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Petrology of the Volcanic Rocks from Bioko Island ("Cameroon Hot Line")

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Abstract

Bioko island (3008 m a.s.l.), is composed of the alkaline basaltic lavas (basalts and hawaiites) with xenoliths. These lavas have a microlitic texture and consisted of euhedral to subhedral phenocrysts (>1 mm) of olivine (0.83 < Mg# < 0.87) and diopside ± Ti-augite. Plagioclase ($An_{62-67}Ab_{35-32}Or_{3-1}$) phenocrysts are present only in hawaiites. In Harker diagrams, SiO_2, Al_2O_3, Na_2O and K_2O contents of the lavas increase and Fe_2O_3, MgO and CaO decrease with increasing differentiation from basalts to hawaiites. The compatible elements Ni, Cr and V decrease strongly in basalts and remain at low levels in hawaiites. Basaltic lavas from Bioko lavas have low Hf contents (4.2 - 9.2 ppm) and consequently higher Hf/Zr ratios (50 - 90) than those (<50) of similar lavas from other volcanoes of the Cameroon Hot Line. Such high ratios are commonly observed in alkaline basaltic lavas associated with carbonatitic and/or nephelinitic magmatism. The Sr and Nd isotopic compositions point to a slightly depleted mantle source.

Keywords

Petrology, Geochemistry, Lavas, Bioko, Cameroon Hot Line

1. Introduction

Bioko Island (formerly Fernando Poo) is the northernmost island of the oceanic sector of the Cameroon Hot

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Line (CHL, inset **Figure 1**); it lies upon the border of the continental plateau, at about 35 km to the SW of the African continent shore. The island is composed of three adjacent large strato-volcanoes (**Figure 1**): Pico Santa Isabel which culminates at 3008 m a.s.l., Pico Biao characterized by a 6 km diameter caldera, and San Carlos. The published ages of these volcanoes are all younger than 1.33 ± 0.07 Ma [1]-[3]. Paleomagnetic data yield ages younger than 0.7 Ma [1]. It is probable that the Bioko ages are similar to those of Mt Cameroon [4]. Mt Cameroon is younger than nephelinites from Mt Etinde that have been dated between 1.10 and 0.65 Ma [3]. Historical eruptions occurred on Bioko in 1898, 1903 and 1923 [5].

The objectives of this paper are to present new mineralogical and geochemical data for volcanic rocks from Bioko Island, in order to compare it to others volcanic rocks from the Cameroon Hot Line.

2. Petrography and Mineralogy

2.1. The Lavas

All the samples of Bioko Island belong to the alkaline series. Only basaltic lavas (basalts and hawaiites) have been found (**Figure 2**) whilst felsic lavas (trachytes and phonolites) are present in the other islands of CHL

