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ARTICLE

Geochemistry of Volcanic Rocks of Beka, North East of Ngaoundéré (Adamawa Plateau, Cameroon): Petrogenesis and Geodynamic Context

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ABSTRACT

Beka area is situated in the Adamaoua Plateau of Cameroon in central Arica. Lavas in this area has not been studied before the present work. The volcanism of Beka is characterized by basalt, trachyte and phonolite domes and flows. The petrographic study shows that basaltic lavas have porphyritic microlitic textures. The felsic lavas indicate trachytic textures. The rocks are composed of olivine, clinopyroxene, plagioclase and iron-titanium oxide minerals for the basalts; clinopyroxene, alkali feldspar (including foids), sphene and titanomagnetite for the felsic lavas. Chemical analyses show that basaltic lavas are basanites. Felsic lavas contain modal feldspathoid (nepheline in phonolites). All these lavas belong to the same series, because the felsic lavas are derived from the differentiation of basaltic lavas by fractional crystallization. They show an alkaline nature according to their geochemistry. Trace elements including Rare Earth Elements characteristics show that rocks emplaced in the Winthin Plate volcanic zone. They derived from an evolved parent magma showing a low degree of partial melting and characteristics closer to a modified and evolved primitive spinel lherzolite.

1. Introduction and Geological Setting

The Beka area is a unit of the Adamawa plateau in Cameroon (Figure 1). It is delineated at its western and northern parts by many mountains namely Tchabal Nganha (1923 m with an average altitude of 1100 m), Tchabal Ngaoundaba (1960 metres), Tchabal Mbabo (2450 metres) and Mount Mambila (2428 metres). Several petrographic, geochemical [1,2], geochronological [3], geophysical [4] and structural [5] studies have been done for the characterization of the Adamaoua plateau. In the structural aspect, the Adamaoua Plateau is made up of a Pan-African metamorphic and plutonic basement bounded to the north by the Adamawa fault and to the south by the << Djérèm and Mbéré >> faults [6]. It is intensely crosscut by a major N70°E fault cluster locally masked by Cenozoic basaltic flows. Studies

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on brittle deformations have been carried out on the northern (Ngaoundéré cliff area) and southern (South-Adamawa trench) edges of the Adamaoua Plateau [6] confirming the Pan-African heritage for the basement.

The southern edge of the Adamawa plateau is affected by the WSW-ENE mylonitic bands extending up to the Foumban area. That structural direction also corresponds in the south (of the plateau) to Pan-African mylonitic faults showing W-E shortening and marked by strike-slip shears and folding. The structure of the plateau corresponds to a horst on the southern edge, whereas the northern part is made up of an escarpment developed during the compressional phase of the Late Cretaceous. The South-Adamawa trench contains important sedimentary evidence of Mesozoic history. However, there are no known Tertiary sediments, as the tectonic reactivation of the trench at this time was accompanied by a general uplift. Other works show that the bedrock of the Adamawa area belongs to the Central African Fold belt and is cut by a N70°E strike-slip fault system [7,8]. It is mainly composed of metamorphic rocks cut by Neoproterozoic granitoids.

The Adamawa Plateau was formed during the Tertiary period and then uplifted up to 1 km from the surrounding areas [9,10]. It is largely covered by huge basaltic and basalto - andesitic volcanic outpourings of mainly Tertiary age, which spill over into the middle part of the southern trough [11]. The plateau is then also presented as a volcanic horst of about 200 km wide, bounded to the north and south, as mentioned above, by Pan-African faults, generally oriented N70 degre.

Depending on several author's work, the volcanism of the Adamawa plateau remains a matter of debate. It either belongs to the Cameroon Volcanic Line (CVL) or rather related to the replay of Pan-African faults, resulting from the reactivation of the N70° E sinistral trans - tensional shear zone, at the onset of the opening of the Central Atlantic Ocean in the Aptian - Albian age [7] and the separation of Africa and South America [12-14]. Indeed, the CVL has a "Y"-shaped distribution of volcanoes, where Adamawa represents the NE branch of the "Y". The dolerite dyke swarms near Biden, 5 km south-east of "Ngaoundéré" [15], Likok, 70 km south-east of "Ngaoundéré" [16] and Mbaoussi, 40 km north-east of "Ngaoundéré", are linked to one or more tectonic events that affected the continental crust of central Africa.

The relationship between the Cameroon Volcanic Line and the Adamawa plateau remains complex. Several hypotheses have been put forward on this subject: the reactivation of the pan-African crust [17], and the orientation of the dyke swarms resulting from the reworked Pan-African fault network of the Adamawa Plateau [7] during Ordovician (450 Ma) and Jurassic episodes; (ii) [18] the opening of the South Atlantic Ocean during the late Jurassic to Cretaceous; (iii) [19] mentioned the development of the Cretaceous Djerem and Mbere basins of northern Cameroon and (iv) [18] the development of the West and Central African rift systems. (v) [20] mentioned that a rapid rotation (20 Ma ago between 8° and 9°) of the African plate would have induced an inflection of the Cameroon Volcanic Line which extends from the Gulf of Guinea and progressively curves from N30°E to N70°E on the Adamawa plateau. (vi) [21] suggests a 7° rotation of the African plate (from a pole in Sudan 80 Ma ago (Santonian)), which would have cut the lithosphere from the Benue trench asthenosphere and moved it to the present geographical location of the Cameroon Volcanic Line. The hypothesis of a gradual shift from N30°E to N70°E is also mentioned [22,23].

Geochemical data on the Adamaoua plateau, consisting essentially of various granitoids, syn- to late tectonic, punctuated by volcanic massifs, have been acquired. Granitoids display negative Nb-Ta and Ti anomalies. They are a calc-alkaline suite with a type I signature, defined by [24]. All the studied granitoids are enriched in Large Ion Lithophile Elements (LILE) compared to High Field Strength Elements (HFSE) [25]. They are believed to be derived from the differentiation of enriched mafic magmas from the subcontinental lithospheric mantle with possible crustal assimilation. The Adamawa plateau basement is intensely dissected by the Pan-African faults (N70° E) [7], which were remobilised during the Albian-Aptian period, exposing numerous types of volcanic rocks: basanite, basalt, hawaiite, mugearite, benmoreite, trachyte, rhyolite, phonolite. The differentiated lavas show peralkaline affinities [16,25,26]. Studies on the dyke swarms of the Adamawa plateau suggest for one of the identified dolerite dykes, a continental tholeiite composition [15] associated with post-PanAfrican extensional magmatism [16]. The chemical characteristics of these rocks have been interpreted as fingerprints of a source with sub-continental lithospheric mantle characteristics as well as E - MORB components that would have been contaminated during an ancient subduction event.

