (67051) has a very high weight loss on ignition (7.25%), and shows petrographic evidence of substantial alteration. The abundances of those trace elements which are immobile under a wide range of alteration/
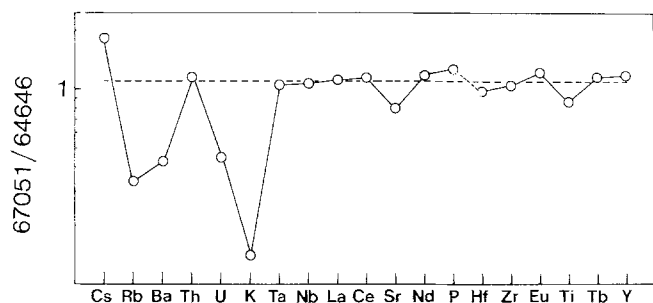
Fig. 2. Incompatible trace-element abundances in altered nephelinite 67051 normalised to abundances in fresh nephelinite 64646 to show the effect of alteration on trace-element abundances. 67051 is slightly more fractionated than 64646, and the *dotted line* drawn through the pattern represents the expected normalised trace-element abundances in 67051 (based on immobile elements)
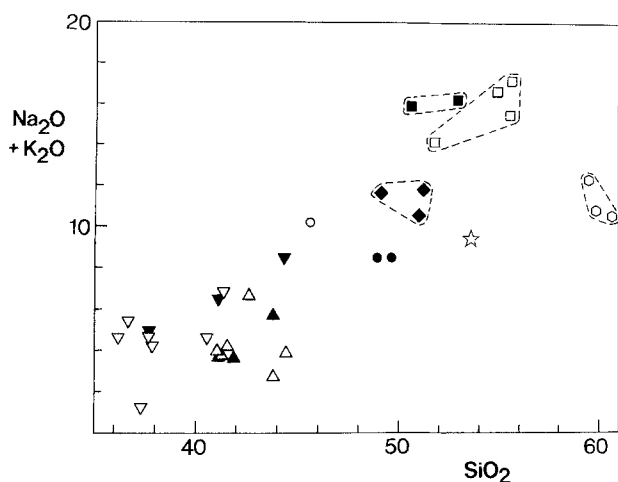

Fig. 3. SiO$_2$ (wt%) vs total alkalies (Na$_2$O + K$_2$O in wt%) diagram for the igneous rocks of Fernando de Noronha and Trindade. *Open symbols* – Fernando de Noronha samples; *filled symbols* – Trindade samples. *Triangles* – basanites; *inverted triangles* – nephelinites; *circles* – phonolitic nephelinite (*open*) and mugearites (*filled*); *star* – benmoreite; *diamonds* and *squares* – phonolites; *hexagons* – trachytes

weathering conditions (Zr, Nb, etc.; Pearce and Cann 1973; Floyd and Winchester 1975), and especially ratios between these elements (e.g. Zr/Nb), indicate that 67051 is a nephelinite. This sample is depleted in Na$_2$O (0.92%) and K$_2$O (0.33%) relative to unaltered and mildly altered nephelinites (2.7–3.55% Na$_2$O; 1.06–2.29% K$_2$O), and has a lower normative nepheline (*ne*) content. The trace-element characteristics of 67051 are compared to those of an unaltered nephelinite in Fig. 2. Abundances of Cs, Th, Ta, Nb, Ce, Nd, P, Hf, Zr, Eu, Tb and Y are comparable to those in the unaltered nephelinite, whereas Rb, Ba, U and K are variably but strongly depleted, and Sr is slightly depleted. In general, the large ion lithophile (LIL) elements are relatively easily mobilised during subaerial weathering, although, for individual samples, the sense of modification (loss or gain) and magnitude of change relative to immobile elements and other LIL elements is not always consistent. In particular, the behaviour of Cs and U is highly erratic; some

samples which have undergone considerable addition or loss of U show little change in Cs abundance, and vice versa. Variable alteration is responsible for the scatter evident (particularly among basanites and nephelinites) in the SiO$_2$ vs Na$_2$O + K$_2$O plot of Fig. 3.

Fernando de Noronha

Quixaba formation nepheline basalts are divisible into two geochemical groups. Nephelinites (Table 1) contain > 12% normative *ne* and have high abundances of compatible trace elements and incompatible trace elements (Fig. 4). The REE pattern for a nephelinite (Table 3; Fig. 5) shows strong LREE enrichment. Basanites (Table 1) contain < 12% normative *ne*, and, relative to nephelinites, have generally comparable, but somewhat variable, concentrations of compatible trace elements (Table 1), comparable Sr and Zr abundances (Fig. 4c, d), and lower Nb and Th abundances (Fig. 4a). Basanites and nephelinites have distinctive trace-element ratios, e.g. Zr/Nb = 4.2–5.4 in basanites, 3.0–3.2 in nephelinites (Table 1). However, REE abundances in basanites (Table 3) and nephelinites are similar (Fig. 5), as is the relative REE fractionation (Table 3, Fig. 5). REE patterns are similar to that for a Quixaba Formation sample reported by Kay and Gast (1973).

A few analysed Fernando de Noronha samples have compositions intermediate between basanites/nephelinites and phonolites (Table 1). Two samples from dykes cutting the Remedios Formation are somewhat more evolved than Quixaba Formation basanite and nephelinite flows, with generally lower abundances of compatible trace elements, and generally higher abundances of incompatible trace elements (Fig. 4). Abundances of LREE and HREE (heavy REE) are higher than in Quixaba Formation flows (Table 1, Fig. 5), but MREE abundances are comparable, and consequently chondrite normalised ratios of La$_N$/Sm$_N$ and Tb$_N$/Yb$_N$ are respectively higher and lower (Table 3). A phonolite nephelinite (Table 1; Fig. 3) has a high normative *ne* content and lower abundances of compatible trace elements than in basanites and nephelinites, higher abundances of incompatible trace elements (Fig. 4), and a REE pattern (Fig. 5) with similar LREE enrichment to the less evolved samples, but greater relative MREE depletion. A benmoreite (Table 1; Fig. 3) contains normative quartz (*qtz*), and has higher incompatible-element abundances, but lower compatible-element abundances, than in the basanites, nephelinites and phonolitic nephelinite (Fig. 4). The REE pattern is similar to that of the phonolitic nephelinite, but with somewhat greater MREE depletion and lower total REE abundances (Fig. 5).

