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New Data on the Genesis and Evolution of the Primitive Magmas of Mount Cameroon: Contribution of Melt Inclusions

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ABSTRACT

Mount Cameroon is a Plio-Quaternary volcanic massif, without a central crater, made up of more than 140 pyroclastic cones. It is one of the active volcanoes of the Cameroon Volcanic Line. Mount Cameroon melt inclusions are found in microdroplets trapped in the early minerals (olivines) from the pyroclastic products. The analysis of these melt inclusions allowed us to find primitive liquids compared to lavas. Major elements study of the magmatic inclusions, trapped in the most magnesian olivines (Mg#84-86) of Mount Cameroon revealed “primitive” liquids of basanite and alkali basalt type with variable composition compared to the much more uniform basalts of the magmatic series of Mount Cameroon. The study of these trapped liquids shows that: (1) the original primitive lavas did not undergo the process of evolution by FC, but rather underwent fundamentally (or exclusively) the process of partial melting; (2) the emitted lavas, evolved essentially by FC; (3) the variations in the trace element contents of the primitive liquids directly reflect a variation in the rate of partial melting of a homogeneous mantelic source. The very high La/Yb ratios of the Mount Cameroon melt inclusions (> 20) characterize a garnet lherzolite source. Spectra of the melt inclusions show a negative anomaly or depletion in K, Rb and Ba as those of HIMU. The “primitive” liquids and lavas of Mount Cameroon represent a co-genetic sequence formed by varying degrees of partial melting of a source considered as homogeneous.

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1. Introduction

During its ascent and evolution, magma can undergo several evolutionary processes, becoming chemically and mineralogically more or less modified compared to the original magmatic liquid. The original primary magma is an uncontaminated or unmodified liquid, directly resulting from the partial melting of the mantle. So, it becomes difficult to find the initial composition of the primary magma, the source of the lava emitted.

Access to primary magmas can be achieved through trapped liquids, known as melt inclusions. Melt inclusions are micro droplets of magma trapped in early lava minerals such as olivine crystals. These liquids trapped at the beginning of the crystallization sequence are isolated from the surrounding environment and preserved in part from any subsequent modifications. Microdroplets are searched for and analyzed [1,2]. In general, melt inclusions have a much wider compositional range of major, trace and isotopic elements than the host lavas [3-8].

So early crystallized minerals may contain melt inclusions, capable of providing information on the geochemical characteristics of the original primary liquid(s). The studies carried out so far on Mount Cameroon show that the basaltic lavas of this volcano evolved essentially through the processes of fractional crystallization, partial melting, magma mixing and metasomatism. [9-11]. Previous work on lava flows from Mount Cameroon focus on mineralogical [11], petrological [12,13], geochemical, volcanological [14,15] and even geochronological studies [10] with very little attention paid to melt inclusions, which are very useful in modern petrology of magmatic rocks and whose study would provide us with crucial information that cannot be obtained with previous approaches. It is therefore clear that there is a scarcity of research on primitive magmas as such and their contribution to the understanding of the magmatism of the Mount Cameroon [16] in particular and the Cameroon Volcanic Line (CVL) in general.

Studying the Mount Cameroon volcano melt inclusions trapped in the early olivines minerals, and comparing their chemical composition to those of the lavas and pyroclastites that have been extensively studied, will enable us to know whether it is the same petrogenetic processes that led to the formation of both the volcanic rocks of Mount Cameroon and the liquids trapped in the olivines.

In the present paper, the melt inclusions trapped in olivines are studied, in order to provide information both on the nature of the source(s) of the primitive magmatic liquid(s) and the evolution of the primary magmas of the Mount Cameroon magmatic series.

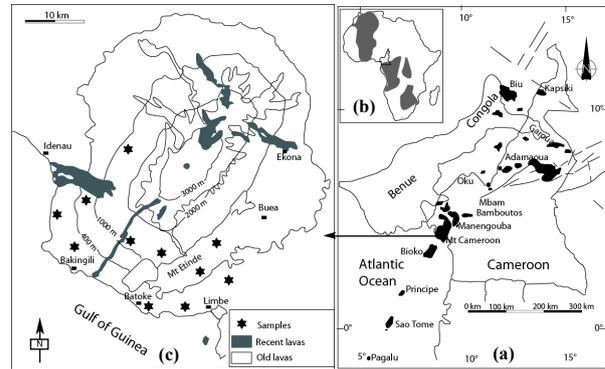


Figure 1. (a) The Cameroon Volcanic Line; (b) Cratons after [19] and (c) Location of pyroclastites on the southern and south-western slopes of Mount Cameroon

2. Geological Setting

Mount Cameroon is a major entity of the CVL (Figure 1). It is an active stratovolcano of Plio-Quaternary age with an altitude of about 4100 m [17]. Located between the sedimentary basins of Douala in the southeast and Rio del Rey in the northwest, it is hosted by a Pan-African granites and gneisses basement. A thick layer (3-7 km) of sedimentary rocks (Douala and Rio Del Rey) of Cretaceous to recent age overlies this basement [10, 18]. The CVL is also defined as a volcano-tectonic megastructure of N30°E direction with about 1600 km length. It extends in both oceanic and continental domains and is formed by an alignment of oceanic and continental volcanoes of Tertiary to present day age (from the volcanic island of Pagalu in the Atlantic Ocean to Lake Chad) [19,20].