The geochronological information consists of Th-U-Pb monazite, Pb/Pb or U/Pb zircon dates are acquired on the Pan-African granitoids. The latter is composed of Neoproterozoic granites of 615 to 575 ± 27 Ma [5,24,27,28], cutting a late Archean bedrock, remobilized and composed of meta-sedimentary and meta-igneous rocks that have undergone medium to high grade Pan-African metamorphism. The Neoproterozoic ages are either those of the recrystallized domains, or those of the deposition of sediments, or are characteristic of the metamorphism of the Tchollíré region [28]. Available volcano dating assigns ages

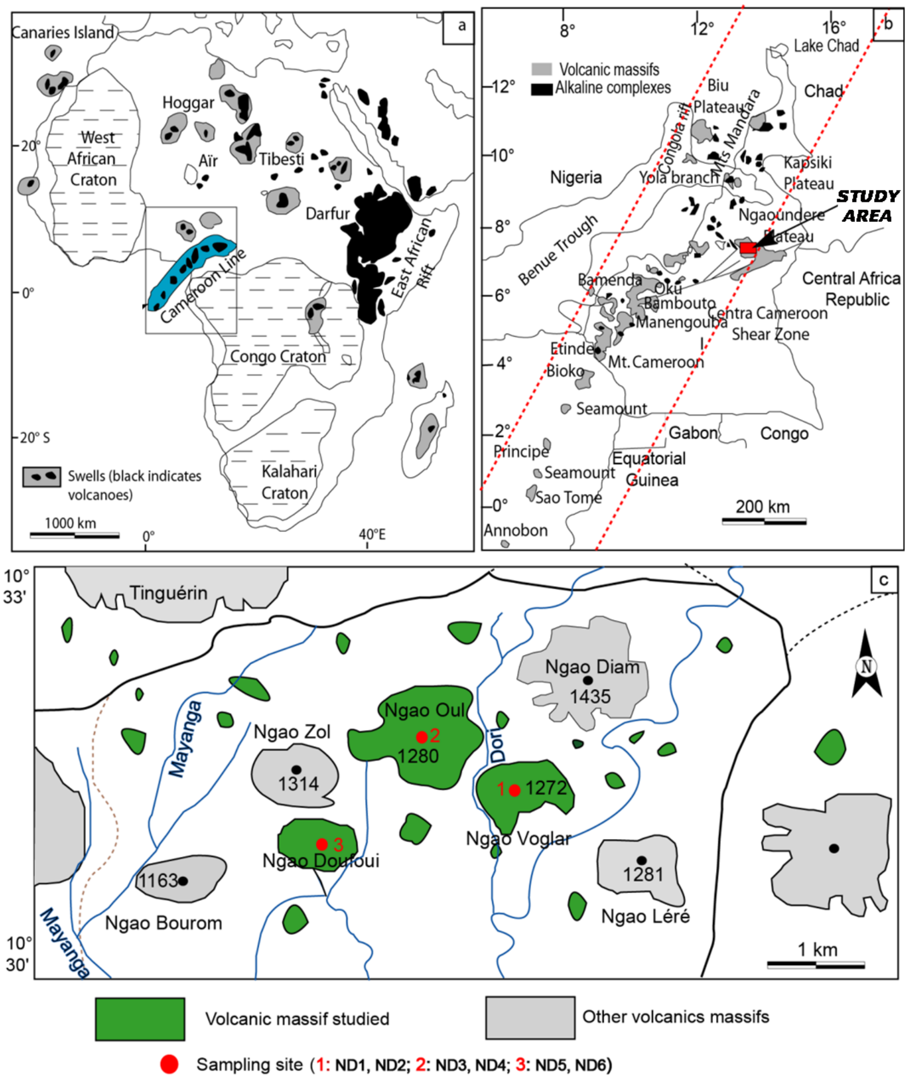

Figure 1: a) Location map of the CVL and the main geological features of Africa. b) Main volcanic centers and alkaline complexes of the CVL from [8] c) Simplified geological map of the study area showing the studied massifs.

of 7-11 Ma (K/Ar method) for the Adamawa lavas [2,25,26,29], and gave probable Mio-Pliocene ages for the Adamawa volcanism.

Geophysical investigations indicate various information on the crust and lithospheric mantle beneath the Adamawa Plateau. According to the gravity data (negative Bouguer anomalies) of [4], and the seismic data of [30], the thickness of the lithosphere beneath the Adamawa plateau is about 80 km. Gravity data suggest a Moho between 18 and 30 km. [22] estimated the depth of the Moho to be 33 km using seismic refraction. According to [31], the Moho discontinuity lies between 33 and 36 km beneath the Adamawa plateau, specifically 33 km beneath the "Ngaoundéré" area. [32] highlighted the isotropic nature of the upper mantle beneath the CVL. The lithosphere - asthenosphere boundary (LAB) is 100 km beneath the CVL, compared to 250 km beneath the Congo craton. The Low Velocity Zone (LVZ) is 200 km below the CVL.

As mentioned above, several research studies have been carried out on the volcanic formations of the Adamawa plateau. In the town of "Ngaoundéré" and its surroundings, effusive flows of alkaline basalts have contributed to the formation of the relief on the plateau [33]. According to the work of [34], the volcanic rocks are derived from the source characterized mainly by spinel lherzolites. The volcanic formations in the vicinity of "Ngaoundéré" have been grouped into three emission series [35,36], and in accordance with the observations of [36] in western Cameroon: (1) the old basaltic series of terminal Cretaceous age [36], (2) the trachytic and phonolitic-dominated intermediate series; (3) the recent basaltic series (south of "Ngaoundéré").

The trachytic and phonolitic dominated series is rep-

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resented by 35 necks, domes and sloped-dome (dome flowed) of differentiated lavas associated with basaltic flows of Mio-Pliocene basalt age (10.0 to 7.0 ± 0.2 Ma), [2,25,33] and differentiated lavas (11.39 ± 0.03 to 9.28 ± 0.03, [7]. Two large strato-volcanoes; Tchabal Nganha [1,3] and Djinga-Tadorgal [37] consist of basaltic, trachytic, phonolitic flows and volcanic breccias, crossed by numerous trachytic and phonolitic necks. One basalt and two trachytes have been dated K - Ar at 7.2 - 7.9 and 7.9 - 9.8 (± 0.2) Ma, respectively [12]. To the west of the Adamawa plateau, the Tchabal Mbabbo massif consists of large basaltic flows accompanied by trachyte necks, phonolite and rhyolitic breccias [26,3]. In the south of “Ngaoundéré”, there are numerous recent strombolian cones (0.4 Ma ± 0.2, [2]. The Dibi projections contain plagioclase peridotite nodules [38]. Nodules of garnet peridotites were discovered in the pyroclastic projections of Youkou [39]. The basaltic flows and domes of trachytic and phonolitic composition that outcrop in the Beka region (Figure 3) will be the subject of the present study.

In this study, we present, for the first time, petrographic and geochemical data (major, trace and rare earth elements) of the Beka lavas, located to the North-East of “Ngaoundéré”. We acquired these data in order to characterize the petrogenesis and geotectonic setting of the Beka rocks in particular and compare them to that of other lavas from the Cameroon Volcanic Line in general.

2. Analytical Method

Six thin slides were made at the GEOPS Laboratory (Geosciences-Environment Laboratory of the University of Paris Saclay) in France; the whole rock chemical analyses of the representative lavas (major, trace including Rare Earth Elements) were carried out by ICP - AES (Inductively Coupled Plasma - Atomic Emission Spectrometry) and ICP - MS (Inductively Coupled Plasma - Mass Spectrometry) at the ACMEL laboratory in Vancouver, Canada. All the samples were carefully selected and then ground. After each sample, the grinder was systematically cleaned with compressed air. These analyses were carried out on 0.2 g of rock powder and the analytical accuracies varied between 0.04 and 0.1 % for major elements and 0.1 to 0.5 ppm for trace and rare earth elements. The loss on ignition was determined by the weight difference after ignition at 1000 °C.

3. Results

3.1 Outcrops and Field Relationships

Basaltic, trachytic and phonolite outcrops are present in the Beka area (Figure 2). The basaltic lava of Beka occurs in the form of sub-rounded ball of approximately 270 cm diameter at an altitude of 1272 m. At about 30 m from the base of the hill, the basaltic lava consists of centimetre (30 - 80 cm) to metric (0.90 cm - 1.3 m) blocks (Figure 2a). The blocks have rough surfaces with many ten centimetre crystals of pyroxene comparable to coal platelets. The balls display a smooth surface with little crystals of olivine and pyroxene. The last 30 m to the upper part consists entirely of prismatic lavas. In place, slabs of basaltic lava flow have covered the granitic bed rocks.

