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Geomaterials (Petrology)

Petrology and geochemistry of monogenetic volcanoes of the Barombi Koto volcanic field (Kumba graben, Cameroon volcanic line): Implications for mantle source characteristics

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Abstract

The Barombi Koto volcanic field (BKVF) is located northeast of Mount Cameroon and constitutes a portion of the Kumba graben, one of the monogenetic volcanic fields of the Cameroon volcanic line (CVL). Tortonian fissural eruptions yielded picritic flows reworked by subsequent explosive eruptions, which generated two maars and ten cinder cones. The lavas comprise picrobasalts, basanites, alkali basalts, and hawaiites. Some clinopyroxene crystals exhibit a Cr-reverse zoning (0.15 to 0.58 wt%) that we attribute to a subsequent magma Cr-enrichment. Lavas are alkaline and range from primitive to moderately evolved. They are similar to volcanics of the other monogenetic volcanic fields of the CVL (e.g., Tombel, Nyos), but contain less incompatible elements than polygenetic volcanics. The absence of correlations on bivariate plots of most of the incompatible elements, the wide variability of Zr/Nb and Ba/La ratios (4.41–6.04 and 6.87–11.14, respectively) and the values of Dy/Yb, La/Yb, Nb/Y and Zr/Y ratios suggest that the different volcanic centres correspond to independent plumbing systems, resulting from low degrees of melting (2.12–6.85 wt%) of a heterogeneous asthenospheric mantle source characterized by a HIMU prevailing component. ***To cite this article: J. Tamen et al., C. R. Geoscience 339 (2007).***

Résumé

Pétrologie et géochimie des volcans monogéniques de Barombi Koto (graben de Lumba, ligne volcanique du Cameroun) : implication pour les caractéristiques du manteau source. Située au nord-est du mont Cameroun, la région de Barombi Koto constitue une portion du graben de Kumba, un des champs de volcans monogéniques de la ligne volcanique du Cameroun (LVC). Des éruptions fissurales tortoniennes de picrobasaltes ont été suppléées par des éruptions phréatomagmatiques (deux maars) et stromboliennes (dix cônes). Les laves comprennent des picrobasaltes, des basanites, des basaltes alcalins et des hawaiites. Certains cristaux de clinopyroxène montrent une zonation inverse en chrome (0,15 à 0,58 Cr_2O_3 en pourcentage

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massique), que nous attribuons à un enrichissement en Cr postérieur à la genèse des magmas hôtes. Les laves sont primaires, sous-saturées (2,07 à 9,68 % de néphéline normative), alcalines sodiques ($1{,}27 < Na_2O/K_2O < 2{,}91$) et enrichies en terres rares légères par rapport aux terres rares lourdes. Elles sont semblables aux laves basaltiques des autres volcans monogéniques de la LVC (par exemple, Tombel, Nyos). L'absence de corrélation entre de nombreux éléments incompatibles et les indices de différenciation, la grande variabilité des rapports Zr/Nb et Ba/La (4,41–6,04 et 6,87–11,14, respectivement) et les rapports Dy/Yb, La/Yb, Nb/Y et Zr/Y permettent de suggérer que chaque volcan est indépendant et proviendrait d'un faible taux de fusion d'un manteau asthénosphérique hétérogène fortement influencé par le pôle HIMU. ***Pour citer cet article : J. Tamen et al., C. R. Geoscience 339 (2007).***

Keywords: Cameroon volcanic line; Kumba graben; Monogenetic volcanoes; Heterogeneous mantle

Mots clés : Ligne volcanique du Cameroun ; Graben de Kumba ; Volcans monogéniques ; Manteau hétérogène

1. Introduction

The Cameroon Volcanic Line (CVL) is a peculiar intraplate tectono-magmatic corridor trending N30°E and stretching over 1600 km, from the Annobon Island, in the Gulf of Guinea, to Lake Chad, in the continental interior of West Africa. The continental sector is a succession of horsts and grabens. The horsts are either large polygenetic volcanoes or volcanic plateaux, typified by complete magmas series; meanwhile, the grabens are monogenetic volcanic fields displaying basic magmas suites (basanites, basalts, and accessory hawaiites). Numerous studies of the CVL aimed at determining the characteristics of the melting mantle source (e.g., [10,11,14,15,24,39], the differentiation processes [7,18,39,40], the dynamisms of melt migration [39], the relation between monogenetic and polygenetic volcanoes [44], but so far, no consensus has been achieved. Two recent reviews of the Cameroon line have proposed rather two conflicting hypotheses on the origin of this line. One suggests a complex interaction between, on the one hand, at least two mantle plume acting in succession (including the St Helena mantle plume) and, on the other hand, lithospheric fractures that induce oblique alignments of magmatic complexes [34], whereas Déruelle et al. [8] propose a 'hot line' hypothesis in a sublithospheric mantle involving depleted mantle (DM) and focal zone (FOZO) components. Most of these studies were focussed on polygenetic volcanoes, despite the large number of monogenetic volcanoes and the apparent difference between monogenetic and polygenetic volcanic rocks. In the current study, (*i*) we present the volcanological, petrological and geochemical data on volcanoes of the Barombi Koto area, (*ii*) we evaluate the relations between the different volcanic centres, (*iii*) we assess the melting processes and the mantle source characteristics, (*iv*) we compare the studied rocks to volcanics from a few monogenetic and polygenetic volcanoes, and (*v*) we compare the source characteristics here with those of the neighbouring Mt Cameroon and of a few transitional tholeiitic basalts of the CVL.