Fernando de Noronha phonolites display a range of compositions (Table 1, Fig. 3), but are *ne* normative. Compatible trace elements are uniformly low (Table 1), Sr (and Ba) are strongly depleted in evolved phonolites (Fig. 4d), while incompatible trace elements are strongly enriched (Fig. 4a–c). The MREE become increasingly fractionated from the LREE and the HREE (Table 3), the most evolved phonolite having a strongly concave-

Table 1. Representative analyses of igneous rocks from Fernando de Noronha

	Quixaba formation												
	N			B			PN	Be	P			T	
	64646	67048	67089	67066	67097	67164	67113	67165	67056	67163	67166	67099	67129
SiO_2	36.69	36.18	37.68	41.51	41.04	44.43	45.57	53.61	51.76	54.90	55.62	59.50	60.71
TiO_2	4.35	4.26	3.68	3.72	3.81	3.04	2.23	1.22	0.55	0.19	0.18	0.46	0.91
Al_2O_3	10.58	9.85	11.41	10.48	10.20	11.27	19.19	19.65	22.15	22.86	22.40	19.37	19.70
Fe_2O_3	15.26	15.17	14.04	13.60	13.81	13.07	7.09	4.98	3.25	2.24	2.34	2.79	2.63
MnO	0.21	0.21	0.20	0.18	0.18	0.18	0.19	0.09	0.13	0.15	0.18	0.20	0.03
MgO	13.42	14.72	12.91	10.58	10.69	9.33	2.60	2.70	0.40	0.16	0.04	0.47	0.32
CaO	12.33	11.59	12.95	12.03	12.10	11.23	5.65	2.92	2.36	0.94	0.71	2.69	1.21
Na_2O	3.12	2.70	2.96	3.43	3.06	2.92	5.62	2.19	9.36	9.80	10.46	6.53	5.00
K_2O	2.29	1.92	1.72	0.68	0.90	0.91	4.57	7.27	4.80	6.85	6.71	5.79	5.54
P_2O_5	1.12	0.97	1.10	1.08	1.09	0.79	0.66	0.27	0.12	0.02	0.01	0.06	0.08
LOI	0.94	2.31	1.54	2.79	2.77	2.67	6.45	5.31	4.71	1.98	1.31	2.25	3.77
Total	100.31	99.88	100.19	100.08	99.65	99.84	99.82	100.21	99.59	100.09	99.96	100.11	99.90
Trace elements in ppm													
Cr	330	295	424	316	331	367	11	62	3	11	4	5	11
Ni	162	181	119	232	264	299	10	48	5	6	3	4	16
Co	67.4	69.0	59.7	–	56.8	59.2	16.5	13.9	2.8	0.8	0.4	1.3	10.2
Sc	33.1	30.8	31.4	–	27.7	26.4	8.6	7.5	2.1	0.7	0.5	1.6	3.1
V	344	331	310	298	299	232	169	93	46	15	10	33	65
Zn	118	116	120	128	123	108	114	88	101	117	156	114	77
Cs	0.39	0.47	0.68	0.87	1.20	0.65	2.44	1.36	1.26	3.68	5.2	7.7	0.68
Rb	58	54	40	20	33	28	161	239	136	252	329	202	155
Sr	939	675	1070	1055	1234	862	1576	1170	1894	32	12	984	856
Ba	987	1014	843	866	1008	633	1465	1000	1645	9	2	1336	888
Th	9.5	9.6	9.2	7.2	7.0	6.08	25.3	28.2	22.8	32.7	45.5	24.5	17.8
U	2.13	2.16	2.28	1.83	1.75	1.81	8.5	6.0	9.0	11.2	15.2	7.6	4.5
Zr	421	380	368	457	454	345	547	741	675	957	1398	1003	1068
Hf	9.5	8.0	8.4	9.2	9.9	7.9	8.2	12.7	9.2	14.3	18.1	18.2	19.2
Nb	132	127	123	105	99	77	166	121	103	99	133	120	145
Ta	8.8	8.7	8.43	6.46	6.47	5.77	9.41	4.37	2.75	1.67	2.0	3.62	9.2
La	78	73	72	72	70	52	104	87	77	86	103	122	100
Ce	131	126	125	122	123	93	156	109	92	87	103	155	162
Nd	59	56	66	76	73	50	60	35	21	14	18	38	77
Eu	4.05	3.75	4.36	4.15	4.15	3.63	3.6	1.84	1.05	0.47	0.38	1.72	3.60
Tb	1.21	1.17	1.27	1.25	1.32	1.12	1.00	0.51	0.35	0.16	0.17	0.45	1.23
Y	30	29	32	33	33	31	29	17	14	11	14	21	50
Trace element ratios													
Zr/Nb	3.2	3.0	3.0	4.4	4.6	4.5	3.3	6.1	6.6	9.7	10.5	8.4	7.4
La/Nb	0.59	0.57	0.58	0.68	0.71	0.68	0.63	0.72	0.75	0.87	0.77	1.02	0.69
Ba/Nb	7.5	8.0	6.9	8.2	10.2	8.2	8.8	8.3	16.0	0.09	0.02	11.1	6.1
Ba/Th	104	106	92	120	144	104	58	35	72	0.3	0.04	55	50
Ba/La	12.7	13.9	11.8	12.1	14.4	12.2	14.1	11.5	21.4	0.1	0.02	11.0	8.9
Nb/Ta	15.0	14.6	14.6	16.3	15.3	13.3	17.6	27.7	37.5	59.3	66.5	33.1	15.8

N, nephelinite; B, basanite; PN, phonolitic nephelinite; Be, benmoreite; P, phonolite; T, trachyte. Analyses by XRF at the University of Leicester and ENAA at Pierre Sue

downward REE pattern (Fig. 5). The REE pattern reported by Kay and Gast (1973) for a Remedios Formation porphyritic phonolite shows moderate MREE depletion.

Silica-oversaturated (*qtz* normative) alkali trachytes occur on Fernando de Noronha (Table 1; Fig. 3). Compatible trace element abundances are low (Table 1), Sr (and Ba) abundances moderate – high (Fig. 4d), and Zr, Nb and Th abundances high (Fig. 4a, c). The less evolved trachyte has moderately high REE abundances (and higher HREE than other Fernando de Noronha samples; Table 3), whereas the evolved trachyte has much lower HREE and MREE abundances (Fig. 5).

