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The volcanic-subvolcanic rocks of the Fernando de Noronha Archipelago, southern Atlantic Ocean: Mineral chemistry

Topical issue

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Abstract: Fernando de Noronha archipelago presents an older Remédios Formation with subvolcanic intrusions, belonging to two different alkaline series, the sodic (undersaturated: basanites, tephrites, essexites, tephriphonolites, phonolites), and potassic ones (mildly undersaturated to silicic, with alkali basalts, basaltic trachyandesites, trachyandesites, trachytes), and lamprophyres. The upper Quixaba Formation presents nephelinite flows and basanites. A third minor unit, São José, is constituted by basanites carrying mantle xenoliths. Magnesian olivines occur in the Remédios basanites and alkali basalts, and in nephelinites. Melilites are present as groundmass grains in melilite melanephelinites (MEM). Clinopyroxenes (cpx) are mostly salites to titaniferous salites (Remédios sodic series), grading into aegirines in the differentiated aphyric phonolites. Cpx in the lamprophyres show disequilibrium textures. In the Quixaba flows, cpx are salites, enriched in Mg (especially in MEM). Amphiboles, remarkably, are common in tephriphonolites and phonolites and in basaltic trachyandesites, sometimes with disequilibrum zoning textures, and a conspicuous phase in lamprophyres. Dark micas are present as groundmass plates in MEM, OLM and PYM (olivine and pyroxene melanephelinites), with compositional variety (enriched in Ti, Ba, Sr) depending on the composition of the parent rock; BaO can be as high as 16-19%. Feldspars crystallize as calcic plagioclases, sanidines and anorthoclases, depending on the rock types, as phenocrysts and in groundmass, both in Quixaba and Remédios rocks; they are absent in nephelinites. Nephelines are found in Remédios sodic series types and Quixaba rocks. Haüyne and noseane are rarely observed in Remédios rocks.

Keywords: OIB • south Atlantic Ocean • mafic and felsic minerals in volcanic rocks

1. Introduction

Fernando de Noronha (FN) constitutes an archipelago in the South Atlantic Ocean, situated at longitudes 32°28′ to 32°24′ west and latitudes 3°52′ to 3°50′ south, at a distance of 345 km from the closest mainland, the Brazilian

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Figure 1. Geologic outline of the Fernando de Noronha Archipelago (after Almeida [3], much simplified). I: Ilha; B: baia; Ens.: enseada; Pr: praia (in the text, rock locations are broadly characterized by geographic names; for a complete list of collected samples, cf. [1]]). A detailed version of this map can be found in [1, 2, 6].

state of Rio Grande do Norte.

The FN group of islands covers 18 km^2, and presents a main island (over 16 km^2, with a general NE-SW orientation) and several smaller ones (Cuscuz, São José, Rasa, Sela Gineta, do Meio, Rata), mainly scattered around the NE border of the main island.

FN is mainly composed of saturated to undersaturated alkaline rocks of a particular kind, the "OIB's", sharing these petrographic characteristics with many within-plate oceanic islands, such as the Azores, Madeira, Canary islands, Cape Verde, Trindade, Ascensão, St. Helena and Tristan da Cunha, all emplaced outside of the mid-ocean ridge crossing de South Atlantic [1, 2].

The initial monograph on FN is a classic work of geologic craftsmanship prepared by Fernando de Almeida [3], resulting in an outstanding map and the first complete description of the large variety of alkaline rocks found in that region (Figure 1). A further development was the work by Cordani [4], attempting to date the rocks observed on the islands (K-Ar method), indicating a rather wide time gap of several Ma between the two main mapped stratigraphic units.

The region received the sporadic visit of several geologists who contributed mainly with data about geochemistry and isotope relations, thus providing information to speculate on origin and evolution of the special rock types found on the islands (cf. bibliography in [2, 5, 6]).

This contribution on the mineral chemistry of the rock-forming minerals in FN is a complement to a paper dealing with petrography and geochemistry [2]. An initial report on the petrography, geochemistry and mineralogy of more melanocratic varieties in FN was presented in a Brazilian journal [7].

2. Geologic and petrographic outline

The rock types present in FN [2–4, 6] were grouped as two main stratigraphic units, the older Remédios Formation and the younger Quixaba Formation, clearly divided by the erosional surface that separates them (Figure 1). The Remédios Formation is mainly pyroclastic, massively invaded by several plugs and dikes of varied alkaline rocks (basanites and related types, phonolites, lamprophyres), while the Quixaba Formation presents melanocratic rocks (basanite and melanephelinite flows). Almeida added a minor third unit, constituted by the basanites of the São Jose Formation, only outcropping on the São José and Cuscuz islands, characterized by the presence of abundant mantle fragments (petrographic data in [1, 2, 8, 9]; for description of mantle xenoliths, see [10, 11]).

The first K-Ar determinations yielded for the Remédios Formation ages between 12 and 8 Ma (Miocene), while Quixaba rocks were emplaced mostly at ages around 3 to 2 Ma (Pliocene), with the youngest age around 1.4 Ma [4]. The São José rocks yielded ages around 9.5 Ma, perhaps on account of the presence of excess Ar, due to a possible contamination of the magmas with partially degasified mantle rocks. Ages cited in more recent work (whole rock K-Ar and high resolution Ar-Ar methodologies, [6]) indicate that the Remédios event erupted between 12.4 and 9.4 Ma, the Quixaba rocks between 6.2 and 1.3 Ma, while older ages were found for the São José basanites (9.2 to 9.0 Ma), therefore coeval with the Remédios event.

The many rock types found in FN will be named according to newer nomenclature, following LeMaitre 2002 [12]; cf. also [8, 9]. Detailed rock descriptions of lamprophyres and phonolites can be found in [13, 14].

The Remédios Formation, with its basal unit of pyroclastics, is intruded by several plugs and domes of three petrographic types of phonolites, a sill-like body of essexite and a small plug of alkali basalt (cf. [12, 14]) and also by dozens of dikes, with early basanites and related rocks such as tephrites, basaltic trachyandesites, trachyandesites, trachytes, tephriphonolites [1] as well as four different types of lamprophyres ([1, 2, 13]). The Remédios Formation presents also fresh plutonic xenoliths, intermingled with finer-grained pyroclastic material, that represent cogenetic products of cumulate crystallization in deeper-seated magma chambers [15].

The Remédios rocks are divided into two different geochemical series, a dominant undersaturated sodic (with predominance of Na_2O over K_2O) and a subordinate moderately potassic one, the second with a tendency for oversaturation, as also observed in several oceanic settings [8, 16–20]. The sodic series is constituted by the sequence basanites-tephrites-essexites-tephriphonolites - phonolites, the moderately potassic series by alkali basalts, trachyandesites and trachytes, trending from ne-normative rock types (alkali basalt) to slightly oversatured qz-normative trachytes (cf. [1], p. 29; [2]).

The Remédios lamprophyres were divided on strictly petrographic grounds as follows: type I, with a mainly glassy groundmass and abundance of amphibole phenocrysts; type II: groundmass with plagioclase and alkali feldspar, with clinopyroxene phenocrysts more abundant than amphibole; type III: similar to former type, with little or no feldspars, and a predominantly glassy groundmass with some dark mica; type IV: groundmass with predominant sanidine, and significant amounts of clinopyroxene phenocrysts and amphiboles, as well (cf. [21], also [13], [1]). Chemically, these rocks constitute types that are unrelated to the sodic and potassic series (cf. geochemistry in [2]).

The petrographically more uniform Quixaba Formation consists mainly of subhorizontal flows showing dark biotite-bearing melanephelinites (the ankaratrites of Almeida 1955 [2]; cf. also [22], for a modern reference to the original rock from Madagascar) and associated basanites, which can be separated from the earlier (and scarcer) Remédios basanites by their geologic positions: Quixaba basanites are observed usually as interstatified units within the nephelinite flows, and may be rare as intrusive dike rocks.

3. Mineral chemistry

The data on mineral chemistry will be presented here in a summary fashion, with proper identification of the different rocks in which these minerals are found; data previously presented on the Quixaba mineralogy in [7] will also be used, whenever necessary, especially when a comparison with the Remédios phases is in order. Detailed information on the mineralogy and petrography of the main FN rock types are summarized in [1]; additional details on phonolites and lamprophyres can be found in earlier work in [14] and [13]. Tables 1 to 9 present selected analytical determinations of the main rock-forming minerals in FN, retrieved from a complete set available in [1], also incorporating information on feldspars and nephelines cited in [14].

Analytical tasks were performed with the Jeol JXA Superprobe, model 8600S, at the Microprobe Laboratory of the Instituto de Geociências, USP, equipped with 5 wavelengths and 1 energy-dispersive spectrometers, and automated by the Thermo-Noran Voyager 4.3.1. system. The analysed minerals were olivines, melilites, pyroxenes, micas, amphiboles, spinels and some ilmenites, feldspars, and nephelines with some other feldspathoids (sodalites, analcimes). Normal analytical conditions were as follows: 15 kV accelerating voltage, electron beam current of 20 nA, beam diameter of 10 μm for the feldspars and felspathoids (5 μm for the other minerals), counting time of 10 sec, with corrections (drift, counts) performed on line with the PROZA software system. For mica analysis, the conditions were as follow: 15 kV accelerating voltage, 20 nA beam current, and 10 or 30 s counting time (major or minor elements, respectively); the setup was controlled to insure minimum interference between the Ti$K\alpha$ and Ba$L\alpha$ peaks.

The calculation of end-member proportions was mostly performed using the MINPET program. In some cases, data sheets were prepared using stoichiometry for these calculations (melilites, oxides, feldspathoids). Most oxide data are considered to be valid within $\pm$1-2% (major elements) or $\pm$5-10% (minor elements). Many micas enriched in BaO (and F), however, show discrepancies (totals around 100%) which are due to difficulties in finding adequate reference materials for data acquisition (even so, stoichiometric considerations do show that the data for these phases behave according to crystallochemical rules; cf. diagrams for micas, below; also [7]). The best data, selected from [1], are presented in Tables 1 to 9 (cf. below).

The number of analysed grains were as follows: 69 olivines, 50 melilites, 370 pyroxenes, 217 micas, 74 amphiboles, 167 magnetites and ilmenites, 205 feldspars, and 153 feldspathoids (mainly nephelines). As a guideline for acceptance of microprobe analysis incorporated into our Tables of mineral chemistry, the following values were (loosely) adopted: for feldspars, olivines and pyroxenes, oxide totals between 99 and 101%; for amphiboles, totals below, or close to, 97.5%; for spinels, corrected totals below, or close to, 98.5%; for micas, totals not over 99.5% (some analysis, close enough to these values, were however listed in our mineral chemistry tables).

3.1. Olivines

Olivines, both as (micro)phenocrysts and groundmass grains, are present in the more magnesian and basic rocks of FN, especially in the basanites (sodic series) and the alkali basalt (moderately potassic series) of the Remédios Formation, and mostly in samples from the Quixaba Formation as well as in the São José basanites (cf. Table 1).

The Remédios olivines are magnesian varieties (Fo_{86} to Fo_{82}), with CaO from around 0.20 to 0.60%, and very little

Table 1. Selected chemical analyses of olivines, Fernando de Noronha.

Rock	Bas[a]	Bas	Bas	Abas	MEM[b]	OLM	OLM	OLM	PYM	PYM	Bas
Sample	97FN15a	97FN15a	97FN23	97FN35b	UCFN37	97FN20	97FN58a	97FN58a	97FN8	97FN14	89FN78a
Grain	Mphen[c]	Phen**[d]	Phen**	Mphen	Mphen	Mphen	Phen*	Phen**	Phen	Grmass[e]	Mphen
SiO_2	39.83	38.72	39.53	37.77	39.63	39.78	39.96	39.76	39.43	37.11	39.67
TiO_2	0.09	0.02	0.04	0.03	0.05	0.08	0	0	0.04	0.02	0.01
Al_2O_3	0.03	0.17	0.04	0.03	0.03	0.04	0.03	0.07	0.04	0.04	0.03
FeO	14.04	15.25	17.19	25.61	15.01	14.65	16.55	16.2	15.83	25.99	14.93
MnO	0.17	0.23	0.28	0.71	0.26	0.26	0.27	0.34	0.25	0.7	0.19
MgO	46.18	43.79	43.42	36.5	44.92	45.61	43.18	43.14	44.14	35.97	43.93
CaO	0.29	0.78	0.3	0.28	0.32	0.48	0.08	0.33	0.28	0.38	0.2
Na_2O	0.04	0.07	0.04	0	0.01	0.01	0.01	0.01	0.03	0.01	0.03
NiO	0.21	0.2	0.15	0.04	0.08	0.05	0.13	0.09	0.2	0.01	0.25
Cr_2O_3	0.02	0.05	0	0	0	0.02	0.04	0	0.03	0	0
Total	100.88	99.28	100.98	100.96	100.3	100.97	100.34	99.42	100.24	100.23	99.24
Si	0.989	0.986	0.994	0.991	0.994	0.989	1.007	1.005	0.994	0.985	1.004
Al	0.001	0.005	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001
Ti	0.002	0	0.001	0.001	0.001	0.001	0	0	0.001	0	0
Fe^{2+}	0.291	0.325	0.362	0.562	0.315	0.305	0.351	0.342	0.334	0.577	0.318
Mn	0.004	0.005	0.006	0.016	0.006	0.006	0.006	0.007	0.005	0.016	0.004
Mg	1.709	1.662	1.628	1.428	1.679	1.692	1.622	1.628	1.658	1.423	1.658
Ca	0.008	0.021	0.008	0.008	0.009	0.013	0.002	0.009	0.008	0.011	0.005
Na	0.002	0.004	0.002	0	0	0	0	0.001	0.001	0.001	0.001
Ni	0.004	0.004	0.003	0.001	0.002	0.001	0.003	0.002	0.004	0	0.005
Cr	0	0.001	0	0	0	0	0.001	0	0.001	0	0
mg#	85.45	83.64	81.81	71.76	84.2	84.73	82.21	82.62	83.23	71.15	83.99

Rock	Bas[f]	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas
Sample	99FN4	99FN4	99FN9c	99FN10a	99FN10b	99FN10b	99FN10b	99FN22	99FN22
Grain	Phen	Phen	Grmass	Phen	Mphen	Grmass	Phen	Mphen	Mphen
SiO_2	39.02	40.07	37.14	37.74	37.35	37.47	37.76	39.87	39.5
TiO_2	0.02	0.03	0.1	0.07	0	0.09	0.05	0.03	0.01
Al_2O_3	0.02	0.03	0.06	0.02	0.02	0.23	0.04	0.04	0.02
FeO	13.67	13.43	25.88	25.82	26.81	27.3	25.3	16.09	17.01
MnO	0.2	0.16	0.51	0.47	0.53	0.52	0.48	0.24	0.24
MgO	46.77	45.08	35.46	35.86	35.01	34.53	36.27	44.28	43.12
CaO	0.18	0.19	0.48	0.33	0.42	0.4	0.39	0.36	0.43
Na_2O	0	0	0.03	0	0.03	0.02	0.02	0	0
NiO	0.2	0.21	0	0	0.11	0.07	0.16	0.08	0.13
Cr_2O_3	0.03	0.02	0.01	0	0	0.02	0.03	0	0
Total	100.11	99.21	99.67	100.31	100.28	100.64	100.5	100.99	100.45

[a]Bas, abas: basanite, alkali basalt.
[b]MEM, OLM, PYM: melilite, olivine, pyroxene melanephelinites.
[c]Mphen: microphenocrysts;
[d]Phen: phenocryst; Phen*, Phen **: core and border of phenocryst.
[e]Grmass: groundmass;
[f]Bas: basanites. Phen, Mphen, Grmass: pheno-, microphenocryst, groundmass.

Table 1. Contd.

Rock	Bas[a]	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas
Sample	99FN4	99FN4	99FN9c	99FN10a	99FN10b	99FN10b	99FN10b	99FN22	99FN22
Grain	Phen	Phen	Grmass	Phen	Mphen	Grmass	Phen	Mphen	Mphen
Si	0.977	1.007	0.99	0.997	0.994	0.994	0.994	0.997	0.998
Al	0.001	0.001	0.002	0.001	0.001	0.007	0.001	0.001	0
Ti	0	0	0.002	0.001	0	0.002	0.001	0.001	0
Fe^{2+}	0.286	0.282	0.577	0.57	0.596	0.606	0.557	0.336	0.359
Mn	0.004	0.003	0.011	0.011	0.012	0.012	0.011	0.005	0.005
Mg	1.745	1.689	1.409	1.412	1.389	1.366	1.424	1.651	1.624
Ca	0.005	0.005	0.014	0.009	0.012	0.011	0.011	0.01	0.012
Na	0	0	0.002	0	0.002	0.001	0.001	0	0
Ni	0.004	0.004	0	0	0.002	0.001	0.003	0.002	0.003
Cr	0.001	0	0	0	0	0	0.001	0	0
mg#	85.92	85.69	70.95	71.24	69.97	69.27	71.88	83.09	81.9

[a]Bas: basanites. Phen, Mphen, Grmass: pheno-, microphenocryst, groundmass.

NiO (less than 0.21%) and Cr_2O_3 (usually below 0.05%). They are relatively fresh in the basanites, but mostly altered in the alkali basalt. Some of the phenocrysts in Remédios basanites show a slight zoning, resulting in somewhat more magnesian cores. In the Quixaba rocks, olivines are usually very homogeneous, with compositions around Fo_{84-82} in MEM, and slightly more magnesian in the OLM and PYM. In the São José basanites, predominant olivines present Fo_{70} (Cuscuz) to Fo_{81-83} (São José); CaO may be as high as 0.50 to 0.33, with low values of NiO (less than 0.2%) and Cr_2O_3 (around 0.02 to 0.06%). The São José basanites, carrying mantle xenoliths, present less magnesian olivines than the Remédios equivalents (cf. data in Table 1). A certain correlation between Quixaba bulk rock chemistry and olivine composition can be observed, such as in CaO-MnO contents, and SiO_2 and CaO abundances in relation to *mg#* (for Fe^{2+}-Mg partitioning, cf. [23]; see diagram in [1]).

