DOI: 10.1590/23174889201500020009

INVITED REVIEW

# Geochemistry of the alkaline volcanic-subvolcanic rocks of the Fernando de Noronha Archipelago, southern Atlantic Ocean

## *Geoquímica das rochas vulcânicas-subvulcânicas alcalinas do Arquipélago de Fernando de Noronha, Oceano Atlântico Meridional*

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**ABSTRACT:** The Fernando de Noronha Archipelago presents, on its main island, a centrally-located stratigraphic unit, the Remédios Formation (age around 8 – 12 Ma) constituted by basal pyroclastic rocks intruded by dikes, plugs and domes of varied igneous rocks, capped by flows and pyroclastics of mafic to ultramafic rocks of the Quixaba Formation (age around 1 – 3 Ma), which is limited from the underlying unit by an extensive irregular erosion surface. A predominant sodic Remédios series (basanites, tephrites, tephriphonolites, essexite, phonolites) can be separated from a moderately potassic Remédios sequence (alkali basalts, trachyandesites, trachytes), both alkaline series showing mostly continuous geochemical trends in variation diagrams for major as well as trace elements, indicating evolution by crystal fractionation (mainly, separation of mafic minerals, including apatites and titanites). There are textural and mineralogical evidences pointing to hybrid origin of some intermediate rocks (e.g., resorbed pyroxene phenocrysts in basaltic trachyandesites, and in some lamprophyres). The primitive Quixaba rocks are mostly melanephelinites and basanites, primitive undersaturated sodic types. Geology (erosion surface), stratigraphy (two distinct units separated by a large time interval), petrography (varied Remédios Formation, more uniform Quixaba unit) and geochemistry indicate that the islands represent the activity of a protracted volcanic episode, fueled by intermittent melting of an enriched mantle, not related to asthenospheric plume activity.

**KEYWORDS:** OIB; South Atlantic Ocean; Mafic to ultramafic volcanic-subvolcanic rocks; Sodic and potassic series.

**RESUMO:** *O Arquipélago de Fernando de Noronha mostra na sua ilha principal, na parte central, a Formação Remédios (idade em torno de 8 – 12 Ma) constituída por rochas piroclásticas basais invadidas por diques, plugs e domos de variadas rochas ígneas, capeadas por derrames e piroclásticas das rochas máficas a ultramáficas da Formação Quixaba (idade de 1 a 3 Ma), separada da unidade inferior por uma superfície de erosão extensa e irregular. Uma série predominante sódica de Remédios (basanitos, tefritos, tefrifonolitos, essexito, fonolitos) pode ser diferenciada da série moderadamente potássica (álcali basaltos, traquiandesitos, traquitos), pertencente à mesma unidade. Ambas as séries mostram tendências geoquímicas geralmente contínuas em diagramas de variação de elementos maiores e traços, indicando origem por cristalização fracionada (principalmente, separação de minerais máficos, incluindo apatitas e titanitas). São encontradas evidências mineralógicas e texturais apontando para origens híbridas em algumas rochas intermediárias (e.g., fenocristais reabsorbidos de piroxênio em traquiandesitos basálticos e alguns lamprófiros). As rochas primitivas do evento Quixaba, também alcalinas, são mormente melanefelinitos fortemente insaturados e basanitos. A geologia (superfície de erosão), estratigrafia (dois eventos magmáticos distintos separados por período prolongado), petrografia (evento Remédios petrograficamente variado, o Quixaba mais uniforme) e geoquímica indicam que as ilhas são o resultado de prolongado vulcanismo, alimentado por fundidos intermitentes de manto enriquecido, não relacionado com atividade de pluma astenoférica.*

**PALAVRAS-CHAVES:** *OIB; Oceâno Atlântico meridional; rochas vulcânicas-subvulcânicas máficas a ultramáficas; séries sódica e potássica.*

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**Manuscript ID:** 30305. **Received:** 04/12/2015. **Approved:** 05/18/2015.

## INTRODUCTION

Within-plate oceanic islands are made up mostly o fa series of diverse alkaline volcanic and subvolcanic rocks of a basaltic ancestry, collectively called oceanic island basalts (OIB), clearly separated from the occurrences related to midoceanic ridge basalts (MORB), which belong to the tholeiitic series. The name OIB, however, covers a wide range of petrographic and chemical variations, as displayed in the literature on these rocks.

Specifically in the Atlantic Ocean, many OIB islands are known and have been extensively studied, such as the Canarias Islands (Hoernle & Schmincke 1993; Araña *et al.* 1994; Gurenko *et al.* 2006), the Cabo Verde Archipelago (Furnes & Stillman 1987; Dyhr & Holm 2010; Ancochea *et al.* 2012) and the islands of Trindade and Martin Vaz (Almeida 1961; Marques *et al.* 1999; Siebel *et al*. 2000).

The Fernando de Noronha (FN) Archipelago is situated in the southern Atlantic Ocean, at longitudes 32º 28' to 32º 24'W and parallels 3º 52' to 3º 50' south. It outcrops at about 345 km from the nearest coastline (the Brazilian state of Rio Grande do Norte), and belongs administratively to the state of Pernambuco, Brazil. It covers 18.4 $km^2$, constituted by one large island (16.9 $km^2$), with a main NE-SW trending course, and many smaller islands (along both the occidental outlines of the main island, as well as a string of them extending to the NE: Cuscuz, São José, Rasa, Sela Gineta, do Meio, Rata).

The archipelago belongs to a vast volcanic edifice positioned along the *Fernando de Noronha ridge* that rests on the ocean floor at a depth of around 4,000 m, stretching some 75 km along an E-W trending fracture zone (Almeida 1955, 2012; Bryan *et al.* 1972), which is supposed to have channeled to the surface mantle-derived magmas. The oldest registered volcanism along this fracture zone is found on its alleged continuation on the continental margin, at Ceará state, there presenting locally alkaline magmatism, dated 40 Ma ago, interpreted by some authors to be the result of the activity of a plume (appropriately called the Fernando de Noronha plume) impacting the westward moving Southamerican plate. This plume is supposedly also the heat source responsible for the eruption of the Fernando de Noronha volcanic rocks (Fodor *et al.* 1998, 2002; Almeida 2012).

The geologic units in FN were mapped by Fernando de Almeida, who presented a classic publication on the geology, petrography, stratigraphy and geomorphology of the islands (Almeida 1955; see Fig. 1). Almeida defined two main mapping units, the products of two volcanic events, the older Remédios Formation, separated by an erosion surface from the overlying, petrographically more uniform Quixaba Formation. Almeida also separated the basanitic rocks outcropping at the São José peninsula, containing mantle xenoliths, from the Quixaba rocks and defined them as the youngest São José Formation.

The next contribution to the FN geology was provided by Cordani (1970), who published K-Ar geochronological data for the various rock types (K-Ar methodology; cf. also Cordani *et al.* 2004). More recent and more precise $^{40}Ar/^{39}Ar$ results can be found in Perlingeiro *et al.* (2013).

The archipelago was visited sporadically by geologists who added geochemical and isotopic data (Gunn & Watkins 1976; Stormer & Whitney 1978; Schwab & Bloch 1985; Cornen 1986; Gerlach *et al.* 1987; Weaver 1990).

More recently, geologists from the University of São Paulo presented contributions on FN (two Master's thesis, one doctorate thesis: Maríngolo 1995; Lopes 1997, 2002), and several abstracts and publications on the subject (Ulbrich & Ruberti 1992; Ulbrich 1993; Ulbrich *et al.* 1994, 2004; Maríngolo & Ulbrich 1997; Lopes & Ulbrich 1997, 1998; Ulbrich & Lopes 2000a, 2000b).A summary paper on the lithogeochemistry and mineral chemistry of the Quixaba Formation was published in a Brazilian journal (Lopes & Ulbrich 2006), and a more recent one on the mineral chemistry of these rocks (Lopes *et al*. 2014). A recent study on FN was presented at Queensland as a Ph.D. thesis, dealing with geochronologic and petrogenetic aspects (Perlingeiro 2012).

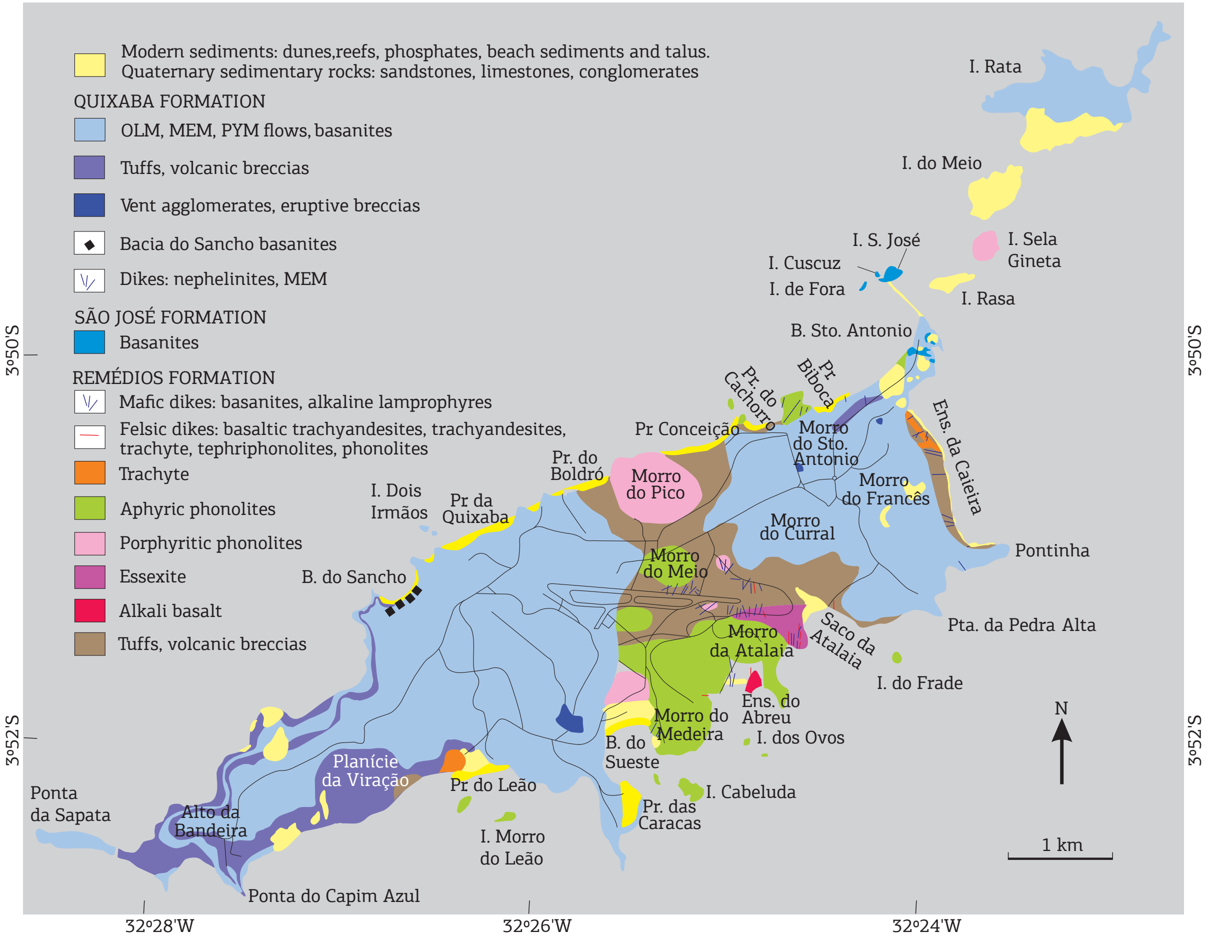
Field work consisted mainly in the recognition and sampling of the several rock types identified by Almeida, adding more detailed information on the presence of dikes and their structural disposition. The whole district is now mostly a natural reserve (*Parque Nacional Marinho* or *Parnamar*, the National Marine Park), subjected to oversight by the Brazilian Environmental Agency (*Instituto Brasileiro de Meio Ambiente* – IBAMA). IBAMA granted permission for collecting samples even in areas of total protection under their jurisdiction. A total of about 109 hand specimens were collected in several field trips (1989, 1997, 1999).

## STRATIGRAPHIC UNITS AND GEOLOGIC OCCURRENCES

Almeida (1955) mapped two units in the Archipelago, the older Remédios Formation, exposed as a centrally located erosion window, constituted mainly by accumulations of pyroclastic material intruded by several dike systems and various plugs and domes, and the subhorizontal flows of the younger Quixaba Formation, bordering the Remédios Formation on both sides (to the NE and to the SW; Fig. 1). The pyroclastic beds in the Remédios Formation are deeply altered and converted to soil (detailed descriptions in Almeida, 1955);

they also contain in some locations different fragments of cogenetic volcanic, subvolcanic and plutonic rocks, in part corresponding to varieties that do not crop out on the island (cf. Ulbrich & Lopes 2000b). Discrete dikes (thicknesses usually up to 50 cm, eventually up to 2 m) are made up of several types of alkaline lamprophyres, tephrites, basanites, trachytes, and trachyandesites, while the largest domes, with subcircular to elliptical outlines, are composed of either aphyric or porphyritic phonolites. The phonolites cover about half of the outcrops corresponding to the Remédios Formation (Fig. 1). Basaltic trachyandesites appear as extended dikes, partly of a composite nature (e.g., grading into more mafic rocks at the center), and are also associated with more homogeneous mafic dikes (e.g., at Enseada da Caiera). Less frequently, some phonolites can also be observed as dikes (up to 2 m in thickness). In addition a single sill of essexite (Baia do Sueste) and a minor plug of alkali basalt (Enseada do Abreu) are also included in the Remédios Formation. Trachytes and trachyandesites are observed as small intrusive domes (e.g., at Praia do Leão) and one larger dike (Enseada da Caiera); two small plugs showing radial fractures, made up of basaltic trachyandesites, invade phonolites at the Baia do Sueste (locations in Fig. 1).

The younger Quixaba Formation is petrographically more uniform, showing subhorizontal flows of variable thicknesses (meters to tens of meters), presenting both massive as well as vesicular structures. They are constituted by melanocratic nephelinites (with subordinate basanites), deposited on top of the marked erosion surface that affected the Remédios Formation. Geology thus clearly indicates the activity of two volcanic events, separated by a very active erosion interval.



MEM: melilite; PYM: pyroxene; OLM: olivine melanephelinites.

**Figure 1. Detailed geologic map of the Fernando de Noronha Archipelago (Almeida 1955; simplified), with some topographic corrections, partly based on more recent nautical charts of 1984 and 1995 (Lopes 2002). The São José Fm is now considered part of the Remédios episode (cf. Geochronology).**

To the NW, on the islands of São José and Cuscuz, Almeida (1955) separated a series of basanite flows as a distinct younger unit, that appears as a discordant deposit over Quixaba rocks, which he defined as the São José Formation, also differentiated from other Quixaba rocks by the presence of sometimes abundant peridotitic mantle xenoliths (sizes between mm to decimeters; descriptions in Rivalenti *et al.* 2000; Kogarko *et al.* 2001). Some authors proposed that the São José flows may represent the culmination of the Quixaba volcanism (e.g. Lopes 2002; Ulbrich 1993), but recent radiometric dating confirmed that these rocks belong, agewise, to the Remédios volcanic event (Perlingeiro *et al.* 2013).