2. Field description

The Kumba graben (also named Tombel graben) is bounded by three CVL horsts: (*i*) Mount Cameroon in the Southwest, made up of basanitic, basaltic and hawaiitic lava flows, and cinder cones [6]; (*ii*) the Rumpi hills in the West, corresponding to two volcanic rock suites, one ranging from basalts to trachytes and phonolites, and the other from alkaline basalts to peralkaline rhyolites [38], and (*iii*) the Manengouba mountains in the North, composed by alkaline rock suites differentiated from basalts to trachytes and rhyolites [18,48]. The Kumba graben is made up of Precambrian metamorphic and plutonic bedrocks [9,36] overlapped by Cretaceous–Cainozoic coastal plain sandstones [16,23,36]. The metamorphic basement is marked by two major tectonic events: (*i*) a NE–SW mylonitic foliation reminiscent of ductile deformation along a sinistral strike-slip fault, and (*ii*) a younger brittle event characterized by three sets of faults (N140E–N150E, N120–N130, and N90E–N110E) that truncate the previous ductile foliation [36]. This brittle event may be related to the early stages of uplift and volcanism. However, two major volcanic episodes took place in the graben: (*i*) a Tortonian flow-type eruption reworked by (*ii*) mildly violent explosive eruptions in the Pleistocene (0.6–0.05 Ma) [24]. The first episode was favoured by an extensional regime and resulted in widespread lavas that covered nearly the whole graben. The explosive eruptions of the second episode generated four maars and about 115 cinder cones trending N30°E, parallel to the elongation axis of the graben. These features suggest that the lineaments in the

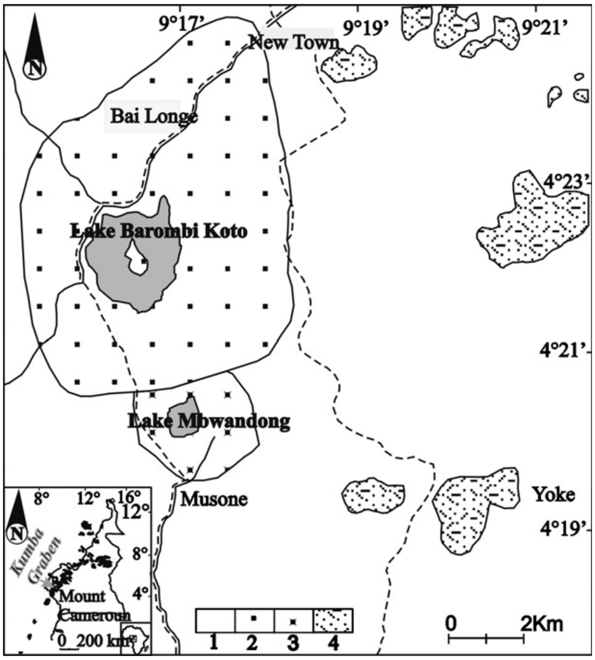

Fig. 1. Geologic map of BKVF. **1**: Tortonian basalts; Pleistocene lavas of Barombi Koto (**2**), Bwandong (**3**) and cinder cones (**4**). Inserted in the lower left corner is the map showing the location of the Kumba graben on the CVL: featured are volcanic centres and islands.

Fig. 1. Carte géologique de BKVF. **1** : Basaltes tortoniens ; laves pléistocènes de Barombi Koto (**2**), de Bwandong (**3**) et des cônes stromboliens (**4**). En encart, localisation du graben de Kumba sur la LVC : îles et massifs volcaniques en noir.

basement rocks worked as pathways for magma ascent [36]. At the southwestern end of the Kumba graben, the Barombi Koto area (Fig. 1) comprises two maar volcanoes (Barombi Koto and Mbwandong) and ten cinder cones that crosscut and overlie the old extensive lava flow [47].

2.1. Barombi Koto maar

The Crater Lake Barombi Koto (Fig. 1) is a lobed sub-circular maar approximately 1400 m in diameter, about 226 ha in surface area and only 6.2 m in depth [47]. The water surface is at 100 m above sea level. Two islets occupy the centre of the lake: the larger one is elliptical (500 × 200 m) and rises up 30 m above the water level, meanwhile the smaller islet is circular (ca. 70 m in diameter) and stands at the water level. The lake is rimmed by a 50-m cliff consisting of two layered units gently sloping (5–10°). The lower unit (35 m thick) is characterised by unbedded coarse-grained blocks, bombs (bread-crust, cauliflower) and lapilli. These characteristics are typical of Strombolian eruptions. Two short basaltic flows, one to the south and the other to the east (30 m wide and 3.5 m thick) are embedded in the tephra deposits. The tephra deposits also enclose xenolithic blocks up to 1 m across of old basalts and sandstone. The upper unit (15 m thick) is made up of well-sorted and layered mildly coarse blocks, lapilli, and cinerites, typical of phreatomagmatic eruptions. The layers are thin and homogeneous and decrease in thickness from 60 cm at the bottom to 2 cm at the top. This unit is thicker on the elliptical islet, where it overlaps reworked coarse tephra deposits, sandstones, and old basalt xenoliths.

The association of hyalotuffs with lava flows suggests that this volcano was constructed through three successive sequences of eruption: a phreatomagmatic phase (Fig. 2A), a Strombolian phase (Fig. 2B) and a latter phreatomagmatic phase (Fig. 2C). Although the term monogenetic volcano is questionable for a volcano resulting from several eruption styles and stages, we rely on the fact that the absence of oxidized or weathered surfaces within the layers can only be the consequence of short time spacing between eruptive phases.

2.2. Mbwandong maar

At 3 km southeast of the Barombi Koto maar, the elliptical Mbwandong maar volcano covers ca. 25 ha. The water surface stands at 110 m above sea level (nearly at the same level as Barombi Koto, 100 m) and the depth is less than 3 m. A small crescent of tuffs rims the lake and exhibits a fining-up sequence, comparable with the one described on the large islet of Barombi Koto. A few sandstone and old basaltic xenoliths occur in the crescent.