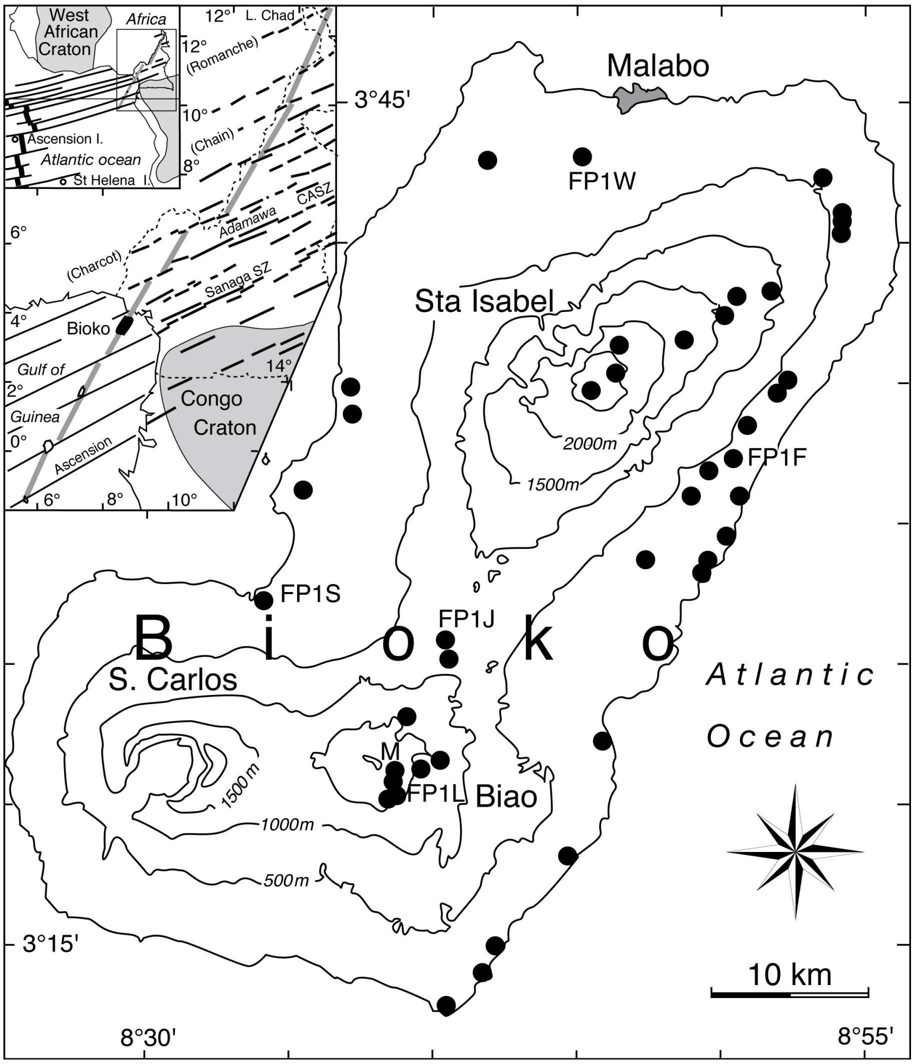

Figure 1. Sample location on Bioko Island. Upper inset: propagation of the N70˚E continental shear zones into the fracture zones of the Atlantic Ocean and the N30˚E Cameroon Hot Line. Lower inset: major volcanoes of the Cameroon Hot Line (black) from Pagalu Island to Lake Chad. Other volcanic areas (Adamawa and Biu plateaus) are shown in grey.

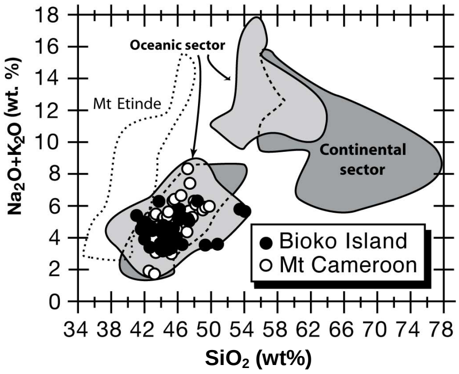

Figure 2. SiO_2 vs (Na_2O + K_2O) diagram for Bioko lavas. All the Bioko lavas plot inside the field of the lavas from the CHL oceanic sector. The data from Mt Cameroon are given for comparison (data after [17]).

(Pagalu, Principe and Sao Tome). A phonolite has been described by [6], but it has been sampled as a loosed block on the sea shore and could originate from Sao-Tome or Principe islands from which it could have been carried as ship ballast: phonolite has never been found anymore on Bioko Island. Basaltic lavas only have also been sampled on the neighbouring continental Mt Cameroon volcano (**Figure 2**). The nomenclature used in this paper is based upon the differentiation index (D.I., [7]) and on peculiar mineralogical distribution. Basalts have D.I. < 35 (42 samples) and hawaiites have 35 < D.I. < 50 (15 samples). Sample FP1K which has hornblende phenocrysts, high SiO_2 content (>53.0 wt%) and normative quartz (>4.0 wt%) has a D.I. of 49.2 (value obtained on a recalculated anhydrous analysis): it is classified as a mugearite.

The lavas have a microlitic texture. Basalts contain euhedral to subhedral phenocrysts (>1 mm) of olivine (0.83 < Mg# < 0.87) and clinopyroxene. Plagioclase ($An_{62-67}Ab_{35-32}Or_{3-1}$) is also present in hawaiites. The matrix contains microlites of clinopyroxene, plagioclase and magnetite and microphenocrysts of olivine. Diopside and Ti-augite occur respectively as euhedral to subhedral microphenocrysts (<2.5 mm) and as phenocrysts of variable size (2.5 to 6.0 mm). One lava sample (B17) of basaltic affinity contains skeletal hypersthene phenocrysts, embayed olivine phenocrysts and euhedral cordierite microphenocryts with opacified core. Cordierite has already been described in hypersthene-bearing lava from St. Helena Island [8].