Trindade

Trindade basanites (Table 2) have <11% normative *ne*, relatively high Cr and Ni abundances (Table 2), and moderate incompatible trace-element abundances
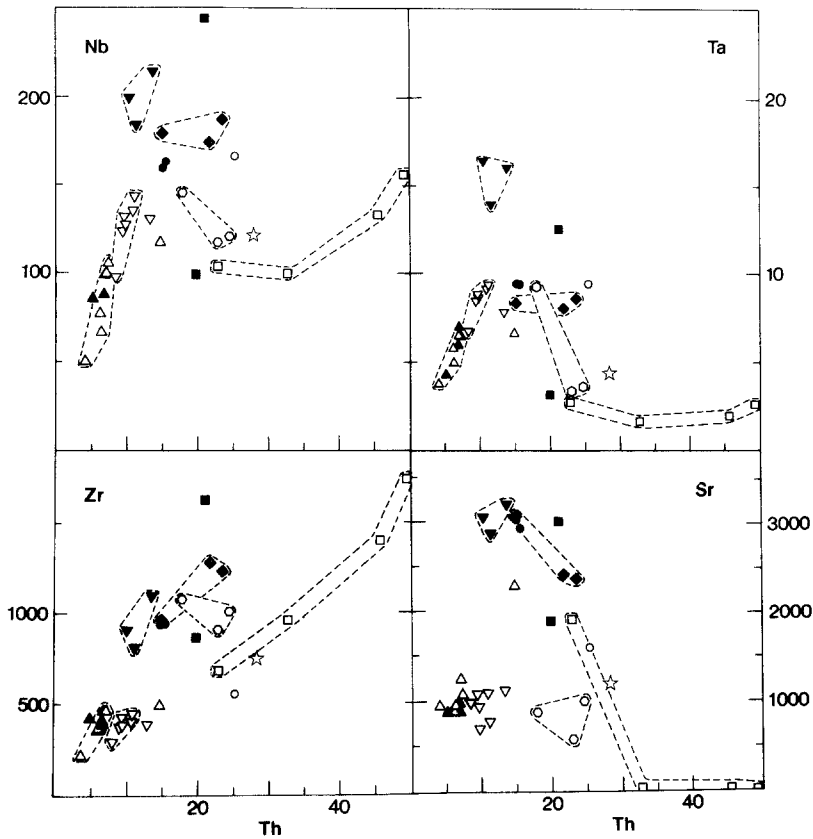
Fig. 4. Plots of Th (a fractionation index) vs Nb, Ta, Zr, Sr for Fernando de Noronha and Trindade igneous rocks. Plotted abundances are in ppm. Symbols as in Fig. 3
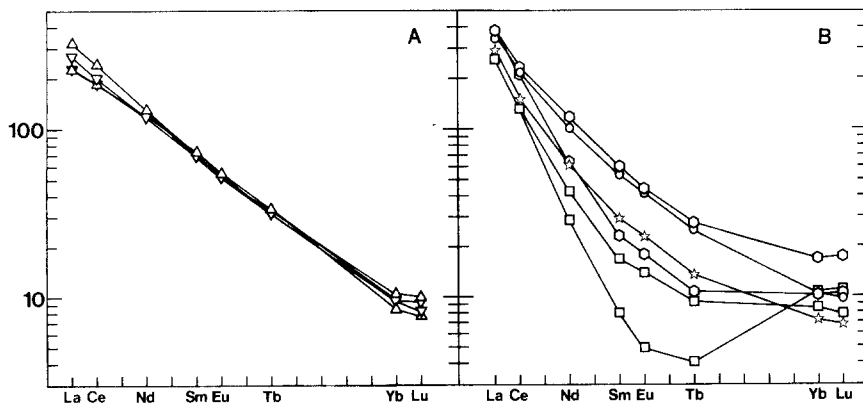

Fig. 5 A, B. Chondrite normalised (Nakamura 1974) REE patterns for Fernando de Noronha igneous rocks: **A** basanites and nephelinites; **B** phonolitic nephelinite, benmoreite and phonolites

(Fig. 4). Patterns for REE show strong LREE enrichment (Fig. 6). Nephelinites (Table 2) have somewhat variable SiO_2, relatively low MgO, generally higher $Na_2O + K_2O$ (Fig. 3), and >11% normative *ne*. Cr and Ni abundances are low, and incompatible trace-element abundances high (Fig. 4). Abundances of REE are higher in nephelinites than in basanites (Table 3, Fig. 6), and there is greater fractionation of LREE from HREE (Table 3). The marked distinction between the two groups is illustrated for incompatible trace elements in Fig. 4, and for the REE in Fig. 6.

Two mugearites (Table 2; Fig. 3) contain only small amounts of normative *ne*. Incompatible trace-element abundances are similar to those in nephelinites (Fig. 4).

Abundances of LREE and HREE, and Ce_N/Yb_N ratios, are intermediate between those of basanites and nephelinites (Table 3), but MREE abundances are similar to the basanites (Fig. 6), resulting in higher La_N/Sm_N and Tb_N/Yb_N ratios than in either basanites or nephelinites.

Trindade phonolites display a range of chemical compositions (Table 2; Fig. 3) and contain variable amounts of normative *ne*. Compatible trace-element abundances are very low, and Sr (and Ba) abundances high (Fig. 4d) in all phonolites. Zirconium, Nb and Th abundances display wide variation (Fig. 4a, c). Abundances of REE in the less evolved phonolite are similar to those of the mugearite (Table 3), with the exception of somewhat greater relative MREE depletion (Fig. 6). The more

Table 2. Representative analyses of igneous rocks from Trindade

	N		B		M	P	
	75357	75346	87171 923	87171 915	75348	87171 929	87171 949
SiO_2	37.68	44.92	41.84	41.12	49.62	51.00	52.91
TiO_2	4.19	2.57	3.80	4.20	1.84	1.19	0.67
Al_2O_3	11.75	16.59	10.97	11.53	18.95	20.61	21.58
Fe_2O_3	16.54	9.24	13.06	14.07	6.37	4.77	3.65
MnO	0.29	0.23	0.17	0.17	0.17	0.18	0.13
MgO	5.67	3.80	10.01	8.01	2.24	1.47	0.41
CaO	12.32	8.35	12.33	11.82	5.16	3.72	2.01
Na_2O	3.48	4.03	2.54	2.45	2.93	4.32	9.21
K_2O	1.47	4.46	1.07	1.25	5.56	6.25	7.05
P_2O_5	3.33	0.92	0.80	0.89	0.51	0.25	0.15
LOI	3.29	5.06	3.31	4.68	6.84	6.00	2.44
Total	100.01	99.54	99.90	100.19	100.19	99.76	100.21

Trace elements in ppm

Cr	21	12	442	307	9	2	5
Ni	20	13	232	172	6	5	3
Co	38.0	16.8	53.8	60.5	10.5	5.1	3.3
Sc	23.3	12.3	32.8	33.7	8.0	4.4	2.5
V	290	155	315	502	108	74	48
Zn	202	143	109	124	113	135	116
Cs	1.06	1.27	1.05	1.29	—	1.50	2.47
Rb	62	82	32	58	142	116	185
Sr	2869	3199	971	876	3043	3074	1879
Ba	1027	1598	752	810	1267	1710	1368
Th	11.3	13.6	6.7	6.8	15.0	15.0	19.8
U	3.72	8.60	1.71	1.73	5.00	4.92	7.40
Zr	805	1092	400	386	938	956	863
Hf	16.3	17.1	8.4	8.5	14.2	14.2	13.9
Nb	184	214	87	98	159	179	99
Ta	13.9	16.0	5.96	6.94	9.41	8.35	3.18
La	150	159	62	71	110	131	65
Ce	342	243	111	124	162	226	80
Nd	157	105	68	71	54	71	21
Eu	8.25	6.53	3.62	4.19	3.93	3.24	1.16
Tb	3.08	2.05	1.08	1.23	1.13	1.24	0.39
Y	64	52	32	36	33	30	15

Trace element ratios

Zr/Nb	4.4	5.1	4.6	3.9	5.9	5.3	8.7
La/Nb	0.82	0.74	0.71	0.72	0.69	0.73	0.66
Ba/Nb	5.6	7.5	8.6	8.3	8.0	9.6	13.8
Ba/Th	91	118	112	119	84	114	69
Ba/La	6.8	10.1	12.1	11.4	11.5	13.1	21.0
Nb/Ta	13.2	13.4	14.6	14.1	16.9	21.0	31.1

N, Nephelinite; B, basanite; M, mugearite; P, phonolite
Analyses by XRF at the University of Leicester and ENAA at Pierre Sue

evolved phonolite has lower REE abundances (Table 3), a lower Ce_N/Yb_N ratio (Table 3), and greater MREE depletion, and an accordingly markedly concave-downward REE pattern (Fig. 6). Evolved SiO_2-saturated compositions appear to be lacking on Trindade.