2.3. Volcanic cones

Ten volcanic cinder and composite cones built up through a Strombolian-type eruption are found in the BKVF. They culminate at 200–283 m and their basal sections range from 900 to 3000 m. The rocks are similar to those of the Barombi Koto and Mbwandong maars. They are black to reddish-brown basaltic scoria embodying sandstones and old basaltic xenoliths.

3. Petrography

Lavas of the BKVF are mainly microlitic or microlitic porphyritic. They contain euhedral olivine, clinopyroxene, oxides, and plagioclase. A few olivine and clinopyroxene mantle xenocrysts exhibit embayments.

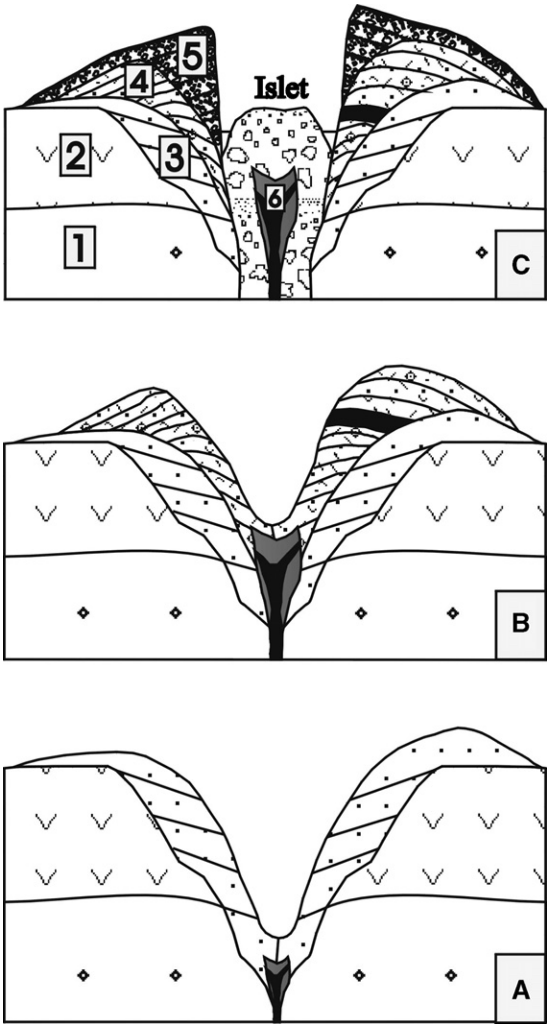

Fig. 2. Evolution of the volcanic dynamism. (**A**) Initial phreatomagmatic stage, (**B**) Strombolian stage, (**C**) late phreatomagmatic stage. **1**: sedimentary basement rocks; **2**: Tortonian basalts; **3**, **4** and **5**: Pleistocene lavas of first, second and last stages, respectively; **6**: crater plug.

Fig. 2. Évolution du dynamisme volcanique. (**A**) Phase initiale phréatomagmatique, (**B**) phase strombolienne, (**C**) phase tardive phréatomagmatique. **1** : substratum sédimentaire ; **2** : basaltes tortoniens ; **3**, **4** et **5** : roches volcaniques pléistocènes des première, deuxième et troisième phases, respectivement ; **6** : culot de la cheminée.

Microcrystalline groundmass made up of plagioclase and oxides contains glass up to 8 vol.%. In some samples, centimetric crystalline clusters are made up of round olivine crystals at the core and a rim of prismatic clinopyroxene crystals. Modal clinopyroxene ranges from 2 to 10% in basalts and up to 35% in ankaramites (porphyritic basalt with modal Cpx > olivine). Most of the phenocrysts display compositional zoning, especially a green core. Oxides also appear as inclusions in olivine and clinopyroxene. Calcite is a post-magmatic phase, grown-up in vugs of vesicular rocks or as occasional pseudomorphs of pyroxene.

4. Mineralogy

Mineral compositions were determined on four samples with an automated spectrometer Cameca Sx50 electron microprobe operating at 15 kV, 20 nA, and 20 s counting time for each element, at the Institute of Mineralogy and Petrography (IMP) of the Swiss Federal Polytechnic High School (ETH Zurich). Natural and synthetic oxides and silicates were used as standards, and the raw data corrected on line for drift, dead time, and background, applying a Zaf-type correction procedure [42]. Mineralogical data are available on request to the authors.

Olivine compositions vary widely from picrobasalts ($Fo_{86–82}$) through basalts ($Fo_{71–62}$) to hawaiites ($Fo_{77–58}$). Microphenocrysts from all samples are systematically less forsteritic ($Fo_{66–76}$ in picrobasalts and $Fo_{62–66}$ in hawaiites). NiO decreases from 0.35 wt% in picrobasalts to 0.03 wt% in hawaiites. CaO ranges between 0.31 and 0.57 wt%, but no correlation exists between the content variation and the rock type. Olivine has similar compositions to olivine of the lavas from the eastern part of the Kumba graben [37] and to volcanics of the other grabens of the CVL (Nyos, [33] Noun, [50], etc.).

Clinopyroxene crystals display a narrow range of composition, from diopside ($Wo_{45}En_{46}Fs_{9}$) to augite ($Wo_{41.9–44.3}En_{39.3–44.3}Fs_{16.1–12.0}$). They are rich in Al_2O_3 (up to 9 wt%) and TiO_2 (1.09 to 4.3 wt%). Al/Ti ratios vary from 3.03 to 4.18. Green core crystals contain up to 0.58 wt% Cr_2O_3, and they are rich in MgO compared with Cr-poor species. In a few peculiar cases, Cr_2O_3 contents increase from the core to the rim of the crystals (0.15 wt% to 0.58 wt%). The geobarometer of Nimis and Ulmer [35], based on crystal-structure modelling, yields a low pressure of crystallization (0–2.96 kbar) and intracrystalline temperatures ranging from 1243 to 1365 °C; old basalts nevertheless display higher pressures (4.5–7.6 kbar), but lower intracrystalline temperatures (1189–1268 °C).