## GEOCHRONOLOGY

The first geochronologic determinations, performed in the 70's (Cordani 1970) by the whole-rock K-Ar method, defined ages ranging between 8–9 to 12 Ma as indicative of the eruption dates of the Remédios Formation. Phonolite ages, varying from 11.2 ± 0.3 to 8.0 ± 0.2 Ma, roughly define the same range as a large trachyte dike (8.8 ± 0.3 Ma). Ages of the Quixaba nephelinite flows are distinctly younger and were deposited between 3.3 ± 0.1 and 1.8± 0.1 Ma. Thin dikes emplaced within the pyroclastic Remédios rocks indicated ages of 8.8 ± 0.3 Ma. The ages obtained for the São José basanites (around 9.5 Ma) were interpreted formerly as misleading because of a possible contamination of the rocks with incompletely degassed mantle material (Cordani 1970, cf. also Cordani *et al.* 2004).

Recent $^{40}$Ar/$^{39}$Ar determinations (Perlingeiro *et al.* 2013) with a high-resolution laser-heating method, performed mostly on the same samples previously dated (WR and some K-feldspar and nepheline ages), indicate that the Remédios rocks erupted between 9.4 to 10.4 Ma (± 0.1 or 0.2 Ma; one rock shows 12.5 ± 0.1 Ma), while the São José basanites (four dated samples) yield ages around 9.0 – 9.5 Ma (± 0.1 to 0.5 Ma) that are coeval with the Remédios volcanism. The Quixaba event (10 ages from 6 rocks) is younger (between 1.3 ± 0.2 and 4.7 ± 0.7 Ma).

## PETROGRAPHY AS A GUIDELINE FOR PETROGENETIC INTERPRETATIONS

Starting with the work by Almeida (1955), a large variety of names was used in the literature to characterize the FN rocks. To define the correspondence between the older names and the newer nomenclature, we follow mainly the discussion presented in Ulbrich (1993), Lopes (2002), and Ulbrich *et al.* (2004), and the definitions given in Le Maitre (2002); other discussions and information on the petrography of FN rocks can be found in Gunn and Watkins (1976), Schwab and Bloch (1985), Cornen (1986), Gerlach *et al.* (1987) and Weaver (1990).Data about mineral chemistry of these rocks can be found in a recent paper by Lopes *et al.* (2014).

A special case is the one posed by *basanites* and *nephelinites*, or "*ankaratrites*", (Almeida 1955, cf. also Melluso *et al.* 2011). By definition, basanites are undersaturated olivine basalts, showing modal or normative nepheline, with plagioclase, while nephelinites are feldspar-free strongly undersaturated types, usually meso- to melanocratic, always enriched in Na, with a wide variety of mafic mineral assemblages (mainly olivine, or clinopyroxene, sometimes also melilite; cf. Almeida 1955; Lopes 2002; Ulbrich *et al.* 2004). The two types, nephelinites and basanites, cannot always be discriminated on a TAS diagram (Le Maitre 2002; for a discussion, cf. Le Bas 1989), giving rise to a common confusion in the literature, especially when only chemical data are used to define these rocks, without considerations about mineralogy.

### Rocks of the Remédios Formation

The igneous rocks belonging to the Remédios Formation are basic, felsic to mesocratic types (alkali basalt, trachyandesites, trachytes, and related rocks), and basic rocks (tephrites, basanites, mela-lamprophyres). Plugs and domes are made up mostly by phonolites, subdivided on textural grounds into aphyric and porphyritic varieties (cf. Fig. 1).

Detailed definitions of the various rocks observed in FN are necessary to avoid confusion with descriptions given in the literature. They will be used as a guide for petrogenetic interpretations.

The *alkali basalts* of FN are porphyritic rocks with altered olivine and colored clinopyroxene phenocrysts, set in an intergranular groundmass with zoned labradorite, clinopyroxene (salite) and opaques; they are present as one mappable plug (Fig. 1).

*Basaltic trachyandesites* to *trachyandesites* present plagioclase (in decreasing amounts when grading into trachytic types), alkali feldspar and feldspathoids. Clinopyroxenes (from salitic to more sodic compositions) and brown kaersutite are found as phenocrysts, together with sanidine, sodalite, and some andesine laths, in a trachytoid groundmass with alkali feldspar, altered plagioclase, isotropic feldspathoids, titanite, green pyroxene, some amphibole and devitrified glass.

The FN *trachytes* have abundant alkali-feldspar phenocrysts with subordinate plagioclase, aegirine-augite, titanite, and opaques, set in a trachytic groundmass with alkali feldspar, idiomorphic feldspathoids and aegirine-augite prisms.

The sill-like body made up of *essexite porphyry* (Fig. 1) presents phenocrysts of greenish pyroxene, some resorbed olivine, labradorite, feldspathoids and opaques, in a groundmass with plagioclase laths, idiomorphic nepheline, opaques, some biotite and apatite.

Two types of aphyric phonolites have been distinguished. Type I is characterized by a fine-grained assemblage with sanidine, nepheline, prisms of ferrosalite to aegirine-augite and some nosean and amphibole. Type II has a groundmass with more evolved clinopyroxenes (aegirine), with sodalite but no amphibole nor nosean; sometimes, a few microphenocrysts (alkali feldspar, nepheline, some sodalite and amphibole) are also observed. The porphyritic phonolites present phenocrysts (modal 20% up to 40%) of K-feldspar and feldspathoids (nepheline and sodalite), also with kaersutite, sodic pyroxene, opaques and titanite, in a trachytic groundmass with alkali feldspar, nepheline, aegirine prisms and interstitial analcime, sometimes showing evidence of strong disequilibrium and/or magma mixing (e.g., resorbed olivine crystals in phonolites; Ulbrich & Lopes 1996).

The *basic dikes* have been subdivided into four groups: basanites-tephrites, limburgites, amphibole-rich tephrites to tephritic lamprophyres, and typical lambrophyres (cf. Lopes 2002).

A few *limburgites* have been observed, showing predominant phenocrysts of salitic clinopyroxene, rounded olivine and opaques, set in a fresh or altered glassy groundmass with some needles of mafic minerals and apatite.

*Basanites* have phenocrysts of clinopyroxene and altered olivine in a groundmass with some fresh or altered glass, clinopyroxene, opaques, some amphibole, and variable amounts of felsic minerals (20 to 35%; labradorite laths, or alkali feldspar, with or without analcime). *Tephrites* were also observed, with much lesser amounts of olivine. These rocks frequently contain enclaves of mafic cumulates as well as xenocrysts and xenoliths of felsic trachytes and trachyandesites, thus pointing to a complex relationship between coexisting rocks and, possibly, to potentially vigorous mingling of magmas and crystallized fragments. The pyroxene *fourchites* and olivine *teschenites* defined by Almeida (1955) belong to this group of dike rocks.

*Amphibole-rich tephrites* and *tephritic lamprophyres*, with transitions to the previous group (tephrites and basanites), present a brown to reddish amphibole in the groundmass or even as phenocrysts (cf. Ulbrich 1993, for details). Olivine (altered to serpentine and carbonates) and sodalite appear in rocks with abundant amphibole phenocrysts which also frequently contain xenoliths of coarser-grained ultramafic rocks. This type of rock, with plenty of amphibole phenocrysts, is equivalent to the *mela-monchiquites* and *fourchites* (Almeida 1955).

The *lamprophyres* in FN always occur as simple or composite dikes (thickness between 0.5 to 1.6 meters), with amygdules concentrated in the marginal zones; they usually cut more felsic dikes (such as in Enseada da Caieira; Fig. 1). They are typically alkaline rocks and are characterized, as usual, by idiomorphic textures, with grouped phenocrysts of kaersutite, titanaugite, magnetite and some serpentine pseudomorphs (after olivine), in a groundmass with amphibole, clinopyroxene, magnetite and apatite needles, with about 50% (or more) of felsic aggregates (andesine-oligoclase, interstitial analcime, some fibrous zeolites). Several of these rocks show a devitrified groundmass. Camptonites were also described, in addition to other alkaline lamprophyres (sannaite, mela-monchiquite and fourchite). These rocks in FN are texturally similar to the ones described in the literature (cf. Le Maitre 2002) but not entirely equivalent; they may be considered, geochemically, related to alkali basalts or basanites, but present as essential components significant amounts of amphibole. This is a unique feature that characterizes the FN lamprophyres, also known from examples in Cape Verde (e.g., Furnes & Stillman 1987).

Recent detailed studies divided the FN lamprophyres into four alkaline petrographic groups (Ulbrich 1993; Maríngolo 1995), a division adopted, with some minor divergence, in Lopes (2002). Type I, similar to the typical lamprophyres of Ulbrich (1993) and the camptonite of Maríngolo (1995), has a glassy groundmass with abundant amphibole and minor clinopyroxene, altered olivine, phlogopite, opaques and clinopyroxene. In type II, clinopyroxene is more abundant than amphibole (both in the matrix and as phenocrysts), set in a feldspathic groundmass. Type III is equivalent to the "tephritic lamprophyre" of Ulbrich (1993) and to the "monchiquite" of Maríngolo (1995); they are similar to type II, but with a glassy base (little or no feldspar crystals). Type IV presents abundant amphibole phenocrysts, in a partly glassy groundmass with sanidine, abundant clinopyroxene and some amphibole.

From these short descriptions, it is clear that the FN "sannaites", "camptonites" and "monchiquites" are not equivalent to the alkaline lamprophyres described in the literature (Le Maitre 2002), which should present, among other mafic phenocrysts, biotite and sodic ("brown") amphibole in a foid-bearing groundmass with Kfeldspar > plagioclase (a sannaite), or plagioclase > Kfeldspar (a camptonite), or with glass (a monchiquite; cf. also Maríngolo 1995; Ulbrich 1993; Lopes 2002). Conspicuously, biotite is missing in the FN equivalent rocks.

In several of these rocks, phenocrysts and groundmass mineralogy may be in partial disequilibrium, as attested by corroded phenocrysts and irregular zoning, a condition that could suggest mixing of two or more magma batches or assimilation and reworking of previously crystallized cumulates by late magmatic influx.

The presence of such a large variety of alkaline rocks, conveniently divided into a sodic and a potassic series, is also known from several other islands with OIB signatures as well as on continental settings (e.g., Fitton & Upton 1987; Halliday *et al.* 1988; Briot *et al.* 1991; Foland *et al.* 1993; Wilson *et al.* 1995]; cf. details in the section on Geochemistry).

Tables 1 and 2 show some modal analyses performed on rocks of the Remédios Formation (respectively, aphyric and porphyritic phonolites, essexite, tephrite and basanite, for the sodic series; trachyte, trachyandesite, basaltic trachyandesite, and alkali basalt, for the moderately potassic series).

## Basanites of the São José unit

These basanites, agewise correlated with the Remédios rocks on the basis of similar extrusion ages, display small olivine and titanaugite phenocrysts, in a highly variable groundmass with bands, layers or lenses of labradorite laths and nepheline grains alternating with areas showing mostly mafic minerals and some analcime (or glass). This texture resembles the features displayed by some of the Quixaba melanephelinites. The São José rocks are also characterized by the abundance of greenish (dunites and peridotites) to dark grey (spinel peridotites) mantle xenoliths (cf. modal analyses of these basanites in Tab. 4; see also Rivalenti *et al.* 2000; Kogarko *et al.* 2001).

## Plutonic fragments within the Remédios pyroclastic rocks

Fragments or xenoliths of phaneritic igneous rocks, with clear alkaline affinities, are found within the volcanic agglomerates and breccias that are part of the pyroclastic Remédios

**Table 1. Modal analyses of rocks of the sodic series, Remédios Formation.**

| | PhAGI | | | PhAGII | | | PhP | | | | | | Es | Te | Bas | Bas |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **01** | **02** | **03** | **04** | **05** | **06** | **07** | **08** | **09** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
| Pheno | 1.5 | 2.0 | 3.5 | 1.0 | 1.5 | 1.9 | 12.3 | 14.7 | 18.5 | 32.5 | 31.6 | 34.9 | 19.5 | 26.7 | 35.5 | 44.0 |
| Feld | 1.0 | 1.0 | 2.0 | 1.0 | 1.2 | 1.9 | 0.9 | 6.0 | 5.7 | 12.8 | 16.1 | 15.9 | 3.6 | – | – | – |
| Neph | Tr | 0.8 | 0.5 | tr | Tr | tr | 5.3 | 0.9 | 2.4 | 1.4 | 1.4 | 5.0 | – | – | – | – |
| Sodal | – | – | – | – | – | – | 1.4 | 4.0 | 4.4 | 2.9 | 5.3 | 5.6 | 2.2 | 4.0 | – | – |
| Oliv | – | – | – | – | – | – | – | – | – | – | – | – | 1.4 | 4.8 | 11.8 | 15.3 |
| Cpyr | Tr | Tr | 1.0 | – | – | – | 4.2 | 2.3 | 4.1 | 2.1 | 3.3 | 1.9 | 12.3 | 17.8 | 23.7 | 28.7 |
| Amph | Tr | – | – | – | – | – | tr | tr | 1.4 | 5.1 | 4.5 | 6.0 | – | tr | – | – |
| Ti-mt | – | – | – | – | – | – | tr | – | tr | tr | tr | tr | – | – | – | – |
| Titan | – | – | – | – | – | – | tr | tr | tr | tr | Tr | tr | – | – | – | – |
| Grmass | 98.5 | 98.0 | 96.5 | 99.0 | 98.5 | 98.0 | 87.7 | 85.3 | 81.5 | 67.5 | 68.4 | 65.1 | 80.5 | 73.3 | 64.5 | 56.0 |
| Feld | 52.0 | 51.6 | 57.0 | 66.0 | 65.7 | 58.7 | 51.3 | 63.2 | 57.8 | 40.2 | 33.9 | 39.8 | 59.0 | 24.7 | 21.6 | 12.6 |
| Neph | 30.0 | 16.7 | 20.1 | 13.7 | 19.4 | 26.4 | 14.9 | 11.5 | 4.4 | 6.1 | 9.6 | 8.0 | – | – | – | – |
| Cpyr | 16.5 | 29.5 | 19.2 | 19.5 | 13.4 | 12.6 | 21 | 10.3 | 18.8 | 19.5 | 24.5 | 15.6 | 14.8 | 30.7 | 24.0 | 17.0 |
| Amph | – | – | – | – | – | – | – | tr | tr | – | – | tr | – | – | – | – |
| Mica | – | – | – | – | – | – | – | – | – | – | – | – | 3.2 | 1.9 | 2.4 | 5.5 |
| Titan | – | – | Tr | tr | Tr | tr | – | tr | tr | tr | Tr | tr | – | – | – | – |
| Ti-mt | Tr | Tr | Tr | tr | Tr | tr | tr | tr | tr | 1.5 | Tr | tr | 3.1 | 13.1 | 12.8 | 18.2 |
| Apat | – | – | – | – | – | – | – | – | – | – | – | – | tr | 2.5 | 3.7 | 2.0 |
| Amyg | | | | | | | 0.5 | | | | | | | | | 0.7 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

PhAGI, PhAGII: phonolite, aphyric, Group I and II; PhP: phonolite, porphyritic; Es: essexite; Te: tephrite; Bas: basanite. Column numbers: 1 (97FN17a), 2 (97FN16), 3 (89FN47), 4 (97FN49), 5 (97FN52), 6 (89FN66), 7 (WWWS-SG), 8 (89FN87), 9 (89FN71), 10 (91FN126), 11 (91FN127), 91FN130), 12 (91FN130), 13 (91FN42), 14 (97FN43a), 15 (97FN23), 16 (97FN34b).

basal unit (Ulbrich & Lopes 2000b). They are set in an altered groundmass with isolated feldspar and mafic minerals and fragments of trachytes, together with microcrystalline silica, carbonates and chlorites. Sampled fragments were classified as clinopyroxenites, hornblendites, kaersutite gabbros and diorites, monzodiorites, and kaersutite monzogabbro. This plutonic suite is considered to be cogenetic with the rocks of the Remédios Formation (cf. Tab. 3).