This limited set of data is an indication that the Remédios magmas may be mostly the result of crystal fractionation in deeper magma chambers, eventually generating the whole set of diverse rock types, as made clear by considerations on rock chemistry (cf. [2]), while the Quixaba types may represent pristine magma flowing directly to the surface, with little or no fractionation induced by crystal settling at depth.

3.2. Melilites

Minerals of the melilite group seem to be stable with a limited number of coexisting phases, such as olivines and pyroxenes, and apparently also with feldspars and feldspathoids enriched in K_2O (e.g., [24–28]). The melilites in samples with less than 2% modal (Table 2, Figure 2) are usually richer in Al_2O_3, Na_2O, SrO and BaO and lower in CaO and MgO than the grains contained in rocks with plenty of melilite (up to almost 10% modal) and less olivine content. The melilite grains are usually homogeneous. In a few instances zoning was detected, measurements indicating that the cores were somewhat higher in SrO, the borders somewhat enriched in CaO, Al_2O_3 and Na_2O, at the same time presenting a decrease in MgO towards the border, coupled with FeO increase (Table 2). The same pattern is observed as a general compositional trend (Figure 2): increases in Na_2O , Al_2O_3, FeO and SrO are generally coupled with decrease in MgO and CaO, which both show a positive correlation.

There is a grouping of cation data points in melilites of different samples, as made clear in the abundances of major oxides (e.g., Al_2O_3, FeO, and Na_2O) as well as a minor one (SrO), which probably reflects the control of bulk rock composition on melilite crystallization (Figure 2). Peg textures are rather frequently observed in altered melilites of various Quixaba rocks, probably caused by a complex mechanism by which the grains are enriched in K, Si, Al and Fe, with extraction of Ca and Mg [29].

End member contents vary mostly from 61 to 68% akermanite, 10 to 13% ferro-akermanite, 20 to 27 % sodic melilite and around 1-2 % gehlenite (Table 2), typical compositions found in other OIB volcanic rocks.

Table 2. Selected chemical analyses of melilites, Fernando de Noronha.

Rock	Melilite melanephelinites, Quixaba Formation									
Sample	97FN31	99FN21b	99FN25	99FN25	99FN62	99FN63	99FN63	99FN63	UCFN37	UCFN47
Grain	Mphen*[a]	Grmass	Mphen*	Mphen**	Mphen*	Mphen*	Grmass	Mphen*	Mphen*	Mphen*
SiO_2	42.99	42.98	41.76	42.03	43.02	42.86	42.58	42.44	42.43	42.91
TiO_2	0.08	0.16	0.2	0.14	0.12	0.17	0.19	0.2	0.09	0.08
Al_2O_3	6.71	5.77	7.65	6.79	7.32	6.25	7.14	6.03	6.27	6.64
FeO	3.9	3.89	3.51	3.78	3.68	4.16	4.04	4.26	3.86	3.28
MnO	0	0.06	0.11	0.11	0.07	0.1	0.1	0.07	0.05	0.11
Mgo	7.34	8.46	7.19	7.49	7.54	8.36	7.62	8.03	7.74	7.73
CaO	32.26	34.09	33.36	32.84	32.86	34.2	33.21	33.64	33.68	34.18
Na_2O	3.84	3.19	4.12	3.98	3.84	3.27	3.7	3.36	3.51	3.78
BaO	0.2	0.05	0.13	0.18	0.26	0.09	0	0.48	0.29	0
SrO	0.94	0.53	0.96	1.03	1.22	0.63	0.6	1.03	0.83	0.72
K_2O	0.15	0.12	0.12	0.12	0.11	0.14	0.38	0.11	0.13	0.14
Total	99.53	99.28	99.11	98.49	100.02	100.23	99.56	99.64	98.88	99.58
Si	3.951	3.95	3.859	3.91	3.928	3.913	3.905	3.92	3.933	3.931
Al	0.727	0.625	0.833	0.744	0.787	0.672	0.771	0.656	0.685	0.717
Ti	0.005	0.011	0.014	0.01	0.008	0.012	0.013	0.014	0.006	0.006
Fe^{2+}	0.299	0.299	0.271	0.294	0.281	0.317	0.31	0.329	0.299	0.251
Mn	0.01	0.004	0.009	0.009	0.005	0.008	0.008	0.005	0.004	0.009
Mg	1.005	1.159	0.99	1.039	1.026	1.137	1.042	1.105	1.07	1.056
Ca	3.275	3.357	3.303	3.274	3.215	3.346	3.263	3.328	3.345	3.354
Na	0.683	0.568	0.738	0.717	0.679	0.579	0.6659	0.601	0.631	0.671
Ba	0.007	0	0.005	0.007	0.01	0	0	0.02	0.011	0
Sr	0.05	0.03	0.052	0.056	0.06	0.03	0.03	0.05	0.045	0.038
K	0.017	0.014	0.014	0.015	0.013	0.017	0.044	0.013	0.015	0.016
Mole%										
Akerm[b]	61.99	67.92	60.64	62.24	62.52	66.49	62.63	66.33	64.62	64.58
Fe-aker	11.54	10.93	10.39	11	10.69	11.6	11.65	12.16	11.19	9.61
Mel Na	25.94	20.48	27.81	26.45	25.47	20.84	24.37	21.85	23.45	25.27
Gehlen	0.54	0.67	1.16	0.32	1.31	1.08	1.35	0.65	0.65	0.55

[a]* Core of crystal; **border of crystal.
[b]Akerm, Fe-aker, Mel Na, Gehlen: resp. akermanite, ferro-akermanite, sodic melilite, gehlenite. Cations per 14 Oxygens.

3.3. Clinopyroxenes

The clinopyroxenes (Table 3) contained in the rocks of the Remédios sodic series vary from calcic to calcic-sodic to sodic varieties; they appear both as phenocrysts (or microphenocrysts) and as grains in the groundmass. The calcic members are classified as diopsides [30] or as salites [31]; the older nomenclature is here preferred, because it can characterize somewhat better the Mg/Fe ratios in the calcic types.

The pyroxene phenocrysts in the basanites, tephrites and essexites (Remédios sodic series), are usually brown (salites) to brownish-pinkish (titaniferous salites), with similar compositions as the ones found in the groundmass; *mg#* values in phenocrysts and groundmass vary from 70 to 80, with about 3.5-9.0% Al_2O_3, 1.8-4.0% TiO_2, less than 1% of Na_2O.

Normal zoning, sometimes oscillatory, is usually present, with Ti increase in the rims. In these rocks, many crystals show a special discontinuous zoning, identified by the presence of chemically homogeneous green cores (enriched in Fe, Na and Mn), surrounded by brownish rims; the cores may present round, sometimes corroded, outlines, with *mg#* values varying between 45 to 69, with variable Al_2O_3 contents (up to 6.5%), TiO_2 between 0.8 to 3.3%, MnO from 0.3 to 4.0%, Na_2O between 1.5 to

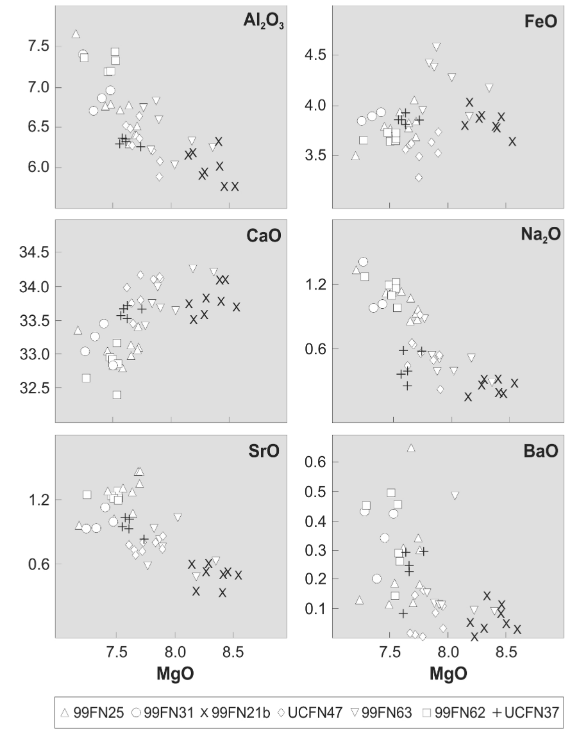

Figure 2. Oxide distribution pattern versus MgO content in melilites of the Quixaba event (seven samples, representing different flows). Source: [1, 2].

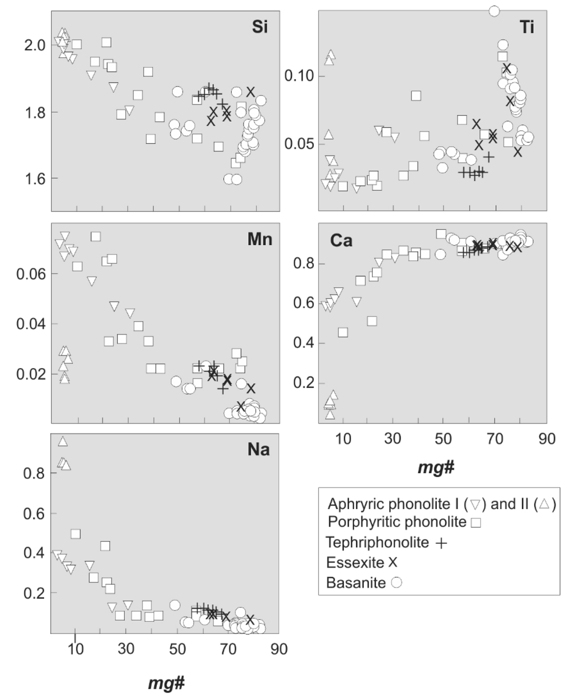

Figure 3. Compositional variations in clinopyroxenes of rocks from the Remédios sodic series, as a function of the corresponding *mg#* number (100 Mg/Mg + Fe$_2$+total). Values as a.f.u. Source: [1, 2].

2.2%. These clinopyroxenes cores probably represent xenocrysts, incorporated into the original magmas by mixing and dispersal of included cogenetic rock fragments that do not outcrop in the district (such as gabbros and monzodioritic types, the "plutonic inclusions", cf. [1, 2]).

In tephriphonolites, pyroxenes are mostly greenish homogeneous crystals (sodic salites to ferrosalites), the brown varieties being rare (cf. [31, 32]). The typical phenocrysts in phonolites are usually green and homogeneous sodic salites to ferrosalites; also present are pyroxenes with brown (salites) to brownish-rosy cores (titaniferous salites), while the groundmass pyroxenes are ferrosalites to aegirine augites, which appear in the more differentiated group II aphyric phonolites as long prismatic aegirine grains (cf. [2, 14]).

Some extraneous xenocrysts such as olivines with reaction rims and diopsides (*mg#* around 90) are found in porphyritic phonolites, as well as in some enclaves of nepheline syenites, showing clear indications of reactions triggered by crystal-magma mixing. Well-defined chemical variations in these phases are related to differences in magma composition and, as a result, pyroxene *mg#* values decrease systematically from the basanite pyroxenes (*mg#* figures varying from 85 to 50) to the ones observed in the aphyric phonolites (*mg#* less than 10; cf. Table 3, Figure 3). Cationic substitutions in these rocks in the pyroxene M1 and M2 positions are depicted in [1].

A triangular diagram shows the trend toward Na enrichment in the sodic series with advancing differentiation (from basanites and tephrites to phonolites; Figure 4A). Zoning in pyroxene phenocrysts of the sodic series are depicted in [1].

Clinopyroxenes of the moderately potassic series are calcic (diopsides or salites). A few appearing with Ti > 0.1 afu may be called "titaniferous", found in the groundmass in alkali basalt, one or two trachyandesites and basaltic trachyandesites. Some pyroxene grains in trachytes are "sodic", presenting Na > 0.1 afu. The less evolved rocks of this series (alkali basalt, basaltic trachyandesite) present values of *mg#* varying between 79 to 66, with variable contents of Si, Ti and Al (Si decreasing with lower *mg#* numbers, Ti and Al increasing at the same time; cf. Figure 5).

Phenocrysts in basaltic trachyandesites are zoned, with green cores and brown borders; they are rich in Al_2O_3, with high values of Al^{VI}. These rocks, presenting indications of disequilibrium, such as observed in their kaersutite phenocrysts with both normal and reverse zoning, sometimes presenting a conspicuous rim of titaniferous

Table 3. Selected chemical analysis of pyroxenes, Fernando de Noronha.

Rock	Basanite					Tephrite				
Sample	97FN15a	97FN15a	97FN23	97FN23	97FN23	97FN43a	97FN43a	97FN43a	97FN43a	97FN43a
Grain	Grmass	Xenoc	Brown phen*	Brown phen**	Grmass	Grmass	Green phen*	Green phen**	Brown phen*a	Brown phen**
SiO_2	49.44	51.77	48.56	47.64	45.2	47.43	48.18	46.13	45.89	48.32
TiO_2	3.37	0.81	1.94	3.11	3.77	2.72	1.11	1.48	3.1	1.99
Al_2O_3	6.01	2.87	5.5	5.37	7.12	5.36	4.47	6.66	7.4	4.17
FeO t	7.65	4.37	6.15	6.43	7.45	7.18	13	14.15	6.3	6.59
Cr_2O_3	0	0	0	0	0	0	0	0	0	0
MnO	0.13	0.04	0.06	0.1	0.13	0.27	4.01	1.91	0.11	0.21
NiO	0	0	0	0	0	0	0	0	0	0
MgO	11.66	16.88	14.52	13.7	12.73	13.27	6.82	6.95	12.99	13.8
CaO	20.89	22.38	23.15	23.29	23.11	22.86	19.37	20.31	23.4	23.6
Na_2O	0.53	0.47	0.68	0.48	0.56	0.72	2.16	2.1	0.56	0.69
K_2O	0.09	0.01	0.02	0	0.04	0.03	0.01	0	0.02	0.01
ZrO_2	0.03	0	0.02	0.06	0.07	0.09	0.02	0.16	0.03	0.08
Total	99.8	99.39	100.6	100.2	100.17	99.9	99.14	99.84	99.78	99.45
Si	1.857	1.896	1.774	1.763	1.68	1.761	1.859	1.762	1.702	1.796
Al^{IV}	0.143	0.104	0.226	0.234	0.312	0.234	0.141	0.238	0.298	0.183
Fe^{3+}	0	0	0	0.003	0.008	0.004	0	0	0	0.021
Al^{VI}	0.123	0.02	0.011	0	0	0	0.062	0.062	0.025	0
Ti	0.095	0.022	0.053	0.086	0.105	0.076	0.032	0.042	0.086	0.056
Fe^{3+}	0	0.072	0.155	0.093	0.133	0.13	0.176	0.247	0.138	0.099
Fe^{2+}	0.128	0	0	0.064	0.056	0.06	0.244	0.205	0.032	0.08
Cr	0	0	0	0	0	0	0	0	0	0
Mg	0.653	0.885	0.78	0.756	0.705	0.735	0.392	0.396	0.719	0.765
Ni	0	0	0	0	0	0	0	0	0	0
Mg	0	0.025	0.01	0	0	0	0	0	0	0
Fe^{2+}	0.112	0.061	0.033	0.039	0.033	0.029	0	0	0.026	0.004
Mn	0.004	0.001	0.002	0.003	0.004	0.008	0.131	0.062	0.003	0.007
Ca	0.841	0.878	0.906	0.924	0.92	0.91	0.801	0.831	0.93	0.94
Na	0.039	0.034	0.048	0.035	0.04	0.051	0.162	0.156	0.04	0.05
K	0.004	0	0.001	0	0.002	0.001	0.001	0	0.001	0
Wo	48.4	45.7	48	49.1	49.5	48.5	45.9	47.7	50.3	49.1
En	37.6	47.3	41.9	40.2	37.9	39.2	22.5	22.7	38.9	39.9
Fs	14	7	10.1	10.7	12.6	12.3	31.6	29.5	10.8	11
mg#	73.1	87.2	80.8	79.2	75.4	76.7	48.3	46.7	78.6	78.9

Rock	Tephrite	Essexite				Tephriphonolite			Porphon	Porphon
Sample	97FN43a	97FN42	97FN42	97Fn42	97FN42	97FN11a	97FN11a	97FN11a	89FN71	89FN71
Grain	Grmass	Brown phen*b Cations per 6 Oxygens.	Brown phen**	Grmass	Green mphen	Green phen*	Green phen**	Green mphen	Brown phen	Green phen
SiO_2	48.15	45.63	44.62	47.76	47.13	48.65	48.67	49.37	44	45.7
TiO_2	2.24	2.93	3.77	1.75	2.72	1.41	0.99	1.02	4.09	1.99
Al_2O_3	5.5	7.93	8.59	4.85	5.94	4.85	4.38	3.63	8.65	6.35
FeO t	7.42	7.55	7.59	11.07	7.14	9.95	12.63	11.05	7.99	19.6
Cr_2O_3	0	0	0	0	0	0	0	0	0.07	0.01

a*: core of phenocryst: ** border. Phen: phenocryst or microphenocryst. Grmass: groundmass. Xenoc: xenocrystal. Cations per 6 Oxygens.
b*: core of phenocryst: ** border. Phen, Mphen: phenocryst, microphenocryst. Grmass: groundmass. Porphon: porphyritic phonolite.

Table 3. Contd.