Crystal size distribution (CSD) measurements have been performed on clinopyroxene crystals from 12 basaltic lavas using CSD Corrections software of [9]. The data were plotted following general convention [10] as linear crystal size vs population density—ln(n) (mm^{-4}) vs l (mm) (**Figure 3**). Most of the CSDs appear curved with nearly straight distribution for small (<2 mm) grains and curved patterns for larger (>2 mm) crystals (**Figure 4**). The small grains are distributed along a steep slope with intercepts between 8.5 and 12.0 mm^{-4} while the larger grains plot along a more gentle slope with lower intercepts (4 to 6 mm^{-4}). Following [11], [9] and [12], these curved CSDs can be interpreted as mixing of two populations of crystals with contrasted crystallization histories. The population of large crystals could represent clinopyroxene that has crystallized under different physical condition. To strengthen this hypothesis, the crystallization pressure of the clinopyroxenes was estimated using the [10] structural barometer of [13]. This barometer is suitable for anhydrous alkaline melts as the Bioko basaltic melt. The small phenocrysts of Ti-augite composition were equilibrated at low P (0 - 2 kbar) while the few larger ones (of diopside composition) crystallized at significantly higher pressure (~6 kbar). In few samples, the clinopyroxene phenocrysts are zoned: the diopside cores crystallized at high pressure and the Ti-augite rims at low pressure.

CSD pattern and P estimate suggest a polybaric crystallization of Bioko basaltic magma. Similar multi-chamber magmatic evolution is common in alkaline [14] and peralkaline [15] volcanic rocks.

2.2. Xenoliths

Some basaltic flows and tephra deposits contain abundant ultramafic and mafic xenoliths. Xenoliths of gabbro are composed of clinopyroxene and cloudy plagioclase (due to the presence of numerous scattered small green

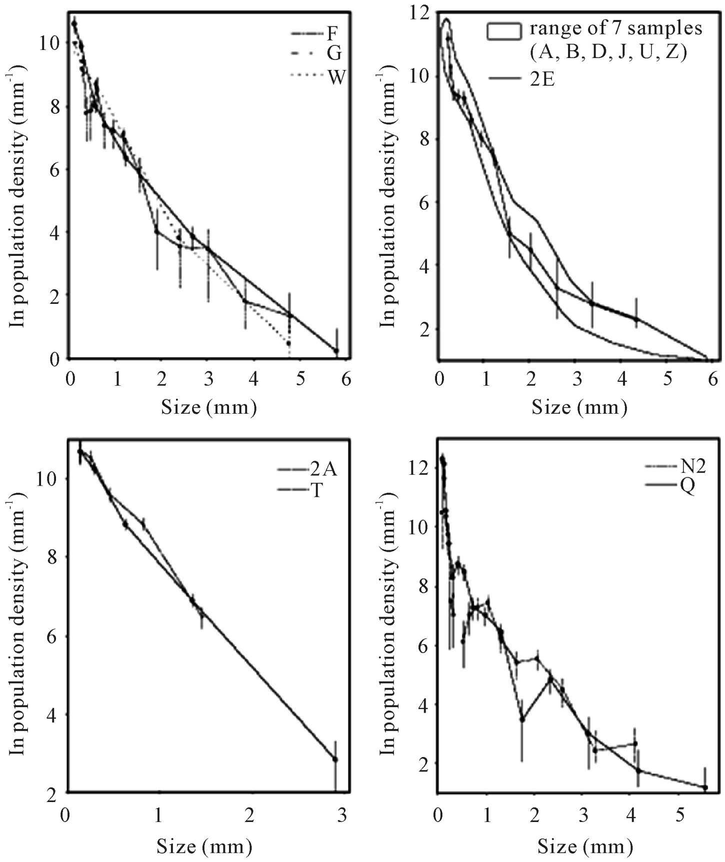

Figure 3. Different types of crystal size distribution (CSD) patterns observed for the clinopyroxene phenocrysts of selected Bioko basaltic lavas.