Petrogenesis

The range of magma compositions present on Fernando de Noronha and Trindade and the consistent decreases in compatible-element abundances with increasing incompatible-element abundances is due to extensive crystal fractionation. Trace element data can be used to place important constraints on fractional-crystallisation processes in the production of the evolved phonolitic/trachytic compositions, and on possible source compositions for Fernando de Noronha and Trindade basanites and nephelinites. However, lack of data for the chemistry of the phenocryst phases precludes quantitative least-squares modelling of major element variation with fractional crystallisation of Fernando de Noronha and Trindade magmas.

Fernando de Noronha

Crystal fractionation results in chemically diverse evolved magmas on Fernando de Noronha, with both highly alkaline undersaturated phonolites and oversaturated trachytes being produced. Compositions such as those represented by the Quixaba Formation nephelinites and basanites are potential parent magmas to the evolved compositions.
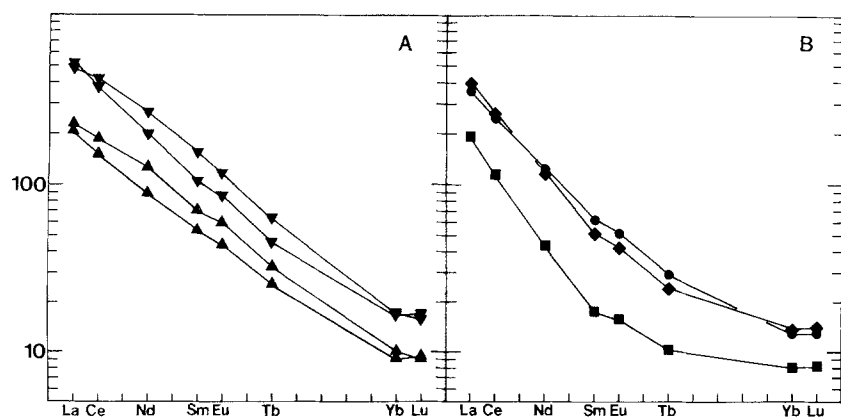
Quixaba Formation basanites and nephelinites cannot be related to each other by crystal fractionation. Abundances of compatible trace elements in sparsely phyric nephelinites and basanites are comparable, and close to those expected in primary magmas (very high abundances of compatible elements in basanites are due to high contents of olivine and clinopyroxene phenocrysts). Ratios of Zr/Nb (Figs. 7, 8) and La/Nb are distinctly different between basanites (Zr/Nb = 4.2–5.4; La/Nb = 0.67–0.80) and nephelinites (Zr/Nb = 3.0–3.2; La/Nb = 0.57–0.65), but these ratios are not significantly fractionated during crystallisation of olivine and clinopyroxene (the dominant phenocryst phases). These two magma types were, therefore, derived either from chemically distinct mantle sources, or by different degrees of melting of a common source. If the basanites and nephelinites were derived from different mantle sources, the nephelinites would be derived from a more enriched source. Isotope data for Sr and Nd reported by Gerlach et al. (1987) for the Quixaba Formation display a restricted range of age-corrected ratios ([87]Sr/[86]Sr = 0.70377–0.70396; [143]Nd/[144]Nd = 0.51280–0.51285), implying a common source, or similar sources, for basanites and nephelinites (ankaratrites and melilitites of Gerlach et al. 1987). For partial melting of a common source, a lower degree of melting would produce the more undersaturated and incompatible-element-enriched nephelinitic magmas. The lower Zr/Nb and La/Nb ratios of nephelinites relative to basanites are consistent with expected relative bulk distribution coefficients (D values) for Zr, Nb and La during partial melting ($D_{Zr} > D_{La} > D_{Nb}$).

The Zr/Nb ratios of the nephelinite dyke and phonolitic nephelinite (3.0, 3.3 respectively) signify an affinity with Quixaba Formation nephelinites (Figs. 7, 8), while the Zr/Nb ratio of the basanite dyke (4.1) suggests a relationship to the Quixaba basanites. The more evolved compositions (benmoreite, phonolites, trachytes) are less

Table 3. REE abundances in igneous rocks from Fernando de Noronha and Trindade

	Fernando de Noronha										Trindade						
	N		B		PN	Be	P		T		N		B		M	P	
	67089	67085	67097	67063	67113	67165	67056	67166	67129	67099	75357	75346	87171 915	87171 920	75348	87171 929	87171 949
La	71.7	82.0	70.4	121	104	87	77.0	103	100	122	150	159	70.6	64.3	110	131	64.7
Ce	154	162	152	237	172	117	103	107	184	175	342	307	151	123	198	226	99.6
Nd	71.1	70.6	72.2	94.0	58.8	34.5	24.0	17.0	66.7	38.4	157	118	74.1	52.4	73.8	70.9	27.7
Sm	13.7	13.2	14.3	16.4	9.9	5.39	3.09	1.54	11.1	4.51	29.2	19.7	13.4	10.1	11.6	10.4	3.65
Eu	3.91	3.84	4.08	4.59	2.94	1.59	0.97	0.36	3.13	1.34	8.25	6.08	4.26	3.17	3.67	3.24	1.25
Tb	1.58	1.60	1.68	1.94	1.20	0.63	0.44	0.20	1.31	0.54	3.08	2.17	1.58	1.23	1.41	1.24	0.55
Yb	2.01	1.96	1.78	2.56	2.10	1.46	1.72	2.22	3.43	2.20	3.54	3.49	2.06	1.88	2.65	2.94	1.80
Lu	0.27	0.30	0.25	0.39	0.31	0.21	0.25	0.35	0.55	0.36	0.51	0.54	0.29	0.31	0.41	0.47	0.29
Ce_N/Yb_N	19.5	21.1	21.7	23.6	20.9	20.5	15.2	12.2	13.7	20.2	24.6	22.4	18.7	16.7	19.0	19.6	14.1
La_N/Sm_N	3.2	3.8	3.1	4.6	6.5	10.0	15.4	41.4	5.6	16.8	3.2	5.0	3.3	3.9	5.9	7.8	11.0
Tb_N/Yb_N	3.3	3.5	4.0	3.2	2.4	1.8	1.1	0.4	1.6	1.0	3.7	2.6	3.3	2.8	2.3	1.8	1.3

N, nephelinite; B, basanite; PN, phonolitic nephelinite; M, mugearite; Be, benmoreite; P, phonolite; T, trachyte. Analyses by INAA at the University of Oklahoma