Grain size in these fragments varies between 0.2 to 2–3 cm. Amphibole (kaersutite) and clinopyroxene are the main minerals in the more mafic samples (color index from 52 to 80), with plagioclase up to 43 and 62% modal proportions in the monzogabbro and monzodiorite. Clinopyroxene appears as a relict phase converted into brown kaersutitic amphibole. Opaques are plentiful (5 to 14% modal), and apatite goes up to 34% modal in an apatite clinopyroxenite lens. Alkali feldspar is an essential constituent in the monzogabbro and monzodiorite. Layering is commonly observed as well as cumulus crystals and intercumulus material, which suggests crystal sorting and accumulation in a deeper-seated magma chamber, beneath the volcanic edifice. The mineral assemblages suggest crystallization from an (alkali) basaltic or basanitic magma. A temperature estimate of ~800°C has been obtained on the basis of the Ti magnetite - ilmenite thermometry (Ulbrich & Lopes, 2000b).Cognate xenoliths such as the ones described are commonly observed in similar volcanic settings, and are samples of deeper-seated crystallization products in closed subvolcanic magma chambers (e.g., Mattioli *et al.* 1997).

## Rocks of the Quixaba Formation.

The most common rocks of the Quixaba Formation are melanephelinites, constituted by mafic minerals, feldspathoids (nepheline and analcime) and opaques, sometimes with interstitial glassy material. Feldspars are totally absent.

The melanephelinites can be properly divided into three distinct mineralogical groups (Lopes 2002), identified as olivine melanephelinites (OLM), pyroxene melanephelinites (PYM) and melilite melanephelinites (MEM).

**Table 2. Modal analyses of rocks of the moderately potassic series, Remédios Formation.**

| Sample | T 1 | T 2 | T 3 | T 4 | Tr 5 | Tr 6 | Trb 7 | Trb 8 | Trb 9 | AB 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Pheno | 13.5 | 18.5 | 10.4 | 12.0 | 11.8 | 6.5 | 3.9 | 7.8 | 13.4 | 3.6 |
| Feld | 6.6 | 11.6 | 2.5 | 9.0 | 9.4 | tr | 1.9 | tr | tr | 2.0 |
| Foid | 4.0 | 4.9 | 5.3 | 0.8 | – | tr | – | 1.5 | 2.8 | – |
| Cpyr | 1.5 | 1.5 | 1.0 | 1.4 | 0.8 | 1.2 | tr | 1.5 | 3.3 | 1.0 |
| Amph | Tr | tr | Tr | – | 0.6 | 3.4 | 1.5 | 3.1 | 5.6 | – |
| Oliv | – | – | – | – | – | – | – | – | – | 0.6 |
| Opaq | Tr | tr | Tr | 0.6 | tr | tr | tr | 1.2 | 1.5 | – |
| Titan | Tr | tr | Tr | tr | tr | tr | tr | tr | – | – |
| Grmass | 86.5 | 81.5 | 89.6 | 88.0 | 87.2 | 93.5 | 89.3 | 87.9 | 84.5 | 96.4 |
| Feld | 60.8 | 57.8 | 66.6 | 71.9 | 65.0 | 61.0 | 56.1 | 53.6 | 42.9 | 36.4 |
| Cpyr | 17.3 | 18.1 | 13.8 | 10.9 | 3.0 | 11.0 | 9.5 | 14.0 | 20.8 | 36.9 |
| Opaq | 8.4 | 5.6 | 9.2 | 5.2 | 5.2 | 8.0 | 9.0 | 8.8 | 10.7 | 18.8 |
| Glass | – | – | – | – | 14.0 | 8.0 | 14.7 | 11.4 | 5.4 | 2.4 |
| Amph | – | – | – | – | – | 5.0 | – | tr | 4.5 | – |
| Titan | – | – | – | – | – | tr | – | – | – | – |
| Apat | – | – | – | – | – | – | – | – | tr | 0.8 |
| Oliv | – | – | – | – | – | – | – | – | – | 1.2 |
| Amyg |  |  |  |  | 1.0 |  | 5.8 | 4.3 | 2.3 |  |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

T: trachyte; Tr: trachyandesite; Trb: basaltic trachyandesite; AB: alkali basalt. Sample numbers: 1 (89FN28a), 2 (97FN30a), 3 (97FN30b), 4 (97FN57), 5 (97FN7a), 6 (97FN5a), 7 (97FN4a), 8 (97FN6a), 9 (97FN6b), 10 (97FN35b).

The OLM show small phenocrysts (up to 10 – 20%) of resorbed or idiomorphic olivine, in a groundmass of clinopyroxene, opaques and nepheline, together with smaller amounts of strongly pleochroic reddish biotite and apatite needles, with perovskite as a rare accessory mineral. The sporadic presence of melilite in the groundmass of olivine-rich melanephelinties identifies the MEM variety. PYM has a lighter color and shows larger amounts of phenocrysts, mainly of clinopyroxene.

The whole group of melanephelinites corresponds to the *ankaratrites* of Almeida (1955). More glassy varieties were also called *limburgites* by Gunn and Watkins (1976). Sometimes, weakly to strongly amygdaloidal to vesicular melanephelinites are also common constituents of the Quixaba flows (good examples can be observed in the chimney of the Morro do Francês; cf. Fig. 1).

*Basanites* were found among Quixaba flows, for example at the Baia do Sancho. They are porphyritic rocks with 15 – 18% of olivine and titanaugite phenocrysts, in a matrix with clinopyroxenes and 20 – 25% of large poikilitic plagioclase, opaques, apatite, some biotite, and abundant interstitial analcime.

Tables 4a and 4b present some modal analyses performed on rocks of the Quixaba Formation (OLM, PYM and MEM).

## WHOLE-ROCK GEOCHEMISTRY

Complete geochemical analytical determinations (major, minor and trace elements) for 23 rock samples were performed at ACTLABS in Ontario, Canada, using ICP-MS and XRF techniques. Four samples were analyzed (complete determinations) at the *Laboratoire de Géochimie* (*Musée Royal de L'Afrique Centrale*) in Tervuren, Belgium, by ICP-MS. Additional seventeen samples were determined at the ICP Laboratory, University of São Paulo, with XRF and ICP methods (major, minor and trace elements; for laboratory details, cf. Janasi *et al.* 1995; Mori *et al.* 1999; Navarro *et al.* 2008); some additional data on trace element contents were determined at ACTLABS.

Data on mineral chemistry were presented and discussed in Lopes *et al.* (2014).

Previous studies (Gerlach *et al*. 1987; Weaver 1990; Ulbrich 1993; Ulbrich *et al*. 1994) recognized the typical alkaline nature of the FN suite of rocks and distinguished, in the Remédios Formation, the sodic, silica-undersaturated feature of a first series (ranging from basanites, tephrites and essexites to tephriphonolites and phonolites) and the "moderately potassic" character of a second series, encompassing from ne-normative to quartz-normative types (alkali basalt, trachyandesites and trachytes). Selected geochemical data are presented on these series in Table 5; a complete set can be found in Lopes (2002).

### The sodic Remédios rocks, a series from basanites and tephrites to phonolites

Harker diagrams (major and minor oxides versus $SiO_2$, Fig. 2) for rocks of the sodic series show smooth variation trends for most oxides with increasing $SiO_2$ contents. MgO, $Fe_2O_3$, CaO, $TiO_2$ and $P_2O_5$ are decreasing while $K_2O$, $Na_2O$ and $Al_2O_3$ increase up to about 50% $SiO_2$, then decrease slightly. This indicates the early removal of mafic minerals from the parental magmas as a cause, such as olivine and clinopyroxene, with accessory magnetite and apatite, and the late fractionation of alkali-feldspar and nepheline. The *mg#* indices change, as expected,

**Table 3. Modal analyses of xenoliths contained in the pyroclastic Remédios rocks.**

| Sample | 1 (60F) | 2 (60F) | 3 (88Z) | 4 (88F) | 5 (150A) | 6 (88E) | 7 (88H) |
|---|---|---|---|---|---|---|---|
| Amphibole | 60.0 | | 33.3 | 38.7 | 39.2 | 35.0 | 7.2 |
| Cpx | 20.8 | 52.0 | 48.1 | 22.4 | 3.9 | 5.0 | 3.0 |
| Plagioclase | | | 1.8 | 29.5 | 49.7 | 43.0 | 62.0 |
| K feldspar | | | | | | 12.0 | 10.8 |
| Opaques | 5.7 | 14.3 | 14.2 | 7.4 | 1.9 | 4.0 | 1.5 |
| Biotite | | | 1.1 | | 1.9 | | 12.5 |
| Apatite | 13.5 | 33.7 | 1.5 | 2.0 | tr | tr | Tr |
| Titanite | | | | | 3.4 | 1.0 | 3.0 |
| Total | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

*Cpx*: clinopyroxene; *opaques*: Ti-Fe oxides. *Rock names.* 1: Cpx hornblendite; 2: cpx-apatite lenses; 3: kaersutite clinopyroxenite with opaques; 4: kaersutite melagabbro; 5: kaersutite diorite; 6: kaersutite monzogabbro; 7: monzodiorite.

from Mg-richer to Fe-richer values, the most differentiated rocks (i.e., phonolites) presenting the lowest *mg#*, as follows: basanites *mg#*= 0.63 to 0.49, tephrite 0.55, essexite 0.56, tephriphonolite 0.41, porphyritic phonolite 0.31 to 0.38, aphyric phonolites type I and II 0.13 to 0.03 (cf. Tab. 5).

Moreover, the Harker diagrams of major elements (Fig. 2) show an hiatus in intermediate $SiO_2$ values (akin to a "Daly gap") between 46 to 52% $SiO_2$, more enhanced if the essexite (a plutonic rock) is left out. The ensuing distribution of points could suggest that the compositions lying between 46 and 55% (in part occupied by the intermediate tephriphonolites) represent hybrid rocks, as suggested in part on textural and mineralogical grounds (cf. section on Petrography), originated by simple mixing of separate magmas, plotting on opposite sides of the diagram (such as

**Table 4a. Modal analyses of rocks from the Quixaba Formation.**

| Sample | 99FN21b | 99FN63 | UCFN37 | 97FN31 | 97FN44b | 97FN32b | 97FN20 |
|---|---|---|---|---|---|---|---|
| | MEM | MEM | MEM | MEM | OLM | OLM | OLM |
| Nephel | 20.2 | 22.0 | 37.0 | 32.8 | 36.2 | 0.0 | 0.0 |
| Glass | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 33.1 | 26.0 |
| Feldspars | – | – | – | – | – | – | – |
| Cpirox | 24.7 | 30.3 | 32.1 | 34.6 | 18.3 | 40.5 | 40.2 |
| Opaques | 25.4 | 23.0 | 12.3 | 19.8 | 24.3 | 15.2 | 20.8 |
| Olivine | 16.7 | 16.0 | 10.3 | 10.1 | 17.8 | 9.3 | 11.0 |
| Melilite | 10.0 | 6.7 | 5.3 | 1.4 | 0.0 | 0.0 | 0.0 |
| Apatite | 1.6 | 1.0 | 2.3 | Tr | tr | tr | Tr |
| Mica | 1.4 | 1.0 | 0.7 | 0.6 | 1.0 | 1.5 | 1.8 |
| Amygd | 0.0 | 0.0 | 0.0 | Tr | 2.0 | tr | 0.0 |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

Rock types.MEM, OLM, PYM: melilite-, olivine-, pyroxene-melanephelinites; BAS: basanites.

**Table 4b. Modal analyses of rocks from the Quixaba Formation.**

| Sample | 97FN39 | 97FN46 | 97FN13d | 99FN4 | 99FN22 | 99FN9a | 99FN10b |
|---|---|---|---|---|---|---|---|
| | PYM | PYM | PYM | BAS | BAS | BAS | BAS |
| Nephel | 0.0 | 13.2 | 0.0 | 4.6 | 0.0 | 0.0 | 0.0 |
| Glass | 17.0 | 12.2 | 24.1 | Tr | tr | tr | 9.4 |
| Feldspars | 1.5 | 0.0 | 0.0 | 21.2 | 20.0 | 22.5 | 34.0 |
| Cpyrox | 43.2 | 40.9 | 45.7 | 42.7 | 48.4 | 49.0 | 39.3 |
| Opaques | 22.2 | 18.9 | 12.7 | 12.7 | 19.4 | 13.5 | 9.6 |
| Olivine | 13.7 | 9.6 | 9.2 | 10.7 | 12.0 | 13.0 | 6.6 |
| Melilite | – | – | – | – | – | – | – |
| Apatite | tr | 1.6 | 4.6 | 3.2 | tr | 2.0 | 1.0 |
| Mica | 0.9 | 2.2 | 3.3 | 4.4 | 0.0 | 0.0 | 0.0 |
| Amygd | tr | 1.4 | Tr | Tr | 0.0 | 0.0 | tr |
| Total | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

MEM: melilite; PYM: pyroxene; OLM: olivine melanephelinites; BAS: basanites. Feldspars: mainly plagioclases. For comparison, data from Cuscuz (99FN9a) and São José islands (99FN10b).