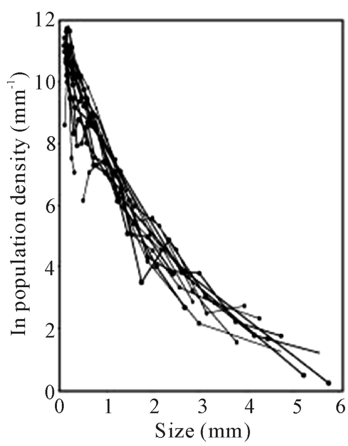

Figure 4. Crystal size distribution of clinopyroxenes from the Bioko lavas show typical curved patterns.

spinel crystals) sometimes with olivine. The variety of ultramafic xenoliths is quite large. In a basalt lava flow at the NE flank of Santa Isabel volcano, harzburgites, lherzolites and dunites occur together scattered in a restricted area of few m^2. In fact, xenoliths are mainly harzburgites with a protogranular texture and lherzolites; dunites are rare. Olivine is Mg-rich (Fo ≈ 90.3 ± 0.5) as well as clinopyroxene and orthopyroxene (Mg#: 0.92 - 0.95 and 0.91 - 0.92, respectively). Clinopyroxene is also Cr-rich (0.13 < Cr a.p.f.u. < 0.31) when compared to other crystals in xenoliths from the CHL (Cr a.p.f.u. < 0.18) ([16] and references therein, [17]). Harzburgites contain holly-leaf and vermicular spinel. This spinel has a composition similar to that of crystals in xenoliths from the Kapsiki plateau but is quite disctinct from xenoliths in other basalts all along the CHL. Rare phlogopite and very scarce plagioclase crystals are present in veinlets between olivine and orthopyroxene grains. Amphibole occurs in veinlets in the dunites. High fO_2 (above the FMQ buffer) characterize dunites. Similar xenoliths have also been found at Mt Cameroon, Mt Bambouto, Mt Oku and Nyos (see [16]) in the continental sector of the CHL. Equilibrium temperatures for pyroxene pairs calculated after [9] are between 889˚C and 1033˚C (mean 943; 2 sigmas: 38˚C).

3. Geochemistry

In Harker diagrams (**Figure 5**), the samples are somewhat scattered due to the limited range of D.I. variations (from 12 to 49). Samples from Santa Isabel and Pico Biao volcanoes roughly plot along the same broad evolution trends (one sample from San Carlos only has been analysed). Nevertheless, increase in SiO_2, Al_2O_3, Na_2O and K_2O and decrease in Fe_2O_3, MgO and CaO are note worthy with increasing differentiation. TiO_2 and P_2O_5 contents do not vary significantly.