Plagioclase spans labradorite to andesine compositions ($An_{68–38.4}Ab_{30.5–54.3}Or_{1.5–7.3}$).

Oxides are titanomagnetite ($Ti_{2.45–3.1}Al_{0.31–0.7}Cr_{0.005–0.015}Fe^{3+}_{1.38–2.65}Fe^{2+}_{5.54–6.54}Mn_{0.09–0.12}Mg_{0.4–0.89}O_{16}$) and spinels, namely Mg–Al chromite ($Ti_{0.34}Al_{2.48}Cr_{3.25}Fe^{3+}_{1.62}Fe^{2+}_{2.62}Mn_{0.01}Mg_{1.66}O_{16}$) with $Cr^{\#} = 55$, [$Cr^{\#} = 100\ Cr/(Cr + Al)$]. Spinels are mantle xenocrysts (present exclusively in picrobasalts) or magmatic phases coexisting with titanomagnetite in many rocks. Along the Cameroon Volcanic Line, the occurrence of magmatic Cr-spinel is not exclusive of the Barombi Koto area, for it has also been reported in some lavas from Mount Cameroon [43] or Tchabal Nganha, Ngaoundéré Plateau [40].

Sparse Cr-reverse zoning of clinopyroxene deserves a petrogenetic explanation. This Cr-reverse zoning seems to be related to a Cr-enrichment, subsequent to the magma genesis, and may result either from (1) mantle-melt interaction [13], (2) mantle disrupted crystals [20] or (3) magma mixing [41]. The latter origins are precluded, because no visual sign of mixing is observed in the studied rocks. Thus, the melting of mantle spinel xenocrysts accounts for the present data. The melting point of pure spinel $MgAl_2O_4$ at 2135 °C [5] requires excessive heat, but the spinel encountered here is iron rich. Moreover, alkaline magmas contain volatiles, which will help lower the temperature of melting. The reaction of an alkaline magma with an upper mantle spinel lherzolite is thought to be followed by the preferential resorption of orthopyroxene and spinel, so that if these minerals are adequately high in Cr, their resorption enriches the melt in Si, Mg, and Cr [13], as observed in Alpine-type chromitite [2]. In the studied rocks, magmatic Cr-spinel, which seems to be directly linked to the Cr bulk contents of the magma [27], coexists with Cr-spinel xenocrysts. The resorption of these xenocrysts [13] could locally enrich the melt in Cr, which is highly compatible with the crystallizing pyroxene lattice.

5. Geochemistry

Nine fresh samples were selected for chemical analyses. After grinding in an agate mill, they were conditioned in di-lithium tetraborate ($Li_2B_4O_7$) glass disks and in polyvinyl alcohol pressed powder pellets. The loss on ignition (LOI) was determined by weight difference after heating to 1050 °C for 90 min. Major and trace elements were determined by X-ray fluorescence (XRF) with an automated sequential spectrometer (Philips PW 1404) and REE by inductively coupled plasma mass spectrometry (ICP-MS) at EMPA Dübendorf (Switzerland). USGS rock samples were used for calibration. Chemical data are available on request to the authors.

Fig. 3 shows that the BKVF volcanics are picrobasalts, basanites, basalts, and hawaiites. They are undersaturated (2.07 to 9.68 wt% normative nepheline) and alkaline sodic (Na_2O/K_2O = 1.3–2.9). They exhibit high to moderate contents of MgO (14.4–

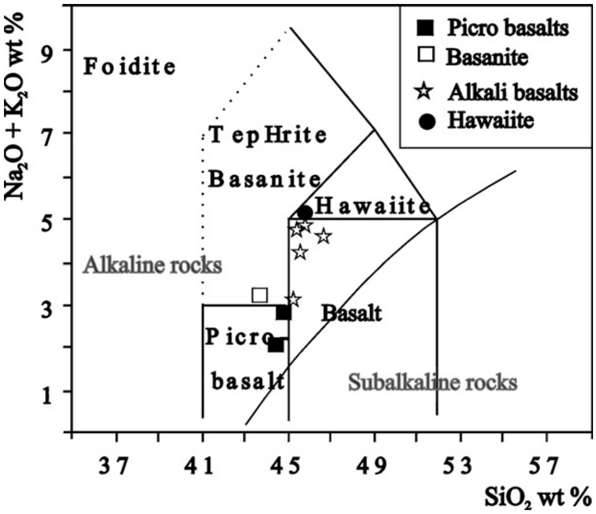

Fig. 3. Nomenclature of the BKVF volcanics in a TAS diagram [22]. Ankaramites have basalt compositions and figure thus in the latter's domain. The boundary between alkalic and subalkaline fields is after Miyashiro [30].

Fig. 3. Nomenclature des laves de BKVF dans un diagramme TAS [22]. Les ankaramites ont les compositions des basaltes et figurent, par conséquent, dans le domaine de ces derniers. Limite entre les roches alcalines et subalcalines d'après Miyashiro [30].