Table 5a. Chemical analyses of selected Fernando de Noronha rocks (for a complete list, see Lopes 2002).

| Type | Basanites | | | Tephrite | Essexite | Tephriph | | Phpor | Phaph I | Phaph II |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN10c** | **97FN53b** | **97FN33c** | **97FN43a** | **97FN42** | **97FN53c** | **WFSG** | **91FN127** | **97FN16** | **89FN6** |
| $SiO_2$ | 40.18 | 41.47 | 44.20 | 45.80 | 49.89 | 51.64 | 55.24 | 55.85 | 56.88 | 58.56 |
| $TiO_2$ | 4.26 | 2.53 | 2.59 | 2.20 | 1.47 | 1.25 | 0.30 | 0.51 | 0.17 | 0.17 |
| $Al_2O_3$ | 13.09 | 12.69 | 15.00 | 15.64 | 17.80 | 19.17 | 21.99 | 21.28 | 22.06 | 20.87 |
| $Fe_2O_3$ | 13.62 | 10.54 | 9.80 | 8.54 | 5.84 | 4.86 | 2.71 | 2.64 | 2.14 | 2.26 |
| MnO | 0.18 | 0.18 | 0.18 | 0.19 | 0.16 | 0.13 | 0.13 | 0.13 | 0.14 | 0.21 |
| MgO | 7.17 | 8.94 | 5.12 | 6.31 | 3.74 | 1.70 | 0.16 | 0.80 | 0.18 | 0.04 |
| CaO | 11.66 | 10.24 | 9.36 | 9.03 | 5.48 | 3.77 | 1.66 | 2.12 | 1.33 | 0.58 |
| $Na_2O$ | 3.01 | 4.36 | 5.63 | 4.16 | 5.93 | 6.76 | 9.98 | 8.35 | 9.60 | 10.72 |
| $K_2O$ | 1.21 | 2.19 | 1.92 | 3.10 | 4.53 | 5.34 | 5.98 | 5.87 | 6.18 | 5.16 |
| $P_2O_5$ | 1.03 | 0.56 | 0.80 | 0.52 | 0.36 | 0.34 | 0.04 | 0.10 | 0.02 | 0.01 |
| LOI | 3.16 | 5.72 | 4.65 | 3.62 | 3.64 | 5.50 | 1.32 | 1.68 | 2.18 | 0.99 |
| Total | 98.57 | 99.42 | 99.25 | 99.11 | 98.85 | 100.45 | 99.51 | 99.33 | 100.88 | 99.57 |
| Ba | 865 | 784 | 1025 | 1078.4 | 646 | 1180 | 963 | 417 | 4.5 | 3.4 |
| Rb | 25.2 | 43.1 | 69.1 | 32 | 122 | 173 | 196 | 199 | 235 | 297 |
| Sr | 1170 | 1177 | 1039 | 1769 | 1033 | 1400 | 1576 | 736 | 80 | 9 |
| Y | 38 | 25 | 32 | 39 | 27 | 22 | 15 | 18 | 12 | 23 |
| Zr | 294 | 324 | 507 | 406 | 527 | 706 | 720 | 737 | 960 | 1461 |
| Nb | 63.1 | 97.9 | 137.9 | 130.7 | 70.0 | 125.3 | 104.3 | 110.0 | 103.2 | 124.0 |
| Th | 5.83 | 9.87 | 17.11 | 11.43 | 14.50 | 25.4 | 28.6 | 24.9 | 34.1 | 46.0 |
| Pb | <4 | <4 | 8.5 | <4 | 12.0 | 17.4 | 10.4 | 14.0 | 15.3 | 30.0 |
| Ga | 18.9 | 21.3 | 26.3 | 23.3 | 24.9 | 33.3 | 32.6 | | 40.1 | 48.8 |
| Zn | <2 | 76 | 121 | 71 | 99 | 71 | 67 | 101 | 54 | 162 |
| Cu | 20 | 44 | 44 | 32 | 19 | <2 | <2 | | <2 | 0.7 |
| Ni | 45 | 208 | 118 | 127 | 72 | <3 | 211 | | <3 | 8 |
| V | 337 | 218 | 222 | 178 | 104 | 107 | 31 | 47 | 15 | 9 |
| Cr | 99 | 319 | 194 | 219 | 104 | 21 | <DL | 20 | <5 | 20 |
| Hf | 7.16 | 6.47 | 9.01 | 7.55 | 7.60 | 11.03 | 9.31 | 10.00 | 13.82 | 22.00 |
| Cs | 1.11 | 0.93 | 2.74 | 0.78 | 2.40 | 2.82 | 2.56 | 3.50 | 3.62 | |
| Sc | | | | | 9.00 | | | 0.00 | | |
| Ta | 4.82 | 4.73 | 6.58 | 6.08 | 3.50 | 4.44 | 1.57 | 4.00 | 1.54 | 2.10 |
| Co | 23 | 48 | 35 | 28 | 21 | 10 | 1 | | <2 | <2 |
| U | 1.59 | 2.56 | 5.98 | 3.68 | 5.90 | 9.10 | 8.80 | | 11.19 | 21.00 |
| W | <0.5 | 0.8 | 0.7 | 0.8 | 1.0 | 1.6 | 0.5 | | <0.5 | 0.7 |
| Sn | 1.1 | 3.6 | 1.7 | 1.6 | | 1.4 | <1 | | <1 | |
| Mo | <2 | 3.4 | 2.4 | 3.3 | | 6.2 | <2 | | <2 | |

Continue...

Table 5a. Continuation.

| Type | Basanites | | | Tephrite | Essexite | Tephriph | | Phpor | Phaph I | Phaph II |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN10c** | **97FN53b** | **97FN33c** | **97FN43a** | **97FN42** | **97FN53c** | **WFSG** | **91FN127** | **97FN16** | **89FN6** |
| La | 65.17 | 69.91 | 99.85 | 116.79 | 115.00 | 88.13 | 84.54 | 97.80 | 88.12 | 132.00 |
| Ce | 153.4 | 120.6 | 178.9 | 182.4 | 167.0 | 126.1 | 93.1 | 129.0 | 87.2 | 138.0 |
| Pr | 17.41 | 12.99 | 18.35 | 17.99 | 14.50 | 11.73 | 6.50 | | 5.25 | 8.30 |
| Nd | 72.20 | 52.47 | 70.21 | 66.50 | 43.00 | 37.23 | 17.45 | 37.00 | 10.92 | 16.73 |
| Sm | 14.05 | 9.55 | 11.81 | 10.93 | 6.60 | 5.92 | 2.12 | 8.01 | 1.19 | 1.60 |
| Eu | 4.57 | 2.93 | 3.56 | 3.25 | 1.91 | 1.82 | 0.64 | 1.90 | 0.36 | 0.34 |
| Gd | 12.35 | 7.42 | 9.69 | 8.36 | 5.50 | 4.96 | 1.69 | | 1.15 | 1.44 |
| Tb | 1.67 | 1.06 | 1.31 | 1.18 | 0.80 | 0.73 | 0.31 | 0.50 | <DL | |
| Dy | 8.20 | 5.15 | 6.40 | 5.62 | 3.80 | 3.76 | 1.81 | | 1.27 | 1.67 |
| Ho | 1.39 | 0.88 | 1.11 | 0.99 | 0.71 | 0.73 | 0.40 | | 0.34 | 0.40 |
| Er | 3.53 | 2.18 | 2.84 | 2.53 | 1.96 | 2.11 | 1.45 | | 1.30 | 1.52 |
| Tm | 0.41 | 0.28 | 0.37 | 0.33 | 0.30 | 0.31 | 0.27 | | 0.25 | |
| Yb | 2.27 | 1.54 | 2.07 | 1.89 | 1.79 | 2.08 | 1.79 | 1.50 | 1.96 | 2.50 |
| Lu | 0.28 | 0.18 | 0.24 | 0.22 | 0.24 | 0.29 | 0.31 | 0.29 | 0.32 | 0.41 |
| F | | | | | | | | | | |
| *mg#* | 0.510 | 0.627 | 0.487 | 0.550 | 0.560 | 0.408 | 0.105 | 0.377 | 0.129 | 0.031 |
| (Na+K)/ Al | 0.47 | 0.75 | 0.73 | 0.68 | 0.87 | 0.93 | 1.06 | 0.98 | 1.05 | 1.11 |
| Na/K* | 2.49 | 1.99 | 2.93 | 1.34 | 1.31 | 1.26 | 1.67 | 1.42 | 1.55 | 2.08 |
| | sodic | Sodic | Sodic | sodic | sodic | sodic | sodic | Sodic | sodic | sodic |

Tephriph: tephriphonolite. Phpor: porphyritic phonolite; Phaph I, II: aphyric phonolites types I, II. *Na/K: $Na_2O/K_2O$. Major, minor elements: wt %; trace elements: ppm. The last lines indicate: 1) peralkalinity (with respect to Al), 2) the Remédios sodic or potassic character of the rock (either belonging to the "sodic" or "potassic" series). *mg#*= MgO/(MgO + $Fe^{2+}O(t)$).

Table 5b. Chemical analyses of selected Fernando de Noronha rocks.

| Type | AB | Btrach | Trachyand | Trachyte | Lamp I | | Lamp II | Lam III | Lam IV |
|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN35b** | **97FN6b** | **P7FN3c** | **97FN57** | **97FN4b** | **97FN3a** | **97FN7** | **97FN25** | **97FN43c** |
| $SiO_2$ | 45.63 | 49.61 | 57.08 | 60.26 | 44.72 | 41.66 | 40.01 | 46.23 | 44.63 |
| $TiO_2$ | 3.22 | 2.36 | 1.18 | 0.42 | 2.40 | 4.20 | 3.86 | 2.26 | 2.28 |
| $Al_2O_3$ | 15.17 | 17.15 | 18.98 | 19.17 | 17.91 | 13.27 | 12.05 | 18.30 | 18.31 |
| $Fe_2O_3$ | 12.69 | 5.99 | 4.57 | 2.74 | 7.71 | 12.92 | 12.54 | 4.79 | 6.50 |
| MnO | 0.21 | 0.15 | 0.21 | 0.19 | 0.18 | 0.20 | 0.21 | 0.12 | 0.14 |
| MgO | 4.99 | 3.15 | 1.25 | 0.53 | 2.98 | 6.29 | 9.97 | 2.50 | 3.50 |
| CaO | 9.59 | 5.80 | 4.10 | 2.47 | 6.81 | 12.17 | 12.53 | 5.73 | 6.00 |
| $Na_2O$ | 3.43 | 3.08 | 5.96 | 6.77 | 5.85 | 1.81 | 2.97 | 1.90 | 1.28 |
| $K_2O$ | 2.10 | 4.85 | 4.68 | 5.24 | 2.92 | 2.26 | 1.83 | 3.67 | 4.56 |
| $P_2O_5$ | 0.76 | 0.90 | 0.19 | 0.04 | 1.67 | 1.29 | 0.62 | 0.97 | 1.15 |

Continue...

Table 5b. Continuation.

| Type | AB | Btrach | Trachyand | Trachyte | Lamp I | | Lamp II | Lam III | Lam IV |
|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN35b** | **97FN6b** | **P7FN3c** | **97FN57** | **97FN4b** | **97FN3a** | **97FN7** | **97FN25** | **97FN43c** |
| LOI | 1.59 | 6.02 | 1.45 | 2.22 | 7.14 | 2.86 | 2.44 | 11.10 | 11.46 |
| Total | 99.38 | 99.06 | 99.65 | 100.05 | 100.27 | 98.93 | 99.03 | 97.57 | 99.79 |
| Ba | 457 | 946 | 1191 | 1234 | 1070 | 727 | 906 | 1330 | 1280 |
| Rb | 59 | 142 | 142.5 | 168 | 81 | 55 | 47 | 97 | 139 |
| Sr | 964 | 821 | 1329 | 1075 | 1620 | 1719 | 1744 | 1520 | 1280 |
| Y | 41 | 40 | 40 | 22 | 30 | 41 | 41 | 35 | 30 |
| Zr | 417.2 | 568 | 792 | 1018 | 394 | 460 | 383 | 536 | 497 |
| Nb | 66 | 116 | 140 | 113.6 | 138 | 109 | 117 | 178.5 | 162 |
| Th | 7.60 | 19.80 | 22.60 | 24.16 | 13.48 | 10.01 | 8.45 | 21.96 | 22.37 |
| Pb | 6 | 13 | 15 | <4 | 14 | <4 | 5 | 12 | 18 |
| Ga | 25 | 27 | 27 | 28 | 26 | 27 | 22 | 28 | 27 |
| Zn | 126 | 97 | 95 | <2 | 94 | 130 | 122 | 80 | 74 |
| Cu | 23 | 8 | 4 | <2 | <2 | 54 | 51 | <2 | 12 |
| Ni | 39 | 24 | 18 | <3 | 62 | 81 | 296 | 19 | <3 |
| V | 288 | 164 | 71 | 31 | 172 | 330 | 294 | 187 | 165 |
| Cr | | 229 | | <5 | 37 | 43 | 303 | <5 | <5 |
| Hf | 10.90 | 13.00 | 17.10 | 16.12 | 6.80 | 10.69 | 8.29 | 8.98 | 7.81 |
| Cs | 2.00 | 1.90 | 2.40 | 3.83 | 3.67 | 0.89 | 0.55 | 4.33 | 2.01 |
| Sc | 18 | 5 | 10 | | | | | | |
| Ta | 4.80 | 8.10 | 10.00 | 3.15 | 7.14 | 6.27 | 5.37 | 9.45 | 8.30 |
| Co | 35 | 19 | 8 | <2 | 16 | 42 | 48 | 9 | 11 |
| U | 1.75 | 4.70 | 5.19 | 5.40 | 3.67 | 2.79 | 2.17 | 5.46 | 4.87 |
| W | 0.9 | 1.9 | 2.8 | 0.2 | 1.8 | 0.5 | 0.7 | 1.4 | 1.3 |
| Sn | 3.0 | | 2.0 | <1 | 1.9 | 2.8 | 6.3 | 1.7 | 1.7 |
| Mo | 2 | | 7 | <2 | 6 | <2 | 2 | 4 | <2 |
| La | 64.00 | 120.00 | 145.00 | 121.34 | 92.13 | 93.51 | 84.25 | 113.80 | 102.13 |
| Ce | 142.0 | 224.0 | 266.0 | 171.7 | 157.0 | 188.1 | 158.7 | 190.8 | 166.2 |
| Pr | 17.60 | 24.00 | 27.00 | 13.21 | 17.05 | 21.42 | 18.36 | 20.51 | 17.36 |
| Nd | 68.00 | 83.00 | 86.00 | 38.75 | 59.44 | 90.41 | 78.15 | 70.47 | 59.29 |
| Sm | 12.40 | 13.10 | 12.00 | 4;57 | 10.23 | 16.47 | 14.36 | 11.61 | 9.64 |
| Eu | 3.70 | 3.90 | 3.50 | 1.35 | 3.30 | 5.05 | 4.29 | 3.74 | 3,12 |
| Gd | 10.80 | 10.60 | 9.40 | 3.65 | 9.02 | 13.82 | 11.61 | 10.35 | 8.52 |
| Tb | 1.49 | 1.50 | 1.36 | 0.52 | 1.20 | 1.90 | 1.63 | 1.38 | 1.16 |
| Dy | 7.60 | 7.10 | 6.60 | 2.90 | 5.94 | 9.05 | 8.11 | 6.90 | 5.86 |
| Ho | 1.39 | 1.33 | 1.29 | 0.59 | 1.04 | 1.48 | 1.38 | 1.24 | 1.06 |

Continue...

Table 5b. Continuation.

| Type | AB | Btrach | Trachyand | Trachyte | Lamp I | | Lamp II | Lam III | Lam IV |
|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN35b** | **97FN6b** | **P7FN3c** | **97FN57** | **97FN4b** | **97FN3a** | **97FN7** | **97FN25** | **97FN43c** |
| Er | 3.40 | 3.20 | 3.40 | 1.96 | 2.74 | 3.69 | 3.53 | 3.27 | 2.85 |
| Tm | 0.44 | 0.43 | 0.51 | 0.33 | 0.34 | 0.44 | 0.45 | 0.42 | 0.37 |
| Yb | 2.50 | 2.70 | 3.00 | 2.17 | 2.07 | 2.31 | 2.44 | 2.50 | 2.29 |
| Lu | 0.36 | 0.32 | 0.42 | 0.36 | 0.27 | 0.26 | 0.28 | 0.34 | 0.30 |
| F | | | | | | | | | |
| *mg#* | 0.438 | 0.509 | 0.352 | 0.276 | 0.435 | 0.491 | 0.611 | 0.508 | 0.518 |
| (Na+K)/Al | 0.53 | 0.69 | 0.83 | 0.92 | 0.71 | 0.46 | 0.58 | 0.46 | 0.49 |
| Na/K* | 1.63 | 0.64 | 1.27 | 1.29 | 2.00 | 0.80 | 1.62 | 0.52 | 0.28 |
| | potassic | Potassic | potassic | potassic | | | | | |

Tephriph: tephriphonolite. Phpor: porphyritic phonolite; Phaph I, II: aphyric phonolites types I, II. * Na/K: $Na_2O/K_2O$. Major, minor elements: wt %; trace elements: ppm. The last lines indicate: 1) peralkalinity (with respect to Al), 2) the Remédios sodic or potassic character of the rock (either belonging to the “sodic” or “potassic” series). *mg#*= MgO/(MgO + $Fe^{2+}O(t)$). Phaph II: aphyric phonolite II; AB: alkali basalt; Btrach: basaltic trachyandesite; Trachyand: trachyandesite; Lamp: lamprophyre types I, II, III, IV.