The trachytic massif of Beka (Figure 2b) is one of the most voluminous trachytic plutons in the study area. It is a sloped-dome (dome flowed) with a length of 300 m and a width of about 150 m. It is located at an altitude of 1280 m at about 110 m above the bedrock. The lava is dark green to dark grey and presents a grayish color when altered. It is covered by a centimeter (1.5 to 5 cm) whitish to light yellow weathering patina. The fresh matrix has a pisolitic-like struc-

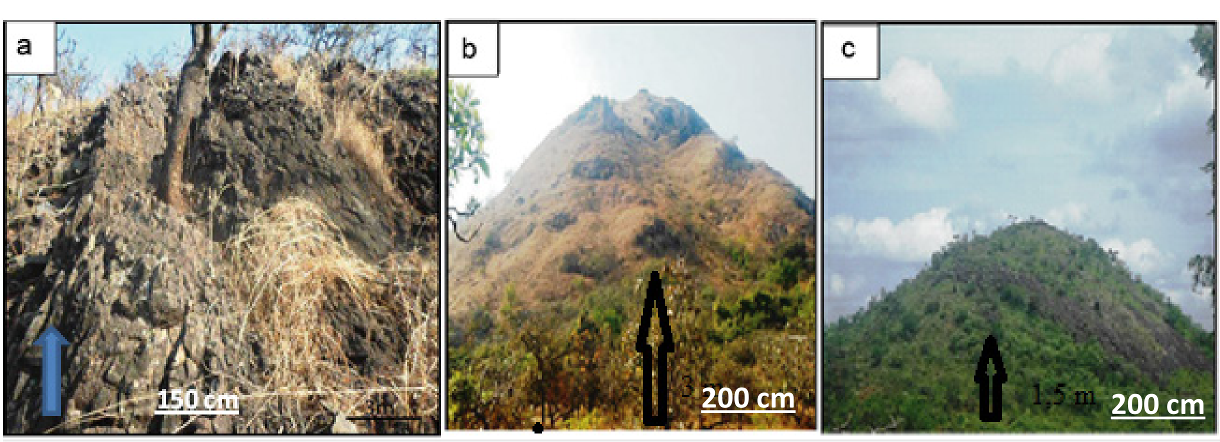

Figure 2. Panoramic view of the Beka lava outcrops, a) prismatic volcanic massif in its upper part; b) trachytic flow dome; c) phonolitic massif.

ture characterized by dark concretions consisting of mineral aggregates of variable diameter (0.5 to 1.5 cm).

The Beka phonolite massif is a roughly conical dome with an almost circular base. It rises to an altitude of 1314 m, with a 12 m high above the bedrock and about 300 m diameter. The massif is prismatic, especially on its southern flank. The massif presents steep slopes hosting mechanically degraded prisms showing intense fracturations. The prismatic rock has an anastomosing appearance. The lava has a dark green color and is characterized by the presence of spherical balls of dark grey color, 0.5 to 2 cm in diameter. The phonolite balls present fine grained texture packed by a grey matrix (Figure 2c).

3.2 Petrography

3.2.1 Basalts

The basalts of Beka have in general a microlitic texture. In place it displays porphyritic texture and consist of olivine, clinopyroxene, feldspars and ferro - titanium oxides. Olivine, clinopyroxene and iron - titanium oxides occur as phenocrysts (Figure 3a) and are distributed in a groundmass consisting of microlites of the same minerals. The olivine phenocrysts (0.5 x 0.3 mm, 20% of the volume of the rock) are automorphic to subautomorphic. They are corroded in the rims and sometimes in the cores (Figure 3a). Inclusions of iron-titanium oxides are sometimes observed on phenocrysts. Some olivine crystals show some corrosion gulfs in the cores while others show cracks filled with serpentine alteration product (Figure 3b). Clinopyroxene phenocrysts (1 x 0.4 mm, 25 % by volume of the rock) are automorphic and occur in various shapes (elongated, stocky and sometimes rectangular) (Figure 3a). Some clinopyroxene crystals are strongly cracked and show in the cores and sometimes at their edges some corrosion gulfs in which microcrystals of titanium iron oxides are observed (Figure 3b).

The iron-titanium oxide phenocrysts (0.4 x 0.3 mm) are not abundant in the rock (10 % of volume of the rock). They are associated with olivine and clinopyroxene phenocrysts or occur as inclusion in olivine and clinopyroxene phenocrysts (Figure 3a).The matrix of the studied basalts consists of plagioclase and clinopyroxene microlites and microcrystals of olivine and iron-titanium oxides. No preferential orientation of the microlites is observed.

The iron-titanium oxide microcrystals are relatively abundant (15% by volume of the rock) in the matrix. They are in the form of dotted lines and small dark squares (Figure 3b). Olivine microcrystals are the least represented in the matrix (5% by volume of the rock). They are mostly observed around phenocrysts of the same phase. Plagioclase microlites are the most abundant (20%). They are elongated in the form of small needles for the smallest and small rods of less than 1 mm for the most developed laths. Clinopyroxene microlites (less than 0.5 mm and 5% by volume of the rock) are stocky or in the form of small elongated rods.

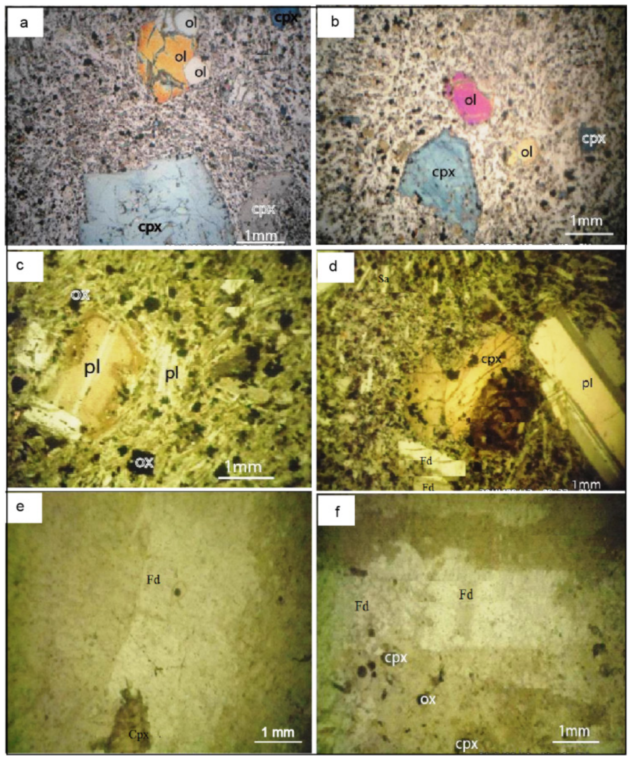

Figure 3. Thin sections microphotographs of representative samples of the Beka study area a) destabilized phenocrysts of olivine in the basalts, b) microlitic porphyitic texture of the basalts, c) destabilized sanidine crystals in its core, d) trachytic texture of the trachytic lavas, e, f) porhyritic texture of the phonolitic lavas. Cpx: clinopyroxene, Pl: plagioclase, Ol: olivine, Ox: oxide.

3.2.2 Trachytes

The trachyte samples have a classical trachytic texture (Figure 3d).They are generally composed of phenocrysts of clinopyroxene, alkali feldspar, plagioclase and iron-titanium oxides. These phenocrysts are distributed in a microlitic matrix composed mainly of plagioclase, clinopyroxene and iron-titanium oxide microcrysts. Alkali feldspar phenocrysts (1.5 x 1 mm,) occur as elongated, automorphic laths. They constitute about 30% of the volume of the rock. They are in place cracked, or resorbed by the matrix. Plagioclase phenocrysts (1.5 x 1 mm, 30% of volume of the rock) are mostly automorphic and others have a xenomorphic appearance. The latter is sometimes corroded in their edg-

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es by mesostasis and contain numerous microcrystals of iron-titanium oxides in these edges (Figure 3b). Clinopyroxene phenocrysts (1.2 x 0.8 mm) occupy about 15 % of volume of the rock. They are automorphic to subautomorphic, cracked and sometimes corroded at the edges by mesostasis. They contain inclusions of iron-titanium oxide crystals and are sometimes completely altered to a brownish product (Figure 3d).