Fig. 6 A, B. Chondrite normalised (Nakamura 1974) REE patterns for Trindade igneous rocks: **A** basanites and nephelinites; **B** mugearite and phonolites
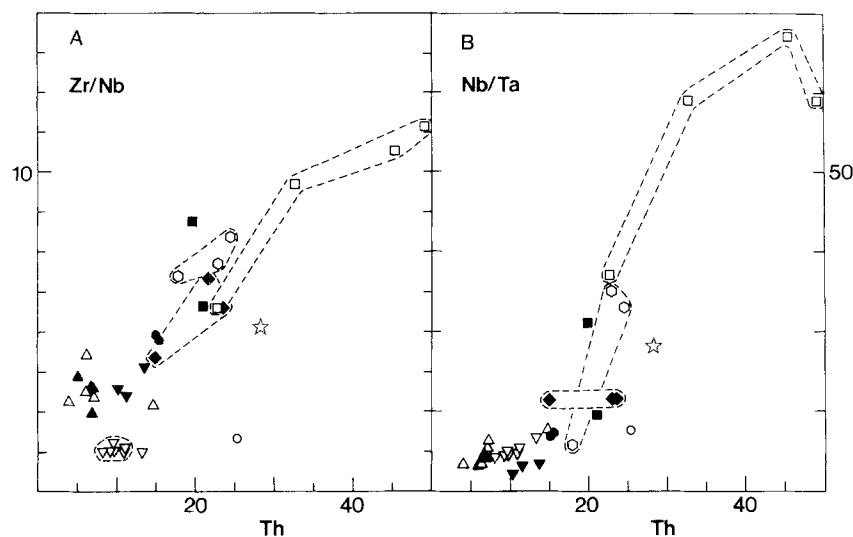
Fig. 7 A, B. Plots showing the variation of: **A** Zr/Nb; **B** Nb/Ta ratios with Th abundance (ppm) for igneous rocks from Fernando de Noronha and Trindade. Symbols as in Fig. 3
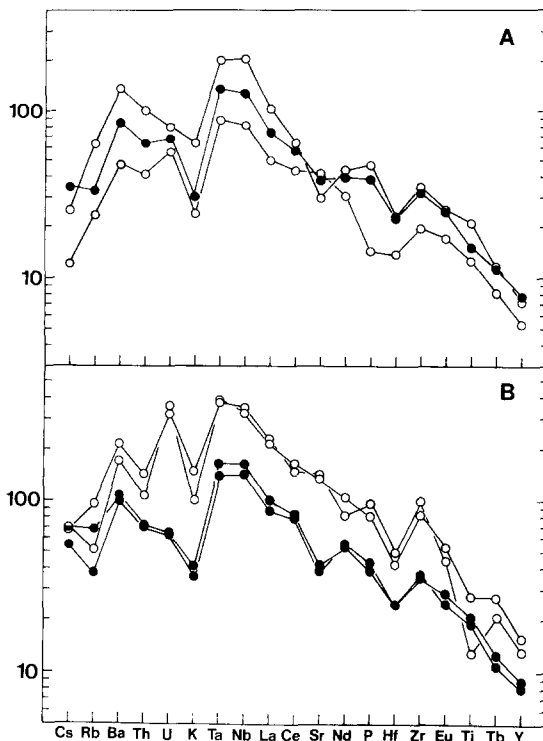
Fig. 8A, B. Primordial mantle normalised (Wood et al. 1981) incompatible trace-element patterns for Fernando de Noronha and Trindade basanites and nephelinites. A Fernando de Noronha basanites and nephelinites; B Trindade basanites (filled circles) and nephelinites (open circles)

easily associated with a particular liquid line of descent (from either basanitic or nephelinitic parents) using trace-element ratios, as strong trace-element fractionation occurs at moderate to advanced degrees of crystallisation. For example, Zr/Nb ratios in the benmoreite, phonolites and trachytes range from 6.1 to 11.1, higher ratios than in either potential parental magma (Figs. 7, 8).

The high field-strength (HFS) elements Zr, Nb, Hf and Ta behave highly incompatibly throughout crystallisation of mildly to moderately undersaturated oceanic island suites (e.g. Weaver 1987; Weaver et al. unpublished). Ratios of Zr/Hf and Nb/Ta are not significantly fractionated in Gough, Tristan da Cunha, St. Helena or Ascension trachytes and comendites relative to parental basalts and hawaiites. In contrast, in the highly undersaturated Fernando de Noronha and Trindade magmas, these element ratios become strongly fractionated even at moderate degrees of crystallisation. Niobium and Ta only behave incompatibly in nephelinitic and basanitic magmas, as illustrated by plots of Th (an index of fractionation) against Nb and Ta (Fig. 4a, b). Tantalum behaves more compatibly than Nb during moderate to advanced degrees of crystallisation, and Nb/Ta ratios increase from around 14 in basanites and nephelinites to very high ratios of around 67 in evolved phonolites (Fig. 7b). The decrease of Nb and, particularly, Ta abundances in moderately and highly evolved magmas (Fig. 4a, b) requires that $D_{Ta} > D_{Nb} > 1$. However, at the advanced degrees of crystallisation represented in the

evolved phonolites, Nb and Ta concentrations increase with Th, although only slightly so for Ta (Fig. 4a, b). Among the major phenocryst phases in the Fernando de Noronha suite, none are capable of producing such high Ds for, and strong relative fractionation of, Nb and Ta. However, experimental work has shown that $D_{Ta} > D_{Nb} > 1$ for sphene (Green and Pearson 1987), and a moderate increase in Nb/Ta ratios (up to values of 23) in phonolitic pumices from Tenerife compared to less evolved compositions was attributed to sphene control (Wolff 1984). The phonolitic Laacher See tephra (Worner et al. 1983; Worner and Schmincke 1984a, b) displays systematic internal variation in Nb/Ta ratios from values of 12–16 in the upper tephra, through 21–34 in the middle tephra, to 45–52 in the lower tephra. These increasing Nb/Ta ratios correlate with increasing Th abundances and increasing relative MREE depletion (Worner et al. 1984a). Sphene is a minor phenocryst phase in the phonolitic tephras (Worner et al. 1984a), the least-squares mixing calculations of Worner and Schmincke (1984b) requiring a maximum of 1.5% sphene fractionation during internal evolution of the Laacher See phonolite. Due to the very high partition coefficients in sphene for a number of otherwise incompatible trace elements (e.g. Worner et al. 1983; Lemarchand et al. 1987; Table 4), even small amounts of sphene crystallisation may control trace-element abundances and abundance ratios during fractionation of highly alkaline magmas. Sphene is a minor phenocryst phase in Fernando de Noronha phonolites and trachytes, and a significant cumulus phase in many of the cognate xenoliths found in lava flows (Almeida 1955).