Table 5c. Chemical analyses of selected Fernando de Noronha rocks.

| Type | MEM | OLM | | PYM | | Bas (main island) | | Bas S. José | | Bas C |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN31** | **97FN32b** | **97FN58a** | **97FN13c** | **97FN40** | **97FN41** | **89FN78a** | **89FN79** | **99FN10b** | **99FN9a** |
| $SiO_2$ | 37.27 | 37.88 | 39.48 | 40.13 | 42.53 | 44.87 | 45.05 | 44.96 | 45.22 | 45.42 |
| $TiO_2$ | 3.96 | 4.68 | 3.81 | 3.82 | 3.05 | 3.06 | 3.01 | 2.61 | 2.57 | 2.56 |
| $Al_2O_3$ | 10.95 | 9.98 | 10.63 | 9.79 | 11.48 | 12.07 | 11.19 | 12.32 | 12.01 | 11.75 |
| $Fe_2O_3$ | 14.39 | 15.12 | 13.02 | 13.13 | 13.20 | 12.45 | 12.90 | 12.09 | 11.99 | 12.30 |
| MnO | 0.23 | 0.22 | 0.21 | 0.18 | 0.20 | 0.18 | 0.19 | 0.18 | 0.16 | 0.16 |
| MgO | 11.25 | 11.63 | 12.35 | 10.96 | 10.40 | 9.71 | 9.28 | 10.21 | 10.39 | 10.95 |
| CaO | 13.06 | 12.90 | 12.89 | 11.98 | 11.95 | 10.72 | 11.01 | 10.99 | 10.83 | 11.35 |
| $Na_2O$ | 3.96 | 2.29 | 3.78 | 3.94 | 3.69 | 4.21 | 3.46 | 3.24 | 3.07 | 3.01 |
| $K_2O$ | 1.79 | 0.89 | 1.97 | 0.79 | 1.00 | 1.54 | 1.01 | 1.21 | 0.99 | 0.88 |
| $P_2O_5$ | 1.07 | 0.95 | 0.80 | 1.91 | 0.82 | 1.32 | 0.77 | 0.69 | 0.69 | 0.72 |
| LOI | 1.27 | 2.93 | 0.04 | 2.08 | 1.20 | 0.30 | 1.54 | 0.41 | 1.85 | 1.28 |
| Total | 99.20 | 99.47 | 98.98 | 98.71 | 99.52 | 100.43 | 99.41 | 98.91 | 99.77 | 100.38 |
| Ba | 951 | 610 | 773 | 721 | 741 | 699 | 565 | 447 | 491 | 419 |
| Rb | 49.5 | 16.6 | 46.7 | 42.9 | 16.0 | 26.0 | 40.6 | 29.8 | 22.2 | 24.2 |
| Sr | 1368 | 1017 | 1009 | 939 | 922 | 829 | 879 | 762 | 1254 | 881 |
| Y | 43.0 | 30.2 | 36.0 | 36.0 | 28.7 | 29.6 | 30.5 | 32.0 | 33.0 | 29.0 |
| Zr | 307.6 | 318.7 | 335.3 | 392.3 | 236.4 | 229.6 | 340.3 | 219.4 | 226.5 | 218.5 |
| Nb | 107.00 | 112.19 | 106.00 | 79.00 | 83.57 | 80.88 | 85.47 | 58.00 | 57.00 | 54.00 |
| Th | 16.20 | 8.27 | 9.00 | 6.80 | 6.57 | 9.82 | 6.27 | 6.30 | 5.90 | 5.50 |
| Pb | 9 | <4 | 2 | 4 | <4 | 13 | <4 | 5 | 4 | 3 |

Continue...

Table 5c. Continuation.

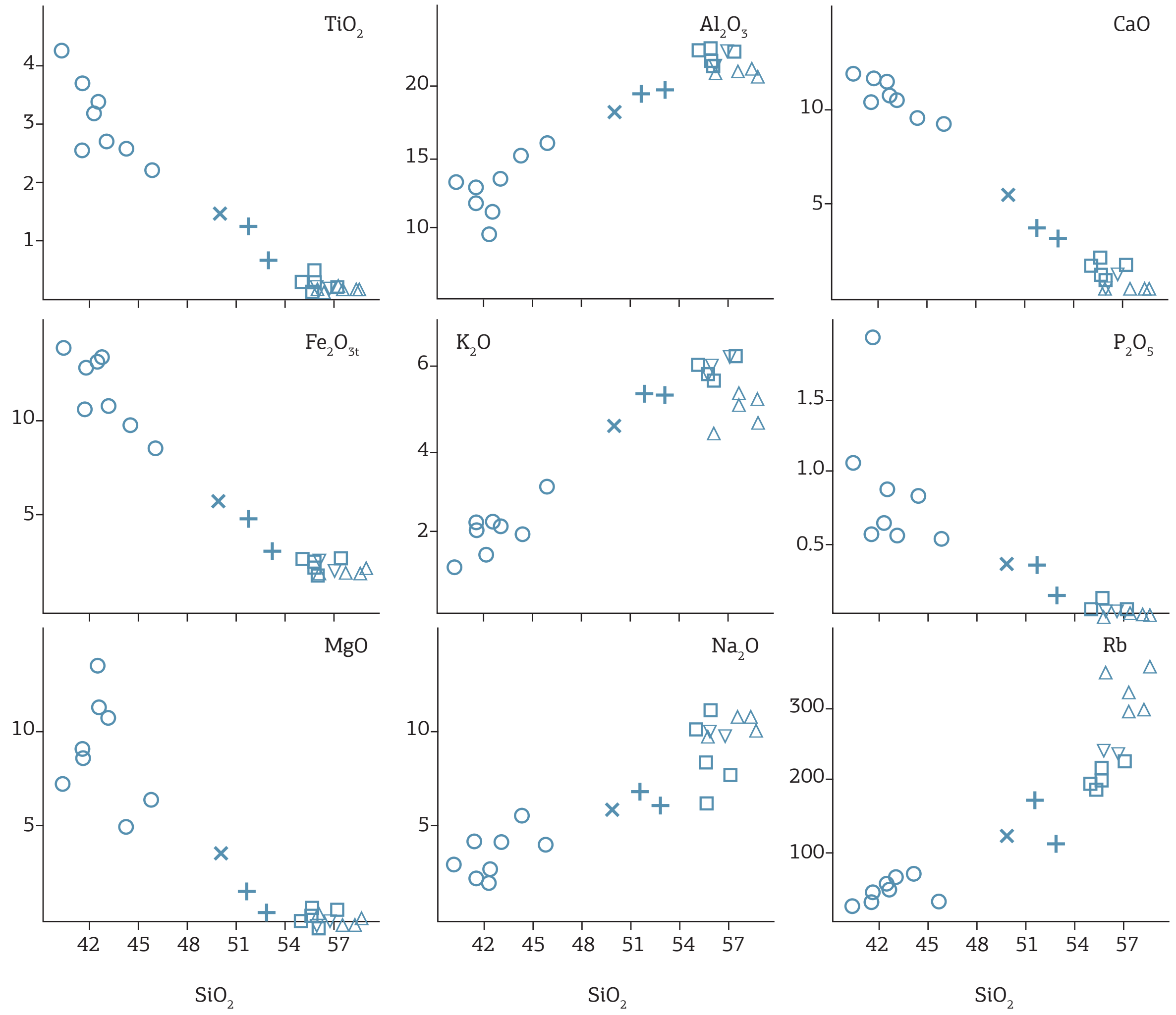
| **Type** | **MEM** | **OLM** | | **PYM** | | **Bas (main island)** | | **Bas S. José** | | **Bas C** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sample** | **97FN31** | **97FN32b** | **97FN58a** | **97FN13c** | **97FN40** | **97FN41** | **89FN78a** | **89FN79** | **99FN10b** | **99FN9a** |
| Ga | 17.8 | 20.4 | 15.9 | 17.6 | 16.8 | 22.3 | 20.7 | 14.8 | 16.5 | 16.2 |
| Zn | 116 | 112 | 112 | 120 | <2 | 107 | 127 | 124 | 98 | 106 |
| Cu | 51 | 50 | 37 | 51 | 37 | 43 | 57 | 56 | 56 | 51 |
| Ni | 183 | 205 | 138 | 256 | 176 | 140 | 306 | 244 | 260 | 271 |
| V | 284 | 334 | 280 | 255 | 225 | 249 | 221 | 182 | 179 | 172 |
| Cr | 247 | 330 | 333 | 321 | 297 | 283 | 345 | 260 | | |
| Hf | 7.70 | 7.71 | 8.20 | 6.50 | 5.24 | 5.66 | 7.42 | 5.60 | 5.70 | 5.40 |
| Cs | 0.70 | 1.01 | 0.80 | 1.10 | 0.72 | 0.83 | 0.73 | 0.30 | | |
| Sc | 22 | | 25 | 25 | | | | 21 | | |
| Ta | 6.70 | 6.34 | 7.20 | 5.40 | 5.61 | 3.95 | 4.82 | 3.90 | 3.70 | 3.30 |
| Co | 46 | 64 | 44 | 42 | 39 | 49 | 70 | 42 | 42 | 40 |
| U | 2.30 | 1.30 | 2.12 | 1.73 | 1.88 | 1.25 | 1.62 | 1.71 | 1.98 | 1.57 |
| W | 2.9 | 0.5 | 1.6 | 2.3 | 0.8 | 2.6 | 0.9 | 0.3 | 1.7 | 1.6 |
| Sn | | 2.6 | | | <1 | 2.2 | 2.1 | 1.0 | | |
| Mo | | <2 | | | <2 | 7.01 | 2.02 | 2.00 | | |
| La | 115.00 | 66.38 | 78.00 | 71.00 | 62.55 | 85.70 | 56.58 | 50.00 | 51.00 | 48.00 |
| Ce | 233.0 | 12.6 | 162.0 | 154.0 | 116.6 | 138.6 | 106.8 | 106.0 | 109.0 | 101.0 |
| Pr | 27.00 | 3.84 | 19.10 | 18.80 | 13.08 | 15.37 | 12.51 | 12.80 | 12.80 | 12.20 |
| Nd | 99.00 | 10.25 | 73.00 | 72.00 | 54.40 | 54.81 | 53.65 | 50.00 | 49.00 | 47.00 |
| Sm | 16.40 | 1.40 | 12.70 | 13.20 | 10.34 | 10.16 | 10.77 | 9.20 | 9.40 | 8.70 |
| Eu | 5.09 | 3.84 | 4.00 | 4.10 | 3.19 | 3.32 | 3.34 | 3.06 | 3.10 | 2.90 |
| Gd | 13.20 | 10.25 | 11.10 | 11.30 | 8.36 | 9.13 | 8.93 | 8.40 | 8.60 | 8.00 |
| Tb | 1.80 | 1.40 | 1.40 | 1.40 | 1.18 | 1.26 | 1.28 | 1.17 | | |
| Dy | 8.50 | 6.60 | 6.90 | 7.30 | 5.75 | 6.27 | 6.28 | 5.90 | 5.60 | 5.30 |
| Ho | 1.45 | 1.05 | 1.22 | 1.22 | 0.95 | 1.08 | 1.04 | 1.04 | 1.01 | 1.00 |
| Er | 3.20 | 2.56 | 2.60 | 2.80 | 2.39 | 2.71 | 2.63 | 2.40 | 2.30 | 2.20 |
| Tm | 0.42 | 0.30 | 0.33 | 0.33 | 0.30 | 0.32 | 0.32 | 0.30 | | |
| Yb | 2.20 | 1.61 | 1.70 | 1.97 | 1.59 | 1.92 | 1.71 | 1.74 | 1.65 | 1.53 |
| Lu | 0.27 | 0.17 | 0.25 | 0.22 | 0.17 | 0.24 | 0.20 | 0.22 | 0.22 | 0.17 |
| F | 1798 | 1988 | 1198 | 1596 | | 1104 | | | | |
| *mg#* | 0.608 | 0.604 | 0.652 | 0.624 | 0.610 | 0.607 | 0.588 | 0.626 | 0.631 | 0.637 |
| (Na+K)/Al | 0.76 | 0.46 | 0.79 | 0.69 | 0.59 | 0.69 | 0.58 | 0.52 | 0.49 | 0.48 |
| Na/K* | 2.21 | 2.57 | 3.06 | 4.99 | 3.69 | 2.73 | 3.43 | 2.68 | 3.10 | 3.42 |

Tephriph: tephriphonolite. Phpor: porphyritic phonolite; Phaph I, II: aphyric phonolites types I, II. * Na/K: $Na_2O/K_2O$.Major, minor elements: wt %; trace elements: ppm. The last lines indicate:1) peralkalinity (with respect to Al), 2) the Remédios sodic or potassic character of the rock (either belonging to the "sodic" or "potassic"series). *mg#*= MgO/(MgO + $Fe^{2+}O(t)$). Trachyand: trachyandesite; Lamp: lamprophrye types I to IV; MEM: melilite; PYM: pyroxene; OLM: olivine melanephelinites; Bas (main island): Quixaba basanites. Bas C, S. José: basanites Cuscuz, São José islands (São José Formation).

basanites, on the one hand, and phonolites, on the other) (D. Demaiffe, pers. commun.).

The variations of some trace element contents (Fig. 3) have been plotted against Zr, continuously increasing from about 300 ppm in the basanites to 1,500 ppm in the aphyric phonolites. The compatible transition elements (Sc, V, Cr) strongly decrease at the beginning of the differentiation process, indicating removal together with their host minerals (mafic phases and oxides). The alkaline-earth elements Sr and Ba first increase from basanites to tephrites, then rapidly decrease to very low contents (< 10 ppm) in the aphyric phonolites (type II). As is usually observed in other instances, the incompatible elements (Rb, Cs, Nb, Ta, U, Th, etc.) increase continuously during magmatic evolution.

The trend in REE diagrams indicates that the least differentiated rocks (basanites) are also the ones that are enriched in these elements, in comparison with the highly fractionated magmas forming the phonolite rocks, which show a distinct pattern (a marked depletion in medium REE; Fig. 4). Normative mineral compositions, plotted within the undersaturated part of the $SiO_2$-nepheline-kalsilite diagram, show that most of these rocks plot rather smoothly in the undersaturated thermal valley (pressure of 1 atm; Fig. 5).