6.1 wt%), Ni (386–64 ppm), Cr (1275–182 ppm) and relatively low SiO_2 compositions (43.8–46.3 wt%). Given that primary magmas in equilibrium with the upper mantle are characterised by a high $Mg^{\#}$ (0.68–0.75), Ni (400–500 ppm) and Cr (>1000 ppm) and low SiO_2 (<50 wt%) [52], picrobasalts (BK9 and BK25) are primitive due to their high Mg# (0.69–0.71), Ni (350–386 ppm), Cr (1130–1275 ppm), and low SiO_2 (43.8–44.7 wt%) and FeO_{tot}/MgO ratios (0.9) values. Other lavas are mildly differentiated (FeO_{tot}/MgO = 1.3–2.2). Owing to the wide range of MgO contents compared to SiO_2, MgO serves as ordinate in the variation diagrams (Fig. 4). Al_2O_3, Na_2O, and K_2O increase with decreasing MgO, while transition elements such as Cr, Co and Ni decrease. Conversely, TiO_2 and Ba are high and almost constant, whereas SiO_2, FeO_{tot}, La, Zr, and Rb are scattered as would have been expected for unrelated rocks.

Chondrite-normalized REE spectra (Fig. 5) show LREE enrichment relative to HREE and a slight Eu anomaly [$(La/Yb)_n$ = 17–25 and Eu/Eu* = 0.86–0.95; Table 1]. Multi-element diagrams (Fig. 6A) depict negative anomalies in K (0.2–0.3), Ti (down to 0.7), and P (0.2–0.4), and positive anomalies in Ba, Nb and Nd (2.1–3.4). A rough comparison between volcanics of the BKVF and that of a few settings of the CVL (Fig. 6B) reveals that: (*i*) there is an obvious similarity between

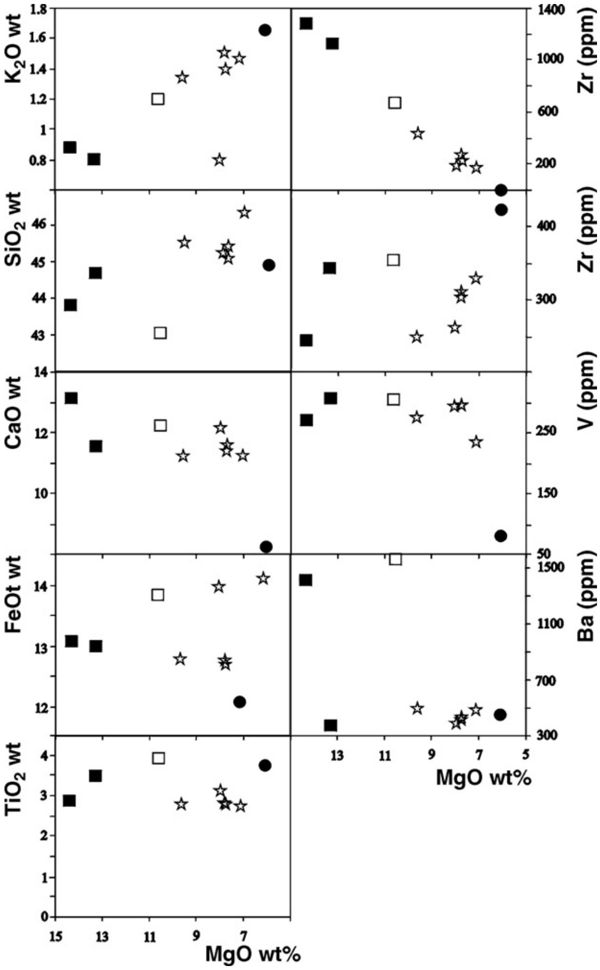

Fig. 4. Variation diagrams for selected major and trace elements vs MgO. Same symbols as in Fig. 3.

Fig. 4. Variation d'une sélection d'éléments majeurs et traces en fonction de MgO. Même légende que sur la Fig. 3.

rocks from Barombi Koto area and those of Tombel and Nyos plains, and (*ii*) polygenetic volcanoes (Mounts Cameroon, Manengouba, and Bamenda) are relatively richer in most of the elements of monogenetic volcanoes.

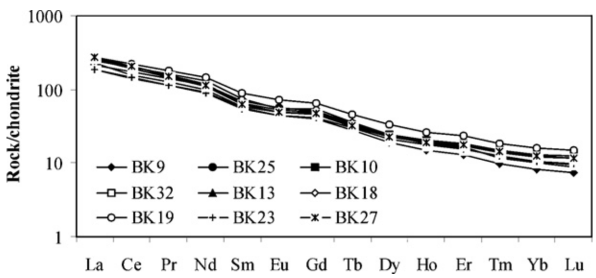

Fig. 5. REE plots of the BKVF volcanics normalized to chondrite [46].

Fig. 5. Spectres des terres rares des laves de BKVF normalisées à la chondrite [46].

The latter observation corroborates the conclusion of Sato et al. [43,44] that lavas from monogenetic volcanoes are characterized by lower HFSE/LILE and La/Ba ratios compared to rocks from polygenetic volcanoes.

6. Discussion

6.1. Differentiation processes

The BKVF lavas show negative anomalies of K, Ti and P, positive anomalies of Ba, Nb and Nd, and variable Ba/La (Table 1), which preclude any crustal contamination as explanation, although Ba/Nb and Ba/La ratios are close to the average continental crust values [51] in samples BK9 and BK18. The most relevant features of the BKVF rocks are: (*i*) the scattering of SiO_2, FeO_{tot}, La, Zr and Rb on bivariate plots, (*ii*) the broad ranging ratios of incompatible elements (e.g., Zr/Nb ratios range between 4.41 and 6.04) rather than a tiny scope of values that characterize cogenetic rocks. Hence, each maar or each cinder cone appears as an independent volcano. In a few cases (Barombi Koto maar for instance), the basaltic magma may have evolved to hawaiites by olivine and titandiopside fractionation, as witnessed by the rapid decrease in MgO, CaO, Cr, Co, and Ni, and the contents of incompatible elements higher in hawaiites than in picrobasalts, basanites and basalts (Fig. 6A). The scattering of elements in Harker plots of lavas from Mount Cameroon was assigned to the absence of any central activity [7].