Rock	Tephrite	Essexite				Tephriphonolite			Porphon	Porphon
Sample	97FN43a	97FN42	97FN42	97Fn42	97FN42	97FN11a	97FN11a	97FN11a	89FN71	89FN71
Grain	Grmass	Brown phen*a Cations per 6 Oxygens.	Brown phen**	Grmass	Green mphen	Green phen*	Green phen**	Green mphen	Brown phen	Green phen
MnO	0.51	0.2	0.21	0.65	0.18	0.43	0.73	0.71	0.9	1.03
NiO	0	0	0	0	0	0	0	0	0	0
MgO	11.74	12.51	11.84	10.35	13.36	11.02	9.21	10.41	11.4	4.11
CaO	21.72	22.25	22.44	21.91	22.62	21.98	21.01	21.4	22.4	20.1
Na_2O	1.51	0.74	0.74	1.39	0.61	1.39	1.8	1.64	0.68	1.21
K_2O	0.46	0.01	0	0.01	0	0.02	0.02	0.01	0	0
ZrO_2	0.11	0.06	0.04	0.19	0.04	0.07	0.12	0.13	0.05	0.05
Total	99.35	99.79	99.82	99.91	99.74	99.75	99.55	99.38	100.23	100.46
Si	1.797	1.697	1.665	1.799	1.752	1.822	1.845	1.865	1.644	1.794
Al^{IV}	0.203	0.303	0.335	0.201	0.248	0.178	0.155	0.135	0.356	0.206
Fe^{3+}	0	0	0	0	0	0	0	0	0	0
Al^{VI}	0.038	0.044	0.042	0.014	0.012	0.036	0.041	0.026	0.024	0.087
Ti	0.063	0.082	0.106	0.049	0.076	0.04	0.028	0.029	0.115	0.059
Fe^{3+}	0.127	0.149	0.136	0.186	0.129	0.163	0.19	0.171	0.116	0.097
Fe^{2+}	0.105	0.032	0.058	0.159	0.043	0.146	0.211	0.178	0.107	0.516
Cr	0	0	0	0	0	0	0	0	0.002	0
Mg	0.653	0.693	0.658	0.581	0.74	0.615	0.521	0.586	0.635	0.24
Ni	0	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{2+}	0	0.054	0.043	0	0.05	0.003	0	0	0	0.028
Mn	0.016	0.006	0.007	0.021	0.006	0.014	0.023	0.023	0.023	0.034
Ca	0.868	0.886	0.897	0.884	0.901	0.882	0.853	0.866	0.866	0.845
Na	0.109	0.054	0.054	0.101	0.044	0.101	0.132	0.12	0.12	0.092
K	0.022	0	0	0	0	0.001	0.001	0.001	0.001	0
Wo	49.1	48.7	49.9	48.2	48.2	48.4	47.4	47.5	47.5	47.9
En	36.9	38.1	36.6	31.7	39.6	33.7	29	32.1	32.1	13.7
Fs	14	13.2	13.6	20.1	12.2	17.9	23.6	20.4	20.4	38.4
mg#	73.8	74.7	73.5	62.5	76.9	66.3	56.5	62.7	62.7	28.1

Rock	Basaltic trachyandesite						Trachyandesite		Trach	Trach
Sample	97FN6a	97FN6a	97FN6b	97FN6b	97FN5a	97FN5a	97FN5a	97FN7a	97FN30a	97FN30a
Grain	Grmass	Grmass	Brown phen*b	Brown phen**	Brown phen*	Brown phen**	Grmass	Green phen*	Grmass	Green phen*
SiO_2	49.09	43.25	47.07	44.77	47.32	46.41	46.36	46.61	44.46	48.16
TiO_2	1.72	3.85	2.4	2.99	2.03	2.37	2.61	1.21	2.79	1.04
Al_2O_3	4.39	8.62	6.03	7.72	5.58	5.17	5.03	5.99	7.25	4.69
FeO t	7.5	9.91	8.44	9.25	8.21	8.51	8.98	12.18	12.91	11.8
Cr_2O_3	0	0	0.03	0.03	0	0	0.02	0.01	0	0
MnO	0.23	0.29	0.28	0.22	0.26	0.31	0.27	0.82	0.68	0.77
NiO	0	0	0.01	0.01	0	0	0	0	0	0

a*: core of phenocryst: ** border. Phen, Mphen: phenocryst, microphenocryst. Grmass: groundmass. Porphon: porphyritic phonolite.
b*: core of phenocryst: ** border. Phen, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Trach: trachyte. Cations per 6 Oxygens.

Table 3. Contd.

Rock	Basaltic trachyandesite					Trachyandesite			Trach	Trach
Sample	97FN6a	97FN6a	97FN6b	97FN6b	97FN5a	97FN5a	97FN5a	97FN7a	97FN30a	97FN30a
Grain	Grmass	Grmass	Brown phen^{*a}	Brown phen**	Brown phen*	Brown phen**	Grmass	Green phen*	Grmass	Green phen*
MgO	13.95	10.43	11.88	10.73	12.3	12.08	12.09	9.21	8.2	9.47
CaO	23.33	22.82	22.71	22.54	22.81	23.04	22.98	21.74	21.35	22.01
Na_2O	0.5	0.83	0.77	0.85	0.68	0.59	0.61	1.11	1.31	1.12
K_2O	0.02	0.06	0	0.01	0	0.01	0.02	0	0	0.01
ZrO_2	0	0	0.02	0.12	0.04	0.23	0.17	0.1	0.27	0.13
Total	100.74	100.05	99.64	99.23	99.22	98.72	99.14	98.98	99.21	99.19
Si	1.805	1.624	1.762	1.692	1.776	1.759	1.752	1.782	1.709	1.837
Al^{IV}	0.19	0.376	0.238	0.308	0.224	0.231	0.224	0.218	0.291	0.163
Fe^{3+}	0	0	0	0	0	0	0.024	0	0	0
Al^{VI}	0	0.005	0.028	0.035	0.022	0	0	0.052	0.037	0.048
Ti	0.048	0.109	0.068	0.085	0.057	0.068	0.074	0.035	0.081	0.03
Fe^{3+}	0.136	0.215	0.128	0.164	0.136	0.148	0.144	0.179	0.184	0.137
Fe^{2+}	0.052	0.087	0.111	0.11	0.096	0.101	0.1	0.209	0.229	0.239
Cr	0	0	0.001	0.001	0	0	0.001	0	0	0
Mg	0.765	0.584	0.663	0.605	0.688	0.683	0.681	0.525	0.47	0.539
Ni	0	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{2+}	0.037	0.01	0.024	0.018	0.025	0.01	0.015	0.001	0.002	0
Mn	0.007	0.009	0.009	0.007	0.008	0.01	0.009	0.026	0.021	0.025
Ca	0.919	0.918	0.911	0.913	0.917	0.936	0.93	0.89	0.879	0.9
Na	0.036	0.06	0.056	0.062	0.049	0.044	0.045	0.082	0.098	0.083
K	0.001	0.003	0	0	0	0	0.001	0	0	0
Wo	47.8	50.4	49.3	50.2	49	49.3	48.9	48.6	49.2	48.9
En	39.8	32	35.9	33.3	36.8	36	35.8	28.7	26.3	29.3
Fs	12.4	17.6	14.7	16.5	14.2	14.7	15.3	22.7	24.4	21.8
mg#	76.8	85.2	71.6	67.4	72.8	71.7	70.6	57.4	53.1	58.9

Rock	Trach	Trach	Trach	Trach	Lamp I	Lamp I	Lamp I	Lamp I	Lamp II	Lamp II
Sample	97FN30a	97FN57	97FN57	97FN57	97FN3d	97FN13a	97FN13a	97FN43c	97FN3a	97FN3a
Grain	Green phen^{**b}	Green phen*	Brown phen*	Grmass	Grmass	Green phen*	Green phen**	Grmass	Brown phen*	Brown phen**
SiO_2	46.29	47.42	44.57	45.59	44.85	47.43	48.72	39.97	47.79	43.26
TiO_2	1.8	1.12	2.87	2.13	3.67	1.02	2.26	6.56	2.16	4.64
Al_2O_3	6.67	5.61	8.54	5.98	8.15	5.39	4.88	11.12	5.78	8.94
FeO t	11.5	11.88	9.6	12.89	7.43	15.52	6.63	10.19	7.09	8.07
Cr_2O_3	0	0	0	0.06	0	0.01	0.06	0	0.04	0
MnO	0.51	0.74	0.21	1.17	0.18	0.46	0.15	0.29	0.15	0.1
NiO	0	0	0	0	0	0	0	0	0.04	0.03
MgO	9.37	9.54	10.5	8.97	12.08	6.87	13.47	8.36	13.52	11.56
CaO	22.01	21.99	22.53	21.98	22.68	20.53	22.65	21.73	22.38	22.66
Na_2O	1.18	1.09	0.69	1.32	0.61	1.98	0.53	1.23	0.64	0.58
K_2O	0	0	0	0.05	0.02	0	0	0.21	0	0.01
ZrO_2	0	0.1	0.08	0.25	0.09	0.16	0.06	0	0.02	0.04
Total	99.31	99.5	99.6	100.39	99.76	99.37	99.39	99.66	99.6	99.89

[a]*: core of phenocryst: ** border. Phen, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Trach: trachyte. Cations per 6 Oxygens.
[b]*: core of phenocryst: ** border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Trach: trachyte; lamp: lamphrophyres I and II. Cations per 6 Oxygens.

Table 3. Contd.

Rock	Trach	Trach	Trach	Trach	Lamp I	Lamp I	Lamp I	Lamp I	Lamp II	Lamp II
Sample	97FN30a	97FN57	97FN57	97FN57	97FN3d	97FN13a	97FN13a	97FN43c	97FN3a	97FN3a
Grain	Green phen^{**a}	Green phen*	Brown phen*	Grmass	Grmass	Green phen*	Green phen**	Grmass	Brown phen*	Brown phen**
Si	1.75	1.801	1.68	1.727	1.675	1.824	1.817	1.52	1.775	1.621
Al^{IV}	0.25	0.199	0.32	0.267	0.325	0.176	0.183	0.48	0.225	0.379
Fe^{3+}	0	0	0	0.007	0	0	0	0	0	0
Al^{VI}	0.047	0.052	0.059	0	0.034	0.0.69	0.031	0.019	0.028	0.015
Ti	0.051	0.032	0.081	0.061	0.103	0.03	0.063	0.188	0.06	0.131
Fe^{3+}	0.188	0.163	0.149	0.249	0.128	0.196	0.062	0.185	0.121	0.143
Fe^{2+}	0.187	0.213	0.12	0.153	0.063	0.303	0.093	0.135	0.04	0.064
Cr	0	0	0	0.002	0	0	0.002	0	0.001	0
Mg	0.528	0.54	0.59	0.507	0.673	0.394	0.749	0.474	0.748	0.645
Ni	0	0	0	0	0	0	0	0	0.001	0.001
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{2+}	0.006	0.001	0.033	0	0.042	0	0.052	0.004	0.059	0.045
Mn	0.016	0.024	0.007	0.037	0.006	0.015	0.005	0.009	0.005	0.003
Ca	0.891	0.895	0.91	0.892	0.908	0.846	0.905	0.885	0.89	0.909
Na	0.086	0.08	0.051	0.097	0.044	0.148	0.039	0.091	0.046	0.042
K	0	0	0	0.002	0.001	0	0	0.01	0	0
Wo	49.1	48.7	50.3	48.3	49.9	48.2	48.5	52.3	47.8	50.2
En	29.1	29.4	32.6	27.5	37	22.5	40.1	28	40.2	35.7
Fs	21.9	21.8	17.1	24.2	13.1	29.3	11.4	19.7	12.1	14.1
mg#	58.1	58.9	66.1	55.3	74.3	44.1	78.3	59.4	77.3	71.9

Rock	Lamp II	Lamp II	Lamp II	Lamp III	Lamp III	Lamp III	Lamp IV	Lamp IV	Lamp IV	MEM
Sample	97FN3a	97FN3b	97FN3b	97FN7	97FN7	97FN7	97FN25	97FN25	97FN25	97FN31
Grain	Grmass	Brown pheno^{*b}	Brown pheno**	Grmass	Brown phenol*	Brown phenol**	Grmass	Brown pheno*	Brown pheno**	Mpheno
SiO_2	45.67	47.26	48.31	47.68	49.02	43.3	42.98	47.67	43.31	49.71
TiO_2	3.67	2.41	2.4	2.74	1.92	4.43	4.83	2.18	4.54	2.46
Al_2O_3	7.15	6.25	5.89	5.57	4.5	8.91	7.97	5.01	8.51	3.1
FeO t	7.17	7.25	7.01	6.2	6.25	6.87	8.47	6.62	8.01	5.32
Cr_2O_3	0	0	0	0	0	0	0	0	0	0
MnO	0.21	0.12	0.16	0.16	0.14	0.13	0.15	0.2	0.18	0.1
NiO	0	0	0	0	0	0	0	0	0	0
MgO	12.59	12.24	13.31	13.67	14.29	11.71	10.89	13.11	11	14.43
CaO	22.7	22.89	22.87	23.42	23.27	23.33	22.57	23.2	22.55	24.38
Na_2O	0.63	0.54	0.55	0.63	0.65	0.73	0.86	0.74	0.83	0.57
K_2O	0.06	0	0.01	0.01	0.01	0.03	0.06	0	0.01	0.04
ZrO_2	0.04	0.05	0.05	0.14	0.03	0.14	0.2	0.04	0.05	0.13
Total	99.88	99	100.55	100.21	100.08	99.58	98.98	98.86	98.97	100.23
Si	1.701	1.777	1.781	1.761	1.805	1.62	1.632	1.785	1.638	1.832
Al^{IV}	0.299	0.223	0.219	0.239	0.195	0.38	0.356	0.215	0.362	0.135
Fe^{3+}	0	0	0	0	0	0	0	0	0	0.033

[a] *: core of phenocryst: ** border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Trach: trachyte; lamp: lamphrophyres I and II. Cations per 6 Oxygens.
[b] *: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Lamp: lamprophyres II, II and IV. MEM: melilite melanephelinite. Cations per 6 Oxygens.

Table 3. Contd.

Rock	Lamp II	Lamp II	Lamp II	Lamp III	Lamp III	Lamp III	Lamp IV	Lamp IV	Lamp IV	MEM
Sample	97FN3a	97FN3b	97FN3b	97FN7	97FN7	97FN7	97FN25	97FN25	97FN25	97FN31
Grain	Grmass	Brown pheno*[a]	Brown pheno**	Grmass	Brown phenol*	Brown phenol**	Grmass	Brown pheno*	Brown pheno**	Mpheno
Al^{VI}	0.015	0.053	0.037	0.003	0	0.013	0	0.006	0.017	0
Ti	0.103	0.068	0.067	0.078	0.053	0.125	0	0.061	0.129	0.068
Fe^{3+}	0.121	0.129	0.086	0.128	0.134	0.169	0.138	0.14	0.147	0.073
Fe^{2+}	0.062	0.064	0.078	0.04	0.028	0.04	0.133	0.062	0.087	0.057
Cr	0	0	0	0	0	0	0	0	0	0
Mg	0.699	0.686	0.732	0.752	0.785	0.653	0.616	0.731	0.62	0.793
Ni	0	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{2+}	0.04	0.035	0.052	0.023	0.031	0.006	0.011	0.006	0.02	0
Mn	0.006	0.004	0.005	0.005	0.004	0.004	0.005	0.006	0.006	0.003
Ca	0.905	0.922	0.904	0.927	0.918	0.936	0.918	0.935	0.914	0.963
Na	0.045	0.039	0.039	0.045	0.046	0.053	0.063	0.053	0.061	0.041
K	0.003	0	0	0	0.001	0.001	0.003	0	0	0.002
Wo	49.4	50.1	48.7	49.4	48.3	51.8	50.8	49.7	50.9	50.1
En	38.1	37.3	39.4	40.1	41.3	36.1	34.1	38.9	34.6	41.3
Fs	12.5	12.6	11.9	10.5	10.4	12.1	15.2	11.4	14.5	8.6
mg#	75.8	75.1	77.2	79.7	80.3	75.2	69.6	77.8	70.9	82.9

Rock		MEM					OLM			
Sample	97FN31	97FN21b	97FN62	97FN20	97FN32b	97FN58a	99FN3	99FN3	99FN51	99FN55
Grain	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Mpheno*[b]	Mpheno**	Grmass	Grmass
SiO_2	44.65	50.74	52.04	47.23	49.17	50.32	44.15	48.98	38.32	45.13
TiO_2	4.41	1.71	1.63	2.69	2.58	2.08	3.92	2.14	6.31	3.81
Al_2O_3	6.91	1.77	1.51	5.43	3.29	3.01	7.83	3.93	11.99	7.05
FeO t	7.05	4.97	4.91	7.13	6.01	5.8	7.33	6.02	8.47	6.69
Cr_2O_3	0	0.02	0	0	0	0	0	0.03	0	0.03
MnO	0.15	0.12	0.16	0.13	0.09	0.15	0.09	0.08	0.07	0.1
NiO	0	0	0	0	0	0.01	0	0	0	0
MgO	12.75	15.4	15.84	12.8	14	13,70	12.32	13.99	10.11	12.79
CaO	23.86	24.03	23.89	23.5	24.16	23.74	23.57	24.12	23.2	23.9
Na_2O	0.61	0.47	0.5	0.48	0.42	0.52	0.4	0.43	0.52	0.52
K_2O	0.08	0	0.02	0.02	0	0.01	0.01	0	0.02	0.03
ZrO_2	0.13	0.05	0	0.05	0.05	0.07	0.02	0.02	0.05	0.02
Total	100.58	99.28	100.48	99.46	99.76	99.41	99.64	99.73	99.06	100.05
Si	1.654	1.879	1.901	1.767	1.827	1.876	1.651	1.816	1.456	1.878
Al^{IV}	0.302	0.077	0.065	0.233	0.144	0.124	0.345	0.171	0.537	0.308
Fe^{3+}	0.044	0.043	0.034	0	0.029	0	0.004	0.012	0.008	0.016

[a]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Lamp: lamprophyres II, II and IV. MEM: melilite melanephelinite. Cations per 6 Oxygens.

[b]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. MEM, OLM: melilite and olivine melanephelinites. Cations per 6 Oxygens.

Table 3. Contd.