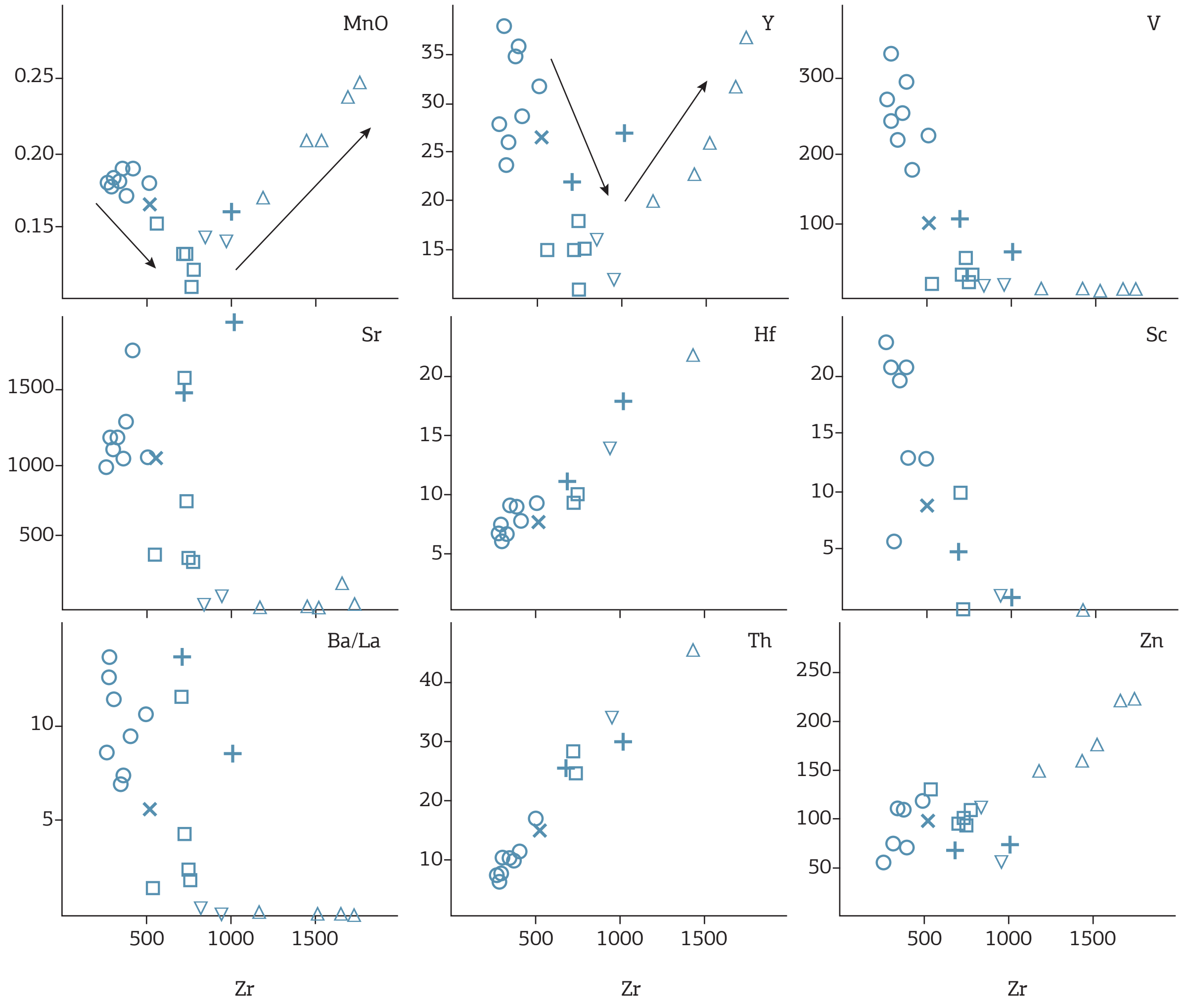
Open circles: basanites and tephrites; x: essexite; crosses: tephriphonolites; open squares: porphyritic phonolites; open inverted triangles: type I aphyric phonolites; open triangles: type II aphyric phonolites.

**Figure 2. Harker variation diagrams of rocks from the sodic series, Remédios Formation. Source: Lopes (2002).**

## The moderately potassic Remédios rocks: from alkali basalts to trachytes

The most primitive rocks of these series, less abundant than the ones of the sodic series, are the alkali basalts (*mg#*= 0.44) found at the Enseada do Abreu (Fig. 1), while the trachytes (*mg#*= 0.28) are the most evolved types (intrusive domes and dikes at the Praia do Leão and Praia da Biboca). Intermediate members such as the basaltic trachyandesites (*mg#*= 0.51) show indications that they intruded simultaneously as more basic magmas (e.g., Enseada da Caiera), leading eventually to magma mixing (they grade, for instance, into more mafic rocks at the center of some dikes); perhaps these characteristics can also be explained by concentration of mafic phenocrysts at the center of the dikes during emplacement, by a mechanism controlled by flowage differentiation (e.g., Nkono *et al.* 2006). Evolved trachytes occur as intrusive domes and dikes at the Praia do Leão and Praia da Biboca.

Geochemical data on these potassic rocks are depicted in Figures 6 to 8 (cf. also Tab. 5). The trend of decreasing MgO, $Fe_2O_3$(t), CaO, $TiO_2$ with increasing $SiO_2$ (from 46 to 61%) are smooth in variation diagrams while enrichment in $K_2O$



Open circles: basanites and tephrites; x: essexite; crosses: tephriphonolites; open squares: porphyritic phonolites; open inverted triangles: type I aphyric phonolites; open triangles: type II aphyric phonolites.

**Figure 3. Minor and trace element abundances *versus* Zr contents for rocks of the Remédios sodic series. Source: Lopes (2002).**

and $Na_2O$ is somewhat irregular (Fig. 6). Fractionation of olivine, clinopyroxene and spinels (magnetite) may explain the observed trends.

An approximately linear variation in some trace elements is shown in Fig. 7, as a function of Nb. The alkali basalt, a basaltic trachyandesite and a trachyandesite present some steep REE normalized variation diagrams while the more differentiated trachyte shows a depletion in medium REE, repeating the tendency observed in the phonolites (sodic series; Figs. 4 and 8).

As far as mineral composition is concerned (Lopes 2002), Mg-rich olivines ($Fo_{72}$) occur only in the alkali basalt, while clinopyroxenes are salites and titaniferous salites in the trachyandesites; sodic salites may be predominant in the matrix of trachytes. Kaersutitic amphiboles are found in the basaltic trachyandesites. Some patterns of irregular zoning in the pyroxene phenocrysts of the basaltic trachyandesites suggest disequilibrium crystallization conditions, possibly indicating at least partial magma mixing (between a basaltic magma and a trachyte, a situation that may be fairly common in oceanic island settings). Fractionation of olivine, clinopyroxene and amphibole, eventually also spinels, can explain the trend in depletion of several oxides observed in the variation diagrams, from the alkali basalt magma to the more differentiated trachytes (Fig. 6).

## The Remédios lamprophyres

All FN lamprophyres are characterized by the ubiquitous presence of amphibole phenocrysts (kaersutite) and the systematic absence of biotite, a feature rarely reported among equivalent OIB rocks. A detailed comparison of the studied samples in Maríngolo (1995) and Lopes (2002) shows some differences, both in geochemistry and mineralogical compositions as well as in texture. These lamprophyres in fact appear variable even at the outcrop scale (e.g., along a short distance in a dike). Moreover, the presence of composite dikes, representing multiple injections along the same conduit, can also give rise to complex interactions and/or magma mingling (i.e., samples 97FN3d and 97FN4b).

Chemical data for the FN lamprophyres plotted in variation diagrams show no tendency, in part because the $SiO_2$ range is very narrow (40 to 46%)(cf. Fig. 9), so that little can be said about fractionation patterns. They are also characterized by a narrow range in *mg#* (from 0.44 to 0.61), usually low to very low Cr contents (with the exception of a type II lamprophyre) and variable Ni abundances (sometimes over 300 ppm); they are systematically enriched in Ba (from 730 to 1,280 ppm) and Sr (from 1,200 to 1,740), unlike the other rocks present in Remédios.

Each lamprophyric rock seems to be unique, possibly representing a special product of partial melting of a mantle protolith, a derivation from more basic primary magmas, or a more complex cause implying magma-crystal interaction (cf. Le Maitre 2002, also Ubide *et al.* 2014, and bibliography cited therein). In fact, each lamprophyre could correspond to a discrete magma batch.

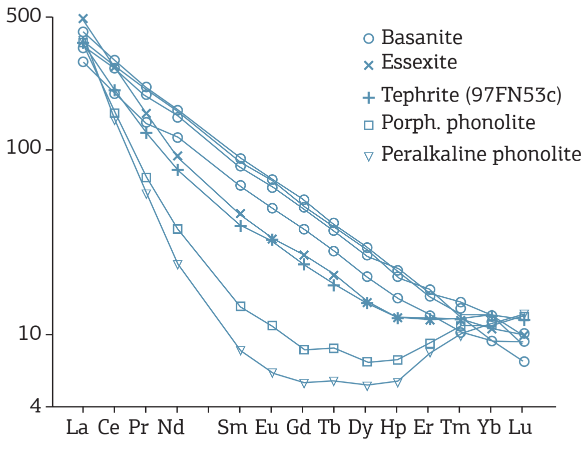
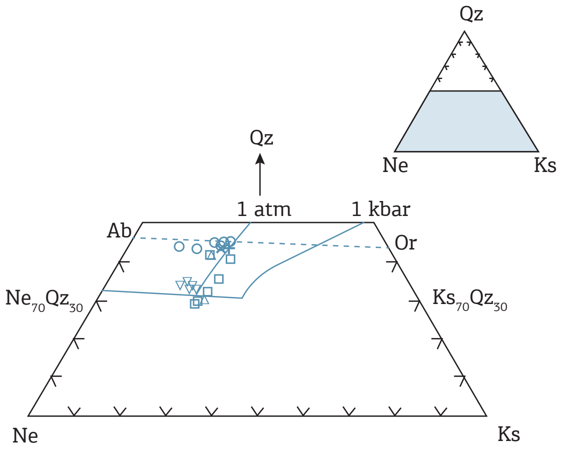


**Figure 4. Chondrite-normalized REE distribution pattern for rocks of the sodic series, Remédios Formation (normalized after Sun & McDonough (1989). Source: Lopes (2002).**



For symbols, see Fig. 3.

**Figure 5. Composition of rocks from the sodic series, Remédios Formation, plotted within the nepheline-kalsilite-quartz triangular diagram, indicating the position of the thermal valleys for 1 atm pressure and 1 kbar $H_2O$ pressure (Hamilton & McKenzie 1965). Source: Lopes (2002).**

## The rocks of the Quixaba event: nephelinites and basanites

The melanephelinites of the Quixaba Formation are strongly silica-undersaturated rocks with $SiO_2$ ranging from 37 to 43%. The basanites (both São José and Quixaba, cf. Tab. 5) are slightly more enriched (45 – 46% $SiO_2$). The major elements of the nephelinites, primitive undifferentiated rocks (*mg#* ranging from 0.60 to 0.65 in nephelinites; Fig. 10; Tab. 5) are generally overlapping in variation diagrams, but melanephelinites are somewhat richer in MgO, $TiO_2$, $Fe_2O_3$

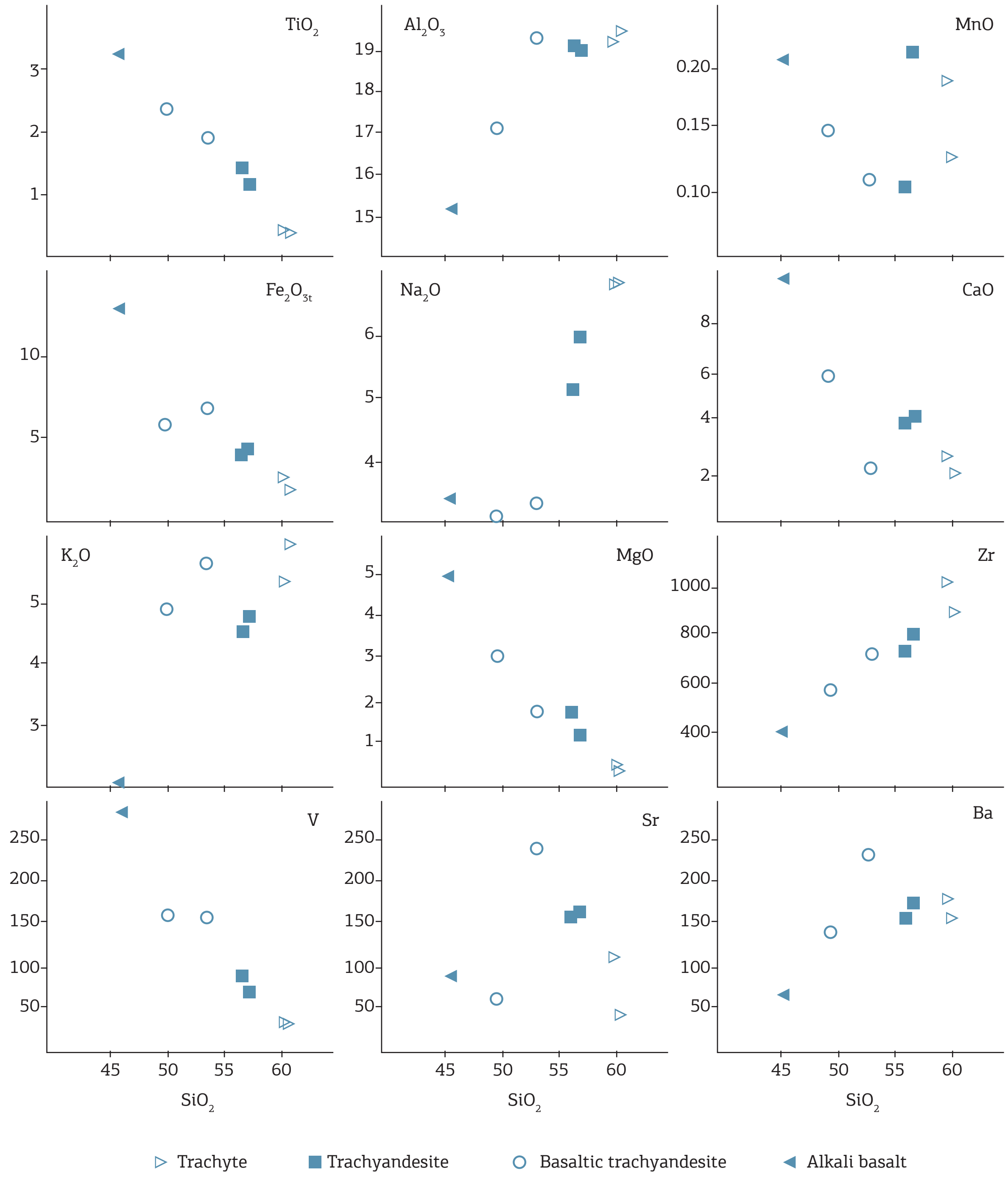
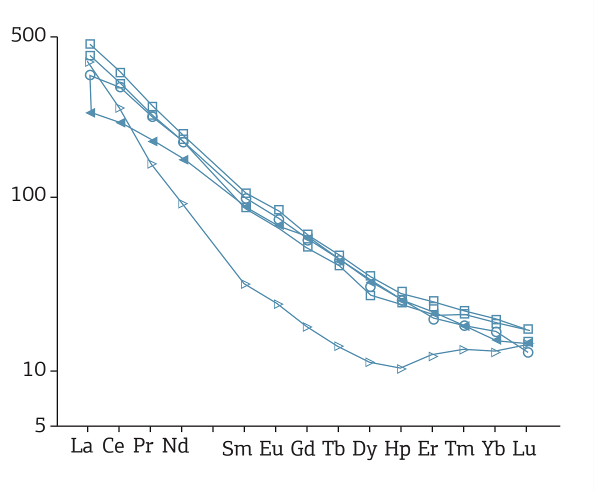


Figure 6. Harker variation diagrams for rocks of the moderately potassic series, Remédios Formation. Source: Lopes (2002).

(t) and CaO (Fig. 10). They are also markedly enriched in $Na_2O$ (from 3 to 4.20%) with respect to $K_2O$ (0.8 to 2.1%; cf. a complete set of analytical data in Lopes 2002).