Table 4. Distribution coefficients for incompatible trace elements between various mineral phases and alkaline melt

	Ol	Cpx	Plg	Kfsp	Amph	Bi	Mt	Ap	Sph
Rb	0.01	0.01	0.01	0.3	0.2	3	0.01	0.01	0.01
Ba	0.01	0.01	3.9	7	0.6	10	0.01	0.01	2.9
Sr	0.01	0.10	2.3	6	0.6	0.2	0.01	2.5	0.01
Th	0.01	0.04	0.01	0.01	0.03	0.04	0.01	1	5
Ta	0.01	0.34	0.01	0.01	1.1	0.30	0.52	0.01	98
Nb	0.01	0.1	0.01	0.01	1	0.30	0.52	0.01	45
Hf	0.01	0.39	0.01	0.01	0.9	0.08	0.09	0.01	10
Zr	0.01	0.27	0.01	0.01	0.77	0.08	0.09	0.01	4
La	0.01	0.25	0.28	0.10	0.78	0.02	0.01	14	22
Ce	0.01	0.51	0.14	0.04	1.5	0.02	0.01	24	44
Sm	0.01	3.7	0.10	0.01	4.9	0.03	0.01	95	126
Eu	0.01	5.9	1.4	0.01	5.7	0.03	0.01	102	112
Tb	0.01	3.8	0.06	0.01	5.2	0.03	0.01	41	135
Yb	0.02	1.2	0.01	0.01	1.8	0.04	0.01	8.8	31

Distribution coefficient values are those determined for mineral-melt partitioning involving alkaline melts. Literature sources for the data are; Kyle (1981), Villement et al. (1981), Worner et al. (1983), Irving and Frey (1984), le Roux (1985), Lemarchand et al. (1987). Values given in the table are average values from these sources; however, K_d values vary as a function of melt composition (e.g. Lemarchand et al. 1987). Where data are lacking, K_ds have been assumed based on mineral chemical controls and K_ds for elements with similar ionic charge/radius. Ol = olivine; Cpx = clinopyroxene; Plg = plagioclase; $Kfsp$ = K-feldspar; $Amph$ = amphibole; Bi = biotite; Mt = magnetite; Ap = apatite; Sph = sphene

Fernando de Noronha phonolites cannot reasonably be produced by crystal fractionation of nephelinitic parental magma. Abundances of highly incompatible elements such as Th and Rb are *higher* in the most evolved nephelinite than in the least evolved phonolite (Fig. 4). Fractionation from evolved nephelinite to phonolite would require that D_{Rb} and $D_{Th} > 1$, which is inconsistent with distribution coefficients for the observed phenocryst phases (e.g. Lemarchand et al. 1987; Table 4). A basanitic magma could be parental to the phonolites, as Fernando de Noronha basanites have lower incompatible trace-element abundances than phonolites (Fig. 4). That phonolitic magmas are the result of fractionation of parental basanites rather than nephelinites has been suggested for a number of highly undersaturated alkaline volcanic suites (Sun and Hanson 1976; Kyle and Rankin 1976; Kyle 1981; Worner and Schmincke 1984b; Garcia et al. 1986). Major element modelling of fractionation sequences from basanite to phonolite generally requires large amounts of clinopyroxene and/or amphibole crystallisation (Sun and Hanson 1976; Kyle 1981; Worner and Schmincke 1984b).

Among incompatible elements in the Fernando de Noronha suite, Rb and K_2O show the greatest increase from evolved basanite (67063) to least evolved phonolite (67056). Assuming that D_{Rb} approximates to zero, the increase in Rb abundance suggests that the phonolite could be derived by 43% crystallisation (fractionation interval (F) = 0.57) of basanite. Bulk distribution coefficients (Ds) calculated for other trace elements from this F are given in Table 5. Among the elements Th, Sr, Ba, Zr, Nb, Ta, and the REE, only Th, Ba and Zr behave

incompatibly (Table 5), the other elements having Ds > 1 (Table 5). For the REE, $D_{LREE} \approx D_{HREE} < D_{MREE}$. Table 4 contains a summary (from the literature) of trace-element partition coefficients for various phases in equilibrium with alkaline magma. Sphene crystallisation is the only mechanism capable of accounting for the behaviour of Nb and Ta during fractionation from basanite to phonolite; the calculated D_{Nb} and D_{Ta} values (Table 5) require 2–3% sphene crystallisation. The only phases with K_d (concentration in mineral: concentration in melt) = > 1 for the REE are clinopyroxene, amphibole, apatite and sphene (Table 4). Both clinopyroxene and amphibole strongly fractionate LREE from HREE ($D_{HREE} > D_{LREE}$), but cannot be the phases controlling REE partitioning, as Ce_N/Yb_N ratios show a slight decrease during fractionation from basanite to phonolite (Table 3). Only apatite and sphene have K_ds greater than unity for all REE, and which are also higher for the LREE than the HREE (Table 4). The P_2O_5 decrease from 67063 to 67056 requires crystallisation of a maximum of approximately 1.8% apatite (with 42% P_2O_5). If apatite were the only phase controlling REE partitioning, $D_{La} = 0.6$, $D_{Sm} = 4.1$ and $D_{Yb} = 0.4$ can be calculated from the K_d values in Table 4. These Ds are substantially lower than those required for this fractionation interval (Table 5), indicating that apatite alone is not controlling REE behaviour. If the TiO_2 decrease from 67063 to 67056 is controlled solely by sphene (which is unlikely, as clinopyroxene and opaques will also fractionate TiO_2), then a maximum of 6.4% sphene crystallisation is required. For this amount of sphene crystallisation, *maximum* values of $D_{La} = 3.3$, $D_{Sm} = 18.6$, and $D_{Yb} = 4.6$ are calculated from the distribution coefficients in Table 4. These values are two to four and a half times higher than the observed Ds (Table 5), indicating that lesser amounts of sphene crystallisation (< 3%) could control not only Nb and Ta, but also REE abundances during fractionation from basanite to phonolite. That Th has a significant D value for this fractionation interval is also consistent with sphene control; a D_{Th} of 0.22 (Table 5) would require approximately 2% sphene crystallisation for a sphene/liquid K_d of 5 for Th (Table 4). Sphene also fractionates Zr from Hf (Table 4), and Fernando de Noronha phonolites have higher Zr/Hf ratios than basanites (ratios of 64–77, 45 respectively).

Within Fernando de Noronha phonolites there is a significant range of fractionation. Rb is the incompatible element most strongly enriched in 67166 relative to 67056, and, assuming that D_{Rb} approximates to zero, the increase in Rb from least to most evolved phonolite implies 59% crystallisation. Calculated Ds (using F = 0.41) for other trace elements are given in Table 5. Thorium, Zr and Hf have low Ds of 0.18–0.24, while Nb, La and Yb behave more compatibly, with Ds of 0.71–0.74, and Ta, Nd, Sm, Tb and Eu are compatible, having Ds of 1.4–2.2 (Table 5). The very high Ds for both Sr and Ba (6.7, 8.5 respectively; Table 5) suggest that the crystallising assemblage in phonolitic magmas was dominated by K-feldspar, in accord with petrographic evidence. Crystallisation of only 0.3% apatite can account for the P decrease from 67056 to 67166, and such a

Table 5. Calculated bulk distribution coefficients for "incompatible" trace elements for the crystal fractionation of basanite to unevolved phonolite to evolved phonolite