Rock		MEM					OLM			
Sample	97FN31	97FN21b	97FN62	97FN20	97FN32b	97FN58a	99FN3	99FN3	99FN51	99FN55
Grain	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Mpheno*[a]	Mpheno**	Grmass	Grmass
Al^{VI}	0	0	0	0.006	0	0.009	0	0	0	0
Ti	0.123	0.048	0.045	0.076	0.072	0.058	0.11	0.06	0.18	0.106
Fe^{3+}	0.146	0.059	0.046	0.111	0.059	0.036	0.156	0.094	0.221	0.148
Fe^{2+}	0.027	0.043	0.047	0.094	0.094	0.136	0.046	0.072	0.026	0.037
Cr	0	0.001	0	0	0	0	0	0.001	0	0.001
Mg	0.704	0.85	0.863	0.714	0.775	0.761	0.687	0.773	0.573	0.706
Ni	0	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{2+}	0.002	0.009	0.024	0.018	0.005	0.009	0.023	0.008	0.014	0.008
Mn	0.005	0.004	0.005	0.004	0.003	0.005	0.003	0.003	0.002	0.003
Ca	0.947	0.954	0.935	0.942	0.962	0.948	0.944	0.958	0.944	0.951
Na	0.044	0.034	0.036	0.034	0.03	0.037	0.029	0.031	0.038	0.037
K	0.004	0	0.001	0.001	0	0	0	0	0.001	0.001
Wo	50.5	48.6	47.9	50	49.9	50	50.7	49.9	52.8	50.8
En	37.5	43.3	44.2	37.9	40.2	40.2	36.9	40.3	32	37.8
Fs	11.9	8.1	8	12.1	9.9	9.8	12.5	9.8	15.2	11.3
mg#	76.3	84.7	85.1	76.2	80.6	80.8	75	80.6	68.1	77.2

Rock					PYM					
Sample	97FN8	97FN13c	97FN13d	97FN32d	97FN37	97FN37	97FN38	97FN39	97FN46	97FN14
Grain	Grmass	Grmass	Grmass	Grmass	Mpheno*[b]	Mpheno**	Grmass	Grmass	Mpheno	Grmass
SiO_2	46.42	46.37	48.19	47.85	48.97	48.98	45.33	49.58	47.25	43.63
TiO_2	3.78	3.22	2.97	2.8	1.9	1.81	3.56	2.03	3.23	4.59
Al_2O_3	5.52	5.01	4.32	4.73	3.68	3.78	6.81	2.63	6.64	8.06
FeO t	6.95	7.33	6.58	6.89	5.88	5.93	7.39	5.95	6.84	7.13
Cr_2O_3	0	0.12	0.01	0	0.1	0.13	0	0	0.06	0
MnO	0.16	0.06	0.08	0.14	0.09	0.11	0.17	0.16	0.12	0.12
NiO	0	0	0	0	0	0	0	0	0	0
MgO	12.87	13.57	13.87	12.87	14.75	14.65	12.18	14.4	12.68	12.01
CaO	23.03	23.08	23.67	23.56	23.65	23.76	23.01	24.38	22.7	23.51
Na_2O	0.73	0.34	0.52	0.56	0.41	0.43	0.76	0.35	0.95	0.45
K_2O	0.03	0	0.02	0.03	0	0	0.03	0.01	0.2	0.03
ZrO_2	0.07	0.08	0	0.04	0.04	0.08	0.06	0.08	0	0.08
Total	99.56	99.18	100.22	99.46	99.45	99.65	99.29	99.57	100.68	99.61
Si	1.735	1.74	1.782	1.789	1.815	1.813	1.7	1.843	1.739	1.637
Al^{IV}	0.243	0.221	0.138	0.208	0.161	0.165	0.3	0.115	0.261	0.356
Fe^{3+}	0.022	0.038	0.03	0.002	0.024	0.022	0	0.042	0	0.008

[a]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. MEM, OLM: melilite and olivine melanephelinites. Cations per 6 Oxygens.
[b]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. PYM: pyroxene melanephelinites. Cations per 6 Oxygens.

Table 3. Contd.

Rock	PYM									
Sample	97FN8	97FN13c	97FN13d	97FN32d	97FN37	97FN37	97FN38	97FN39	97FN46	97FN14
Grain	Grmass	Grmass	Grmass	Grmass	Mpheno*[a]	Mpheno**	Grmass	Grmass	Mpheno	Grmass
Al^{VI}	0	0	0	0	0	0	0.001	0	0.027	0
Ti	0.106	0.091	0.083	0.079	0.053	0.05	0.1	0.057	0.089	0.13
Fe^{3+}	0.106	0.098	0.09	0.095	0.105	0.113	0.154	0.068	0.13	0.138
Fe^{2+}	0.071	0.048	0.062	0.109	0.024	0.024	0.064	0.075	0.056	0.061
Cr	0	0.003	0	0	0.003	0.004	0	0	0.002	0
Mg	0.717	0.759	0.765	0.717	0.815	0.809	0.681	0.798	0.695	0.672
Ni	0	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0	0	0	0
Fe^{2+}	0.019	0.046	0.021	0.009	0.029	0.024	0.014	0	0.024	0.017
Mn	0.005	0.002	0.002	0.004	0.003	0.003	0.005	0.005	0.004	0.004
Ca	0.922	0.928	0.938	0.944	0.939	0.942	0.925	0.971	0.895	0.945
Na	0.053	0.024	0.037	0.041	0.029	0.031	0.055	0.025	0.068	0.033
K	0.001	0	0.001	0.001	0	0	0.001	0	0.01	0.001
Wo	49.5	48.4	49.2	50.2	48.4	48.6	50.2	49.6	49.6	51.2
En	38.5	39.6	40.1	38.1	42	41.8	37	40.7	38.5	36.4
Fs	12	12.1	10.7	11.6	9.5	9.6	12.9	9.7	11.9	12.4
mg#	76.7	76.7	79	76.9	81.7	81.6	74.6	81.2	76.8	75

Rock	Bas S	Bas S	Bas S	Bas S	Bas Cz	Bas Cz	Bas SJ	Bas SJ	Bas SJ	Bas Vir
Sample	89FN78a	89FN78a	99FN4	99FN7e	99FN9c	99FN9c	99FN10a	99FN10b	99FN10b	99FN22
Grain	Pheno*[b]	Pheno**	Mpheno	Grmass	Mpheno*	Mpheno**	Xenoc	Grmass	Pheno*	Grmass
SiO_2	48.52	46.75	44.84	48.09	48.73	47.26	51.6	48.33	46.04	48.56
TiO_2	2.4	2.99	3.55	2.42	1.46	2.54	0.04	2.34	2.75	2
Al_2O_3	4.31	6.59	7.75	4.99	5.39	5.24	6.67	4.51	7.22	4.9
FeO t	6.97	7.14	7.31	6.88	5.65	7.01	5.9	6.75	6.72	6
Cr_2O_3	0.03	0.09	0	0.02	0.66	0	1.76	0.04	0.05	0.7
MnO	0.14	0.13	0.13	0.13	0.08	0.1	0.13	0.09	0.08	0.09
NiO	0.03	0	0	0	0	0	0	0	0	0
MgO	14.08	13.04	12.32	13.82	14.14	13.53	32.22	13.06	12.87	14.53
CaO	22.11	22.59	23	22.59	21.99	22.52	1.06	22.1	22.74	23.04
Na_2O	0.49	0.59	0.56	0.75	0.6	0.5	0	0.91	0.5	0.49
K_2O	0	0	0.02	0.02	0	0	0	0.08	0.02	0.03
ZrO_2	0.09	0.02	0	0.06	0.02	0.04	0	0.02	0	0.01
Total	99.19	99.94	99.47	99.75	98.72	98.75	99.36	98.23	98.99	100.34
Si	1.813	1.736	1.677	1.782	1.817	1.774	1.794	1.821	1.723	1.785
Al^{IV}	0.187	0.264	0.323	0.218	0.183	0.226	0.206	0.179	0.277	0.212
Fe^{3+}	0	0	0	0	0	0	0	0	0	0.003

[a]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. PYM: pyroxene melanephelinites. Cations per 6 Oxygens.

[b]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Bas: basanites; S, Cz, SJ, Vir: respectively Sancho, Cuscuz, São José, Viração. Cations per 6 Oxygens.

Table 3. Contd.

Rock	Bas S	Bas S	Bas S	Bas S	Bas Cz	Bas Cz	Bas SJ	Bas SJ	Bas SJ	Bas Vir
Sample	89FN78a	89FN78a	99FN4	99FN7e	99FN9c	99FN9c	99FN10a	99FN10b	99FN10b	99FN22
Grain	Pheno*a	Pheno**	Mpheno	Grmass	Mpheno*	Mpheno**	Xenoc	Grmass	Pheno*	Grmass
Al^{VI}	0.003	0.024	0.018	0	0.053	0.006	0.066	0.021	0.042	0
Ti	0.067	0.084	0.1	0.067	0.041	0.072	0.001	0.066	0.077	0.055
Fe^{3+}	0.083	0.111	0.146	0.137	0.071	0.113	0.089	0.093	0.115	0.119
Fe^{2+}	0.06	0.056	0.05	0.032	0.029	0.052	0	0.085	0.047	0.009
Cr	0.001	0.003	0	0.001	0.019	0	0.048	0.001	0.001	0.02
Mg	0.785	0.722	0.687	0.763	0.786	0.757	0.795	0.733	0.718	0.796
Ni	0.001	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0.874	0	0	0
Fe^{2+}	0.075	0.054	0.033	0.044	0.076	0.055	0.083	0.035	0.049	0.053
Mn	0.005	0.004	0.004	0.004	0.003	0.003	0.004	0.003	0.003	0.003
Ca	0.885	0.899	0.921	0.897	0.878	0.906	0.039	0.892	0.912	0.908
Na	0.036	0.043	0.041	0.054	0.043	0.036	0	0.066	0.036	0.035
K	0	0	0.001	0.001	0	0	0	0.004	0.001	0.001
Wo	46.8	48.7	50	47.8	47.6	48	2.1	48.5	49.5	48
En	41.5	39.1	37.3	40.6	42.6	40.1	88.5	39.8	38.9	42.1
Fs	11.8	12.2	12.7	11.6	9.7	11.8	9.3	11.7	11.8	9.9
mg#	78.3	76.6	75	78.2	81.7	77.5	90.7	77.5	77.3	81.2

a*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Bas: basanites; S, Cz, SJ, Vir: respectively Sancho, Cuscuz, São José, Viração. Cations per 6 Oxygens.

diopside (*mg#* around 68), may be formed by magma mixing.

The clinopyroxenes of the potassic series present an overall increase from alkali basalt to trachytes in the (Fe^{2+} + Fe^{3+} + Mn – Na) parameter, in part also in Na content (Figure 4B). Zoning patterns in pyroxene phenocrysts of the moderately potassic series are represented in [1].

The clinopyroxenes in the Remédios lamprophyres present very diverse values in *mg#*, and Ti, Na and Al contents, in general with a crystallization trend towards enrichment in Na, Mn and Fe total, with decrease in Mg (Figure 4C). Pyroxenes of the type I lamprophyres occur as brownish crystals (salites) with purple borders (titaniferous salites). In the other types of lamprophyres, pyroxenes are rather similar (brownish salite crystals, rarely with green cores of sodic ferrosalites and Ti-enriched borders). Zoning patterns in the lamprophyre pyroxenes are represented in [1]]. The green cores are characterized by low Ti and *mg#* values and higher ones in Na, Mn and total Fe abundances.

Clinopyroxenes in the Quixaba rocks (Table 3), the predominant phase in the PYM and basanites, are mostly salites with concentric zoning and a thin border of brownish-pinkish titaniferous salite; in some basanites, alveolar textures are observed at the center of the crystals. The *mg#* values in these rocks vary between 85 to 95, the highest ones concentrated in MEM (between 98 to 90). Little Na is present, Ca is relatively abundant, more so in the MEM and OLM salites; Al^{IV} is variable, and Cr a rare constituent.

3.4. Amphiboles

Amphiboles (Table 4) are relatively rare phases in the Remédios sodic series, found mostly in the groundmass of tephriphonolites and as phenocrysts in the porphyritic phonolites (in this case, totally or partially replaced by titaniferous opaque phases). The composition varies from kaersutite to ferro-kaersutite, in part subsilicic, with Si < 0.75 afu, towards ferro-pargasite enriched in Ti (0.38 to 0.49 afu; cf. [33]).

All amphiboles are enriched in K, around 0.28 afu in the tephriphonolites, up to 0.305 to 0.401 afu in the porphyritic phonolites (data in [14]).

In the basaltic trachyandesites (from the Remédios moderately potassic series), amphiboles are observed as zoned phenocrysts, or microphenocrysts, and groundmass grains; they are much scarcer in the trachyandesites and are absent in the trachytes. They are brownish phases. In the amphibole nomenclature [33], these phases are mostly calcic kaersutites or magnesian hastingsites (with Ti < 0.5 afu and Al^{VI} < Fe^{3+}). The passage from kaersutites to Mg-hastingsites occurs by a decrease in the *mg#* values,

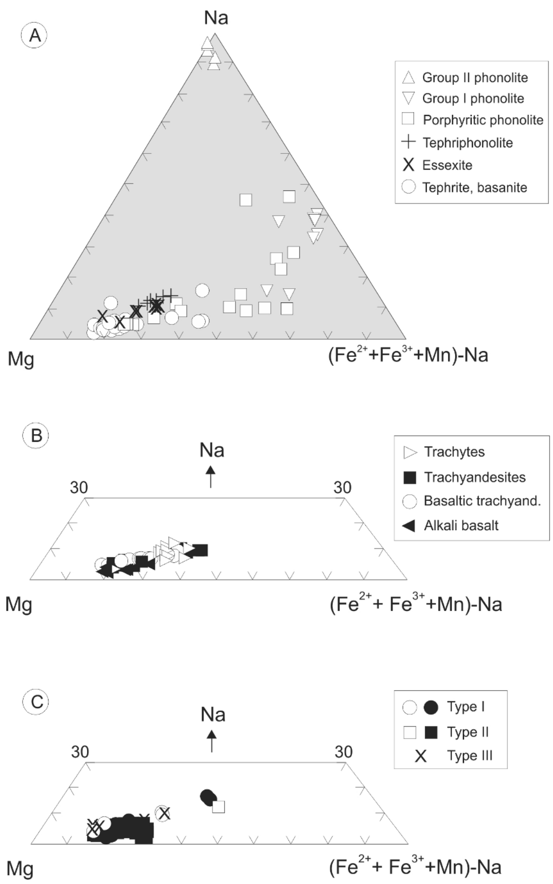

Figure 4. A: Clinopyroxenes of rocks of the Remédios sodic series showing the increase in Na (and decrease in Mg, Fe_{total} and Mn) in more differentiated rocks. B: Clinopyroxene compositions in rocks of the Remédios moderately potassic series showing a slight increase in Na with differentiation. C: Clinopyroxenes in Remédios lamprophyres. Source: [1, 2, 13].

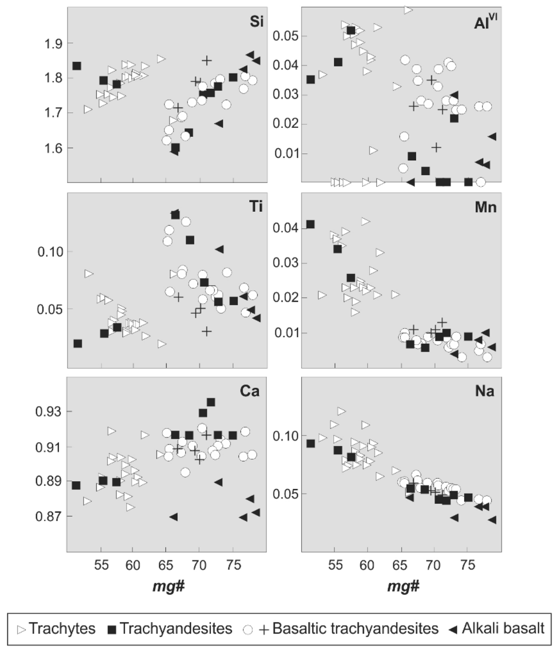

Figure 5. Compositional variations of the clinopyroxenes observed in rocks of the Remédios moderately potassic series as a function of *mg#*. Values in a.f.u. Source: [1, 2].

as well as in Ti contents, coupled with an increase in Al^{VI}, Mg and Na; K shows little variation (Figure 6).

Zoning patterns observed in amphibole phenocrysts of basaltic trachyandesites are depicted in [1] (cf. also [34, 35]).

The Remédios lamprophyres show, as a rather peculiar feature, almost always the presence of amphiboles and a conspicuous absence of micas, making these FN rocks rare representatives of amphibole-bearing types in oceanic islands. The mineral is present as homogeneous microphenocrysts or zoned phenocrysts, with normal, oscillatory or even inverse zoning. Potassium content in these phases varies significantly, even within a certain lithologic type, as also observed in the basaltic trachyandesites. Na and Al^{VI} vary in an inverse fashion to Ti, this element showing an erratic behavior, either enriched in the cores or in the borders. Zoning patterns are depicted in [1] (cf. also Ubide et al. 2014 [35], for interpretations of zoning patterns in a camptonite). Amphiboles from types II and III lamprophyres are, in general, enriched in Mg (up to 3.1 afu).

Amphiboles are absent in the Quixaba rocks.

3.5. Fe-Ti magnetites

Titaniferous magnetites occur in all FN rock types, usually as microphenocrysts or groundmass grains. Chemical analysis of these phases plot mostly along the ulvospinel-magnetite tie line in the triangular TiO_2-FeO-Fe_2O_3 diagram (Table 5).

Magnetites in the Remédios basanites (sodic series) present normally higher amounts of Cr_2O_3 (0.5 to 4.5%) and of the ulvospinel component, while the ones observed in phonolites are enriched in the magnetite end-member (cf. [1]).

In the moderately potassic series, these phases are ubiquitous as well, again as microphenocrysts or as groundmass grains, with an evolutionary trend (alkali basalts to trachyandesites and trachytes) indicating a decrease in Mg and Ti, and an increase in Fe^{2+}, Mn and Zn (Table 5). In the lamprophyres, magnetite grains (as substitution products) are usually found coexisting with amphiboles. TiO_2

Table 4. Selected chemical analyses of amphiboles, Fernando de Noronha.