The volcanic activity of this stratovolcano began 3 million years ago [21,22]. However, the first certified eruption was in 1909, although evidence of prehistoric eruptions is found in the remains of lava flows and pyroclastic cones [23]. Mount Cameroon has recently experienced several major volcanic eruptions, including those of 1922, 1954, 1959, 1982, 1999 and 2000, and is therefore within the most active volcanoes in Africa [24]. The last two eruptions of this volcano took place during the following periods: 28 March-22 April 1999 and 28 May-19 June 2000 [9,17,25]. Several studies on the intra-plate magmatism of Mount Cameroon, helped to determine both the mechanisms that govern the evolution of the magmas and the origin of these magmas. Those previous works reveal that the major process at the origin of the diversity of lava on the Mount Cameroon is fractional crystallization [9,10,12,13,17,26-33].

According to [13], Mount Cameroon is mainly made of basanites (60% by volume), alkali basalts (25% by volume), Hawaiiites (10% by volume) and rarely of mugearites (5% by volume). Camptonites, a type of lamprophyre composed mainly of plagioclase and brown

hornblende, have been described [13]. In addition, enclaves (1-5 cm × 0.5-4 cm) of dunites, wehrlites and clinopyroxenites have been found in the basanites of the Batoke Strombolian cone [22,30]. Similar enclaves of wehrlites and clinopyroxenites have been found in basaltic tephros of a strombolian cone [12,27]. Taking into account the granulometry and shape of the pyroclastic products resulting from the fluidity and gas pressure of the magma, ashes, bombs, slag, pumice, lapilli and blocks are encountered at Mount Cameroon (Figure 2). The lavas have porphyritic microlitic, aphyritic microlitic, trachytic; and doleritic textures (Figure 3). They have fairly homogeneous mineralogical compositions. Regularly encountered minerals are olivines, pyroxenes, plagioclases, magnetite and ilmenite (Figure 3). Apatite and calcite are rarely present.

The order of mineral crystallization within these lavas generally follow the crystallization pattern of alkali basalts, at least as far as essential minerals are concerned (olivines, clinopyroxene, plagioclase).

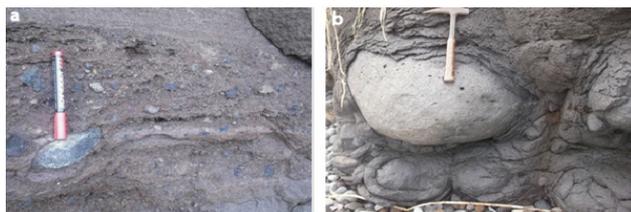


Figure 2. (a) Blocks of various sizes encased in volcanic ash in Batoke; (b) Blocks of ancient lava enclosed in a recent lava in Batoke



Figure 3. Mount Cameroon lavas textures: (a) Microlitic texture in Bakingili alkaline basalt; (b) Microlitic to porphyritic texture with pyroxene phenocrystals in Debundcha basanite; (c) Porphyritic texture with olivine phenocrystals in Batoke's picrate; (d) Microlitic to porphyritic textures in Batoke's basalts. Note plagioclase phenocrists regrouped into separated beds giving a banded structure to the rock

Notes:

Ol = Olivine; *Cpx* = Clinopyroxene; *Pl* = Plagioclase; *V* = Vacuole; *Ap* = Apatite; *Ca* = Calcite.

3. Methodology

3.1 Sample Preparation and Selection of Melt Inclusions

(1) Crystal Extraction

The first preparation step consists in the extraction of olivine crystals from the fresh sample. This extraction varies according to the nature of the material. The study of melt inclusions requires the use of a material that has cooled as quickly as possible. For this reason, the sampling of olivine phenocrystals focused on slag and volcanic ash. Slag samples are firstly crushed using a jaw crusher or manually in an agate mortar, depending on their size and hardness. Grinding separates the crystals from their matrix and fragments the aggregates. After grinding or fragmentation, the samples are sieved to select the fraction with sizes varying from 0.5 to 1 mm. This fraction is preferred because the crystals it contains are visible to the naked eye and easier to handle. Previously crushed slag and volcanic ash samples, once sieved, are manually sorted under a binocular magnifying glass to extract the olivine crystals.

(2) Preparation of Thin Sections

After separation, the olivine crystals from the 0.5 to 1 mm fractions are bonded to a glass slide in a grid pattern (about 50 crystals per slide) using a thermo-active resin (Crystalbound) at about 200°C on a hot plate. The thin sections are then manually polished on one side. Flattening of the crystals is obtained by polishing on silicon carbide mats with a grain size index of 1200 then 2000, then scratches, fractures, and pull-outs are erased by polishing on diamond mats coated with diamond solution 6 μm, 3 μm, ¼ μm and finally with colloidal silica. On a hot plate, the crystals are peeled off from the slide and introduced into a pellet with resin in order to be polished and observed under a microscope under transmitted light. Crystals containing uncrystallized inclusions of sufficient volume (diameter > 20 μm) are removed from the resin using a soldering iron, then mounted separately in small metal cylinders (diameter: 4 mm, height: 10 mm) and embedded again in resin. Each crystal is then polished until the inclusions are flush with the surface and then passed through an ultrasonic bath to remove the impurities induced by the polishing. The various cylinders are mounted on a metal support that can accommodate six studs. The whole is carbon metallized to eliminate electrical charges on the surface during electron microprobe analysis.