6.2. Melting processes in the mantle

Quantitative evaluation of the amount of partial melting using the concentration ratio (CR) method [25] was attempted. The method is based on a set of algorithms associating the ratios of trace elements (Nd and Sm) with their distribution coefficients (*D*-values estimated using the distribution coefficients of Johnson [17]: $D_{Nd} = 0.00192$ and $D_{Sm} = 0.0429$) and the melting reaction (*P*-values for alkali olivine basalt: $P_{Nd} = 0.1105$ and $P_{Sm} = 0.2679$). The computations yielded degrees of melting ranging between 2.12 and 6.85 wt%. Though the relevance of this method, as recognised by its authors, is strongly affected by the source concentration, the melting reaction and the distribution coefficient of the trace elements, our results are within the range of values (2% to 11%) estimated for similar rocks [1,45]. On the Zr/Y vs. Zr/Nb diagram of Menzies and Kyle [28] (not shown), the BKVF lavas plot in the field of low-degree melts. Other ratio diagrams

Table 1
Incompatible element ratios of the primitive mantle (PM), of the continental crust (CC), of the mid-ocean ridge basalts (MORB), of the ocean island basalts (OIB), and of the studied rocks

Tableau 1
Rapports d'une sélection d'éléments trace des laves de BKVF, comparés à ceux du manteau primitif (PM), de la croûte continentale (CC), des basaltes de ride médio-océanique (MORB) et d'îles océaniques (OIB)

	P M	**C C**	**MORB**	**OIB**	BK9	BK25	BK18	BK10	BK32	BK13	BK23	BK27	BK19
Na_2O/K_2O		**1.33**			1.27	2.43	1.53	2.34	2.91	2.21	2.16	2.09	2.01
FeO_t/MgO		**1.69**			0.87	0.94	1.26	1.58	1.68	1.57	1.28	1.63	2.23
Ba/Nb	**9.8**	**30.74**	**5.9**	**7.3**	30.93	6.65	23	5.84	6.77	6.38	9.22	6.53	6.11
Ba/La	**10.2**	**19.47**	**7.2**	**9.5**	32.65	7.45	26.63	6.87	7.04	7.17	11.14	7.54	7.01
La/Nb	**0.96**	**1.58**	**0.83**	**0.77**	0.95	0.89	0.86	0.85	0.96	0.89	0.83	0.87	0.87
Zr/Nb	**15.73**	**10.68**	**31.76**	**5.83**	5.3	6.04	5.22	4.26	4.61	4.47	4.61	4.41	5.743
Zr/Y	**2.5**	**8.46**	**2.9**	**9.7**	7.87	9.55	9.59	8.18	6.92	8.69	7.78	8.71	9.04
Ti/Zr	**116**	**20.08**	**95**	**61**	71.01	60.65	66.2	53.78	71.8	55.81	67.42	49.81	52.62
(La/Sm)n	**1**	**3.66**	**1.09**	**2.4**	3.31	3.05	3.3	3.98	3.97	4.13	3.46	4.39	4.39
(Ti/Ti*)n	**1**		**0.93**	**0.88**	0.93	0.87	0.96	0.74	0.9	0.8	0.88	0.77	0.73
(La/Yb)n	**1**	**10.76**	**1.2**	**12.1**	22.21	20.37	24.55	20.13	18.76	21.19	17.93	22.01	17.09
(K/K*)n	**1**				0.23	0.17	0.22	0.17	0.27	0.24	0.32	0.24	0.28
(P/P*)n	**1**		**0.96**	**0.9**	0.24	0.3	0.23	0.28	0.27	0.26	0.36	0.29	0.4
(Nd/Nd*)n	**1**				2.18	2.67	2.14	3.08	3.20	3.42	2.20	2.98	2.50
(Eu/Eu*)n	**1**		**1.03**	**1.02**	0.93	0.93	0.87	0.94	0.91	0.92	0.92	0.91	0.95

Sources des données : PM, MORB et OIB [46], et CC [51].

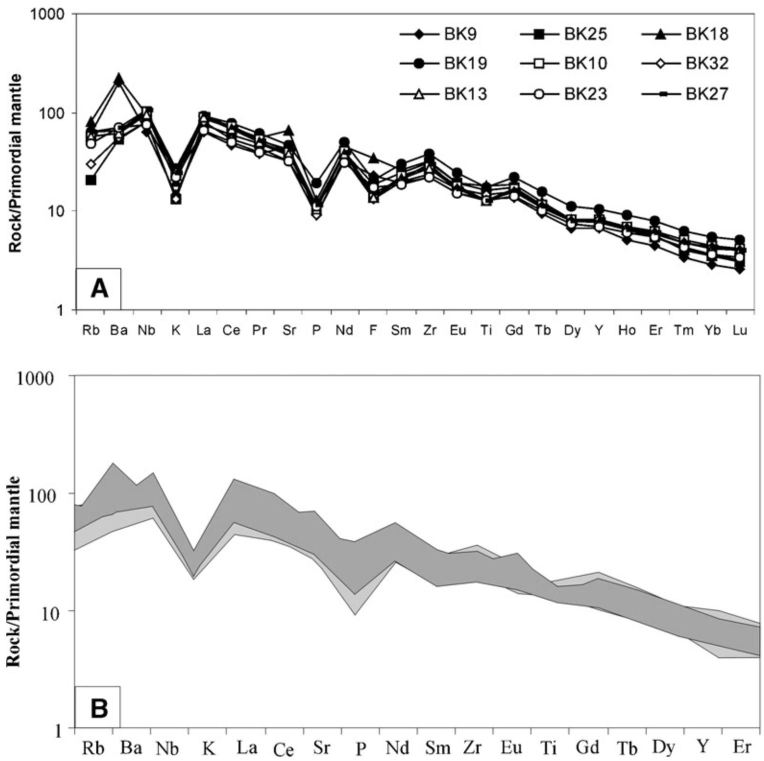

Fig. 6. Multi-element diagrams showing rocks normalized to primordial mantle [46]: (**A**) BKVF volcanics; (**B**) comparative diagrams for rocks from monogenetic volcanic fields of Barombi Koto, Tombel [37] and Nyos [33] (light grey) and from polygenetic volcanoes of Mounts Cameroon [7], Manengouba [18] and Bamenda [19] (deep grey).