Rock	Btrach	Btrach	Btrach	Btrach	Btrach	Btrach	Btrach	Trachan	Lamp I
Sample	97FN4a	97FN4a	97FN6a	97FN6a	97FN6a	97FN6b	97FN6b	97FN5a	97FN3d
Grain	Pheno*[a]	Pheno**	Phen*	Phen**	Grmass	Phen*	Grmass	Grmass	Grmass
SiO_2	38.46	38.83	39.07	38.57	39.3	38.2	38.26	38.53	37.36
TiO_2	4.97	5.16	5.51	5.56	5.61	6.33	5.87	6.11	6.88
Al_2O_3	13.77	13.86	13.45	13.78	13.28	13.73	13.39	12.87	14.44
FeOt	14.35	13.72	12.09	12.68	10.75	12.01	11.78	10.86	11.54
Cr_2O_3	0	0	0	0.01	0.01	0	0.02	0	0
MnO	0.35	0.27	0.21	0.23	0.21	0.16	0.17	0.18	0.22
MgO	10.84	11.14	11.84	1.5	12.81	12.13	12.03	12.51	11.29
CaO	11.77	11.9	11.94	11.85	11.98	11.68	11.87	12.03	12.12
Na_2O	2.44	2.46	2.36	2.28	2.33	2.35	2.24	2.26	2.27
K_2O	1.46	1.42	1.58	1.62	1.58	1.63	1.61	1.56	1.3
F	0.06	0.11	0.1	0.12	0.04	0.12	0.14	0	0.31
Cl	0.02	0.02	0.03	0.04	0.02	0.02	0.02	0	0.02
Total	98.5	98.88	98.18	98.22	97.9	98.35	97.37	96.9	97.75
O-F-Cl	0.03	0.05	0.05	0.06	0.02	0.06	0.06	0	0.13
CTotal	98.47	98.83	98.13	98.16	97.88	98.29	97.31	96.9	97.62
Si	5.755	5.78	5.839	5.769	5.843	5.682	5.758	5.813	5.634
Al^{IV}	2.245	2.22	2.161	2.231	2.147	2.318	2.242	2.187	2.366
Al^{VI}	0.183	0.21	0.206	0.195	0.169	0.088	0.131	0.099	0.198
Cr	0	0	0	0.001	0.001	0	0.002	0	0
Fe^{3+}	0.182	0.082	0	0.016	0	0.105	0	0	0
Ti	0.559	0.578	0.619	0.626	0.628	0.708	0.664	0.694	0.781
Mg	2.418	2.471	2.638	2.563	2.839	2.69	2.698	2.814	2.537
Fe^{2+}	1.614	1.626	1.511	1.571	1.336	1.389	1.483	1.37	1.455
Mn	0.044	0.033	0.027	0.029	0.027	0.02	0.022	0.023	0.029
Ca	1.887	1.897	1.912	1.899	1.908	1.862	1.915	1.944	1.958
Na	0.113	0.103	0.088	0.101	0.092	0.138	0.085	0.056	0.042
Ca	0	0	0	0	0	0	0	0	0
Na	0.561	0.607	0.595	0.56	0.581	0.539	0.569	0.605	0.623
K	0.279	0.269	0.302	0.309	0.299	0.309	0.309	0.299	0.249
Cl	0.006	0.006	0.007	0.009	0.004	0.005	0.005	0	0.006
F	0.03	0.05	0.048	0.057	0.021	0.057	0.067	0	0.147
mg#	57.63	59.25	63.58	61.78	68	64.45	64.53	67.26	63.55

[a]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Btrach: basaltic trachyandesites; Trachan: trachyandesites; Lamp I: lamprophyre group I. Cations for 23 oxygens.

Table 4. Contd.

Rock	Lamp I	Lamp I	Lamp I	Lamp I	Lamp II	Lamp II	Lamp III	Lamp III	Lamp IV	Lamp IV
Sample	97FN3d	97FN43c	97FN43c	97FN43c	97FN3a	97FN3a	97FN7	97FN7	97FN25	97FN25
Grain	Grmass	Phen*[a]	Phen**	Grmass	Pheno*	Pheno**	Pheno*	Pheno**	Pheno*	Pheno**
SiO_2	38.05	38.47	38.61	37.38	39.05	37.97	40.6	40.26	38.67	38.27
TiO_2	7.17	6.36	6.07	6.98	5.88	7.33	4.6	5.46	5.57	5.81
Al_2O_3	14.28	13.87	13.62	13.49	13.64	13.93	13.52	13.34	13.87	12.74
FeOt	9.75	10.01	11.12	10.49	9.88	9.61	9.17	9.13	10.15	10.27
Cr_2O_3	0	0	0	0	0.01	0	0	0	0	0
MnO	0.18	0.2	0.26	0.14	0.11	0.22	0.1	0.13	0.17	0.13
MgO	12.35	12.75	12	13.33	13.5	13.51	14.46	14.29	13.11	13.13
CaO	12.29	11.9	11.96	11.96	12.06	11.97	12.15	12.06	12.1	12.1
Na_2O	2.27	2.26	2.25	2.5	2.23	2.29	2.42	2.45	2.21	2.35
K_2O	1.18	1.78	1.74	1.46	1.74	1.37	1.59	1.61	1.58	1.66
F	0.33	0.31	0.46	0.1	0.12	0.19	0.12	0.26	0.14	0.29
Cl	0.04	0.02	0.03	0.02	0.01	0.03	0.03	0.03	0.02	0
Total	97.88	97.92	98.11	97.66	98.21	97.41	98.77	99	97.58	97.74
O-F-Cl	0.2	0.13	0.2	0.16	0.05	0.09	0.06	0.11	0.06	0.12
CTotal	97.77	97.79	97.91	98.68	98.16	97.32	98.71	98.89	97.52	97.62
Si	5.639	5.74	5.795	5.556	5.767	5.689	5.911	5.872	5.754	5.713
Al^{IV}	2.361	2.26	2.205	2.444	2.233	2.311	2.089	2.128	2.246	2.287
Al^{VI}	0.156	0.176	0.202	0.098	0.139	0.147	0.229	0.164	0.185	0.128
Cr	0	0	0	0	0.001	0	0	0	0	0
Fe^{3+}	0	0	0	0	0.006	0	0.082	0.006	0.018	0
Ti	0.85	0.713	0.685	0.78	0.653	0.826	0.504	0.599	0.623	0.652
Mg	2.781	2.837	2.684	2.766	2.972	2.794	3.138	3.107	2.908	2.922
Fe^{2+}	1.199	1.249	1.395	1.328	1.215	1.205	1.034	1.106	1.245	1.282
Mn	0.014	0.025	0.034	0.028	0.014	0.028	0.013	0.016	0.021	0.017
Ca	1.983	1.902	1.923	1.908	1.908	1.922	1.895	1.884	1.93	1.935
Na	0.017	0.098	0.077	0.092	0.092	0.078	0.105	0.116	0.07	0.065
Ca	0	0	0	0	0	0	0	0	0	0
Na	0.63	0.556	0.577	0.568	0.547	0.588	0.579	0.577	0.567	0.615
K	0.244	0.338	0.333	0.36	0.327	0.261	0.295	0.299	0.3	0.316
Cl	0.006	0.006	0.007	0.006	0.004	0.008	0.007	0.007	0.005	0.001
F	0.216	0.144	0.217	0.17	0.055	0.09	0.054	0.119	0.066	0.135
mg#	69.87	69.43	65.8	67.56	70.89	69.87	73.91	73.62	69.75	69.51

[a]*: core of phenocryst; **: border. Pheno, Mpheno: phenocryst, microphenocryst. Grmass: groundmass. Lamp I to IV: lamprophyres group I to IV. Cations for 23 Oxygens.

increases usually in amphiboles of type II lamprophyres (16 to 20%), and decreases in the type I rocks (e.g., the type II 97FN13a sample presents a marked increases in Mg, Al and up to 4% of Cr_2O_3 (cf. Table 5).

In the Quixaba rocks, titaniferous magnetites are plentiful, with TiO_2 contents ranging from 24 to 15% and Cr_2O_3 changing widely from trace amounts to 4-5%; some grains, with as much as 16 and 23% of Cr_2O_3% and then with low

Table 5. Selected chemical analyses of Fe-Ti spinels, Fernando de Noronha.

Rock	Bas[a]	Abas	Abas	Lamp I	Lamp II	Lamp II	Lamp III
Sample	97FN23	97FN35b	97FN35b	97FN43c	97FN3a	97FN3b	97FN7
Grain	Grmass	Mpheno	Grmass	Inc amp	Mpheno	Mpheno	Grmass
TiO_2	20.46	19.75	20.27	15.52	17.18	19.25	15.78
Al_2O_3	4.76	3.21	2.94	5.01	5.62	4.62	5.61
Cr_2O_3	0	0.04	0	0.04	0.18	0.26	0.63
FeOt	65.95	67.03	66.47	65.73	66.86	67.51	67.86
MnO	0.84	0.81	0.86	0.64	0.9	0.63	0.82
MgO	3.18	4.84	4.78	7.46	5.43	5.57	6.18
ZnO	0.15	0.06	0.13	0.09	0.09	0.14	0.04
Total	95.35	95.75	95.45	94.48	96.27	98.06	96.91
FeO	44.29	41.16	41.51	33.38	38.4	40.74	36.53
Fe_2O_3	24.06	28.75	27.73	35.83	31.62	29.86	34.81
Total	97.75	98.62	98.22	98.06	99.43	101.05	100.39
Al	1.647	1.097	1.012	1.678	1.878	1.524	1.851
Ti	4.52	4.312	4.449	3.322	3.668	4.06	3.327
Cr	0	0.009	0	0.009	0.041	0.057	0.139
Fe^{2+}	10.877	9.99	10.131	7.97	9.116	9.553	8.562
Fe^{3+}	5.311	6.273	6.083	7.667	6.747	6.294	7.334
Mn	0.209	0.198	0.212	0.154	0.217	0.149	0.194
Mg	1.394	2.096	2.079	3.167	2.298	2.327	2.584
Zn	0.03	0.01	0.03	0.02	0.02	0.03	0.01

Rock	Btrachyan[b]	Btrachyan	Trach	Lamp I	Lamp I	MEM	OLM	OLM	OLM
Sample	97FN6a	97FN6b	97FN57	97FN11b	97FN13a	97FN31	97FN20	97FN20	97FN58a
Grain	Mpheno	Grmass	Pheno	Grmass	Mpheno	Inc oliv	Inc oliv	Grmass	Grmass
TiO_2	14.58	14.6	8.56	18.01	14.23	16.8	22.73	23.32	18.2
Al_2O_3	3.3	3.42	1.09	5.54	5.75	1.01	1.83	1.69	2.42
Cr_2O_3	0.03	0.04	0.02	0.02	1.19	5.49	2.1	0.28	1.3
FeOt	73.34	72.95	79.15	65.27	67.19	67.45	65.77	65.94	65.51
MnO	0.93	1.15	3.43	0.76	0.46	0.66	0.6	0.6	0.75
MgO	3.49	3.4	0.63	6.35	6.57	3.9	3.52	3.64	6.45
ZnO	0.11	0.14	0.36	0.09	0.06	0.11	0.12	0.01	0.11
Total	95.77	95.7	93.24	96.04	95.45	95.42	96.65	95.49	94.73
FeO	38.61	38.6	33.87	37.77	34.32	39.66	46.03	46.15	17.31
Fe_2O_3	38.59	38.17	50.31	30.56	36.52	30.88	21.93	21.99	53.55
Total	99.63	99.52	98.27	99.1	99.1	98.51	98.84	97.68	100.09
Al	1.132	1.177	0.395	1.845	1.914	0.353	0.631	0.591	0.638
Ti	3.199	3.208	1.96	3.831	3.028	3.743	5.019	5.209	3.061
Cr	0.006	0.009	0.005	0.005	0.265	1.283	0.486	0.065	0.229
Fe^{2+}	9.418	9.428	8.712	8.931	8.118	0.823	11.302	11.461	8.758
Fe^{3+}	8.462	8.38	11.632	6.495	7.765	6.875	4.84	4.909	8.999
Mn	0.23	0.284	0.894	0.181	0.111	0.166	0.148	0.151	0.142
Mg	1.515	1.479	0.287	2.678	2.771	1.721	1.539	1.612	2.148
Zn	0.02	0.03	0.08	0.02	0.01	0.02	0.03	0	0.02

[a]Bas: basanites; Abas: alkali basalt; Tephr: tephrite; Tphon: tephriphonolite; Ess: essexite; Abas: alkali basalt; Lamp I to III: lamprophyre I to III. Mpheno: microphenocryst; Grmass: groundmass. Incl amp: inclusion in amphibole. Cations for 32 oxygens.

[b]Btrachyan: basaltic trachyandesite; trach: trachyte; lamp: lamprophyre; MEM and OLM: melilite and olivine melanephelinites. Inc oliv: inclusion in olivine; grmass: groundmass. Pheno, Mpheno: pheno-, microphenocryst. Cations for 32 oxygens.

Table 5. Contd.

Rock	Rock	PYM[a]	PYM	Bas	Bas	Bas	Bas	Bas
Sample	Sample	97FN8	97FN13c	89FN78a	99FN4	99FN7e	99FN7e	99FN22
Grain	Grain	Grmass	Grmass	Grmass	Grmass	Mpheno	Grmass	Grmass
TiO_2	TiO2	13.95	21.71	16.28	15.75	18.56	22.2	25.34
Al_2O_3	Al2O3	0.95	1.04	1.4	1.56	1.46	1.94	1.68
Cr_2O_3	Cr2O3	0.16	2.11	0.34	0.11	0.39	0.23	0.46
FeOt	FeOt	76.59	67.12	72.04	72.58	70.24	64.85	65.6
MnO	MnO	0.47	0.51	0.56	0.69	0.71	0.63	0.85
MgO	MgO	2.05	2.97	3	2.7	3.73	5.33	2.11
ZnO	ZnO	0.08	0.13	0.14	0.17	0.2	0.1	0.15
Total	Total	94.25	95.59	93.75	93.57	95.28	95.27	96.2
FeO	FeO	39.94	45.61	40.28	40.04	41.4	43.42	49.99
Fe_2O_3	Fe2O3	40.72	23.9	36.29	36.15	32.05	24.91	17.35
Total	Total	98.32	97.98	97.28	97.18	98.49	97.77	97.94
Al	Al	0.339	0.366	0.498	0.558	0.509	0.671	0.592
Ti	Ti	3.177	4.88	3.699	3.59	4.134	4.891	5.7
Cr	Cr	0.038	9.499	0.082	0.027	0.09	0.053	0.11
Fe^{2+}	Fe2+	10.109	11.399	10.176	10.145	10.253	10.393	12.501
Fe^{3+}	Fe3+	9.265	4.757	8.014	8.233	7.135	5.485	3.9
Mn	Mn	0.12	0.241	0.142	0.177	0.177	0.157	0.216
Mg	Mg	0.923	1.67	1.349	1.22	1.647	2.326	0.941
Zn	Zn	0.02	0.03	0.03	0.04	0.04	0.02	0.03

[a]PYM: pyroxene melanephelinite; Bas: basanites; Inc oliv: inclusion in olivine; Grmass: groundmass; Mpheno: microphenocryst. Cations for 32 oxygens.

TiO_2 (3 to 6%) and high Al_2O_3 (up to 28-29%), appear as inclusions in olivine and are actually Mg-Al chromites, paragenetically not related to the Ti-magnetite crystallization. MgO is more predominant in MEM and OLM (up to 6.5%) than in PYM and basanites, the last ones showing an increase in FeO(total) abundances (cf. Table 5).

3.6. Ilmenites

Ilmenites were found in some of the Remédios rocks (moderately potassic series), especially in basaltic trachyandesites and trachytes, and in one type II lamprophyre and some Quixaba rocks (OLM and basanites), where they appear mostly as phenocrysts and microphenocrysts, sometimes as inclusions in pyroxene (Table 6).

Compositions of the mineral in the Remédios rocks are rather homogeneous, TiO_2 varying from 42.6 to 44%, FeO from 27.9 to around 29.8% (Fe_2O_3 from 19 to 22%), and MgO from 4.4 to 6.1%. The Quixaba samples are enriched in TiO_2 with variations from 46.5 to 50.6%, as well as in FeO (30.8 to 35.3%), while MgO values are similar to the ones present in Remédios samples (4.4 to 7.6%).

3.7. Micas

Dark micas (biotites and phlogopites; cf. [36]) are rather scarce minerals in the Remédios rocks, where they appear as accessory phases only in samples of the sodic series, such as some of the Remédios basanites, tephrites and essexites. (Table 7). They present MgO contents of around 11 to 17%, indicative of biotite chemistry.

In the Remédios basanites and essexites (sodic series), the micas show MgO contents of around 11 to 17%, indicative of biotites.

In the Remédios lamprophyres, pyroxenes and amphiboles are the main mafic minerals. Biotites are observed more frequently only in type I rocks, with similar MgO values as in the Remédios biotites; BaO content can go as high as 3.6%.

They are, on the other hand, a significant component of the MEM, OLM and PYM (ankaratrites: i.e., mica-bearing melanephelinites, [12]; cf. also [22]), and can also appear as subordinate phases in some Quixaba basanites,

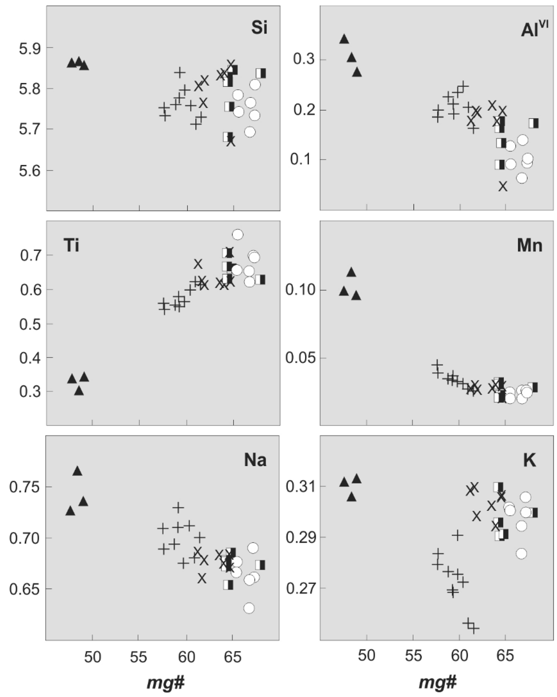

Figure 6. Compositional variations in amphiboles of rocks of the Remédios moderately potassic series. Cations per formula unit versus *mg#* number. Filled triangle: 97FN7a trachyandesite; open circle: 97FN5a trachyandesite; cross: 97FN4a; x sign: 97FN6a; half-filled square: 97FN6b (last three rocks are basaltic trachyandesites).

Table 6. Selected chemical analysis of ilmenites, Fernando de Noronha.