	Basanite 67063 ⏐ (F = 0.57) ⏐ Phonolite 67056	Phonolite 67056 ⏐ (F = 0.41) ⏐ Phonolite 67166
	D	D
Ti	3.9	2.3
P	4.5	3.8
Th	0.22	0.23
Ba	0.36	8.5
Sr	1.3	6.7
Zr	0.41	0.18
Hf	0.98	0.24
Nb	1.2	0.71
Ta	2.6	1.4
La	1.8	0.71
Ce	2.7	0.99
Nd	3.4	1.4
Sm	4.0	1.8
Eu	3.8	2.2
Tb	3.6	1.9
Yb	1.7	0.74

For both fractionation intervals bulk distribution coefficients are calculated using F derived from the abundances of Rb in parent and daughter magmas and assuming that $D_{Rb} = 0$

small amount of apatite would only yield D_{Sm} of 0.29 using the K_d data in Table 4. If sphene controls Ti abundances, then 1.3% sphene (with 38% TiO_2) would be required to produce the Ti depletion in 67166. This would give $D_{Sm} = 1.6$ using the K_d data in Table 4, similar to the calculated value for the fractionation interval (Table 5). This proportion of sphene would satisfactorily account for the high calculated Ds for Nb and Ta (Table 5); 1.3% sphene would give $D_{Ta} = 1.3$, $D_{Nb} = 0.6$.

In contrast to the other Fernando de Noronha magma types, the benmoreite and trachytes are silica oversaturated. The relationship of these compositions to less evolved parental magmas is more obscure than for the phonolites, but the trachytes might be derived from similar parental basanite magmas by dominant amphibole fractionation, as opposed to clinopyroxene + amphibole fractionation in the case of the phonolites. The least evolved trachyte could be derived by approximately 50% crystallisation of evolved basanite, based on Rb or Zr abundances and $D_{Rb,Zr} = 0$. Abundances of Nb and Ta increase in this fractionation interval (Fig. 4a, b), suggesting a negligible role for sphene. There are, however, a number of difficulties with such a model, the major problem being that Th increases only moderately for this fractionation interval. Within the three trachyte samples, with increasing Rb or Th abundances there are trends towards decreasing Nb and Ta abundances (Fig. 4a, b), but increasing Nb/Ta ratios (Fig. 7b), and decreasing Zr abundances (Fig. 4c). Sphene must have been a significant minor phase during crystallisation of the Fernando de Noronha trachytes.

Trindade

There are no significant differences in incompatible trace-element ratios between Trindade nephelinites and basanites (Zr/Nb ratios 3.9–5.1 in both). The high MgO, Ni, Cr, Co and Sc contents of the basanites (allowing for phenocryst content) imply that they have undergone relatively little crystal fractionation; on the other hand, low abundances of these elements in Trindade nephelinites require extensive crystal fractionation. The nephelinites and basanites are not, however, easily related by crystal fractionation. For example, Th abundances are slightly less than a factor of two greater in nephelinites compared to basanites, while Nb, Ta, Zr and Hf are over a factor of two higher, and Sr abundances are over a factor of three higher (see Fig. 4); all of these elements should display similar enrichment during crystal fractionation. Trindade basanites and nephelinites are most likely derived from similar sources by different degrees of melting, and have undergone different degrees of crystal fractionation (a smaller degree of melting but greater crystal fractionation in the case of the nephelinites).

Relationships between Trindade basanites and nephelinites and evolved phonolites are similar to those on Fernando de Noronha, and suggest a fractionation sequence from basanite to mugearite to phonolite. The high abundances of Nb, Ta, Zr and Hf in Trindade nephelinites make them unsuitable parents to the phonolites because of the unrealistically high Ds required during crystal fractionation. Ratios of Nb/Ta are high in Trindade phonolites (about 30) compared to basanites (about 14), but are not as extreme as in Fernando de Noronha phonolites. Nevertheless, the trace-element characteristics of Trindade phonolites (moderate MREE depletion relative to LREE, HREE; compatible behaviour of Nb, Ta) require that sphene crystallisation played a key role in controlling trace-element fractionation during the evolution of Trindade magmas. Although Trindade and Fernando de Noronha basanites have similar trace-element characteristics (Figs. 4, 7, 8), the less evolved Trindade phonolites have, at an equivalent degree of fractionation, higher Nb and Ta abundances than Fernando de Noronha phonolites (Fig. 4a, b), implying a lesser proportion of sphene in the crystallising assemblage of Trindade magmas.

The similar overall chemical characteristics of the Trindade and Fernando de Noronha suites suggests a comparable petrogenetic evolution. Regardless of the effect of the major crystallising phases on trace-element partitioning, the trace-element characteristics of evolved compositions in these highly undersaturated suites are controlled by minor phases, and specifically by sphene crystallisation. Distribution coefficients for many "incompatible" trace elements (REE, Nb, Ta, Zr, Hf) are sufficiently high in sphene (Table 4) that even a few percent sphene in the crystallising assemblage will dominate the bulk distribution coefficient for these elements, and cause severe trace-element fractionation in evolved rock types. Amphibole, clinopyroxene and opaques are commonly considered to exert the dominant control on incompatible-element partitioning in alkaline suites; this clearly is not the case in highly undersaturated alkaline suites.

Comparison to other South Atlantic Ocean islands and constraints on mantle sources for Fernando de Noronha and Trindade basanites and nephelinites

The volcanics of Fernando de Noronha and Trindade are highly alkaline and strongly undersaturated relative to those of other South Atlantic Ocean islands such as Ascension, Bouvet, Saint Helena, Gough and Tristan da Cunha (Weaver et al. 1987), which are only mildly or moderately undersaturated. There is no isotopic evidence for fundamentally different mantle sources for Fernando de Noronha or Trindade magmas compared to those of South Atlantic hot-spots such as Ascension or Bouvet. The highly undersaturated magmatism of Fernande de Noronha and Trindade is most simply related to a lower degree of partial melting than is involved in the genesis of these other South Atlantic Ocean OIB suites. Fernando de Noronha and Trindade volcanics are similar compositionally in many respects to those of the Cape Verdes archipelago (Gunn and Watkins 1976; Gerlach et al. 1988).