Fig. 6. Diagrammes multiéléments des roches normalisées au manteau primordial [46] : (**A**) laves de BKVF ; (**B**) diagramme comparatif des laves des champs de volcans monogéniques de Barombi Koto, Tombel [37] et Nyos [33] (gris clair) et des volcans polygéniques des monts Cameroun [7], Manengouba [18] et Bamenda [19] (gris sombre).

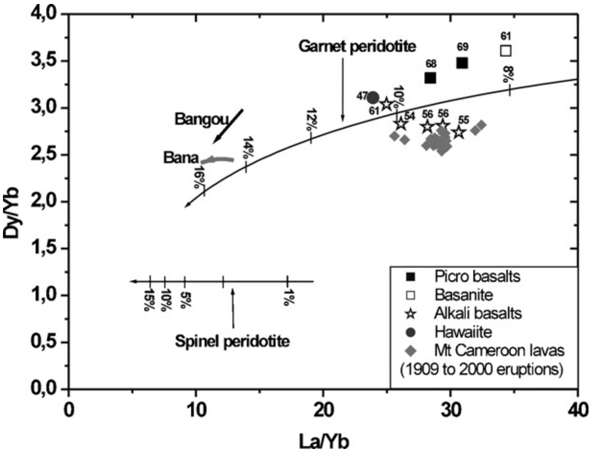

Fig. 7. La/Yb vs Dy/Yb for rocks from BKVF (Mg# of each sample of the BKVF indicated). Melt curves for garnet peridotite and spinel peridotite are from Bogaard & Wörner [3]. Also shown are the basic lavas from Mounts Cameroon [7,53], Bana [21], and Bangou [12].

Fig. 7. La/Yb vs Dy/Yb des laves de BKVF (Mg# de chacun des échantillons BKVF indiqué). Courbes de fusion d'une péridotite à grenat et d'une péridotite à spinelle d'après Bogaard et Wörner [3]. Les laves basiques des monts Cameroun [7,53], Bana [21] et Bangou [12] sont aussi présentées.

as Dy/Yb vs. La/Yb (Fig. 7) and La/Sm vs. Sm/Yb (not shown) also point to low degrees (<10%) of partial melting of a garnet-rich peridotite to produce the ratios' values observed in picrobasalts and basanites from BKVF. Lavas from Mt Cameroon plot close to alkali basalts of BKVF. Yokohama et al. [53] estimated that 2–3% of accumulated melts are necessary to produce the La/Yb and Gd/Yb ratios of the neighbouring Mt Cameroon lavas from a lherzolitic source comprising only 4–8% garnet. In Fig. 7, the values of the Dy/Yb ratio may be reached almost at 8% of melt accumulation. Along the Cameroon pluto-volcanic line, transitional tholeiitic basalts are reported in many massifs (Mbam [31], Bangou [12], Bana [21]), and in the Bamoun Plateau [32]. Their origin by high-degree melting of the mantle has been proposed, based on their low Zr/Y values (5.3–6.6 at Bangou, 5.4–7.4 at Bana and 6–11 on the Bamoun Plateau). This conclusion is in agreement with their position in Fig. 7.

6.3. Mantle source characteristics

One of the most critical issues when basaltic magma source is addressed is that of its lithospheric or asthenospheric origin. Hopefully, highly incompatible trace elements in mantle minerals and in less differentiated basalts are valuable indicators. Table 1 provides worthwhile highly incompatible elements ratios of the primitive mantle (PM), the continental crust (CC), mid-ocean ridge basalts (MORB), ocean islands basalts (OIB), and rocks of this study. It appears that the latter display values in the range of primordial mantle and OIB. Bogaard and Wörner [3] used Dy/Yb vs La/Yb diagrams to discriminate between melting of garnet and spinel peridotite based on the compatibility of Yb and the incompatibility of La in garnet and the different rates of fractionation of La/Yb and Dy/Yb ratios during melting stages in the garnet stability field. The studied rocks display two trends (Fig. 7). The trend formed by basanite and picrobasalts fairly parallels the melting curve of garnet peridotite with decreasing values of La/Yb and Dy/Yb ratios, pointing probably to different degrees of melting of a garnet peridotite. On the contrary, the trend formed by alkali basalts is located in the garnet-poor peridotite field and shows decreasing values of La/Yb ratio at constant or increasing Dy/Yb ratio values. This figure shows that BKVF lavas resulted from low degrees (8–10%) of partial melting of a garnet-peridotite mantle compared to the high degrees (15–16%) of melting that yielded transitional lavas of Mts Bangou and Bana. Taking into consideration the scattering of its values, we suggest an interpretation in terms of heterogeneity of the characteristics of the mantle source. Lavas from Mt Cameroon plot close to alkali basalts of BKVF and corroborate the mantle heterogeneity recently demonstrated [53]. More mantle source characteristics, as mantle components, can be inferred from element ratio systematics [4]. In Fig. 8, BKVF define a population above the Δ*Nb line* in the plume basaltic source. They range from the HIMU end-member to mid-way to EM2. These chemical features may suggest that the mantle source region was modified prior to the melting by recycled oceanic crust (HIMU) with trapped melt fractions (EM2) or probable subducted continental sediments (EM2) [4]. As a result of such multi-component mixing, the mantle source is likely heterogeneous. Fig. 8 also shows that alkaline basaltic lavas from Mount Cameroon [7,53], Bamoun Plateau [31,32] and Bana [21] are rather close to the recycled component. Indeed, in order to unravel the source and processes of basaltic magmatism in Mount Cameroon, Yokoyama et al. [53] acquired various data comprising major and trace elements, Sr–Nd–Pb isotopes and precise measurements of ^{238}U–^{230Th}–^{226}Ra disequilibria in lavas. The data point out the involvement of various components (HIMU, FOZO, mantle heterogeneity, subcontinental lithosphere, plume activity). These authors suggested that the geochemical characteristics of Mt Cameroon samples might result from an interaction of melt derived from the astheno-