Rock	Btrachan[a]	Btrachan	Lamp II	PYM	Bas
Sample	97FN6a	97FN6b	97FN3b	97FN8	87FN78a
Grain	Mpheno	Mpheno	Mpheno	Bor oliv	Mpheno
SiO_2	0	0.02	0	0.01	0.01
TiO_2	42.6	43.38	43.08	50.34	48.85
Al_2O_3	0.46	0.46	0.78	0.07	0.06
Cr_2O_3	0.06	0.01	0	0.1	0
FeO	29.,53	29.46	27.88	34.42	32.56
Fe_2O_3	19.3	19.85	21.86	7.19	8.24
MnO	0.86	0.69	0.41	0.64	0.65
MgO	4.45	4.96	5.84	5.74	5.96
NiO	0	0.01	0	0.03	0.06
Total	97.25	98.84	99.85	98.52	96.37
FeOtotal	46.92	47.35	47.57	40.9	39.97
RIIO	80.88	80.8	78.8	93.06	92.02
R_2O_3	19.12	19.2	21.2	6.94	7.98

[a]Btrachan: basaltic trachyandesite; Lamp: lamprophyre; PYM: pyroxene melanephelinite; Bas: basanite. Bor oliv: inclusion in border of olivine. Mpheno: microphenocryst.

where they are observed as microphenocrysts and groundmass interstitial grains (Table 7). Additional data on mica chemistry, together with compositional diagrams, can be found in [7].

The highest MgO abundances in micas are found in the Quixaba MEM, around 18 to 19%, and 20 to 21%, microphenocrysts and groundmass grains appearing with very similar compositions; FeO(total) abundances are correspondingly low (around 5 to around 7%, a transitional composition towards phlogopites). The micas which are enriched in Ti are strongly pleochroic, while the ones with less Ti (and F) present lighter colors. Micas with most BaO (17 to 19%) and TiO_2 (13 to 14%), but with little F (< 0.04%) where found in some OLM samples, with a composition similar to the mineral described in the Oahu nephelinites [37].

BaO is one of the oxides that shows in a clear way the compositional behavior of micas (cf. [38–40]; cf. also mica compositions in lamproites, [41]). In all MEM analyses, BaO abundances are conspicuous, as high as 11 to 14.3%, and as low as 6 to 9.5% (in a single case, a mica in contact with olivine, only 0.6%). BaO contents are also significant in the OLM, but very variable, depending on the analysed sample: variations from 4.6 to 15%, or 3.9 to 6.7%; maximum values are 17.4 to 18.6%. In PYM, BaO values, always conspicuous, are lower than in OLM micas (e.g., BaO from 4.1 to 5.8%, or from 2.8 to 9.2%; higher values go up to 11.7 to 15.2% in other samples; lowest ones are not higher than 0.21%). Dark micas also crystallize in amygdules in some of those rocks, with rather high BaO abundances (up to 12.6%) in one sample, but very low (<0.34%) in another. In a diagram showing BaO concentrations against other oxides, the various micas in Quixaba rocks cluster around concentrations characterizing different petrologic behaviors (e.g., basanites clearly separated from PYM and other rocks; cf. figures in [7]; Figure 7). The diagram also indicates that the FN micas show compositions which range from very MgO-rich phases (>18-20%, actual phlogopites) to others with moderate FeO contents (biotites).

A diagram comparing F distribution [cf. [1, 7]] against oxides again illustrates the clustering of mica compositions according to rock type, a further indication of the control of rock chemistry on the mica crystallization (cf. [7]; cf. also micas data from lamproites, with a similar behavior, [41]).

The extreme enrichment in BaO (up to 15.49%) and TiO_2 (up to 11.94%) observed in many of the FN micas led to the discovery of a new species named oxykinoshitalite with the end-member formula $Ba(Mg_2Ti^{4+})(Si_2Al_2)O_{10}O_2$, which is related to the previously discovered kinoshitalite (in 1973) from Iwate Prefecture, Japan, possibly by a coupled substitution such as $M^{2+} + (OH)_2 = Ti^{4+} + O^{2-}$

Table 7. Selected analysis of dark micas, Fernando de Noronha.

Rock	Bas[a]	Essexite	Lamp I	MEM	MEM	MEM	OLM
Sample	97FN15a	97FN42	97FN43c	99FN56b	99FN63	UCFN47	97FN20
Grain	Grmass	Grmass	Grmass	Mpheno	Grmass	Grmass	Grmass
SiO_2	34.06	39.23	34.86	36.01	34.52	33.16	29.31
TiO_2	8.77	6.72	8.42	9.77	3.52	5.48	8.94
Al_2O_3	16.32	12.67	17	13.7	13.18	14.06	15.86
Cr_2O_3	0.03	0.04	0	0	0	0	0
FeO	11.22	10.21	11.78	7.46	5.77	6.64	11.89
MnO	0.09	0.29	0.21	0.08	0.07	0.09	0.03
MgO	14.47	17.17	13.16	17.17	21.12	19.24	13.04
BaO	3.03	0.08	3.63	5.82	6.53	9.72	14.2
CaO	0.05	0	0.05	0.04	0.13	0.08	0.06
Na_2O	0.96	1.09	0.68	0.12	0.23	0.14	0.34
K_2O	7.86	9	7.35	7.97	6.22	6.74	4.63
F	0.65	2.67	0.53	2	5.97	3.52	2
Cl	0	0	0	0	0	0.01	0.04
Total	97.52	99.17	97.66	100.14	97.26	98.87	100.35
O-F-Cl	0.27	1.12	0.22	0.84	2.51	1.49	0.85
Ctotal	97.25	98.05	97.44	99.3	94.75	97.38	99.5
Si	5.049	5.669	5.15	5.27	5.39	5.137	4.66
Al^{IV}	2.849	2.157	2.959	2.36	2.423	2.565	2.969
Al^{VI}	0	0	0	0	0	0	0
Ti	0.978	0.73	0.935	1.075	0.414	0.636	1.069
Fe^{3+}	0	0	0	0	0	0	0
Fe^{2+}	1.392	1.234	1.456	0.912	0.754	0.86	1.58
Cr	0.003	0.004	0	0	0	0	0
Mn	0.011	0.035	0.026	0.01	0.006	0.011	0.004
Mg	3.198	3.699	2.9	3.746	4.917	4.444	3.09
Ba	0.176	0.004	0.21	0.333	0.399	0.59	0.885
Ca	0.008	0	0.009	0.006	0.022	0.014	0.01
Na	0.276	0.307	0.195	0.035	0.07	0.043	0.106
K	1.486	1.66	1.385	1.489	1.24	1.332	1.485
T	7.896	7.826	8.109	7.63	7.813	7.702	7.629
Oct	5.582	5.702	5.317	5.743	6.094	5.951	5.743
Intra	1.946	1.971	1.799	1.863	1.731	1.979	1.941
Tetr def	0.102	0.174	-0.109	0.37	0.187	0.298	0.371

Rock	OLM[b]	OLM	OLM	OLM	OLM	OLM	OLM	OLM	OLM
Sample	97FN32b	97FN32b	97FN44b	97FN58a	97FN58a	99FN3	99FN51	99FN51	99FN54
Grain	Pheno*	Pheno**	Mpheno	Mpheno	Grmass	Mpheno	Mpheno	Grmass	Grmass
SiO_2	35.8	36.91	29.83	26.08	26.99	32.47	28.69	27.32	30.98
TiO_2	5.84	5.4	7.99	13.54	13.28	8.87	810	8.89	13.04
Al_2O_3	13.4	13.11	15.81	16.86	16.8	15.2	18.34	17.27	16.64
Cr_2O_3	0	0	0.05	0.04	0	0	0	0	0
FeO	7.99	7.73	7.64	10.94	11.39	9.14	8.31	8.86	12.71
MnO	0.1	0.05	0.07	0.01	0.03	0.06	0.03	0.05	0.06
MgO	19.29	19.53	15.92	9.74	9.8	14.88	13.99	14.21	10.3

[a]Bas, lamp: basanite, lamprophyre. MEM, OLM: melilite and olivine melanephelinites. Mpheno: microphenocryst; Grmass: groundmass.
[b]OLM: olivine melanephelinites. Pheno*, Pheno**: core and border of phenocryst; Mpheno: microphenocryst; Grmass: groundmass.

Table 7. Contd.

Rock	OLM[a]	OLM	OLM	Olm	OLM	OLM	OLM	OLM	OLM
Sample	97FN32b	97FN32b	97FN44b	97FN58a	97FN58a	99FN3	99FN51	99FN51	99FN54
Grain	Pheno*	Pheno**	Mpheno	Mpheno	Grmass	Mpheno	Mpheno	Grmass	Grmass
BaO	6.69	6.39	15.52	18.64	16.43	0.47	16.03	16.32	10.33
CaO	0.07	0.07	0.03	0.1	0.14	0.07	0.34	0.16	0.36
Na_2O	0.43	0.5	0.29	0.22	0.26	0.38	0.78	0.26	0.3
K_2O	7.63	7.71	4.44	3.08	3.79	5.98	3.92	3.84	5.45
F	4.82	4.7	2.84	0.39	0.38	2.71	2.03	2.17	0.57
Cl	0.01	0	0.02	0.01	0.01	0	0	0	0
Total	101.87	102.11	100.45	99.64	99.31	99.21	100.53	99.34	99.58
O-F-Cl	1.95	1.98	1.2	0.17	0.18	1.14	0.85	0.91	0.24
Ctotal	99.92	100.13	99.25	99.47	99.15	98.07	99.68	98.43	99.34
Si	5.336	5.46	4.719	4.229	4.333	4.996	4.519	4.406	4.751
Al^{IV}	2.353	2.284	2.945	3.222	3.175	2.754	3.402	3.281	3.005
Al^{VI}	0	0	0	0	0	0	0	0	0
Ti	0.656	0.601	0.951	1.652	1.603	1.028	0.959	1.078	1.372
Fe^{3+}	0	0	0	0	0	0	0	0	0
Fe^{2+}	0.997	0.956	1.011	1.484	1.528	1.175	1.095	1.195	1.63
Cr	0	0	0.006	0.006	0	0	0	0	0
Mn	0.013	0.007	0.01	0.001	0.004	0.008	0.004	0.007	0.007
Mg	4.287	4.307	3.755	2.356	2.345	3.414	3.284	3.416	2.356
Ba	0.391	0.371	0.962	1.185	1.033	0.571	0.989	1.031	0.621
Ca	0.011	0.011	0.006	0.018	0.024	0.011	0.057	0.029	0.058
Na	0.144	0.144	0.089	0.068	0.08	0.113	0.231	0.08	0.088
K	1.451	1.454	0.896	0.637	0.777	1.173	0.788	0.79	1.066
T	7.689	7.744	7.664	7.451	7.508	7.75	7.921	7.687	7.756
Oct	5.953	5.871	5.733	5.499	5.48	5.625	5.342	5.696	5.365
Intra	1.977	2.003	1.963	1.908	1.914	1.868	2.065	1.93	1.833
Tetr def	0.256	0.254	0.336	0.549	0.492	0.25	0.079	0.313	0.244

Rock	PYM	PYM	PYM	PYM	PYM	PYM	PYM	Bas[b]	Bas
Sample	97FN8	97FN13c	97FN13c	97FN32d	97FN32d	97FN46	99FN37	99FN4	99FN4
Grain	Mpheno	Grmass	Mpheno	Grmass	Mpheno	Mpheno	Amygd	Grmass	Grmass
SiO_2	36.05	39.81	34.94	32.88	33.17	34.76	32.81	37.55	37.54
TiO_2	9.63	5.82	8.03	7.75	7.32	10.73	10.72	8.62	8.71
Al_2O_3	14.03	13.04	13.58	14.84	14.97	13.06	15.2	13.82	14.23
Cr_2O_3	0.01	0	0.01	0	0	0.01	0	0	0
FeO	10.46	6.9	11.43	9.72	9.36	11.8	11.67	12.32	10.08
MnO	0.12	0.05	0.03	0.1	0.11	0.1	0.07	0.15	0.1
MgO	14.52	19.99	14.73	13.99	14.5	13.16	12.17	15.05	16.08
BaO	4.02	1.9	6.5	11.03	11.59	4.55	8.05	0.53	0.43
CaO	0.01	0.11	0.19	0.06	0.05	0.02	0.06	0.02	0.01
Na_2O	0.87	0.79	0.67	0.85	0.49	0.74	0.76	0.68	0.65
K_2O	7.46	8.76	6.7	5.6	5.64	7.09	5.82	9.01	8.78
F	1.81	2.79	1.8	3.13	3.83	1.53	1.65	1.34	1.58
Cl	0.02	0	0.02	0	0	0	0	0	0
Total	99	99.77	98.63	99.76	101.03	97.54	98.97	99.1	98.18

[a]OLM: olivine melanephelinites. Pheno*, Pheno**: core and border of phenocryst; Mpheno: microphenocryst; Grmass: groundmass.
[b]Bas: basanite. PYM: pyroxene melanephelinites. Mpheno: microphenocryst; Grmass: groundmass; Amygd: amygdule.

Table 7. Contd.

Rock	PYM	PYM	PYM	PYM	PYM	PYM	PYM	Bas[a]	Bas
Sample	97FN8	97FN13c	97FN13c	97FN32d	97FN32d	97FN46	99FN37	99FN4	99FN4
Grain	Mpheno	Grmass	Mpheno	Grmass	Mpheno	Mpheno	Amygd	Grmass	Grmass
O-F-Cl	0.77	1.17	0.78	1.32	1.61	0.64	0.69	0.57	0.67
Ctotal	98.23	98.6	97.87	98.44	99.42	96.9	98.28	98.53	97.52
Si	5.321	5.664	5.296	5.096	5.139	5.262	5.005	5.435	5.425
Al^{IV}	2.439	2.196	2.423	2.725	2.732	2.238	2.73	2.356	2.421
Al^{VI}	0	0	0	0	0	0	0	0	0
Ti	1.069	0.626	0.915	0.909	0.853	1.221	1.23	0.939	0.947
Fe^{3+}	0	0	0	0	0	0	0	0	0
Fe^{2+}	1.291	0.825	1.449	1.268	1.254	1.494	1.489	1.492	1.219
Cr	0.001	0	0.001	0	0	0.001	0	0	0
Mn	0.015	0.007	0.003	0.013	0.014	0.012	0.01	0.019	0.012
Mg	3.194	4.262	3.327	3.252	3.349	2.97	2.768	3.249	3.465
Ba	0.232	0.107	0.386	0.674	0.704	0.27	0.481	0.03	0.024
Ca	0.001	0.017	0.031	0.01	0.008	0.003	0.01	0.002	0.002
Na	0.249	0.219	0.197	0.255	0.147	0.217	0.226	0.191	0.82
K	1.404	1.598	1.296	1.113	1.115	1.369	1.133	1.663	1.618
T	7.76	7.86	7.719	7.821	7.871	7.59	7.735	7.761	7.846
Oct	5.57	5.72	5.695	5.442	5.43	5.698	5.497	5.699	5.643
Intra	1.886	1.941	1.91	2.052	1.974	1.859	1.85	1.886	1.826
Tetr def	0.24	0.14	0.281	0.179	0.129	0.41	0.265	0.209	0.154

[a]Bas: basanite. PYM: pyroxene melanephelinites. Mpheno: microphenocryst; Grmass: groundmass; Amygd: amygdule.

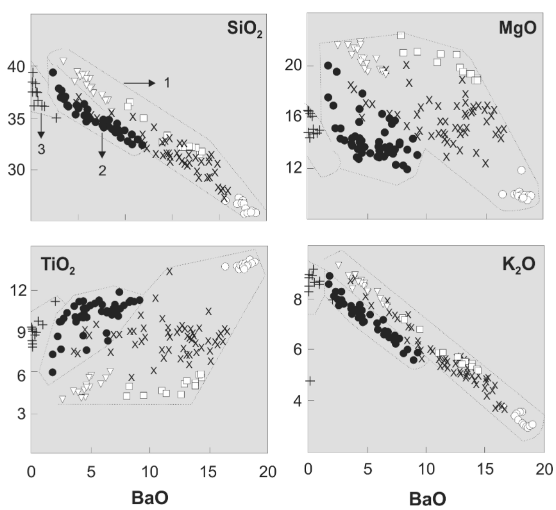

Figure 7. Oxide variations versus BaO content in biotites and phlogopites of rocks from the Quixaba Formation. OLM, olivine melanephelinites: *open circles, x signs*, among other samples), *inverted triangles*; MEM, melilite melanephelinites: *open squares*; PYM, pyroxene melanephelinites: *filled circles*; Quixaba basanites: *crosses*. Composition cluster in definite areas (e.g., in the SiO_2 diagram: field 1, MEM and OLM; field 2, PYM; field 3, Quixaba basanites; and so on). Source: [1, 2, 7].

(c.f discussion and references in [42]). Many of the analized micas in the Quixaba melanephelinites, as described above (cf. also Table 7), belong to one or the other of these mica species.

The calculation of mica structural formulae can lead to different results, depending on the composition of the phases and the adopted calculation scheme. The method based on 22 (O, F), in micas with plenty of Ba and Ti results in deficiencies in the tetrahedral occupancy (Si + Al < 8), as already mentioned [43–47]. In the FN rocks, this deficiency varies from 0.05 to 0.7 afu, larger in the OLM, MEM and PYM, smaller in the Quixaba basanite micas. In the literature, other methods were proposed, such as the one cited in [45], applied for Ba-rich phases, based on 12 (O,F), but which may yield excess cations for the octahedral and interlayer occupancies.

In any case, mica formulae calculation based on compositions obtained with microprobe analyzers can only yield partially satisfactory results, given that F replaces O in the case of a marked presence of the halogen and that the attribution of Fe^{3+} into tetrahedral positions may be only tentative.

The correlation between Ba and (K + Na+ Ca) is practically 1:1, indicating that Ba enters interlayer positions. Excess charge may be compensated by the following substitution:

$$K^{(xii)} + Si^{(iv)} = Ba^{(xii)} + Al^{(iv)}$$

as suggested in [48] and depicted in diagrams in [1, 7]; cf. also [37, 39, 49]. Other cited substitution mechanisms ([38, 44]), are as follows:

$$Mg^{vi} + 2Si^{iv} = Ti^{vi} + 2Al^{iv}$$

$$\left(Mg, Fe^{2+}\right)^{vi} + 2Si^{iv} = Ti^{vi} + 2\left(Al, Fe^{3+}\right)^{iv}$$

or the Ti-oxygen substitution [43]:

$$\left(Mg, Fe^{2+}\right)^{vi} + 2OH^{-} = Ti^{vi} + 2O^{2-} + H_2$$

In FN, the possible substitution mechanism to be applied should involve a relationship between octahedral cations and vacancies in the structure, such as

$$2\left(R^{2+}\right)^{vi} = Ti^{vi} + \Delta^{vi}$$

as proposed by [50]. An application of this concept shows, in the diagram Ti versus Mg + Fe^{2+}, that vacancies may indeed exist in the Ba micas of FN (cf. [7]).