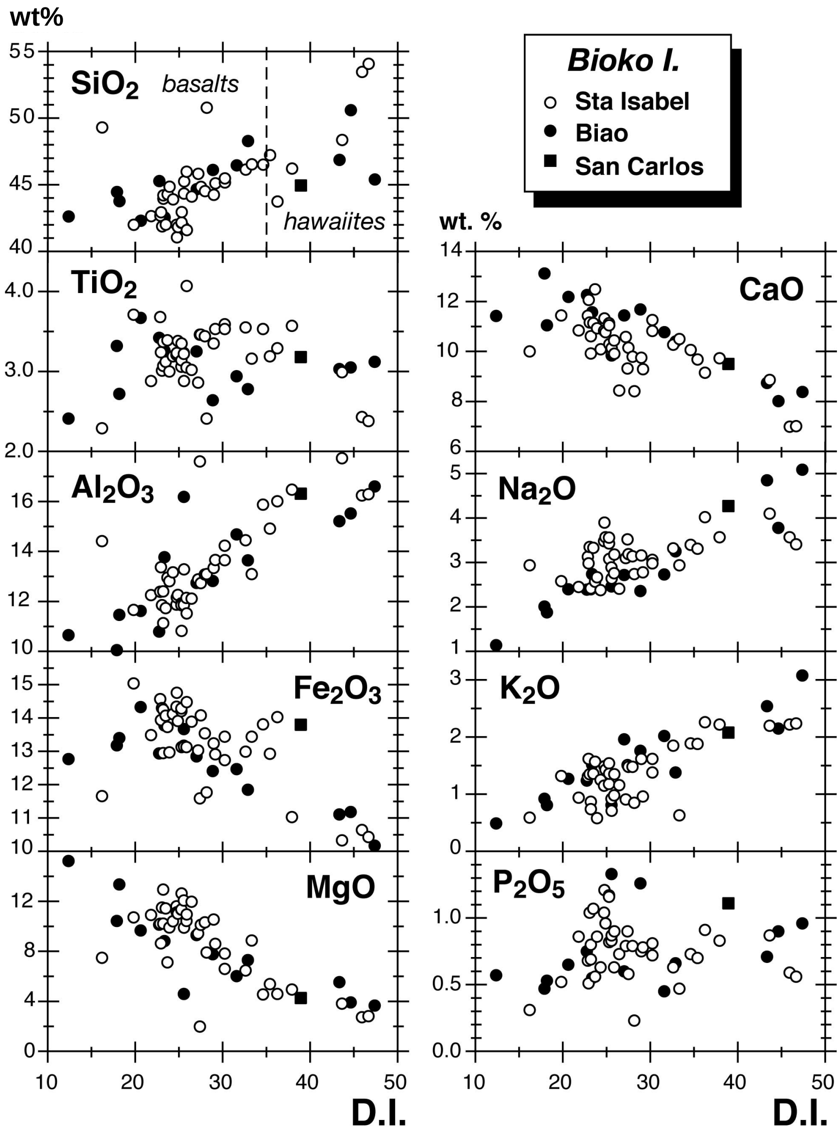

Figure 5. Major element (in wt%) versus I.D. (used as a geochemical differentiation index) diagrams for Bioko Island.

The trace element contents of Bioko lavas (**Figure 6**) are plotted against Th content (incompatible element used as geochemical differentiation index) and compared to data from Mt Cameroon ([18] and unpublished). The compatible elements Ni, Cr and V decrease strongly in basalts and remain at low levels in hawaiites. The incompatible LIL elements (Rb, Sr, Ba, Zr, and Ta) and the REEs increase with increasing Th contents. The limited Bioko differentiation series as a whole and the Mt Cameroon data are very similar except for Ba and Zr that are higher in Bioko lavas. Zr/Hf ratios are higher at Bioko (50 - 90) than at Mt Cameroon (18, unpubl. data).

In primitive mantle normalized multi-element diagram (**Figure 7**), the patterns of Bioko lavas have the classical shape of alkali basaltic lavas; they have high LIL incompatible element abundances (50 to 100× chondrites) and lower HFSE and HREE abundances (<20× chondrites). They also show pronounced negative anomaly for