3.2 Analytical Techniques of Melt Inclusions

The analytical tool used in this study is the electron micro-

probe. The microprobe work was carried out at the Geochemical and Petrophysical Petrology Laboratory of the University of Liège (Belgium). This technique was used to determine the major and minor elemental composition of the inclusions and their host minerals. The model used is the CAMECA SX100 microprobe. It has four WDS (Wave Dispersion Spectrometers) and eight monochromator crystals. In point mode, the volume of matter analyzed is in order of $1\mu\text{m}^3$.

(1) Analysis of Major Elements

Point analyses allow determining the concentration of elements present in a volume of $1\mu\text{m}^3$. The calibration of measurements is made for each element on natural or

artificial standards of known compositions. In addition, in order to verify the calibrations and determine the uncertainty of the measurements, internal standards were used. For each inclusion, two to three points of analysis were performed, depending on the size of the inclusions.

(2) Analytical Conditions

The set of analytical conditions used in electron microprobe analysis is a power of 15 nA and a 2-3 μm spot beam for olivines (Table 1).

In order to limit sodium loss during lens analysis [34], the power is reduced to 8 nA and the beam is defocused at 5, 10 or 20 μm , depending on the size of the inclusion (Table 2).

Table 1. Analytical conditions used for measurement of major element concentrations in olivines (“olivines” programme), and inclusions (“glasses” programme)

Programme	Voltage	Power	Spot size	nber of cycles	Crystal	Element	Time per cycle (s)	Calibrated on:
Olivines	15 kV	15 nA	ponctuel (2 to 3 μm)	1	TAP	Mg	40	Forsterite
					PET	Ca Ti	30 20	Wollastonite Titanomagnetite
					LIF	Fe Mn	40 10	Fayalite Titanomagnetite
					TAP	Si	20	Wollastonite
Glasses	15 kV	8 nA	5 to 20 μm	1	TAP	Na Mg	10 30	Albite Periclase
					LIF	Fe Mn	40 30	Hematite Titanomagnetite
					PET	Ti	20	Titanomagnetite
						P	10	Apatite
						K	40	Orthoclase
						Ca	10	Wollastonite

Note:

Analyzer crystal: TAP, PET, LIF.

Table 2. Detail of the various errors associated with electron microprobe analyses

Programme		Analytical error (%)	Detection limit	Reproducibility on a sample. Mean (n=5). Standard Deviation (%)		Reproducibility on the standard. Mean (n=5). Standard Deviation (%)		Accuracy (%)	Standard
Olivines	SiO2	1.2	0.06	39.30	1.1	41.16	0.87	0.57	San Carlos
	TiO2	200	0.07	0.02	93.1				
	FeO	2	0.05	17.31	1.2	9.07	1.22		
	MnO	40	0.10	0.31	9.3	0.14	24.09		
	MgO	1	0.04	43.60	0.4	49.45	0.59		
	CaO	20	0.04	0.25	7.1	0.02	27		
Glasses	SiO2	1.3	0.11	37.09	0.8	50.80	0.4	0.5	VG2
	TiO2	7.7	0.06	1.79	2.4	4.18	1.3		
	Al2O3	1.5	0.06	14.06	0.9	12.51	0.9		
	FeO	4.3	0.16	10.98	2.7	13.08	1.7		
	MnO	60-150	0.17	0.10	43.3	0.23	30.8		
	MgO	1.6	0.05	9.31	1.2	4.99	1.6		
	CaO	1.4	0.04	16.07	0.8	9.12	0.6		
	Na2O	7.3	0.10	3.99	2.7	2.67	3.6		
	K2O	2.2	0.02	2.05	2.9	0.85	4.4		
	P2O5	28	0.10	2.28	5.8	0.48	11.8		

Notes:

Standard: San Carlos: olivine Fo91 [35] VG2: basaltic glass [36]

(3) Analysis of Trace Elements, Rare Earths

Trace element and rare earth element analysis in the inclusions was performed by IMS 3f ion probe. These elements were measured during the same 16-cycle measurement, using a projected beam of primary ions of about 30 μm , an accelerating current of 10kV for the primary beam and 4.5kV for the secondary current. The source used is the duoplasmatron. Each element is measured for 10 seconds.

3.3 Analytical Techniques of Bulk - rock (Lavas)

The major and some trace elements were analyzed by X-ray fluorescence spectrometry at the Laboratory of Petrology Geochemistry and Petrophysics of the University of Liege (Belgium). The sample, composed of solid materials crushed then compacted or melted into pellets, is subjected to an X-ray bombardment which causes the emission of a secondary X-ray radiation called X-ray fluorescence. This radiation is sent through a crystal which diffracts it at an angle characteristic of the element entrusted by the sample and whose intensity measured at the exit of the crystal makes it possible to determine its concentration.