For low degrees of partial melting, incompatible trace-element ratios of melts may become significantly fractionated from those of the source. In addition, minor

Table 6. Comparison of trace element ratios of Fernando de Noronha and Trindade basanites with basalts and hawaiites of other South Atlantic Ocean islands

	$\dfrac{Zr}{Nb}$	$\dfrac{Ce_N}{Y_N}$	$\dfrac{La}{Nb}$	$\dfrac{Ba}{Nb}$	$\dfrac{Th}{Ta}$	$\dfrac{Ba}{La}$	$\dfrac{La}{Th}$	$\dfrac{Nb}{Ta}$	$\dfrac{Th}{U}$	$\dfrac{Ba}{Th}$
Fernando de Noronha[a]	4.5	8.7	0.69	8.9	1.08	12.9	9.5	15.0	3.76	123
	0.1	1.9	0.02	1.1	0.03	1.2	0.9	1.5	0.35	20
Trindade[b]	4.3	8.9	0.72	8.5	1.05	11.8	9.8	14.4	3.92	116
	0.4	1.2	0.01	0.3	0.10	0.5	0.8	0.3	0.01	5
Ascension	5.3	4.6	0.65	6.8	1.05	10.3	8.7	14.0	3.54	92
	0.4	0.5	0.04	0.5	0.09	1.2	1.0	0.4	0.17	12
Bouvet	6.9	3.9	0.68	6.0	1.00	8.9	9.3	13.7	3.68	83
	0.3	0.1	0.04	0.3	0.03	0.4	0.4	0.2	0.19	4
St. Helena	4.5	7.3	0.69	5.9	1.09	8.7	8.9	14.0	3.78	77
	0.2	0.9	0.03	0.2	0.07	0.7	0.5	0.4	0.10	8
Gough	6.8	8.0	0.97	16.1	1.47	16.6	9.1	14.1	4.86	154
	0.8	0.9	0.13	2.8	0.15	1.6	0.6	0.4	0.28	20
Tristan da Cunha	4.2	10.8	0.86	11.4	1.50	13.2	7.8	13.9	4.50	103
	0.4	1.2	0.06	0.8	0.12	0.7	0.8	0.5	0.08	12

[a] Fernando de Noronha averages calculated from 3 basanites
[b] Trindade averages calculated from 2 basanites
First line is average ratio, second line is one sigma standard deviation

phases (e.g. phlogopite, amphibole) capable of strongly fractionating some incompatible trace-element ratios may be residual at low degrees of melting. Incompatible trace-element abundances and ratios must, therefore, be carefully assessed in interpreting the petrogenesis of highly undersaturated OIB suites. The incompatible trace-element ratios of Fernando de Noronha and Trindade nephelinites and basanites are compared to those of basalts and hawaiites from other South Atlantic Ocean islands in Table 6. Relative to the other islands (except Tristan da Cunha), Fernando de Noronha and Trindade basanites have high Ce_N/Y_N ratios (8.7–8.9) attributable to a smaller degree of partial melting. Assuming that the REE characteristics of the source of Fernando de Noronha magmas are similar to that modelled for Massif Central alkali basalts (Chauvel and Jahn 1984) and observed for St. Paul's Rocks (Roden et al. 1984), with $La_N/Yb_N \approx 10$ and $Yb_N \approx 2$, the REE abundances in Fernando de Noronha basanites can be produced by about 8% melting, leaving a residue of 65% ol +20% opx +12% cpx +3% gt (distribution coefficients from Frey et al. 1978). A less REE-enriched source would obviously require lower degrees of melting.

Among the South Atlantic islands of Ascension, Bouvet, St. Helena, Gough and Tristan da Cunha, Weaver et al. (1986; 1987) identified significant trace-element ratio differences between the isotopically anomalous EMI OIB of Gough and Tristan da Cunha, and the isotopically more typical OIB of Ascension and Bouvet. In particular, Gough and Tristan da Cunha lavas display a lack of enrichment in Nb and Ta, and enrichment in Ba compared to abundances of other highly incompatible trace elements (Weaver et al. 1987). This is manifested in Table 6 by high values for La/Nb, Th/Ta, Ba/La, Ba/Th and, particularly, Ba/Nb ratios in Gough and Tristan lavas compared to Ascension and Bouvet lavas, although for Tristan the effects are somewhat moderated

by low degrees of melting (Weaver et al. 1987). These characteristics of Gough and Tristan da Cunha lavas were attributed by Weaver et al. (1987) to contamination of the OIB source by a component depleted in Nb and Ta and enriched in Ba, and identified as ancient pelagic sediment. Fernando de Noronha and Trindade basanites and nephelinites display enrichment in Nb and Ta relative to abundances of other highly incompatible trace elements (Table 4; Fig. 8), consistent with derivation from a "typical" Nb-Ta enriched OIB source rather than the "anomalous" (DUPAL) source which gave rise to Gough and Tristan da Cunha volcanism. This is in accord with the Sr, Nd and Pb isotopic signatures of Fernando de Noronha and Trindade volcanics (Sun 1980; Gerlach et al. 1987), which are similar overall to those of Ascension and Bouvet volcanics. However, the fine-scale isotopic heterogeneity recognised among Fernando de Noronha volcanics by Gerlach et al. (1987) implies mixing of perhaps three isotopically discrete mantle sources, one of which may be similar to the St. Helena HIMU source. It is not possible to make such a fine discrimination of source characteristics with the present trace-element data for the Fernando de Noronha samples (which, unfortunately, have relatively poor stratigraphic control).

Some features of the primordial mantle normalised incompatible element patterns of Fernando de Noronha and Trindade basanites and nephelinites (Fig. 8) are suggestive of trace-element fractionation caused by a residual minor mantle phase(s). Such patterns for Ascension and Bouvet basalts and hawaiites are smooth in the segment from Nb(Ta) to Rb, with normalised abundances generally decreasing with increasing incompatibility (Weaver et al. 1987). Fernando de Noronha and Trindade nephelinites and basanites, however, display marked depletion in K compared to other incompatible trace elements in Fig. 8, consistent with the presence of

a residual minor K-bearing phase in the source region (also noted by Gerlach et al. (1987) for Fernando de Noronha, and by Gerlach et al. (1988) for highly under-saturated Cape Verde lavas). Such relative K depletion is also seen in St. Helena HIMU OIB (Weaver et al. 1987), and may be a characteristic of the HIMU source. The magnitude of the K depletion is, however, greater in Fernando de Noronha and Trindade OIB, implying that any K depletion at source (a function of a HIMU component, as indicated by isotopic evidence) was enhanced during partial melting, and the presence of a residual K-bearing minor phase is still required at small degrees of melting. In addition, Ba enrichment relative to Rb, Th and U is evident in Fig. 8, producing a variable Ba "spike" in the patterns, in contrast to the patterns for Ascension, Bouvet or St. Helena OIB (Weaver et al. 1987) which show coherent behaviour of a Ba with Rb, Th and U. Relative Ba enrichment is explicable if D_{Rb}, D_{Th} and D_U are somewhat enhanced over D_{Ba} at low degrees of melting, perhaps indicative of a role for residual phlogopite rather than amphibole (K_d data of Philpotts and Schnetzler 1977) in the source (as also argued by Gerlach et al. 1988). Ratios of La/Nb and Th/Ta are comparable in Fernando de Noronha and Trindade basanites relative to Ascension, Bouvet and St. Helena basalts and hawaiites (Table 6), but Ba/Nb, Ba/La, Ba/Th and La/Th ratios are somewhat elevated (Table 6; Ba/Rb, Nb/Rb ratios are also higher). This suggests that, for variable degrees of melting of sources with similar incompatible-element ratios, at low degrees of melting Ba behaves more incompatibly than La and Nb, which behave more incompatibly than Th and Rb. This is unlikely to be simply a function of degree of melting (although this may be a factor), but is more likely related to the presence of residual phlogopite at the lower degree of melting, and indicates that phlogopite may also exert a mild fractionating effect on the LREE and HFS elements.

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