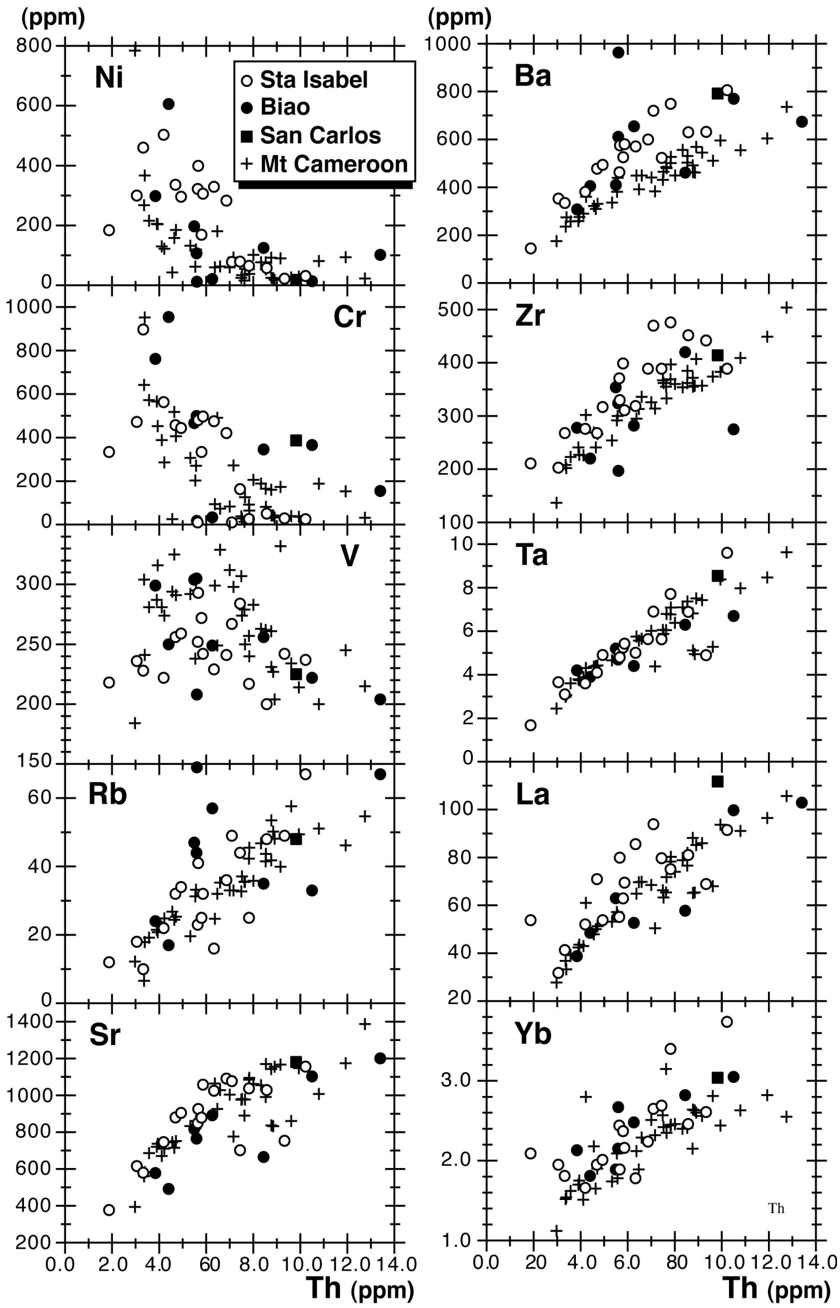

Figure 6. Trace element variations (in ppm) versus Th (used as a geochemical differentiation index) diagrams for Bioko lavas compared to Mt Cameroon.

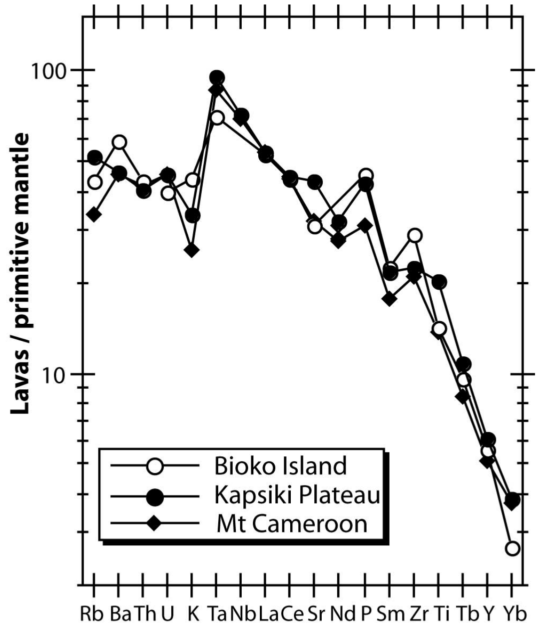

Figure 7. Spider diagram for representative lavas from Bioko compared with basalts from Mt Cameroon and St Kapsiki Plateau ([16] and ref. therein). Normalisation values from [22].

K, a less important one for Hf and positive anomalies for Ba, U, Ta, P and Zr. The LaN/CeN ratios (1.4 - 1.6) are roughly similar for all the lavas from the three Bioko volcanoes but are significantly higher than those from the neighbouring continental volcanoes of Mt Etinde (1.25 - 1.27, [19]). The range of measured $^{87}Sr/^{86}Sr$ isotope compositions (0.70319 - 0.70343; n = 4) by [20] and our unpublished data (0.70321 - 0.70352; n = 4) are largely overlapping and in the range of data for the basaltic lavas of the CHL (0.70299 - 0.70343, compilation of [17]). The Nd isotopic compositions (ε_{Nd}: + 2.6 to + 4.0; same ref as Sr) point to a slightly depleted upper mantle source.