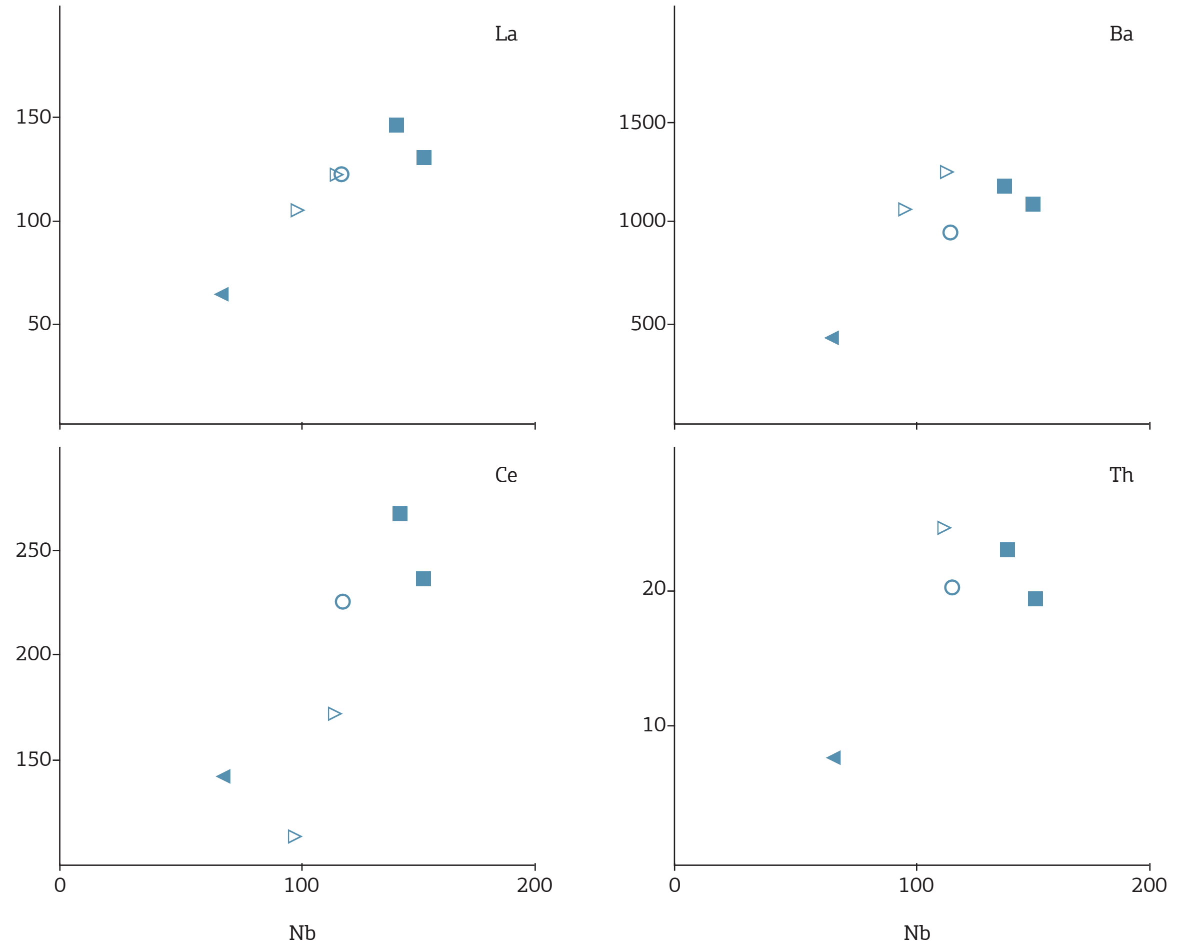
The basanites (*mg#* ranging from 0.59 to 0.61; Tab. 5) present similar or somewhat higher percentages in both sodium and potassium oxides. The best way of separating chemically the nephelinites from basanites (with compositions that overlap in the TAS diagram) is by pointing out the relative enrichment (or depletion) in silica and the possibility of feldspar crystallization, such as proposed by Le Bas (1989; cf. Fig. 11).

Chemical characteristics of basanites and melanephelinites are represented in variations diagrams of Fig. 12, in spidergrams normalized to primitive mantle (Fig. 13) and in chondrite-normalized REE patterns (Fig. 14). All are strongly enriched in K, Rb and Sr with negative Zr and Hf anomalies (compare Fig. 14 with the more complex variations presented in similar diagrams for the differentiated rocks making up the Remédios Formation).



Open squares: trachyandesite; for other symbols, see Fig. 6.

**Figure 8. Chondrite-normalized REE distribution pattern for rocks of the moderately potassic series, Remédios Formation (after Sun & McDonough 1989).**



For symbols, see Fig. 6.

**Figure 7. Trace element abundances versus Nb content for rocks of the Remédios moderately potassic series. Source: Lopes (2002).**

## PETROLOGIC CONSIDERATIONS

The origins of the alkaline suites in both oceanic and continental environments are still largely debated. Some authors present evidence indicating the presence of two parental magmas (basanite and alkali basalt) in oceanic islands, that provide for two different paths of differentiation towards strongly undersaturated and peralkaline types (i.e., phonolites), on the one hand, and into saturated to oversaturated types (e.g., trachytes and eventually rhyolites), on the other (in the case of FN, respectively the Remédios sodic and potassic series; cf. Wilson *et al.* 1995), a hypothesis that is substantiated by geochemical data.

This situation has been found both in oceanic and continental domains (e.g., the Hawaiian islands and the French Central Massif; cf. Wilson *et al.* 1995). By contrast, other

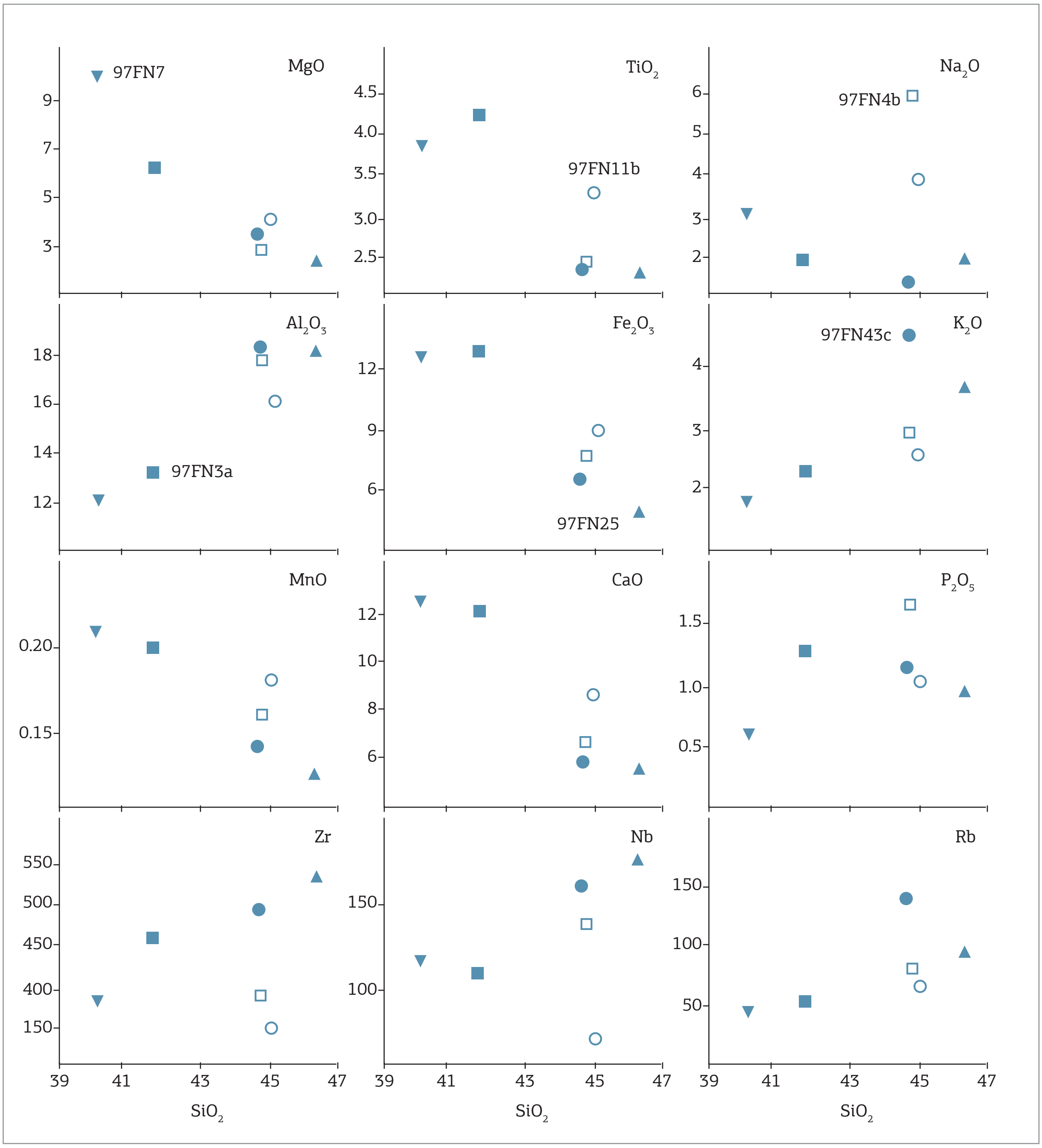


**Figure 9. Harker variation diagrams for lamprophyres of the Remédios Formation (sample numbers as follows: type I: 97FN4b, 43c, 11b; type II: 3a; type III: 7; type IV: 25). Source: Lopes (2002); cf. also Maríngolo (1995).**

authors consider that the two series derive from a single parental magma, later separated into the two different lineages which, during magmatic differentiation, could lead to oversaturated types, a hypothesis that can be applied to basaltic provinces being subjected to different degrees of assimilation of continental crust (e.g., Foland *et al.* 1993). This situation is nicely illustrated by the Cameroon Hot Line (review in Déruelle *et al.* 2007), a unique example on Earth of within-plate alkaline magmatic activity represented by the alignment of many volcanic centers, extending over more than 2,000 km from the Gulf of Guinea, located in the oceanic domain, to the Lake Chad region on the African continent, where anorogenic plutonic ring-complexes were emplaced along the same line. Volcanic activity has been reported in historic times both on the Bioko Island and on Mount Cameroon. Along the line, the differentiated lavas are typically undersaturated types (phonolites) in the oceanic sector, and saturated ones (trachytes) on the continental side. Nephelinites and alkaline lamprophyres (camptonites and monchiquites) are also reported in some volcanic localities.

Geochemical data of the Remédios Formation in FN, which constitutes the oldest volcanic event, suggest that two differentiated suites of rocks were derived from two parental magmas: a basanitic one giving rise to the sodic series (basanite, tephrite, tephriphonolite, phonolite) while alkali basalts generated the moderately potassicseries, which evolved into trachyandesites and trachytes. The two series evolved independently by fractional crystallization. In the sodic series, the sequence of fractionation separated from the parental magmas olivine, clinopyroxene, apatite, some titanite and oxides (especially magnetite), possibly in that order, to be

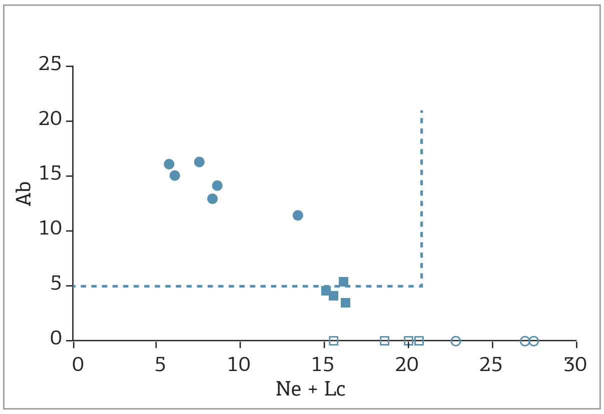


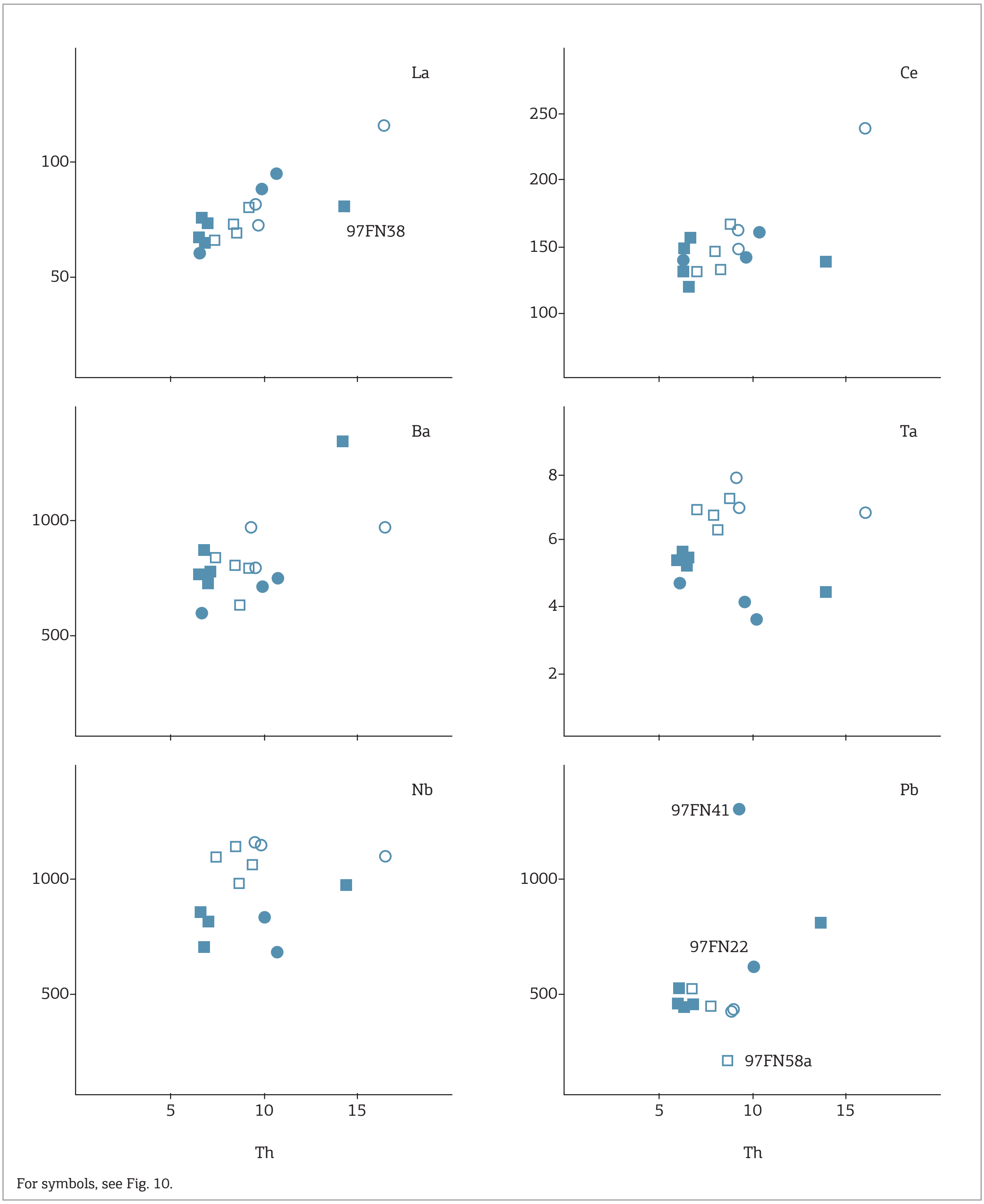
**Figure 11. Diagram showing normative *ab* versus normative *ne* + *lc* for the various Fernando de Noronha basanites (filled circles) and Quixaba melanephelinites (squares, open circles); space defined by broken lines indicates the field occupied by basanites, in contrast to nephelinites (after Le Bas 1989).**

Open circles: melilite melanephelinites; open squares: olivine melanephelinites; filled squares: pyroxene melanephelinites; filled circles: basanites.