The matrix of the trachytic lavas consists mainly of plagioclase, clinopyroxene and iron-titanium oxide microcrystals. The iron-titanium oxide microcrystals are less than 0.1 mm in size, and occupy about 10% of volume of the rock. They are present in the matrix and or as inclusions in plagioclase phenocrysts (Figure 3c). Alkali feldspar microlites (10%) are the most abundant in the matrix. They occur as small elongated needles or acicular rods. They are in place preferentially oriented (Figure 3d). Clinopyroxene microlites are automorphic and less abundant (5% of volume of the rock).

3.2.3 Phonolites

The phonolite lavas have a classic, porphyritic and microlitic texture (Figure 3f) with more or less hyalloclastic varieties. Alkali feldspar phenocrysts (1.5 x 0.8 mm in size and 25% of volume of the rock) are abundant in phonolites. They are automorphic with a tabular shape and display a cloudy, hazy appearance (Figure 3e). Clinopyroxene phenocrysts (1.3 x 0.8 mm, about 20% of volume of the rock) are automorphic. They are green and are regularly corroded in the cores and sometimes in the rims by matrix. The iron-titanium oxide phenocrysts (1.2 x 0.9 mm, 10% of volume of the rock) are sub-automorphic and often corroded in the cores and rims.

The groundmass of the Beka phonolite consists mainly of alkali feldspar microlites, clinopyroxene and iron-titanium oxide microcrystals. The iron-titanium oxide microcrystals (less than 0.1 mm, about 10% of volume of the rock) are scattered in the matrix and sometimes included in clinopyroxene phenocrysts or placed at the edges of alkali feldspar phenocrysts. Alkali feldspar microlites (less than 0.1 mm) are the most abundant in the matrix (30% of volume of the rock). They are small acicular rods showing a preferential orientation in some places. Clinopyroxene microlites are rare (5% of volume of the rock) and occur as sub-tabular or xenomorphic crystals.

3.3 Geochemistry

3.3.1. Major Elements

The geochemistry of major and trace elements including Rare Earth Elements was carried out on selected samples based on their freshness and representativeness. According to the TAS (Total Alkali vs. Silica) diagram from [40,41], the volcanic rocks of the Beka area are basalts, trachytes and tephri-phonolites (Figure 4, Table 1). These lavas are compared to other alkaline lavas of the LVC (Figure 4), namely those of the Kapsiki Plateau (tephrite basanite and trachyte) [42], Mt Cameroon (tephrite basanite) [43] and the Bamoun Plateau (basalts) [44]. On the SiO_2 - K_2O after [45], all the sample from the Beka area plot within the shoshonitic fields (Figure 4).

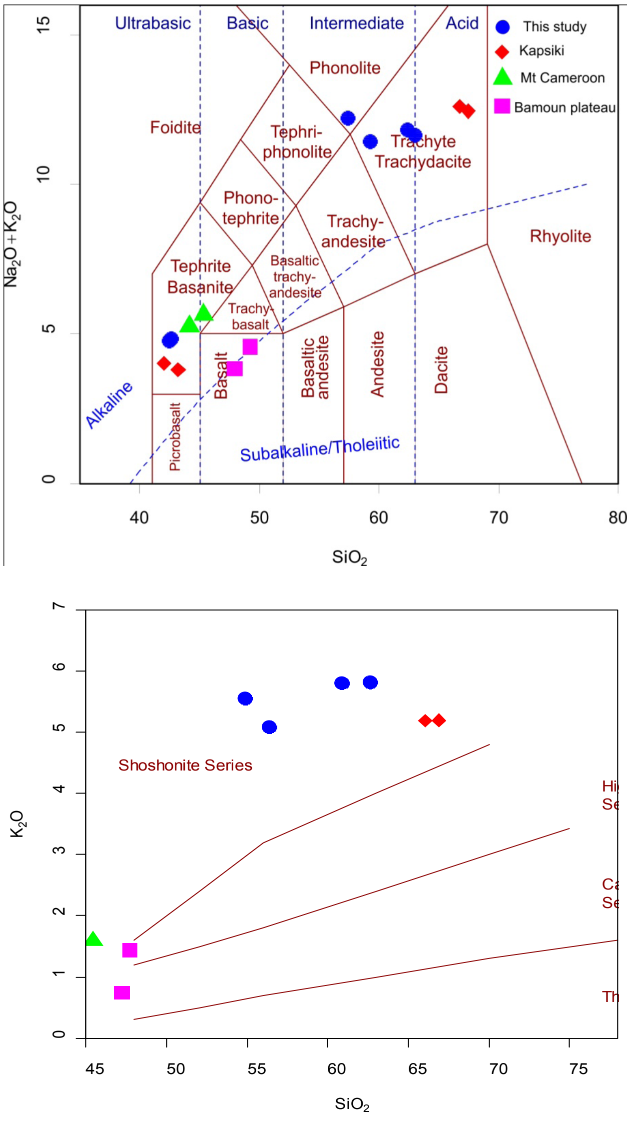

Figure 4. a)Total alkali-silica diagram of the Beka lavas after [40]; the line separating the alkaline - subalkaline domain is from [41]. Datas from the Kapsiki Plateau [42], Mt Cameroon [43] and the Bamoun Plateau [44] are taken for comparison; b) SiO_2 - K_2O diagram after [45]

On the binary diagrams of major elements versus silica, (Figure 5a-c) the Beka samples show positive correlations between SiO_2 and K_2O, Na_2O and Al_2O_3 indicating feldspar accumulation. While in (Figure 5d-h), the elements MgO, Fe_2O_3, CaO, TiO_2 and P_2O_5 show negative correlations with SiO_2, thus indicating the fractionation of minerals, such as olivine, clinopyroxene and iron-titanium oxides.

3.3.2. Trace Elements

The trace elements of the Beka lavas are represented in Table 1. The Ni, Co and Cr contents vary respectively from 22.51 to 23.42 ppm; 43.15 to 42.12 ppm and 24.42 to 25.2 ppm in the basalt. Trace element contents are low and are sometimes near the detection limit in the differentiated lavas. In Figure 6d - h, the binary diagrams of Ba, Nd, La, Rb and Zr elements as a function of silica show positive correlations, indicating globally incompatible behaviour throughout the series. The elements Co, Sc, V, Cu, although not represented in this diagram, show positive correlations in the evolved terms, contrary to the basaltic lavas where negative correlations are observed. Their concentration decreases according to the evolution of the silica content (Table 1). These same variations are observed on the Beka lavas as well as on the Kapsiki Plateau, Mont Cameroon and Bamoun Plateau lavas.

The Rare earth spectra normalized to the primitive mantle of [46], are presented in Figure 7. They are characterized by the enrichment in Light Rare Earth Elements contents that reach 90 to 300 times the mantle values (Figure 7). The lowest values of light rare earths are found in basalts. The multi-element spectras of the Beka lavas are normalized to the primitive mantle of [47] (Figure 8). Basalts are characterized by very strong negative anomalies in Sc and slightly in Th and Ta. Slight positive anomalies are observed in Nb, Ba, Sr and Ce in the basalts.