4. Discussion

4.1. Basaltic Lavas and Scattering of Data

The three volcanoes of Bioko Island only emitted basaltic lavas (basalts and hawaiites); this is similarly to what is observed on the nearby Mt Cameroon. These volcanoes are the only ones of the CHL that have only basaltic lavas. Moreover, apart the phreatic eruptions of Monoun and Nyos lakes, Bioko and Mt Cameroon are the only volcanoes that had eruptions during the last century. Mt Etinde which is located at the very shore of the continent between Bioko and Mt Cameroon only consists of nephelinitic lavas which are completely unknown on the other volcanoes.

4.2. Fractional Crystallization Modelling

Evolution by crystal fractionation has been modeled for the short differentiation series of Bioko. Despite the restricted compositional range observed for the data set, the mineralogical (progressive evolution of mineral compositions with increasing differentiation) and geochemical (regular and progressive major and trace element evolution) data suggest that fractional crystallization had a major role in the differentiation of the lava series. Mass balance modelling for major elements gave results that are consistent with the distribution of mineralogical phases present as phenocrysts in the lavas. For example, the evolution from basalt (D) to hawaiite (W) can be modeled by fractional crystallization of ol + cpx + pl + ox in the proportions 6.9 + 0.7 + 0.3 + 0.1 ($\Sigma r^2 < 0.6$) and to hawaiite FP1F by fractionation of ol + cpx + ox in the proportions 5.3 + 14.2 + 2.0 ($\Sigma r^2 < 0.5$). The limited number of mineral phases involved in the process lead to quite large Σr^2.

Basaltic lavas from Bioko lavas have low Hf contents (4.2 - 9.2 ppm) and consequently higher Zr/Hf ratios (50 - 90) than those (<50) of similar lavas from other volcanoes of the CHL. Such high ratios are commonly observed in alkaline basaltic lavas associated with carbonatitic and/or nephelinitic magmatism. It is interesting to remind that Bioko is situated quite near the nephelinitic Mt Etinde volcano.

4.3. Metasomatism

The occurrence of amphibole (pargasite) in ultramafic xenoliths of Bioko and of many other volcanoes of the CHL (see review in [17]) suggests that the lithospheric mantle beneath the CHL has been metasomatized. Metasomatized peridotites are likely to be representative of enriched lithosphere, the commonly accepted metasomatic agent being partial melts that form a network of thin veins lacing mantle peridotite beneath zones of recent volcanism and that induce the crystallization of K-rich amphibole [21]. The low Al_2O_3 (<4 wt%) and high CaO (21 - 24 wt%) contents of clinopyroxenes and also the relatively high fO_2 (above the FMQ buffer) in dunites are suggestive of a metasomatic influence by carbonatitic liquids.

5. Conclusions

Bioko Island (formerly Fernando Poo) belongs to the "Cameroon Hot Line" (CHL), a major geological structure of Central Africa. It lies on the continental plateau, close (~35 km) to the continent shore and consists of three large strato-volcanoes (Pico Santa Isabel culminating at more than 3000 m).

The differentiation series is incomplete: only mafic lavas—basalts and hawaiites—have been found as on the huge Mount Cameroon volcano. Ultramafic and mafic xenoliths are locally abundant; they contain pargasite and rare phlogopite pointing to a metasomatic mantle beneath CHL. A polybaric differentiation process is inferred from the curved CSD patterns of clinopyroxene phenocrysts and from pressure estimates: the large diopside phenocrysts were equilibrated at ~6 kbar while the small Ti-augite crystals equilibrated at low (<2 kbar) pressure.

Variations of major and trace element content can be related to fractional crystallization implying olivine, clinopyroxene, plagioclase and oxides. The Zr/Hf ratios (>50) are significantly higher than those of most basalts from CHL (<50); these high values could be related to the presence of the nearby Mt Etinde nephelinites. The Sr and Nd isotopic compositions point to a slightly depleted mantle source.

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