Other trace elements were analyzed by ICP-MS at the Geology Laboratory of Tervuren (Belgium).

4. Results

4.1 Description of Trapped Melt Inclusions and Host Olivines

Numerous vitreous inclusions are present in olivines from the pyroclastites of Mount Cameroon. They have a primary or secondary nature (Figure 4a, 4b) and are spherical to subspherical in shape (Figure 4c). They contain one or more thermal shrinkage bubbles. Some have thread minerals with epitaxial distribution.

The olivine crystals samples selected from the pyroclastites are phenocrysts of homogeneous composition. Their shape is sometimes polyhedral (Figure 4a), attesting to growth by slow cooling at thermodynamic equilibrium with the parent liquid. For each sample, the selected olivines showed no apparent signs of alteration or fracturing.

The melt inclusions trapped in euhedral olivine crystals of Mount Cameroon selected for this study, are primary in nature. It means the liquid was trapped during the growth of the host mineral. Their size varies between 20 and 300 μm and they sometimes contain a thermal shrinkage bubble, which demonstrated rapid cooling linked to a rapid rise of the magma towards the surface (Figure 4a). The formation of some of these inclusions seems to have been favored by the presence of spinel crystals during the

growth of the host olivine (Figure 4d).

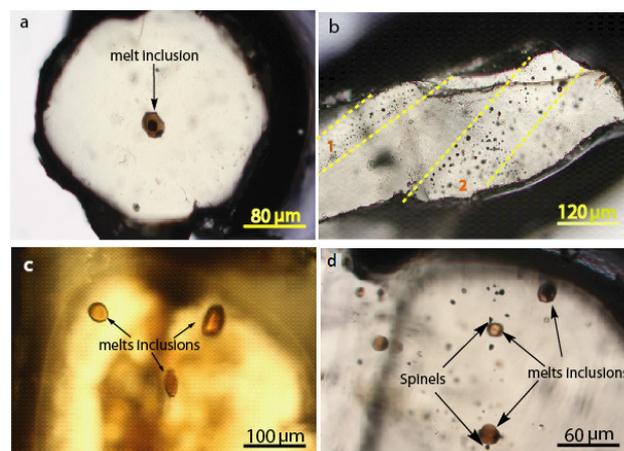


Figure 4. Different types of magmatic inclusions: (a) Primary melt inclusion with shrinkage bubble in an olivine from Idenau; (b) Preferential alignment of secondary melt inclusions in a Batoke olivine; (c) Primary melt inclusions without shrinkage bubbles trapped in olivine at Bakingili, (d) Spinel crystals trapped within or associated with melt inclusions in Mount Cameroon olivine. These spinel crystals were formed before the liquid was trapped

4.2 Geochemistry

4.2.1 Major Elements

To characterize the composition of the trapped magmas, the “whole rock” geochemistry data of the inclusions are reported in the Total Alkali-Silica (TAS) classification diagram after ^[35] (Figure 5, Table 3). The whole rock geochemistry data from the Mount Cameroon lavas has also been added for comparison (Figure 5, Table 4). The magmas trapped as inclusions are basanitic and basaltic in nature (Figure 5). Their compositions display a very wide silica range (SiO_2 of 43.44 - 51.50 %). These liquids contain significant amounts of TiO_2 (2.23 - 4.42%) and Al_2O_3 (12.67 - 16.23%). The MgO contents (4.16 - 11.44%) are relatively low with an overall average of 7.48%. Those of CaO (9.29 - 13.87%) and MnO (0.07 - 0.24%) are variable with MnO showing very low values. (Table 3).

The Mount Cameroon lava samples present variable SiO_2 compositions and plot from micro-basalt to mugearite fields (Figure 5).

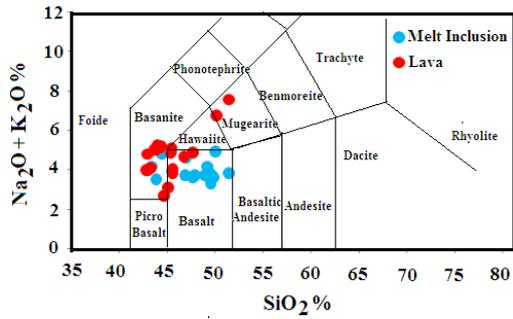


Figure 5. Total Alkali-Silica classification diagram of liquids trapped in the olivines of the Mount Cameroon pyroclastites according to the nomenclature of [37]. The positions of lava from Mount Cameroon are added for comparison

Titanium (4.42 to 2.23), iron (13.96 to 7.91), magnesium (11.44 to 4.16), alkali (6.76 to 3.29) and phosphorus (1.07 to 0.23) of trapped primary liquids show a negative correlation in the major elements versus silica variation diagram. The behavior of Ti, Fe, and Mg is explained by the fractional crystallization process of clinopyroxene, the behavior of phosphorus is due to apatite crystallization especially in mugearites.