4. Discussion

4.1 Crustal Contamination

In the absence of isotopic analyses, arguments presented for crustal contamination are speculatives. The contamination of the Beka felsic and basaltic lavas is discussed here on the basis of their geochemical characteristics. The interaction

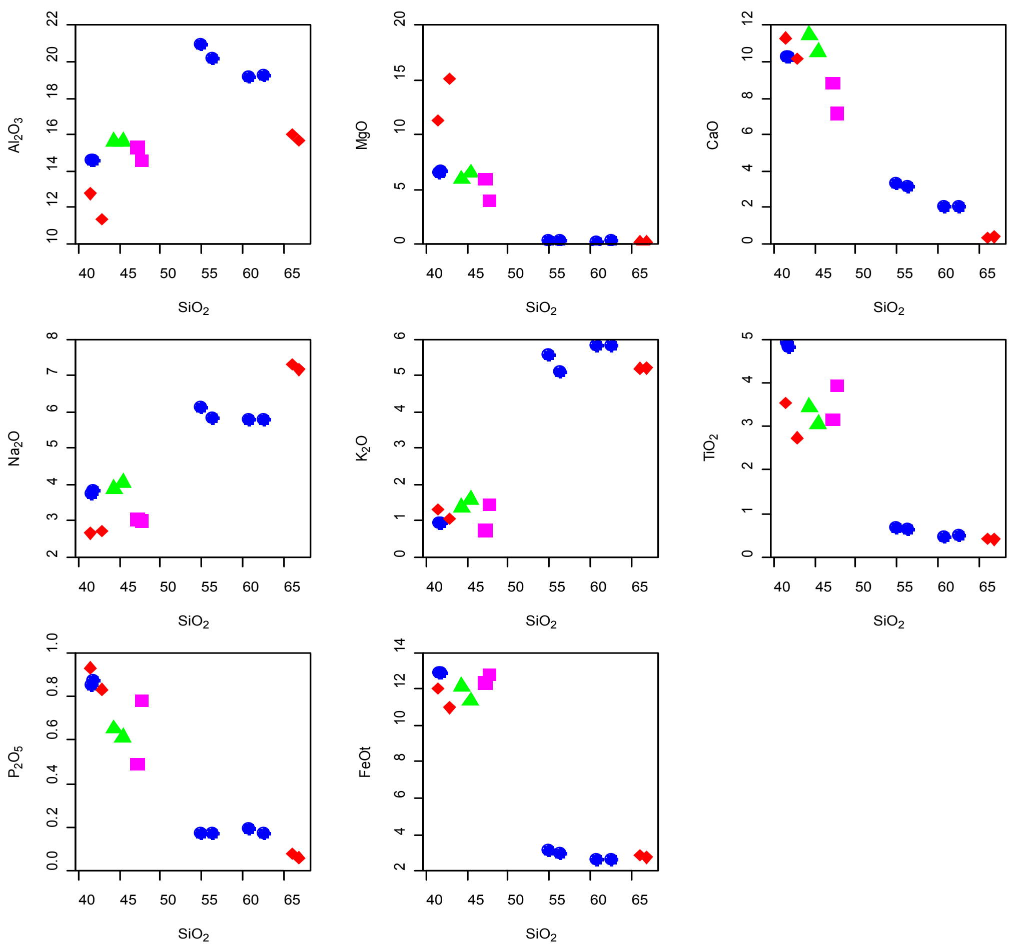

Figure 5. Variation in major element composition as a function of silica (SiO_2).

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Table 1. Geochemical data for representative lavas of the Beka area

Lavas	Basalt		Trachyte		Phonolite	
Samples	**ND1**	**ND2**	**ND3**	**ND4**	**ND5**	**ND6**
Majors elements (%)						
SiO_2	41.57	41.91	62.66	60.87	54.89	56.37
TiO_2	4.9	4.8	0.48	0.47	0.68	0.65
Al_2O_3	14.58	14.59	19.21	19.19	20.9	20.16
Fe_2O_3	14.31	14.33	2.92	2.93	3.49	3.24
MnO	0.2	0.2	0.2	0.19	0.24	0.23
MgO	6.55	6.57	0.21	0.2	0.24	0.25
CaO	10.3	10.25	2.02	2.03	3.28	3.14
Na_2O	3.73	3.81	5.78	5.77	6.13	5.8
K_2O	0.94	0.93	5.82	5.8	5.55	5.09
P_2O_5	0.85	0.87	0.17	0.19	0.17	0.17
LOI	1.79	1.88	1.97	1.98	3.07	4.05
Total	99.72	100.14	101.44	97.64	98.64	99.15
Traces elements (ppm)						
Be	1.89	1.9	94	93	4.9	4.8
Rb	45.2	45.19	203	204	137	138
Sr	967.14	967.1	377	375	1820	1923
Sc	0.44	0.44	1.55	1.6	1.3	1.2
Ba	563.52	563.5	1150	1152	840	841
V	320	319	25	23	27	29
Cr	24.42	26.2	5.3	4.7	0	0
Co	43.15	42.12	2.4	1.8	1.8	1.2
Ni	22.51	23.42	2.5	2	0	0
Cu	31.4	31.39	178	180	10	11
Zn	159.1	158.9	245	244	158	156
Y	32.08	32.07	74.2	74.4	40.1	32.3
Zr	434	435	956	955	820	812
Nb	86.9	86.91	227.2	228	193	196.8
Hf	9.29	9.29	18	19	19.5	18
Ta	5.86	5.86	14.2	15	13.1	12.3
Th	6.12	6.12	22.7	23	22.56	23.9
U	1.776	1.774	3.96	3.88	5.9	4.41
REE (ppm)						
La	53.1	53.06	131.7	131.9	157.5	159
Ce	114.9	114.08	186	187	231	223
Pr	12.83	12.82	40	39.5	23	23
Nd	55.85	55.83	131	132	72	73
Sm	11.36	11.37	8.2	8.3	9.84	8.3
Eu	3.56	3.56	2.88	2.89	2.86	2.73
Gd	9.66	9.67	14.18	14.25	8.07	8.08
Tb	1.31	1.31	0.96	0.98	1.12	1.03
Dy	6.88	6.88	12.6	12.5	6.95	6.96
Ho	1.15	1.16	2.43	2.42	1.5	1.4
Er	2.91	2.91	7	7.01	3.78	3.77
Tm	0.37	0.368	1.07	1.06	0.59	0.58
Yb	2.3	2.29	4.03	4.05	4.8	4.6
Lu	0.34	0.34	1.11	1.09	0.66	0.65

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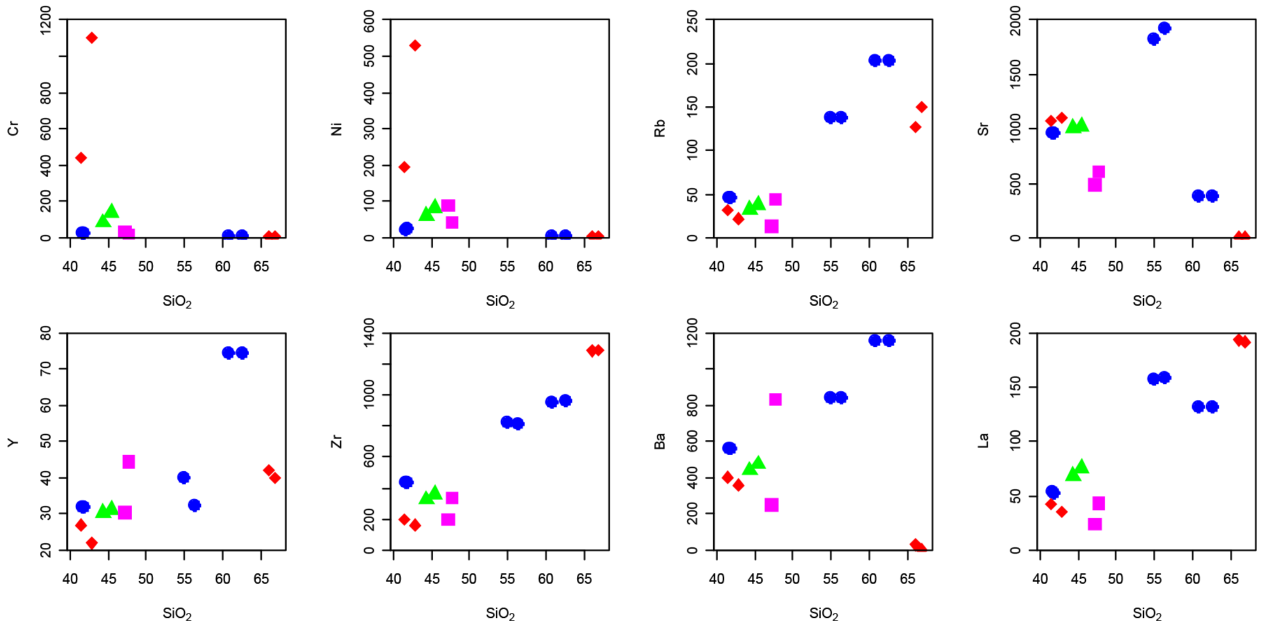