**Figure 10. Harker variation diagrams for rocks of the Quixaba Formation. Sources: Lopes (2002); Ulbrich *et al.* (2004); Lopes & Ulbrich (2006).**

joined in late stages of fractionation by alkali feldspar, kaersutite and nepheline. In the potassic series, fractionation included the separation of olivine, clinopyroxene, followed by feldspars, possibly in lesser amounts.

The presence of xenocrysts (olivines, especially clinopyroxenes) as well as inclusions of rock fragments (with banding and cumulus textures) clearly indicates that magma chambers existed in FN, obviously the sites where the fractionation



For symbols, see Fig. 10.

**Figure 12. Trace element abundances *versus* Th contents for the Quixaba melanephelinites and basanites (cf. also Lopes & Ulbrich 2006).**

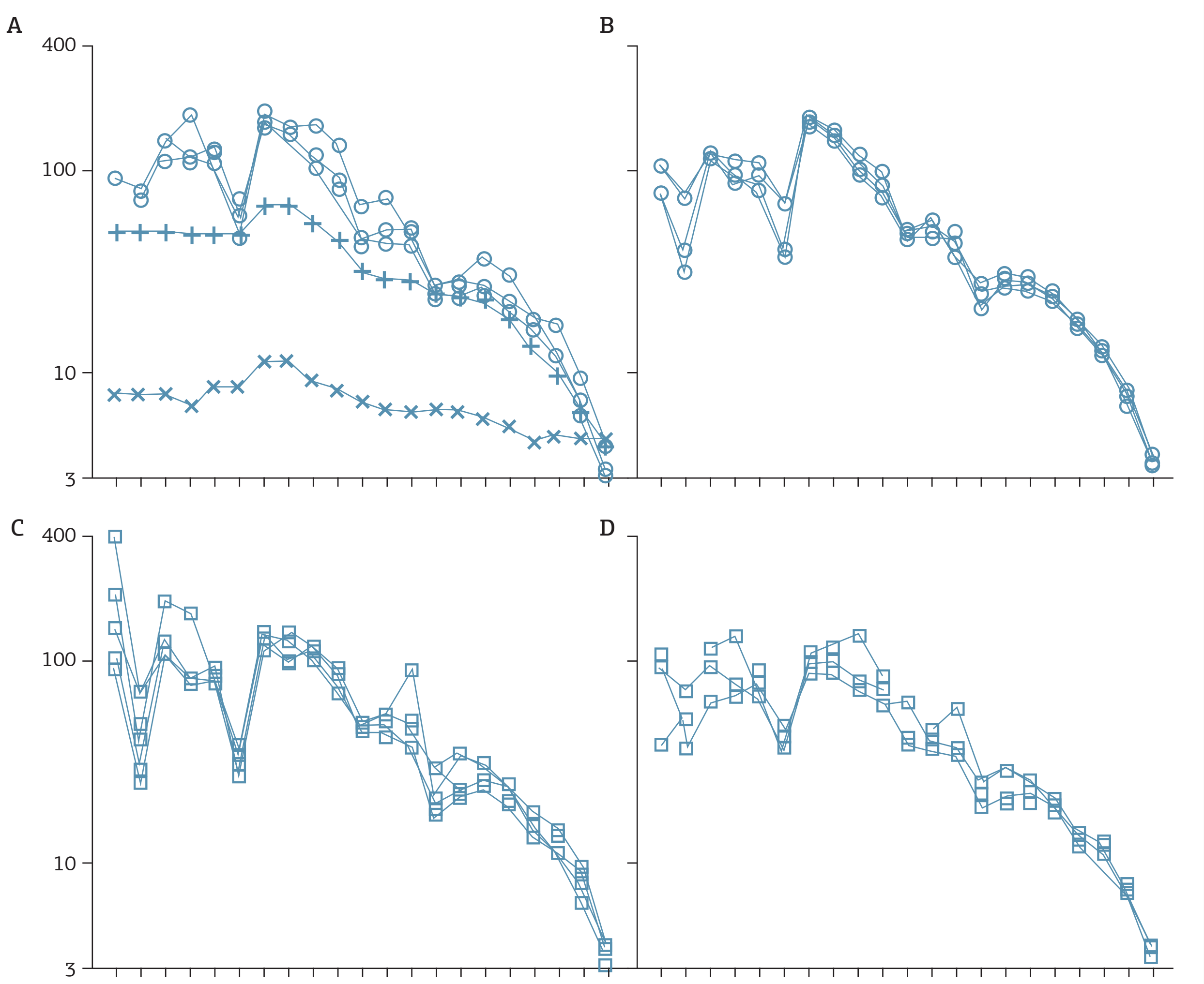
took place. In addition, the intermediate rocks hosting these xenocrysts and rock fragments were possibly formed at least in part by crystal-magma interaction, generating products of hybrid origin. The mechanism can be applied to the origin of the basaltic trachyandesites in the potassic series, representing a product created mostly by mixing of basaltic and trachytic magmas.

Lamprophyres occur as dike rocks without a clear geochemical relationship with the other rock types (cf. section on Geochemistry). They present, though, some shared geochemical characteristics, such as a narrow range in *mg#* and other distinctive features (cf. section on Geochemistry).

The Quixaba rocks, on the other hand, are mainly melanephelinites with some associated basanites, indicating an origin by direct melting of mantle protoliths. A similar origin is indicated for the (chemically correlated) São José basanites.

## SUMMARY AND CONCLUSIONS

1. The pioneering work of Almeida (1955) considered that at least two main volcanic events took place in FN, the older one constituting the Remédios Formation (9.4 to 10.4 Ma) and the latter the Quixaba Formation (1.3 to 4.7 Ma), separated by a clearly marked erosion surface.
2. The Remédios Formation shows mainly pyroclastic rocks as a basal unit, cut by many different magmatic rocks, covered several million years later by the Quixaba flows.
3. A minor event (São José) was also proposed (Almeida 1955) which more recent geochronologic dating (Perlingeiro *et al.* 2013) identified as a unit with ages of 9.0 to 9.4 Ma, contemporaneous with the Remédios volcanics, though different from them geochemically. These São Jose rocks were subjected to a direct eruption mechanism that

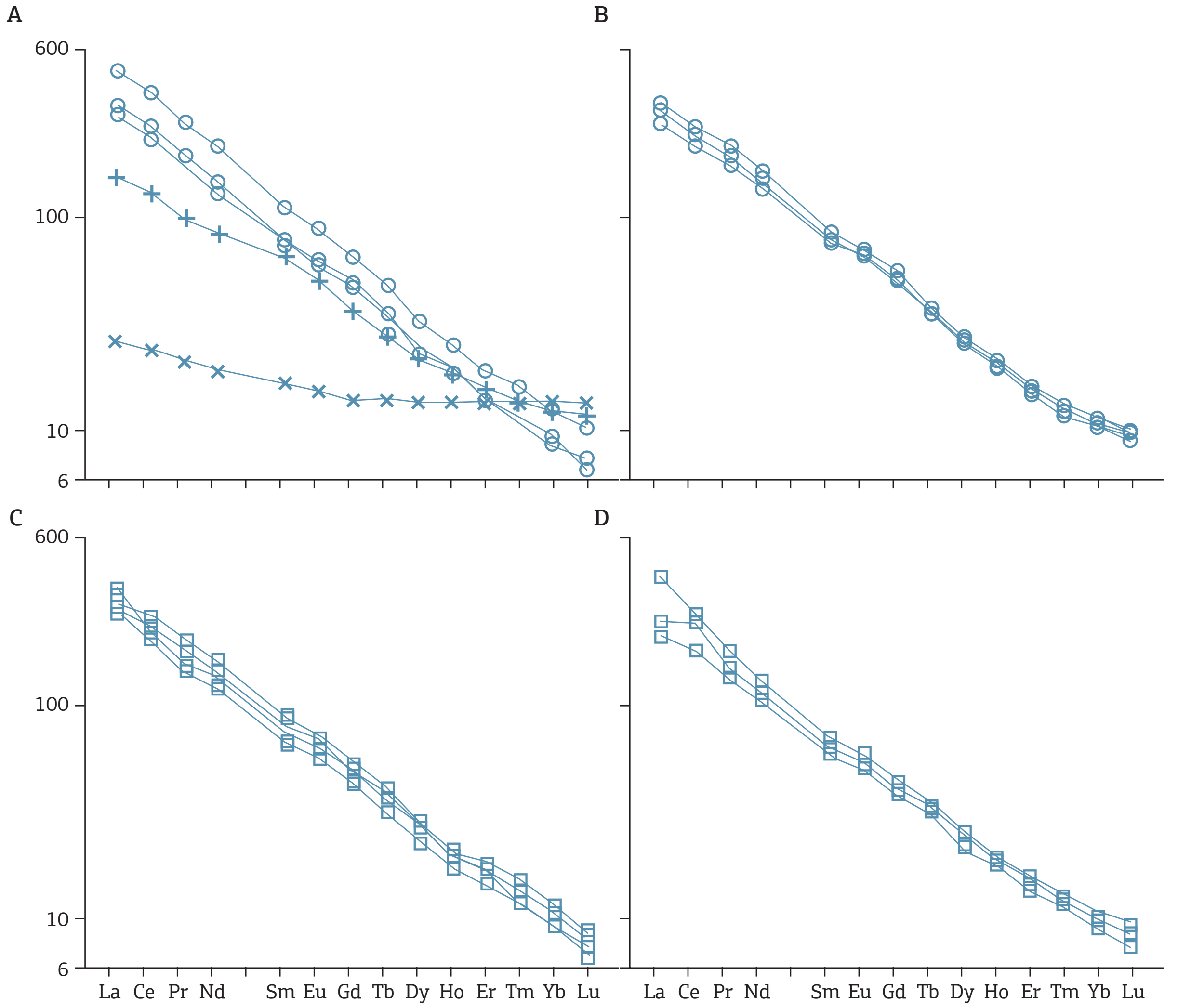


A: melilite; B: olivine melanephelinites; C: pyroxene; D: basanites; crosses:E-MORB; plus sign: oceanic island basalts.

**Figure 13. Spidergrams for the Quixaba rocks, normalized after primitive mantle (after Sun & McDonough 1989; cf. also Lopes & Ulbrich 2006).**

connected the surface with the original melting protolith, as attested by the abundance of mantle xenoliths.

4. The rocks described in the Remédios Formation comprise two series, a moderately potassic one with alkali basalt, basaltic trachyandesite, trachyandesite and trachyte, and a predominant sodic series, with basanite, tephrite, tephriphonolite, essexite and phonolites, as well as several types of alkaline lamprophyres. The nomenclature here used simplifies the previously available descriptions, which identified (not always correctly) dozens of different rock types. The Quixaba rocks are petrographically more uniform, composed mostly of melanephelinites, grouped into the ones with melilite (MEM), with pyroxene (PYM) and with abundance of olivines (OLM), and subordinate basanites.
5. Geochemical data (Harker diagrams for major and minor elements) shows a continuous trend for the sodic Remédios series, indicating an evolutionary control by fractional crystallization of mafic minerals (olivines, pyroxenes, oxides, apatite, titanite) and, at the end, also of some alkali feldspar and nepheline. Normalized REE pattern show linear, strongly LREE-enriched patterns (e.g., in early basanites) changing into a concave pattern with relative depletion of medium REE in evolved phonolites, possibly representing the effect of fractionation of apatite and titanite.
6. The observed trends are repeated in the moderately potassic Remédios series, again indicating that the more evolved magmas (trachytes) were derived from a less evolved alkali basalt by crystal fractionation.



A: melilite melanephelinites; B: olivine melanephelinites; C: pyroxene melanephelinites; D: basanites; crosses: E-MORB; plus sign: oceanic island basalts.

**Figure 14. Chondrite-normalized REE distribution pattern for Quixaba rocks (after Sun & McDonough 1989). Source: Lopes (2002); Lopes & Ulbrich (2006); also Ulbrich *et al.* (2004).**

7. The hypothesis suggesting the existence of two parental magmas generating the two cited Remédios series is here preferred (cf. Lopes 2002). Crystal fractionation in basanite and alkali basalt magmas, reflecting differences possibly inherited from variable degrees of partial melting of an enriched mantle, provide for two separate paths of differentiation towards strongly undersaturated and peralkaline types, on the one hand, and into saturated to slightly oversaturated trachytic types, on the other (respectively, the Remédios sodic and the potassic series; cf. Wilson *et al*. 1995).
8. Magma mixing/mingling may have played an important part in forming some Remédios rocks, as suggested by disequilibrium textures observed in some trachyandesites, among other rocks (cf. also Ubide *et al.* 2014). The presence of enclaves with an igneous phaneritic cumulus texture within the basal pyroclastic Remédios unit clearly indicates the presence of (several?) magma chambers during crystallization, controlling complex interactions between evolving magmas and previously crystallized cumulates.
9. The Quixaba rocks are less evolved types, derived from primitive magmas, which did not differentiate, or did so only slightly (to basanites). In the normalized REE patterns, both Quixaba basanites and the melanephelinites of the three types (MEM, PYM, OLM) show a moderately steep linear REE trend very similar to the one observed in the "mean" OIB trend of the literature.
10. The whole volcanic edifice was built as a result of separate volcanic pulses, triggered by intermittent melting of an enriched mantle source in a "hot spot" in the suboceanic mantle. It is, according to Fodor *et al*. (1998, 2002), a process supposedly triggered by the appearance of a FN asthenospheric plume, beginning earlier on at the mainland and moving into oceanic realms (Pernambuco state). Ages of the Quixaba and Remédios magmatism, however, being separated by an interval of 5 to 8 Ma, time enough to build a distinctive erosion surface between the two formations, are difficult to correlate with the activity of a plume rising in the asthenosphere and impacting a drifting oceanic lithosphere (cf. also Knesel *et al.* 2011, Perlingeiro *et al.* 2013). Similar age clusters of volcanic activity are also observed in other oceanic islands, as in the three chronologically separate volcanic stages defined at Boa Vista, Cape Verde (cf. Dyhr & Holm 2010; Ancochea *et al.* 2012).

## ACKNOWLEDGMENTS

The authors are grateful for the support given for field and laboratory work by the São Paulo Science Foundation Agency FAPESP (to M.N.C.U). R.P.L. thanks CNPq (Brasilia) for a fellowship that enabled to pursue a doctoral program and, before that, the studies that led to a Master´s degree. Leila Marques is thanked for comments on several aspects of Lopes' doctoral thesis. H.Ulbrich contributed with discussions and revisions of the text. Finally, the review by Prof. Daniel Demaiffe provided new insights and suggestions, many of which were incorporated into the final text. Maintenance of the Chemical Laboratory at ULB (Brussels) was financially supported by grants from the Belgian Science Foundation (FNRS) to Daniel Demaiffe.

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