The evolution of major elements in inclusion trapped liquids is therefore not governed by a simple fractional crystallization process, as already observed in the evolution of alkalis (Figure 6).

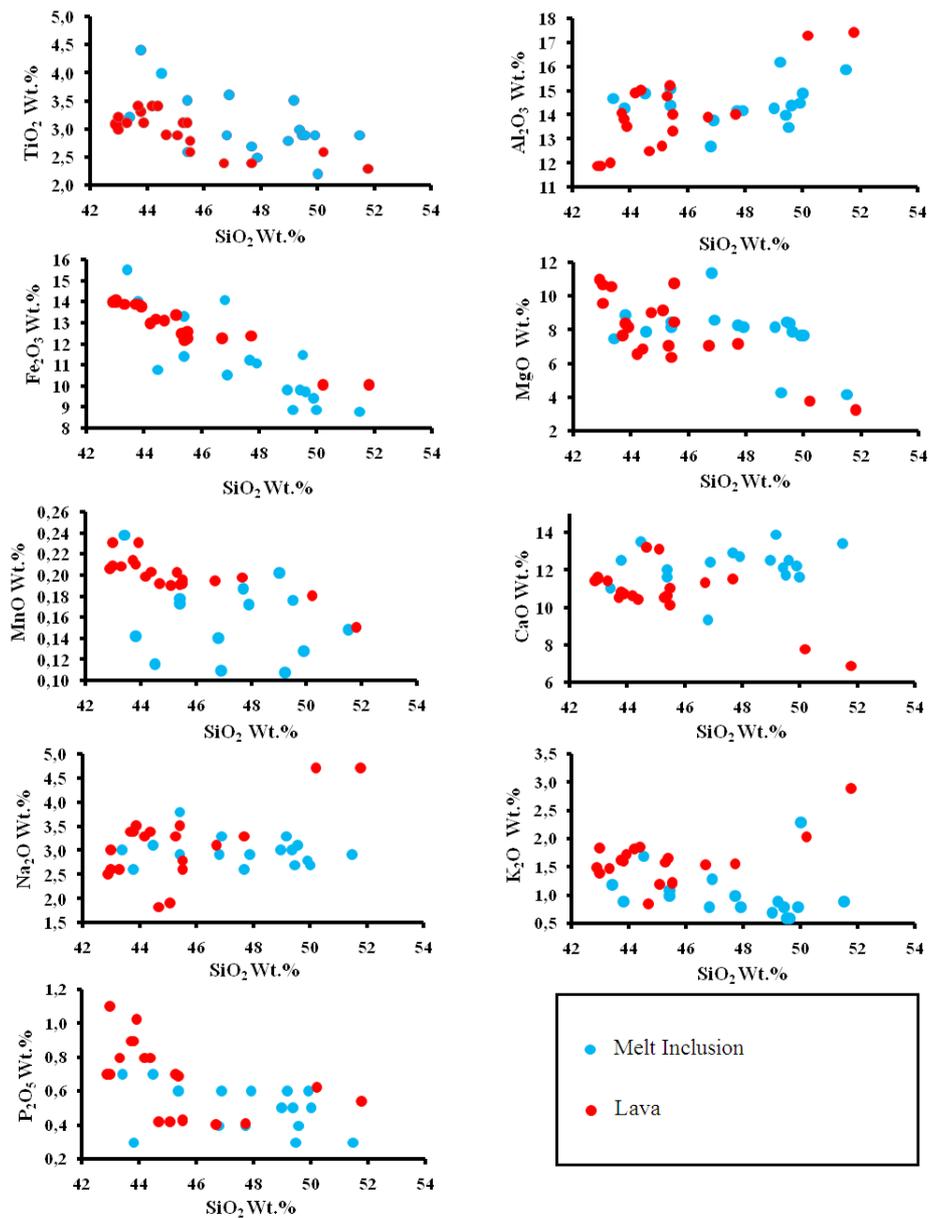


Figure 6. Major elements versus SiO_2 variation diagrams of the Mount Cameroon melt inclusions

Table 3. Whole-rock analyses (major, trace and Rare Earth Elements) of the Mount Cameroon melt inclusions.
 $Fe_2O_3^t = Fe_2O_3$ total; n.d. = not determined