Figure 6. Variation of some trace elements (ppm) as a function of silica (SiO_2) (wt%), and comparison with datas from the Kapsiki Plateau, Mt. Cameroon and Bamoun

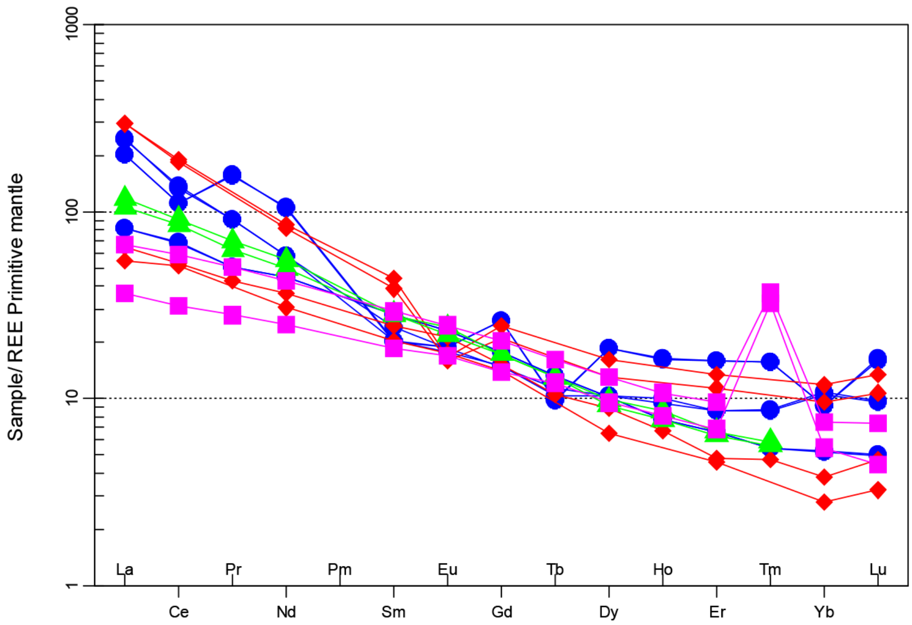

Figure 7. Rare earth spectra of lavas normalized to the primitive mantle [46], and compared to some lavas from Mt. Cameroon, Bamoun Plateau and Kapsiki Plateau.

of the magma with the rocks can modify its composition. The influence of the crustal contamination can be analyzed through major and trace element contents and ratios.

Contamination is sometimes suggested by the presence of basement enclaves and/or other rocks. This was not observed in the Beka formations. The contents of major elements such as SiO_2 and TiO_2 can be used to detect a magma contamination. The high TiO_2 (4.8 - 4.9 %) and the low SiO_2 (41.57 - 41.91 %) contents of the basalts reflect their non-contamination or very negligible degree of contamination. Their TiO_2 contents are close to those of other uncontaminated lavas of the Cameroon Volcanic Line with a mantle origin similar to that of the OIBs [46,47,48,49].

In general, the behaviour of certain trace elements,

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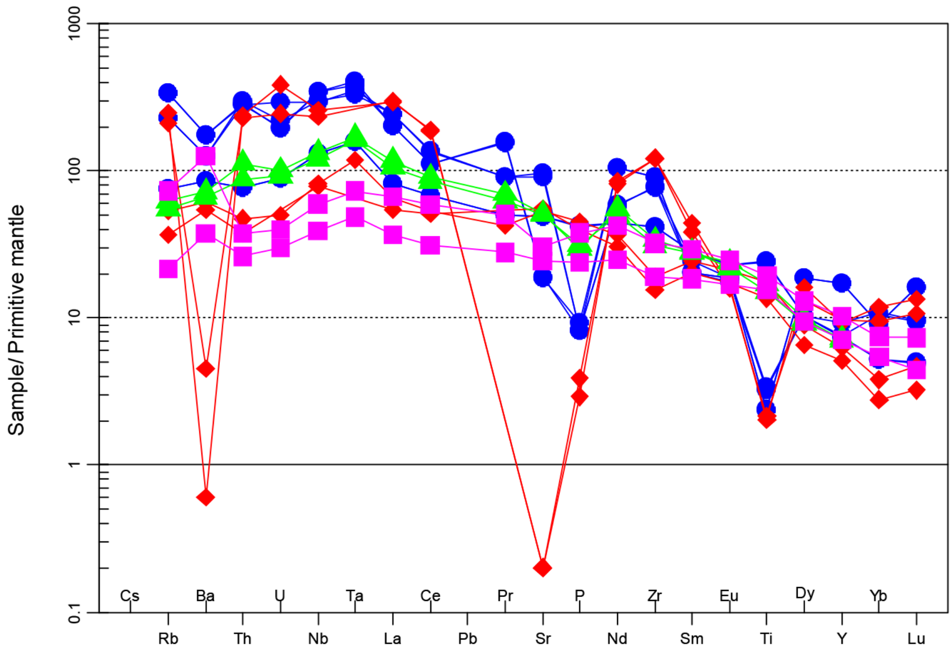

Figure 8. Multi-element spectra of Beka lavas normalized to the primitive mantle [46].

such as Sr, Zr, Ta and Nb are used to test the implication of crustal contamination, [50]. Very often crustally contaminated mafic rocks show significant negative Nb and Zr and positive Sr anomalies on the multi-element diagram [51]. Also high LREE values with flat HREE spectra indicate contamination of the mafic rocks by the crust. The Rare Earth Elements and multi-element spectras show respectively a steep slope and the absence of systematic negative anomalies in Nb and Ta. This leads us to believe that the Beka rocks have not been contaminated, or are contaminated in a negligible way. Basaltic alkaline magmas are often enriched in Nb and then have relatively low Rb/Nb ratio. Crustal rocks and melts derived therefrom on contrary generally have higher Rb/Nb ratios [52]. The Rb/Nb ratio of the Beka rocks is comprised between 0.41 and 1.22, with only one sample showing a ratio >1. This is consistent with the fact that the majority of the Beka rocks are not contaminated by the crust.

On the Nb/Y vs Rb/Y diagram [53,54,55] (Figure 9), several samples of the Beka rocks as well as those of Mount Cameroon, and of the Kapsiki plateau formations are plotted within the field of uncontaminated alkaline basaltic and felsic rocks. The Nb/Y vs Rb/Y diagram of [54,55], shows that melts could be separated into contaminated and uncontaminated groups. The first ones have higher Rb/Y ratios and low Nb/Y values, and the second ones are positively and steeper slope.