3.8. Feldspars

The Remédios basanites and tephrites, of the sodic series, present both ternary and alkali feldspars feldspars, with Or as high as >30% molar in tephrites, and >13% molar in basanites; Table 8), and only exceptionally plagioclase (andesine, in one sample). The mineral is probably hidden in the glassy and analcime-rich groundmass; partial microprobe analyses of glasses indicate CaO varying from 2.5 to 5%, with around 5% of Na_2O and similar values of K_2O. In these rocks with glass, some tiny groundmass laths of alkaline feldspar are observed, with BaO content varying from 0.5 to 4% and SrO from 1.4 to 4%. Essexites and tephriphonolites present plagioclase (labradorite and andesine, respectively; cf. Figure 8A). The several phonolite types display phenocrysts of anorthoclase and sanidine, with rather large compositional intervals (Or70-20Ab30-80An<4; Table 8).

In the alkali basalt (moderately potassic series), the feldspars appear as plagioclase phenocrysts: labradorite with andesine borders, and andesine, sanidine and anorthoclase laths in the groundmass. In the basaltic trachyandesites, zoned phenocrysts of labradorite are observed, with slightly less calcic andesine borders, together with sanidines and anorthoclase as groundmass laths (Figure 8B). SrO is a conspicuous minor element (0.52 to 0.76%) present principally in Ca-rich feldspars.

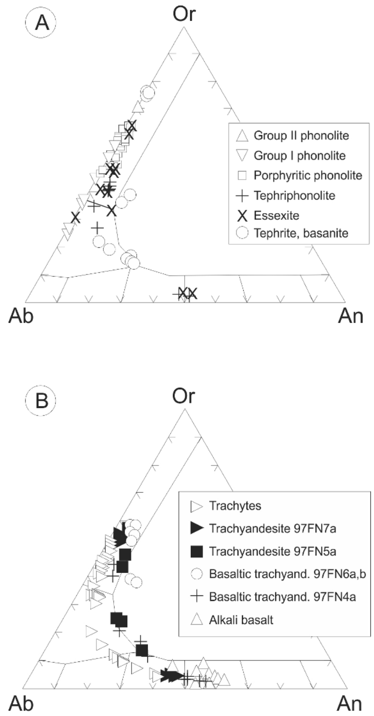

Figure 8. A: Composition of the feldspars of rocks of the Remédios sodic series in the feldspar triangle (see also next figure). B: Composition of feldspars in rocks of the Remédios moderately potassic series. Source: [1, 2, 14].

In trachytes and trachyandesites, the plagioclase phenocrysts are somewhat less calcic (andesines) and rather homogeneous, with thin oligoclase or sanidine borders; sanidine and anorthoclase laths are predominant in the groundmass (cf. Figure 8B). Correlation between K-Si and K-Al in these feldspars is well defined, but rather loose between Sr-K and Sr-Ca.

Feldspars are found in all Remédios lamprophyres. In type I rocks, however, the groundmass is usually very glassy, with a more or less homogeneous composition (CaO 1-2%, Na_2O 5-6%, K_2O around 5%, Fe_2O_3 1-2%, and traces of BaO and SrO). In type II rocks, feldspars are very abundant, with frequent plagioclase phenocrysts (andesine and labradorite) and anorthoclase and sanidine laths; some plagicolases are enriched in K_2O (13-20% molar Or). Albite-rich alkali feldspars are predominant in type III lamprophyres; plagioclases are missing. Feldspars in type IV are enriched in K_2O (60-70% molar Or; cf. Figure 9; Table 8). Trace amounts of SrO and BaO are found in all lamprophyre feldspars, more so in type IV rocks (up to 5% BaO; Figure 9).

Plagioclases are found especially in the Quixaba basanites (andesine to labradorite) also accompanied with some ternary feldspars and sanidines (molar Or up to 50%; Fig-

Table 8. Selected analysis of feldspars, Fernando de Noronha.

Rock	Basan[a]	Tephrite	Tephrite	Essexite	Essexite	Essexite	Essexite	Essexite	Tphon	Tphon
Sample	97FN23	97FN43a	97FN43a	97FN42	97FN42	97FN42	97FN42	97FN42	97FN11a	97FN11a
Grain	Grmass	Pheno*	Grmass	Pheno*	Pheno**	Pheno**	Mpheno*	Mpheno**	Grmass	Pheno*
SiO_2	57.4	57.99	64.54	61.62	62.97	62.44	54.92	55.88	62.25	55.65
TiO_2	0.32	0.22	0.22	0.02	0.1	0.15	0.15	0.26	0.07	0.09
Al_2O_3	24.57	22.59	18.73	20.78	20.24	22.39	27.47	27.32	20.33	27.23
Fe_2O_3	0.25	0.38	0.48	0.29	0.28	0.4	0.6	0.86	1.23	0.48
MnO	0.01	0	0.01	0.06	0.06	0.08	0.08	0.04	0.02	0
MgO	0.06	0.01	0	0	0	0	0.03	0.01	0.1	0.01
SrO	3.41	3.76	0.25	1.86	1.09	0	0.63	0.72	1.15	0.42
BaO	1.59	3.72	0.15	2.03	1.66	0.82	0.01	0.04	0.92	0.17
CaO	4.35	1.93	0.2	1.14	0.64	2.07	9.96	9.38	1.09	9.81
Na_2O	6	4.81	2.78	5.75	6.24	6.32	6.225	5.57	5.71	5.39
K_2O	2.51	4.84	12.88	6.04	6.53	5.37	0.56	0.56	6.21	0.41
Total	100.47	100.23	100.24	99.58	99.8	100.05	99.59	100.43	99.08	99.68
Si	10.57	10.907	11.841	11.404	11.553	11.269	9.994	10.075	11.461	10.091
Al	5.328	5.003	4.047	4.529	4.373	4.759	5.886	5.801	4.409	5.816
Fe3+	0.034	0.063	0.066	0.041	0.039	0.054	0.082	0.088	0.17	0.066
Ti	0.044	0.031	0.031	0.003	0.014	0.021	0.02	0.036	0.01	0.013
Mn	0.002	0	0.002	0.01	0.009	0.013	0.012	0.005	0.003	0
Mg	0.017	0.003	0	0	0	0	0.007	0.001	0.027	0.004
Sr	0.364	0.41	0.027	0.2	0.116	0	0.066	0.075	0.123	0.044
Ba	0.116	0.274	0.011	0.147	0.119	0.058	0.001	0.003	0.066	0.012
Ca	0.858	0.388	0.039	0.225	0.125	0.4	1.941	1.812	0.215	1.907
Na	2.143	1.755	0.989	2.062	2.22	2.212	1.843	1.946	2.037	1.897
K	0.589	1.162	3.015	1.425	1.528	1.236	0.127	0.13	1.457	0.094
Or	15.1	31.6	75.1	37.3	39.4	33.2	3.3	3.4	39	2.5
Ab	51.9	44.9	23.2	50.8	53.9	56	44.7	47.5	51.4	46.5
An	33	23.5	1.7	12	6.7	10.8	52	49.2	9.6	51

Rock	Rock	Tphon[b]	Tphon	Abas	Abas	Abas	Btrachan	Btrachan	Btrachan	Btrachan	Btrachan
Sample	Sample	97FN11a	97FN11a	97FN35b	97FN35b	97FN35b	97FN4a	97FN4a	97FN4a	97FN6a	97FN6b
Grain	Grain	Pheno**	Grmass	Pheno*	Pheno**	Grmass	Pheno*	Pheno**	Grmass	Grmass	Grmass
SiO_2	SiO2	56.18	61.93	55	54.09	52.12	54.8	56.28	65.46	65.77	63.26
TiO_2	TiO2	0	0.06	0.03	0.09	0.13	0	0	0	0.17	0.2
Al_2O_3	Al2O3	27.13	20.9	28.47	28.82	28.74	28.74	27.85	19.82	19.51	20.11
Fe_2O_3	Fe2O3	0.54	0.56	0.41	0.83	1.16	0.6	0.59	0.6	0.44	0.32
MnO	MnO	0.03	0	0	0.03	0.04	0	0.02	0	0	0
MgO	MgO	0.02	0	0	0	0	0	0	0	0.01	0
SrO	SrO	0.36	1.91	0.34	0.29	0.27	0.51	0.56	0	0	0.53
BaO	BaO	0.07	1.86	0	0.1	0.12	0	0	0	0	1.97
CaO	CaO	9.38	1.06	10.94	11.42	12.1	10.77	9.69	1.2	0.86	1.02
Na_2O	Na2O	5.89	5.64	5.12	4.44	4.19	4.77	5.43	5.71	4.19	4.03
K_2O	K2O	0.48	6.51	0.36	0.3	0.59	0.43	0.57	7.33	9.39	8.4
Total	Total	100.08	100.42	100.87	100.91	99.45	100.81	100.97	100.11	100.32	99.83

[a]Basan, Tphon: basanites, tephriphonolites. Pheno*, Pheno **: core and border of phenocryst. Grmass: groundmass. Cations for 32 Oxygens.
[b]Tphon, Abas, Btrachyan: tephriphonolite, alkali basalt, basaltic trachyandesite. Pheno*, Pheno**: core-border of phenocryst.

Table 8. Contd.

Rock	Rock	Tphon[a]	Tphon	Abas	Abas	Abas	Btrachan	Btrachan	Btrachan	Btrachan	Btrachan
Sample	Sample	97FN11a	97FN11a	97FN35b	97FN35b	97FN35b	97FN4a	97FN4a	97FN4a	97FN6a	97FN6b
Grain	Grain	Pheno**	Grmass	Pheno*	Pheno**	Grmass	Pheno*	Pheno**	Grmass	Grmass	Grmass
Si	Si	10.139	11.382	9.89	9.752	0.574	9.862	10.071	11.759	11.841	11.622
Al	Al	5.767	4.524	6.028	6.118	6.217	6.091	5.87	4.193	4.136	4.361
Fe3+	Fe3+	0.073	0.077	0.066	0.113	0.161	0.081	0.079	0.081	0.06	0.046
Ti	Ti	0	0.008	0.004	0.013	0.018	0	0	0	0.022	0.028
Mn	Mn	0.005	0	9	0.004	0.007	0	0.003	0	0	0
Mg	Mg	0.006	0	0	0	0	0	0	0	0.002	0
Sr	Sr	0.038	0.203	0.036	0.03	0.028	0.063	0.057	0	0	0.056
Ba	Ba	0.005	0.134	0	0.007	0.009	0	0	0	0	0.142
Ca	Ca	1.814	0.209	2.107	2.206	2.382	2.078	1.858	0.23	0.164	0.2
Na	Na	2.062	2.008	1.786	1.553	1.492	1.663	1.885	1.989	1.461	1.436
K	K	0.111	1.526	0.083	0.184	0.137	0.099	0.13	1.681	2.156	1.968
Or	Or	2.8	39.5	2.1	4.7	3.5	2.6	3.4	44.4	58.3	54.9
Ab	Ab	49.7	49	43	37.6	36.5	41.2	46.4	49.5	37.1	37.7
An	An	47.5	11.6	54.9	57.6	61	56.2	50.2	6.1	4.4	7.4

Rock	Trachan[b]	Trachan	Trachan	Trachyte	Trachyte	Trachyte	Trachyte	Trachyte	Trachyte
Sample	97FN5a	97FN5a	97FN7a	97FN30a	97FN30a	97FN30b	97FN57	97FN57	97FN57
Grain	Grmass	Grmass	Pheno**	Pheno*	Pheno**	Pheno*	Grmass	Pheno*	Pheno**
SiO_2	63.89	62.04	57.8	62.09	61.99	66.65	66.46	58.59	59.05
TiO_2	0.26	0.18	0.06	0	0	0	0	0	0
Al_2O_3	19.37	21.75	25.96	23.79	23.1	19.79	20.31	26.53	26.24
Fe_2O_3	0.38	0.38	0.44	0.36	0.34	0.21	0.51	0.36	0.38
MnO	0.02	0.01	0.03	0	0	0	0	0.01	0.02
MgO	0	0.02	0.01	0	0	0	0	0	0
SrO	0.1	0.54	0.66	0.5	0.52	0.04	0.08	0.69	0.61
BaO	0.34	0.65	0.11	0	0	0.01	0	0.01	0.02
CaO	0.84	3.16	7.89	5	4.31	0.62	1.4	7.8	7.45
Na_2O	4.55	6.53	5.07	7.18	7.32	5.81	6.98	6.37	6.41
K_2O	9.88	4.07	0.66	1.58	1.99	6.72	5.5	0.72	0.85
Total	99.43	99.33	98.67	100.51	99.57	99.85	101.24	101.06	101.02
Si	11.714	11.271	10.49	11.021	11.113	11.905	11.735	10.424	10.495
Al	4.182	4.663	5.548	4.973	4.873	4.164	4.223	5.568	5.494
Fe3+	0.052	0.052	0.061	0.048	0.046	0.028	0.068	0.046	0.048
Ti	0.036	0.022	0.008	0	0	0	0	0	0
Mn	0.002	0.002	0.005	0	0	0.001	0	0.002	0.003
Mg	0	0.005	0.002	0	0	0	0	0	0
Sr	0.011	0.057	0.069	0.052	0.054	0.004	0.008	0.071	0.063
Ba	0.024	0.046	0.008	0	0	0.001	0	0.001	0.002
Ca	0.165	0.615	1.534	0.951	0.828	0.119	0.265	1.486	1.418
Na	1.617	2.302	1.783	2.472	2.546	2.011	2.389	2.196	2.211
K	2.265	0.944	0.153	0.358	0.456	1.532	1.239	0.163	0.193
Or	57.1	24.9	4.4	9.7	12.2	43.2	32.9	4.3	5.1
Ab	38.4	57.2	48.7	63	64.1	53.4	59.8	54.4	56.3
An	4.5	18	46.8	27.3	23.3	3.5	7.3	41.3	39.6

[a]Tphon, Abas, Btrachyan: tephriphonolite, alkali basalt, basaltic trachyandesite. Pheno*, Pheno**: core-border of phenocryst.
[b]Trachan: trachyandesite; Pheno*, Pheno**: core-border of phenocryst.

Table 8. Contd.

Rock	Lamp II	Lamp II	Lamp II	Lamp III	Lamp IV	Lamp IV	PYM	PYM	Bas	Bas
Sample	97FN3a	97FN3b	97FN3b	97FN7	97FN25	97FN25	97FN40	99FN37	89FN78a	89FN78a
Grain	Grmass[a]	Mpheno	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass
SiO_2	61.43	56.77	58.24	54.84	59.28	64.16	60.71	60.26	52.19	52.19
TiO_2	0	0.06	0.22	0.9	0.4	0.85	0.22	0.17	0.11	0.11
Al_2O_3	23.56	28.13	25.86	23.51	21.2	18.99	23.81	19.84	31.54	31.54
Fe_2O_3	0.44	0.71	0.94	2.49	0.65	1.03	0.4	0.39	0.78	0.78
MnO	0	0	0.03	0.04	0	0.03	0	0	0	0
MgO	0	0.03	0.12	1.06	0.04	0	0.01	0.01	0	0
SrO	1.66	0.62	0.48	0.27	2.47	0.01	0.63	1.03	0	0
BaO	0	0.06	0.13	0.18	3.28	0.15	1.21	4.87	0.15	0.15
CaO	3.57	10.2	7.63	0.62	0.49	0.27	4.42	0.35	0.32	0.32
Na_2O	6.17	5.17	5.81	10.8	3.13	2.47	7.3	4.06	12.62	12.62
K_2O	3.47	0.6	1.56	5.03	8.86	12.54	1.59	8.31	2.09	2.09
Total	100.3	101.33	101.02	99.73	99.79	100.49	100.29	99.28	99.8	99.8
Si	11.045	9.976	10.416	10.227	11.201	11.724	10.918	11.45	9.535	9.535
Al	4.987	5.925	4.446	5.163	4.718	4.088	5.042	4.439	6.785	6.785
Fe^{3+}	0.08	0.096	0.127	0.349	0.092	0.141	0.054	0.055	0.107	0.107
Ti	0	0.007	0.029	0.126	0.056	0.117	0.03	0.024	0.015	0.015
Mn	0	0	0.004	0.007	0	0.005	0	0	0	0
Mg	0	0.008	0.033	0.295	0.011	0	0.001	0.002	0	0
Sr	0.173	0.064	0.05	0.029	0.271	0.001	0.065	0.114	0	0
Ba	0	0.004	0.009	0.013	0.243	0.011	0.085	0.362	0.011	0.011
Ca	0.688	1.954	1.463	0.124	0.099	0.052	0.851	0.072	0.063	0.063
Na	2.149	1.794	2.014	3.907	1.148	0.874	2.544	1.494	4.469	4.469
K	0.796	0.135	0.356	1.196	2.135	2.164	0.366	2.014	0.488	0.488
Or	21.5	3.5	9.4	23.8	58.8	76.9	9.9	56.5	10.3	103
Ab	54.6	43.9	50.3	73.1	29.8	21.7	65	38.8	88.4	88.4
An	24	52.6	40.3	3.1	11.4	1.4	25.1	5.7	1.3	1.3

Rock	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas
Sample	99FN4	99FN4	99FN7e	99FN7e	99FN9c	99FN10a	99FN10b	99FN10b	99FN22	99FN22
Grain	Grmass[b]	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Mpheno*	Mpheno	Grmass
SiO_2	65.46	60.54	55.56	66.29	56.3	52.89	53.77	53.17	56.94	55.59
TiO_2	0.2	0.19	0.15	0.22	0.15	0.19	0.17	0.09	0.17	0.15
Al_2O_3	19.68	23.26	26.98	19.44	27.62	29.19	28.67	29.37	27.2	27.95
Fe_2O_3	0.28	0.38	0.56	0.35	0.69	0.69	0.8	0.61	0.44	0.72
MnO	0	0.02	0	0	0.03	0.01	0.03	0	0.01	0.02
MgO	0	0.02	0.04	0.01	0	0	0	0	0	0
SrO	0	1.15	0.65	0.05	0.29	0.43	0.32	0.32	0.57	0.41
BaO	0.07	1.03	0.09	0.26	0	0.2	0.08	0	0.35	0.09
CaO	1.16	4.16	9.42	0.85	10.25	11.84	10.97	11.9	9.15	9.81
Na_2O	6.08	7.19	5.71	6.34	5.17	4.3	4.89	4.29	5.99	5.54
K_2O	7.14	1.59	0.41	6.76	0.37	0.18	0.38	0.28	0.46	0.35
Total	100.07	99.49	99.56	100.57	99.88	99.91	99.75	100.02	101.27	100.62

[a]Grmass: groundmass; Mpheno: microphenocryst; Bas: basanite; Lamp: lamprophyre; PYM: pyroxene melanephelinite.
[b]Grmass: groundmass; Mpheno*: microphenocryst, core; bas: basanite.