Majors (%)																	
<i>Samples</i>	<i>TCI-1</i>	<i>TCI-2</i>	<i>TCI-4</i>	<i>TCI-11</i>	<i>TCI-14</i>	<i>TCI-15</i>	<i>TCI-17</i>	<i>TCI-18</i>	<i>TCI-19</i>	<i>TCI-5</i>	<i>TCI-6</i>	<i>TCI-7</i>	<i>TCI-9</i>	<i>TCI-10</i>	<i>TCI-12</i>	<i>TCI-13</i>	<i>TCI-16</i>
SiO ₂	43.8	44.5	43.4	51.5	49	49.2	45.4	46.9	47.7	49.4	49.5	46.8	49.6	45.4	49.9	50	47.9
TiO ₂	4.4	4	3.2	2.9	2.8	3.5	2.6	3.6	2.7	3	2.9	2.9	2.9	3.5	2.9	2.2	2.5
Al ₂ O ₃	14.3	14.9	14.7	15.9	14.3	16.2	15.1	13.8	14.2	14	13.5	12.7	14.4	14.4	14.5	14.9	14.2
Fe ₂ O ₃ ^t	14	10.8	15.5	8.8	9.8	8.9	11.4	10.5	11.2	9.8	11.5	14.1	9.7	13.3	9.4	8.9	11.1
MnO	0.14	0.12	0.24	0.15	0.20	0.11	0.17	0.11	0.19	0.09	0.18	0.14	0.09	0.18	0.13	0.07	0.17
MgO	8.9	7.9	7.5	4.2	8.2	4.3	8.2	8.6	8.3	8.5	8.4	11.4	7.9	8.5	7.7	7.7	8.2
CaO	12.5	13.5	11	13.4	12.5	13.9	12	12.4	12.9	12.1	11.7	9.3	12.5	11.6	12.2	11.6	12.7
Na ₂ O	2.6	3.1	3	2.9	3	3.3	3.8	3.3	2.6	3	2.7	2.9	3.1	2.9	2.8	2.7	2.9
K ₂ O	0.9	1.7	1.2	0.9	0.7	0.9	1.1	1.3	1	0.8	0.6	0.8	0.6	1	0.8	2.3	0.8
P ₂ O ₅	0.3	0.7	0.7	0.3	0.5	0.6	0.6	0.6	0.4	0.5	0.3	0.4	0.4	0.6	0.6	0.5	0.6
Total	101.8	101.1	100.5	100.9	101	100.9	100.5	101.1	101.1	101	101.2	101.4	101	101.3	100.9	100.9	101.1
Traces (ppm)	<i>TCI-1</i>	<i>TCI-2</i>	<i>TCI-4</i>	<i>TCI-11</i>	<i>TCI-14</i>	<i>TCI-15</i>	<i>TCI-17</i>										
Ni	360	363	361	370	362	344	355	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr	870	867	860	787	722	699	755	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Co	69	67	67	71.4	70.9	69.8	66	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sc	37	39	36.1	38.1	35.2	36.6	36.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rb	39.4	38.9	38.5	36.7	40.6	37.9	39.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ba	389	396	390	400	402	402	386	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sr	856	799	1155	901	900	1009	1071	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zr	325.1	327.2	339.6	309.2	267	289.2	299.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Y	40.4	39.8	39.8	36.9	37	35.9	38.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nb	101.3	103.6	90.2	86.6	96	79.4	80.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ta	5.6	6.2	5.2	7.4	4	6.5	5.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Hf	8.7	8.8	8.2	8.9	8	9.3	7.8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	3.9	4	3.3	5	4.5	3.3	3.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Th	3.2	4	6	5.9	5.1	5	5.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
U	2	1.9	1.7	2.6	2.2	2.2	1.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
REEs (ppm)																	
La	74.8	69.8	73.7	60.2	59.5	36	62.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ce	130.5	132.1	129.6	129.6	123.2	119.3	117.2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pr	21.6	19.6	19	16.1	13.2	12.1	12.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nd	65.4	64.8	60.8	69.1	69	70.2	73.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sm	11.2	12.1	11.3	9.8	11.6	10.6	9.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Eu	3.2	3.6	3.7	4	4.1	4	3.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Gd	10.1	10	10.2	10.1	10.7	10.7	10.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Tb	1.5	1.3	1.4	1.2	1.2	1.2	1.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Dy	7.1	6.9	7	6.5	6.5	6.5	6.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ho	1.4	1.5	1.2	1.4	1.5	1.5	1.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Er	3.6	3.3	3.6	3.1	3.3	3	3.1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Yb	1.9	1.9	1.9	1.8	1.7	1.6	1.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lu	0.4	0.4	0.4	0.4	0.5	0.5	0.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

Table 4. Whole-rock analyses (major, trace and Rare Earth Elements) of the Mount Cameroon lavas. Fe₂O_{3t} = Fe₂O₃ total