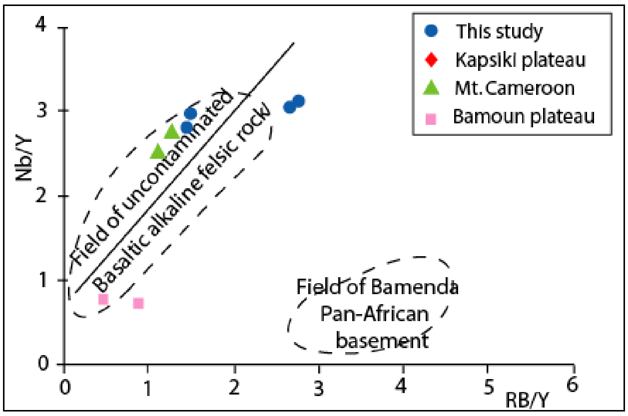

Figure 9. Nb/Y vs Rb/Y plot according to [54,55] used for the studied lavas

4.2 Beka Rocks Emplacement and Magmatic Evolution

The study of the different processes and mechanisms that led to the magmatic differentiation and petrographic diversity gives an idea about the different petrogenetic processes involved in the formation of the rocks. These processes and mechanisms are amount others the fractional crystallization, partial melting, magma mixing or crustal contamination.

4.2.1 Fractional Crystallization

The geochemical analyses of major, trace and rare earth elements in Table 1 show that SiO_2, Al_2O_3, Na_2O and K_2O contents are low in the basalts compared to those of the same oxides in the trachytes and phonolites. On the other hand, TiO_2, Fe_2O_3, MgO, CaO and to a lesser extent P_2O_5 contents are high in basalts compared to felsic lavas. The decrease in TiO_2, MgO, CaO and P_2O_5 reflects the crystallization of iron-titanium oxide minerals, olivine and plagioclase in basalts. The high contents of SiO_2, Al_2O_3, Na_2O and K_2O in the differentiated lavas suggest the accumulation of alkali feldspar crystals in these rocks.

Such a consideration is supported by the high percentages of alkali feldspar crystals in the differentiated lavas. The positive Hf and Zr anomalies could reflect the accumulation of feldspars in the Beka lavas. The trace element data show that the transition element contents of the first series (Co, Ni, Cu and Zn) are low compared to those of the primitive lavas deriving directly from the partial melting of a mantle source [53].

The Beka Basalts may have evolved through the crystallization of olivine crystals, clinopyroxene, plagioclase and iron-titanium oxide crystals from an already evolved parent magma. Such variations underlining an evolution of the parent magma by the process of fractional crystallization are indicated in some other volcanic rocks of the Cameroon Volcanic Line (the lavas of the Kapsiki Plateau, Mount Cameroon and the Bamoun Plateau).

4.2.2 Geotectonic Setting

In Figure 10, two models through the combination of four presumed immobile trace elements (Th, Ta, Y and Hf) are used to determine the geotectonic setting of the Beka rocks. The Th/Ta vs. Y discrimination diagrams of [54,55] and the Th/Hf vs Ta/Hf diagrams of [56] show that the rocks plot in the Within Plate Volcanic Zone fields. This geotectonic framework is consistent with the evolution of the alkaline rocks of the Cameroon Volcanic Line which are intraplate in character. In Figure 10a, all lavas from the Kapsiki, Bamoun and Mount Cameroon plateaus are in the same geotectonic field as the Beka lavas, with the exception of two samples from the Kapsiki Plateau, which are plotted in the Active Continental Margin (ACM) field. This would indicate contamination of the Kapsiki Plateau lavas by the basement rocks. Using the Zr - Ti diagram after [57] and on the Zr - Zr/Y diagram after [58], all the samples (Beka area, Bamoun plateau, Mount Cameroon and Kapsiki) plot in and outside the within plate basalts fields. (Figure 11).

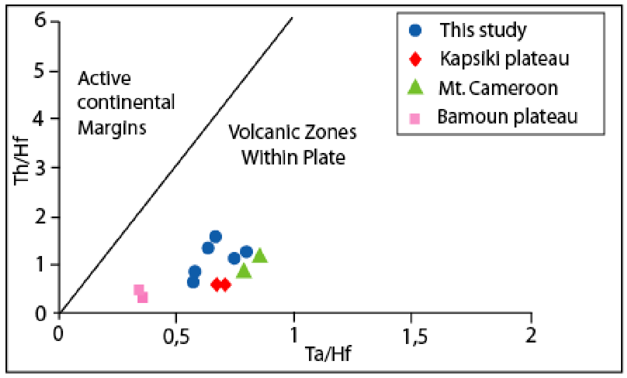

Figure 10. Geotectonic context of the Beka lavas according to Th/Hf vs Ta/Hf diagram of [56].

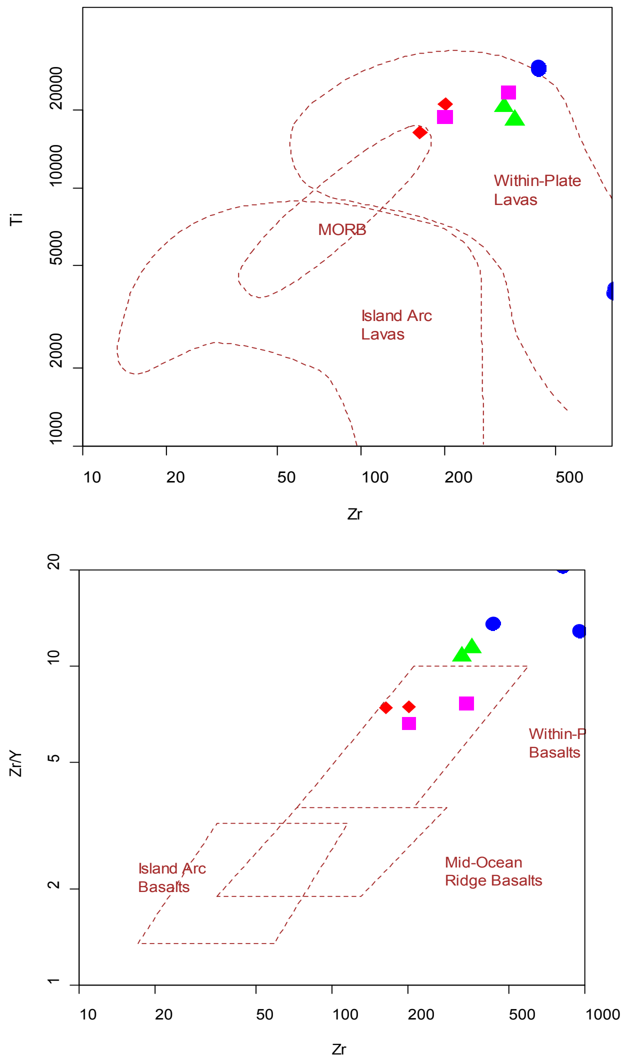

Figure 11. a) Geotectonic context of the Beka lavas according to Ti vs Zr after [57] and **b)** Zr/Y vs Zr diagrams after [58].

4.2.3 Petrogenesis and Origin of Magmas

It is generally known that Large Ion Lithophile Ele-

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ments (LILE) such as Rb, Ba and Cs can be mobile during crustal contamination. They show extreme fractionation between the earth's crust and mantle during magma rising, [58,59]. Zr, Hf, Nb, Ta, Th, Y, P and Ti High Field strength elements (HFSE) are immobile during magmatic processes [59,60]. In addition transition metals (Sc, V, Cr and Ni), HFSE are relatively stables during crustal contamination [61,62]. So, they are usually used to study the petrogenesis of rocks, magma sources and even the tectonic contexts of rocks.

The Major elements of the studied lavas show that they are alkaline to hyperalkaline in nature (Figure 4).

Understanding melting conditions can be obtained through the gradient of REE patterns of rocks [63]. The fusion of a mantle source at low percentage shows a slightly inclined (fractionated) REE patterns, and denote an origin from an enriched mantle source. A higher degree of mantle fusion [64] is compatible with flat REE patterns, showing a depleted mantle source.