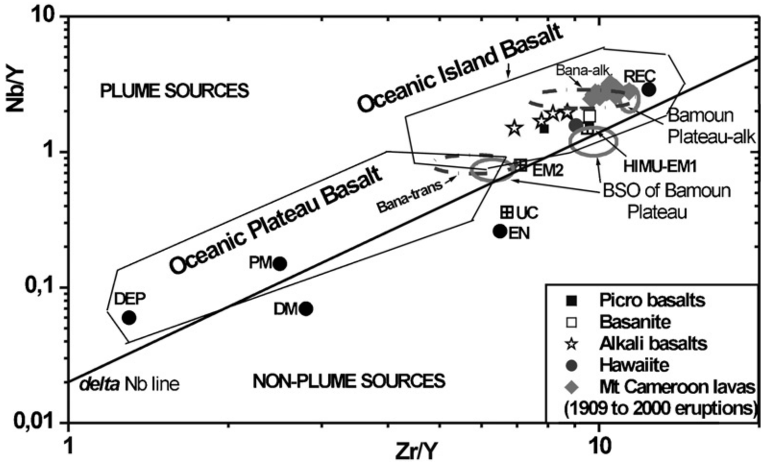

Fig. 8. Zr/Y vs Nb/Y for rocks from BKVF along with alkaline rocks from Mount Cameroon [7,53], alkaline and transitional tholeiitic lavas from Bana [21], Bangou [12] and Bamoun Plateau [31,32]. DEP, deep depleted mantle; DM, depleted mantle; PM, primitive mantle; UC, upper crust; HIMU, high U/Pb mantle source; EM1 and EM2, enriched mantle sources; EN, enriched component; REC, recycled component [4].

Fig. 8. Diagramme Zr/Y vs Nb/Y des laves de BKVF et du mont Cameroun [7,53] ; les domaines des basaltes alcalins et des basaltes à affinité transitionnelle de Bana [21], de Bangou [12] et du plateau Bamoun [31,32] sont présentés. DEP, manteau fortement appauvri ; DM, manteau appauvri ; PM, manteau primitif ; UC, croûte continentale ; pôles mantelliques HIMU (rapport $^{238}U/^{204}Pb$ élevé), EM1 and EM2 (enrichis) ; EN, composant enrichi ; REC, composant recyclé [4].

spheric mantle with the overlying sub-continental lithospheric mantle, which has suffered a Late Mesozoic metasomatism, presumably related to ancient St Helena plume activity. Many previous studies of volcanics of the Cameroon line have concluded that the magma mantle source is heterogeneous [14,15,26,39]. A recent study of lherzolite xenoliths encountered in alkali basalts from the northern part of the Kumba plain [49] reveals that they display a narrow mineralogical and chemical composition range. Therefore, the sampled mantle zone is fertile or simply affected by a very low degree of partial melting and cryptic metasomatism. These authors conclude that the upper mantle beneath the corresponding volcanoes is homogeneous and very different from the one beneath the Nyos volcanic plain. This assertion is valuable only with the assumption that the sampled mantle zone ranges from the bottom to the top of the upper mantle, and does not correspond to a limited pocket [29]. However, a study of the basalts (host of the peridotite xenoliths) is needed for highlighting the characteristics of the magma mantle source there.

The metasomatic effects constitute another relevant point on the mantle source characteristics. Magmas resulting from the melting of a metasomatised mantle may display modal or cryptic testimonies. Along the CHL, Déruelle et al. [8] indicated that hydrated (kaersutite and biotite) and/or carbonate minerals in the lamprophyres (e.g., camptonites from Mt Cameroon) may be considered as the fingerprints of the melting of an infra-lithospheric metasomatised mantle. In Mt Etinde, modal and cryptic metasomatic effects coexist. In addition to carbonate minerals, nephelinites show unusual (high) values of Zr/Hf (92–50) ratio, which probably reflects a carbonate metasomatism in the mantle source [39]. Cryptic metasomatism is also evidenced in the peridotite xenoliths from the Kumba graben [49]; this cryptic metasomatism may have reached the BKVF mantle source.

Key results on the mantle source characteristics of BKVF comprise the low degrees of partial melting of a garnet-peridotite infra-lithospheric mantle, their chemical characteristics, similar to those of an OIB mantle source, the heterogeneity of the mantle and a possible cryptic metasomatism. The mantle modifier component as the HIMU should remain a hypothesis until it is confirmed or challenged by He, Sr, Nd, Pb isotopes.

7. Conclusion

Lavas from BKVF range from picrobasalts to hawaiite through basanites and alkali basalts. Due to their high Ni, Co, Cr, and MgO contents, they correspond to primitive or less differentiated rocks. Their major and trace element compositions are similar to those of alkaline lavas from other monogenetic volcanic fields of the Cameroon Volcanic Line.

The scattering of many elements on bivariate plots and the wide range of values of incompatible element ratios are interpreted in terms of independent volcanoes formed by low-degree melting of distinct zones of a heterogeneous asthenospheric mantle. The ratios preclude any crustal contamination of the magmas en route to the surface. They rather indicate a mantle source characterized by a HIMU prevailing component.

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