Major Elements (%)																		
Samples	DB5	DB13	ID21	ID20	ID15	ID13	ID10	ID6	ID11	BK12	ID26	ID30	DB18	DB20	DB10	BK11	ID35	ID36
SiO ₂	43.9	43	44.2	42.9	44.4	43,8	43	43.3	43.7	45.3	45,5	45.5	46.7	47.7	45.1	45.4	51.8	50.2
TiO ₂	3.1	3	3.4	3.1	3.4	3.3	3.2	3,1	3.4	3.1	2,6	2.8	2.4	2.4	2.9	3.1	2.3	2.6
Al ₂ O ₃	13.5	11.9	14.9	11.9	15	13.8	11.9	12	14.1	14.8	13,3	14	13.9	14	12.7	15.2	17.4	17.3
Fe ₂ O _{3t}	13.8	14	13.0	14	13.2	13.9	14.1	13.9	13.9	12.5	12,6	12.3	12.3	12.4	13.4	12.2	10.1	10.1
MnO	0.23	0.23	0.20	0.21	0.20	0.21	0.21	0.21	0.21	0.21	0,20	0.19	0.19	0.20	0.19	0.19	0.15	0.18
MgO	8.2	9.6	6.6	11	6.9	8.4	10.7	10.6	7.7	7.1	10,8	8.5	7.1	7.2	9.2	6.4	3.3	3.8
CaO	10.7	11.5	10.6	11.4	10.4	10.8	11.6	11.4	10.5	10.5	10,1	11	11.3	11.5	13.1	106	6.9	7.8
Na ₂ O	3.5	3	3.3	2.5	3.4	3.4	2.6	2.6	3.4	3.3	2,6	2.8	3.1	3.3	1.9	3.5	4.7	4.7
K ₂ O	1.7	1,78	1.8	1.5	1.8	1.6	1.4	1.5	1.6	1.6	1,2	1.2	1.5	1.5	1.2	1.7	2.9	2
P ₂ O ₅	1	1,71	0.8	0.7	0.8	0.9	0.7	0.8	0.9	.7	0,4	0.4	0.4	0.4	0.4	0.7	0.5	0.6
LOI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	99.6	99.1	98.8	99	99.7	100	99.4	99.4	99.4	98.9	99.4	98.8	98.8	100.7	100.1	98.9	100	9.3
Traces (ppm)																		
Ni	116	171	75	194	72	92	183	184	102	85	393	151	83	94	128	76	70	71
Cr	197	302	111	101	105	118	220	433	199	277	615	339	84	83	322	126	102	98
Co	44	52	45	49	44	41	52	58	41	37	47	53	43	63	52	48	35	34
Sc	26	25	24	34	29	30	27	31	35	26	33	30	30	30	33	25	25	24
Rb	49	50	50	39	50	46	38	40	47	41	35	35	56	53	24	37	49	70
Ba	614	659	522	330	529	520	490	461	331	440	385	406	613	608	n.d.	462	553	693
Sr	1447	1716	1189	939	1186	1042	917	1134	1049	961	945	973	1383	1383	815	1118	955	1012
Zr	537	591	443	344	444	411	341	407	416	352	326	343	559	563	280	393	516	576
Y	39	40	33	30	33	33	30	31	34	32	26	28	36	36	25	33	36	37
Nb	144	148	112	83	111	97	82	101	97	82	98	81	135	136	67	102	144	164
Cs	0.5	0.7	0.8	0.2	0.8	0.4	0.4	0.7	0.4	0.3	0.4	0.3	0.7	0.7	n.d.	n.d.	n.d.	n.d.
Ta	8.7	8.3	6.2	4.4	6.4	5.5	6.3	5.7	6.1	6.2	4.5	4.6	7.6	7.6	4	6.1	7.6	8.1
Hf	10.9	11.6	8.8	6.1	9.9	7.4	8.1	8.2	7.3	8.1	6.6	7.1	10.3	10.5	6.5	8.1	10.2	11.1
Pb	6.1	7	4.7	5.1	4.7	5	6	4.9	5.2	5.6	4.3	4	6.1	6.5	3.2	5.6	4.9	8
Th	11.9	12.2	8.3	6	8.4	8	6	8	6	5	6.3	6.5	12.3	12.2	5.3	8	10	13
U	3.2	3.3	2.1	1.6	2.2	2.3	3	2.1	2.3	2.4	1.7	1.8	3.3	3.2	1.4	2.1	2.9	2.8
REEs (ppm) La	103	114	77	50	78	86	77	73	66	66	54	55	97	96	46	67	86	96
Ce	224	248	164	115	166	159	156	160	150	147	114	119	201	199	105	145	171	194
Nd	93	101	69	52	71	70	74	70	64	66	49	52	78	77	49	65	73	80
Sm	15.2	17.2	12	8.6	12.3	11.9	12.1	12.2	14.1	13.4	8.8	9.4	13.1	12.8	9	11.1	13.1	14
Eu	4.4	4.9	3.8	2.8	3.8	2.5	3.1	3.3	3.7	3.6	2.7	3	3.9	3.9	2.7	3.5	3.9	4
Gd	11.4	13.5	10.6	7.1	10.7	9	10.1	10	9.2	8.8	7.7	8.5	10.5	10.6	7.5	8.9	10.3	10.6
Tb	1.4	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.2	1.1	1.2	1.2	1.3	1.7	1.5	1.5
Ho	1.5	1.5	1.2	0.9	1.2	1.3	1.2	1.1	1.4	1.2	0.9	1	1.2	1.2	0.9	1.2	1.3	1.3
Er	3.4	3.6	3	2.1	3.1	3.4	3.1	2.9	2.4	3	2.4	2.6	3.3	3.2	2.4	3	3.4	3.3
Yb	n.d.	2.8	2.4	1.9	2.4	1.9	2.3	2.3	1.9	2.4	1.9	2.1	2.6	2.6	1.9	2.5	2.9	2.9
Lu	0.4	0.4	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.2	0.4	0.4	0.4

4.2.2 Trace Elements

Ni, Cr, Co and Sc contents of the lava from Mount Cameroon decrease according to the rate of differentiation (Figure 7), illustrating the fractionation of clinopyroxene and spinel respectively. It is also noted that the Cr contents of the least differentiated lavas are low (303 ppm) compared to a primary magma (600 - 800 ppm); the Ni contents are relatively low (138 ppm) compared to values of 300 to 400 ppm in a primary magma. This confirms the existence of a previous fractionation at least of olivine and spinel.