In the Beka studied lavas, the Rare Earth Elements are normalized to the primitive mantle [46] and are steeply sloping and characterized by enrichment in Light Rare Earth contents that reach 90 to 300 times the mantle values (Figure 7, Table 1). These values show that the lavas studied resulted from much evolved mantle parental magma [65,66]. The low values for Heavy Rare Earth Element may suggest the presence of garnet residue in the source of the lavas. The REE profiles of the Beka samples are inclined (Figure 10) and may indicate their derivation from a relatively low degree of partial melting from a mantle source. The negative Eu anomalies attest a fractionation of the feldspar (Figure 7).

There is an increase in incompatible elements from Rb to Ta. These high incompatible element contents compared to the compatible one are an argument for a low partial melt rate of the source. The trace element spectra, normalized to the primitive mantle of [46] of the Beka lavas in Figure 10, show correlations with each other. There is a parallelism with the trace element spectra of the Bamoun, Kapsiki and Mount Cameroon lavas. This would indicate a similarity in some of their geochemical characteristics. Contents of compatible elements decrease progressively, indicating that the magma has evolved with the fractionation of minerals rich in Cr and Ni as olivine and clinopyroxene. The low Ni (22-23 ppm) and MgO (6.55-6.57 wt%) contents of the basalts are worthy and reveal the evolved character of their parent magma.

Magmas with intermediate or felsic composition can be formed through several process such as assimilation, fractional crystallization, interaction of felsic and coeval mafic magmas [64]; partial melting of crustal material [67,68]; or partial melting of the metasomatized mantle wedge. The absence of mafic enclaves or mafic-felsic mingling in the study area excludes the hypothesis of interaction of felsic and coeval mafic magmas. Also the geochemical variations of majors and traces (geochemistry section) suggested an evolution of lavas by fractional crystallization from a basaltic magma to trachytic and hyper alkaline phonolitic lavas. [15,24,25] have already shown this kind of differentiation from basalt towards rocks with peralkaline affinities.

The plot of Ta/Yb vs. Th/Yb according to [69] in Figure 12a, shows that the studied samples are placed in the mantle array, in the vicinity of the E-MORB pole for trachytes and basalts, and the sub-continental lithospheric mantle (SCLM) one for the phonolites, suggesting the mantle as their magma source. The source of the Beka phonolitic lavas located around the SCLM, would then be closer to the crust-mantle boundary, which is between 20 and 30 km in the Adamaoua plateau according to [4]. Such results have been evoked in the neighboring area of Beka, by [15,16]. Indeed, these authors interpreted chemical characteristics of their studied rocks as fingerprints of a source with SCLM characteristics as well as E - MORB components that would have been contaminated during an ancient subduction event. The Ce/Y vs Zr/Nb diagram after [70] (Figure 12b) of the partial melting and mantle source melting rates of this work show that the composition of studied lavas is close to mantle spinel lherzolites. But the low Ni and MgO contents of the Basalts lead us to conclude that this "mantle spinel lherzotite" source has undergone a notable modification and evolution. [33] has already evoked mantle spinel lherzotite source for the volcanism of some area in the Ngaoundéré district.

The geochronological data of volcanic products (basalt, trachyte and phonolite) of the present study are not yet available. But it is important to mention the Miocene - Pliocene ages of the neighboring lavas in the NE part of "Ngaoundéré", dated by different authors [2,3,25,26].

5. Conclusions

Beka area is a North East of Ngaoundéré's locality situated in the Adamaoua Plateau of Cameroon in central Africa. Lavas in this area have not been studied before the present work. The volcanism of Beka is characterized by basalt domes, trachyte and phonolite domes and flows. The basaltic lava are blocks which show rough surfaces with visible crystals of olivine and pyroxene. The upper basalt dome is entirely of prismatic lavas. The trachytic massif with an altitude of 1280 m is one of the most voluminous trachytic plutons in the study area. The fresh matrix has a pisolitic - like structure characterized by dark

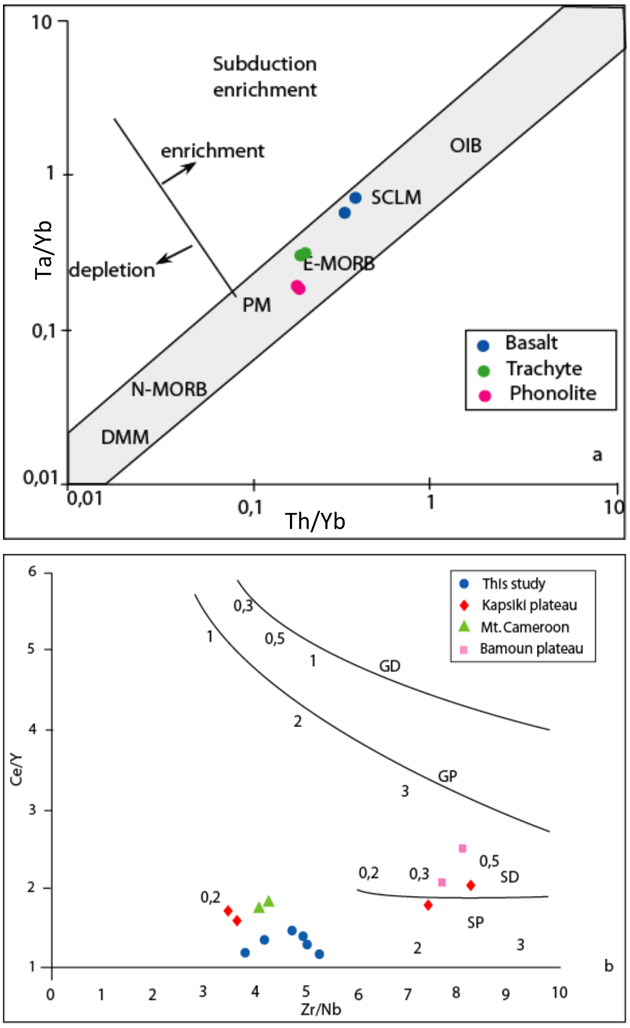

Figure 12. (a) Ta/Yb vs. Th/Yb log-log diagram of [69] for the Beka lavas. Note the placement of samples in mantle array; (b) Ce/Y vs Zr/Nb diagram by [70] of the partial melting and mantle source melting rates applied to studied lavas. GD = depleted garnet lherzolite; GP = Primitive Garnet Lherzolite; SD = depleted spinel lherzolite; SP = primitive spinel lherzolite

concretions consisting of mineral aggregates of variable diameter up to 1.5 cm. The phonolite massif is a roughly conical dome with an almost circular base which rises to an altitude of 1314 m. The massif is prismatic, especially on its southern flank.

Basalts rocks have in general a microlitic texture. In place they display porphyritic texture and consist of olivine, clinopyroxene, feldspars and ferro-titanium oxides minerals. The phenocrysts are distributed in a groundmass consisting of microlites of the same minerals. The trachyte samples have a classical trachytic texture. They are composed of phenocrysts of clinopyroxene, alkali feldspar, plagioclase and iron-titanium oxides. These phenocrysts are distributed in a microlitic matrix composed mainly of plagioclase, clinopyroxene and iron-titanium oxide microcrysts. The phonolite lavas have a classic, porphyritic and microlitic texture with more or less hyalloclastic varieties. Minerals are a mixture of phenocrysts and microcrysts: Phenocrysts are alkali feldspar, clinopyroxene, iron-titanium oxide, the groundmass consists mainly of alkali feldspar microlites, clinopyroxene and iron-titanium oxide microcrystals.

The lavas belong to the same magmatic series, and show an alkaline and probably uncontaminated nature. They have evolved through fractional crystallization from basaltic magma to felsic lavas. Their geotectonic characteristics indicate a “Within Plate Volcanic Zone”. The geochemical features show that the studied lavas may derive from evolved parent magma showing a low degree of partial melting of an evolved primitive spinel lherzolite source.

Conflicts of Interest

There is no conflict of interest.

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