Table 8. Contd.

Rock	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas	Bas
Sample	99FN4	99FN4	99FN7e	99FN7e	99FN9c	99FN10a	99FN10b	99FN10b	99FN22	99FN22
Grain	Grmass[a]	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Mpheno*	Mpheno	Grmass
Si	11.765	10.981	10.099	11.838	10.005	9.63	9.772	9.648	10.173	9.992
Al	4.165	4.968	5.777	4.088	5.886	6.258	6.138	6.275	5.722	5.917
Fe3+	0.037	0.045	0.078	0.047	0.094	0.094	0.082	0.083	0.06	0.097
Ti	0.027	0.027	0.02	0.03	0.021	0.026	0.036	0.012	0.023	0.02
Mn	0	0.003	0	0	0.005	0.002	0.005	0	0.002	0.002
Mg	0	0.005	0.01	0.002	0	0	0	0	0	0
Sr	0	0.121	0.068	0.005	0.031	0.046	0.034	0.0.34	0.059	0.043
Ba	0.005	0.074	0.006	0.018	0	0.014	0.004	0	0.025	0.006
Ca	0.223	0.809	1.835	0.162	1.986	2.109	2.136	2.313	1.752	1.889
Na	2.119	2.529	2.014	2.195	1.813	1.518	1.661	1.508	2.075	1.93
K	1.638	0.367	0.094	1.541	0.085	0.042	0.089	0.084	0.104	0.08
Or	42.5	9.9	2.4	40.8	2.2	1.1	2.3	1.7	2.7	2.1
Ab	51.8	64.4	48.6	54.8	44.8	37.3	40.7	37	50.4	47.4
An	5.8	25.7	49	4.4	53	61.6	57	61.3	46.9	50.5

[a]Grmass: groundmass; Mpheno*: microphenocryst, core; bas: basanite.

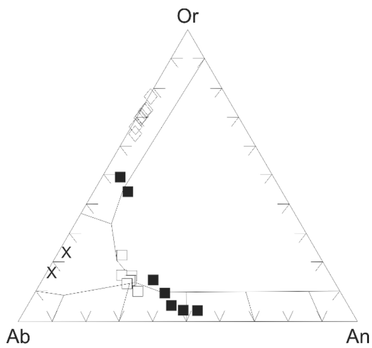

Figure 9. Compositions of feldspars in the Remédios lamprophyres. *Type II*: filled square and empty square; *Type III*: x sign; *Type IV*: diamond. Source: [1, 13].

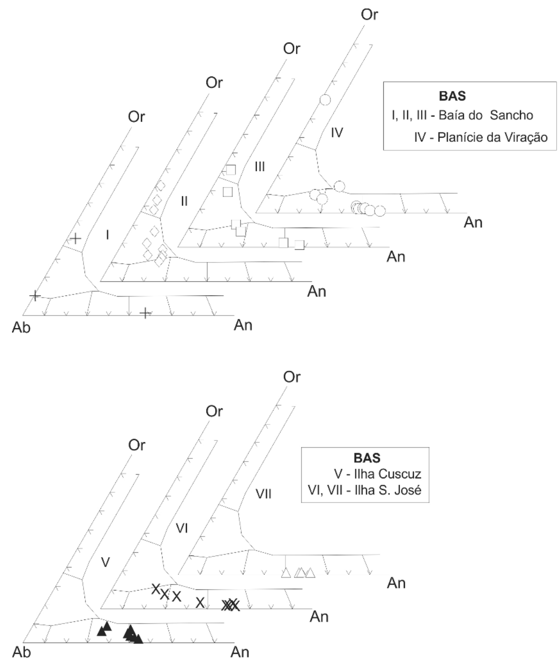

Figure 10. Feldspar compositions in basanites of the São José (I. Cuscuz, I.S. José) and Quixaba (B. Sancho, Pl. Viração) formations, represented in the feldspar triangle. Source: [1, 2].

ure 10). Some of the PYM also present ternary feldspars and some sanidines (42 to 56% molar Or). In the São José basanites, on the other hand, plagioclase (oligoclase, andesine, labradorite) is the sole occurying feldspar; the rocks are devoid of alkali feldspars, contrary to what is observed in the reported Quixaba basanites (Table 8, Figure 10).

3.9. Nephelines and other feldspathoids

Nepheline and several other feldspathoids are mostly found in the rocks of the Remédios sodic series. Mesopotassic nephelines are present in the essexites, as well as in the three phonolite types (Table 9). Haüynite was observed sporadically in some of the Remédios basanites, while nosean (6 to 8.5% SO_3) occurs in tephriphonolites, the porphyritic phonolites and the Group I aphyric phonolites. Sodalite (around 24% Na_2O, up to 6.5% Cl) was also

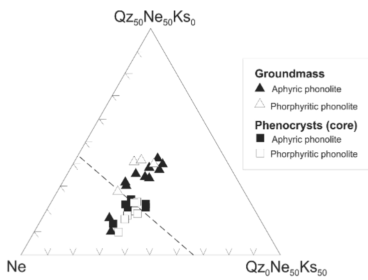

Figure 11. Nepheline compositions in phonolites represented in the silica-nepheline-kalsilite triangle. Dashed line represents the 700°C silica-saturation in nephelines [51, 52]. Source: [1, 2, 14].

encountered in the most differentiated Group II aphyric phonolites (cf. [1, 14]).

Nephelines are present as microphenocrysts and, mainly, as groundmass grains in Quixaba basanites and melanephelinites, where they show a marked variation in chemical compositions: less evolved MEM foids are somewhat enriched in Mg, Na and total Fe_2O_3 and K_2O, a feature shared with OLM, accompanied by a decrease in those values for PYM and the basanite foids (cf. Table 9).

Nephelines of the phonolites represented within the silica-nepheline-kalsilite triangle plot loosely clustered alongside the 700°C silica-solution line [51, 52]; (Figure 11; data in [14]).

4. Discussion

The Remédios Formation is composed by a basal pyroclastic unit intruded by many dikes and several plugs, the last ones made up mostly by phonolites. Some xenocrysts (olivines, pyroxenes, some amphiboles) are observed in dike rocks and phonolites, showing corroded borders and outer reaction rims [1, 2, 13, 14], interpreted as evidence of disequilibrium conditions and indication of "crystal-magma" mixing, observed especially in some lamprophyres, tephriphonolites and phonolites. The presence of cm-sized fragments of plutonic cumulates [1, 2, 15] points clearly to the existence of deeper seated magma chambers, connected by fractures that are passageways of the magmas that crystallized as dikes and plugs. Probably, some of the xenocrysts with corrosion textures may represent crystals dragged out of these cumulates, then reacting with the surrounding magmas.

Mineralogy, petrography and geochemistry [1, 2] point to the presence of the Remédios sodic series, with SiO_2 abundances grading from 41.5% to 59%, and a trend towards undersaturation [1, 2, 7, 8]. Basanites and tephrites are considered likely parental compositions for this series, an argument that is also enhanced by the presence in these rocks of Mg-rich olivines (Fo_{86} to Fo_{82}). Clinopyroxenes, the most abundante mafic phases, are salites to ferrosalites in these rocks, replaced in more evolved types (tephriphonolites) by aegirine-augites and, finally, by aegirines in the Group II phonolites.

Green cores in clinopyroxenes, enriched in Na, surrounded by Ti-rich brownish margins, probably represent xenocrysts derived from peridotitic (or pyroxenitic?) mantle rocks [1, 7, 53]. On the other hand, the already mentioned xenocrysts found in phonolites (olivines and diopsides) are clearly out of equilibrium in these rocks, as indicated by reaction rims formed around their corroded cores [1, 54]; cf. also [55].

The second Remédios series is a moderately potassic one, with a trend towards slight oversaturation and alkali basalts as the most primitive types, evolving towards trachyandesites and trachytes [1, 2, 9, 18]. Intermediate rocks in this series (especially basaltic trachyandesites) present partially corroded xenocrysts, an indication of "crystal-magma" mixing, a feature commonly observed in oceanic islands (cf. discussion above; also [55]). Olivine (Fo_{72}) is found only in the alkali basalt, the presumed parental composition in the potassic trend, an indication that this rock is geochemically more differentiated than the Remédios basanites present in the sodic series. In the alkali basalt, the clinopyroxenes are salites and titaniferous salites (*mg#* between 79-66), evolving towards less magnesian salites in the trachytes (*mg#* around 67-51), up to sodic types in the trachytic groundmass.

The abundant Remédios lamprophyres (cf. [1, 2, 13, 21]) are characterized by the presence of amphiboles, a peculiar situation in oceanic islands, thus pointing to a lack of surplus potassium in the corresponding magmas, as a probable inhibiting factor for the crystallization of micas. Features pointing to disequilibrium conditions, such as complex zoning patterns in amphiboles, are also obvious in many lamprophyres (cf. also [13, 54]). Green cores are also commonly present in their clinopyroxenes [1, 7, 13, 53].

Melanephelinite flows (MEM, OLM and PYM, melanephelinites with melilite, olivine or pyroxenes as defining phases) together with some basanites, compose the late Quixaba Formation. Magnesian olivines are important in all melanephelinites, representing probable equilibrium conditions with melts derived from mantle peridotites. Melilites in MEM show compositions that are related both to olivine content and the original whole rock composition: crystals present in OLM are typically somewhat depleted in Mg and enriched in Al_2O_3 when compared with rocks with lesser olivine (cf. also [22, 28, 56]). Melilite crystallization in magmas is

Table 9. Selected analysis of nephelines, Fernando de Noronha.

Rock	Essexite	Porphon[a]	Aphon I	Aphon II	MEM	MEM	MEM	MEM	OLM	OLM
Sample	97FN42	89FN71	89FN47	89FN66	97FN31	97FN31	99FN56b	99FN63	97FN20	97FN58a
Grain	Mpheno	Mpheno	Pheno	Grmass	Mpheno	Grmass	Mpheno	Grmass	Grmass	Grmass
SiO_2	47.93	44.1	44.5	46.7	47.92	41.85	41.24	42.33	42.5	41.37
TiO_2	0.08	0	0	0	0.09	0.09	0	0.05	0.09	0.14
Al_2O_3	30.95	34.1	34.3	32	3.28	32.84	33.5	32.77	33.41	32.73
Fe_2O_3	0.69	0.51	0.34	1.12	1.18	1.43	0.85	1.02	1.01	1.31
MnO	0.02	0	0	0	0	0	0.03	0.01	0.02	0
MgO	0.07	0	0	0	0.25	0.9	0.16	0	0.07	0.3
CaO	0.03	0.63	0.02	0	0.2	0.73	0.2	2.87	1.19	1.02
Na_2O	16.71	16.,10	16.9	16.1	15.13	14.3	14.21	13.08	14.58	14.2
K_2O	3.46	4.27	4.6	4.36	8.45	7.81	9.17	5.93	6.65	7.91
SrO	0	0	0.06	0.06	0.04	0.03	0.03	0.08	0.18	0.11
BaO	0.01	0	0.02	0	0	0.02	0.03	0.16	0.19	0.05
Total	99.94	99.71	100.74	100.34	100.53	100	99.42	98.28	99.89	99.15
Ne	78.99	79.72	79.34	78.09	72.75	73.67	69.36	76.67	75.4	73.12
Ks	11.44	14.94	15.47	14.31	27.25	26.33	30.64	23.33	23.27	26.88
Qz	9.57	5.34	5.19	7.6	0	0	0	0	1.33	0

Rock	OLM[b]	OLM	OLM	OLM	PYM	PYM	PYM	Bas	Bas
Sample	99FN3	99FN51	99FN54	99FN55	97FN8	97FN38	99FN14	99FN4	99FN4
Grain	Grmass	Grmass	Grmass	Grmass	Grmass	Grmass	Mpheno	Grmass	Grmass
SiO_2	42.77	41.01	43.08	41.63	46.32	47.06	42.87	45.8	50.36
TiO_2	0.04	0.16	0.16	0.05	0.16	0.19	0.12	0.03	0.08
Al_2O_3	33.11	33.5	33.67	33.66	31.96	30.64	33.13	32.47	30.38
Fe_2O_3	1.11	1.1	1.11	1.19	0.94	0.74	0.96	0.69	0.57
MnO	0.01	0	0	0.03	0.01	0.04	0	0	0.02
MgO	0.04	0.17	0	0.12	0.02	0	0	0.03	0.03
CaO	1.02	0.63	0.87	0.61	0.6	1.99	0.35	0.75	0.51
Na_2O	15.4	14.62	15.27	14.41	16.31	15.52	14.63	15.66	16.32
K_2O	5.94	7.91	6.56	8.26	3.85	3	6.98	3.81	2.35
SrO	0.2	0.06	0.1	0.14	0	0	0.05	0	0
BaO	0.13	0.08	0	0	0.12	0	0.03	0.05	0
Total	99.77	99.23	100.81	100.1	100.26	99.17	99.11	99.26	100.8
Ne	78.49	73.33	78.63	72.33	80.25	81.06	73.2	78.68	78.42
Ks	20.46	26.67	22.23	27.67	13.01	10.88	23.74	13.32	7.94
Qz	1.05	0	1.14	0	6.74	8.06	3.08	8	13.63

[a]Aphon, porphon: aphyric, porphyritic phonolite; MEM, OLM: melilite, olivine melanephelinites. Pheno, Mpheno: pheno-, microphenocryst. Grmass: groundmass.
[b]OLM, PYM: olivine, pyroxene melanephelinites; Bas: basanite. Grmass: groundmass; Mpheno: microphenocryst.

strongly influenced by an increase in CO_2 fugacities, while a decrease would favor olivine nucleation [57–59]. Clinopyroxenes are homogeneous in these rocks (salites, with rims of titaniferous salite), with some differences observed in their *mg#* numbers and Ca contents, thus somewhat dependent on magma composition. The micas are usually late interstitial minerals, enriched in Ti, F and Ba, late-magmatic components (up to 19% BaO, 6% of F, and 14% TiO_2 [40, 42]); they belong mostly to the kinoshitalite-oxykinoshitalite series, as defined in [42].

Fluor substitutes OH in the mica structure, probably more by a control of the relative availability of H_2O in the residual magmas [60, 61]. On the other hand, nephelines with more K_2O are found in MEM and OLM, and less so in PYM, controlled by the Na/K whole-rock ratios. Ba is also a conspicuous presence in many feldspars found in the Quixaba basanites, less so in the basanites of the São José Formation (that is, the basanites related agewise to the older Remédios event, [6]).

Ages show that the Remédios and the Quixaba events are not related to a moving plume activity, but to the action of a"stationary" hot spot (cf. also [6]), which generated abundant magmas in these two episodes, separated by a period of relative quietness. On mineralogical grounds, the older episode generated basic liquids as possible parental magmas, by the melting of an enriched mantle source (peridotitic or pyroxenitic?). The Quixaba volcanic episode melted a different mantle protolith, presumably enriched in phases such as phlogopites and titanites (cf. [62, 63]), as suggested by the relative enrichment of F, Ba and Ti in the generated magmas, from which phases could crystallize that are enriched in Ba, Ti and F (micas) and Ba (feldspars).

5. Summary and conclusion

The older Remédios Formation in FN represents a largely eroded volcanic edifice, exposing pyroclastic rocks with many dike and plug intrusions, with two distinct geochemical series (the sodic and the moderately potassic ones). The sodic series is represented by the rock sequence basanites and tephrites, essexites, tephriphonolites and phonolites, the potassic one by the sequence alkali basalt, basaltic trachyandesite, trachyandesite and trachyte. Mineral chemistry shows a progressive enrichment in alkalies and FeOt (and a decrease in Mg and Ca) in the crystallizing magmas with differentiation, generating a liquid line of descent controlled by separation of olivines (first), then by clinopyroxenes and, eventually, opaque and accessory phases (apatite and titanite; cf. [1, 2]). Lamprophyres present in the Remédios Formation show mineralogical-chemical variations that are not directly related either to the sodic or potassic trend [1, 2, 13].

The basanites of the São José Formation, now assigned agewise to Remédios [6], carry significant amounts of mantle enclaves, thus representing crystallized magmas that were in equilibrium with mantle peridotes [10, 11].

The uppermost Quixaba Formation is represented by volcanic rocks with some pyoclastic interlayers, petrographically composed by melilite, olivine and pyroxene melanephelinites or "ankaratrites" (MEM, OLM, PYM) and some basanites; dikes are very rare. Micas in the more mafic rocks show a systematic presence of mostly interstitial dark mica, enriched in F, Ti and Ba; feldspars in these rocks also present higher values of Ba.

At least two conspicuous melting episodes did occur in FN, the first one (Remédios, Miocene) related to the generation of the older pyroclastics and the myriad of dikes and several plugs, the last one (Quixaba, Pliocene) generating the more mafic nephelinite and basanite flows, separated from the earlier one by a large erosion interval. Therefore, the FN volcanism cannot be adscribed to the evolution of a travelling mantle plume [cf. also [6]), but to the activity of stationary heat sources. On mineralogical grounds alone, the last episode was related to the melting of a more enriched mantle source than the earlier one, as attested by the peculiar chemistry of its minerals.

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