The melt inclusions have relatively low Th contents and are consistent with the most basic terms of the lava from Mount Cameroon. Sc contents are relatively high and do not show a significant decrease as a function of Th, showing that clinopyroxene fractionation does not play a major role in the evolution of liquids trapped as inclusions. On the other hand, Cr contents are highly variable (83 to 898 ppm). However, one or more spinel droplets are sometimes trapped in the walls of some analyzed inclusions (Figure 4d) suggesting some possible interaction which can drastically modify the chromium contents of the melt inclusions. The inclusions of the olivines of Mount Cameroon show a net decrease in Cr as a function of Th, reflecting the influence of spinel in the evolution of

these liquids.

As shown in Figure 8, the incompatible trace elements of the trapped melt are positioned at the end of the trend. The evolution of the highly incompatible (Ba, La) or moderately incompatible (Sr, Eu) elements of the lavas is consistent with a process of fractional crystallization of clinopyroxene, olivine and spinel for the most basic lavas and then phases such as plagioclase for the less basic ones. The incompatible trace elements of the melt inclusions tend to follow the evolution of the most basic lavas, and even have slightly lower Th contents, which underlines the primitive character of these liquids compared to lavas.

4.2.3 Rare Earth Elements

Primary mantle-normalized trace element concentrations^[38] are plotted in Figure 9 according to the order of MORB incompatibility established by^[39].

As the lavas from Mount Cameroon, the melt inclusions present variable but very high concentrations of incompatible elements, typical of continental and oceanic islands basalts^[38,40].

The inclusions multi element patterns have some common features, such as positive anomalies in Zr and Gd, and negative anomalies in K, Pb and Ti.

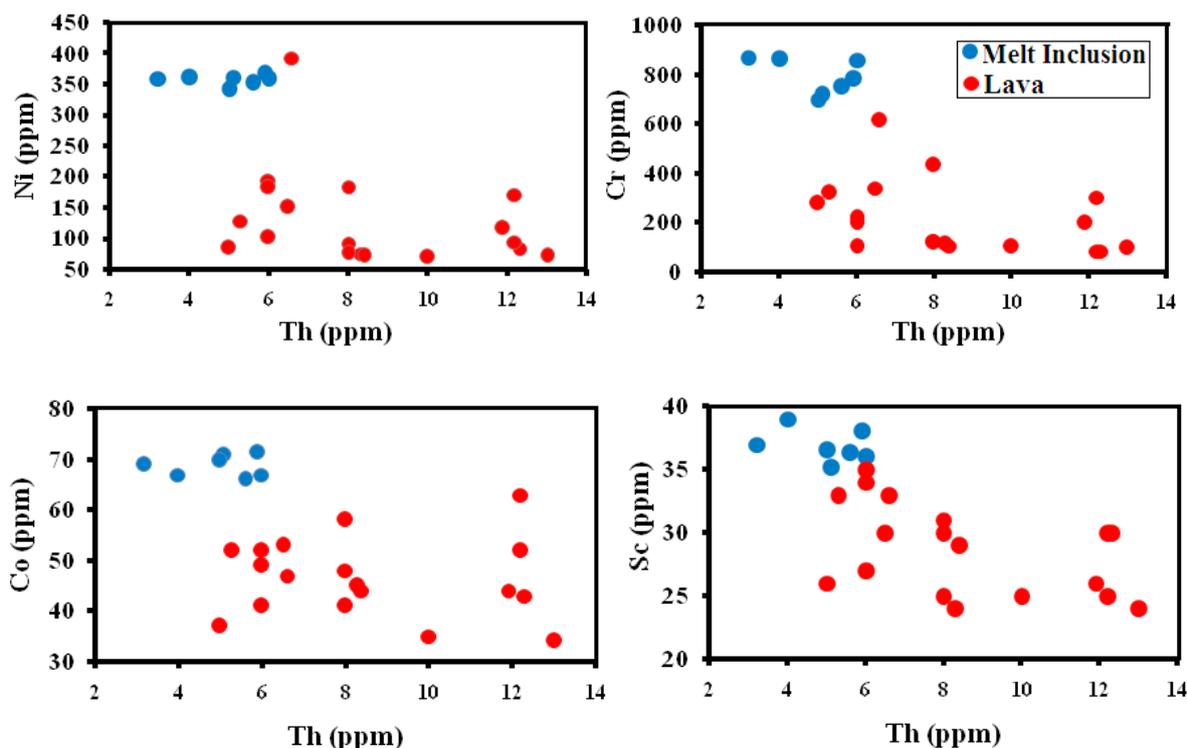


Figure 7. Evolution of the Ni, Cr, Co and Sc contents of the melt inclusions versus Th compared to those of the lavas of Mount Cameroon

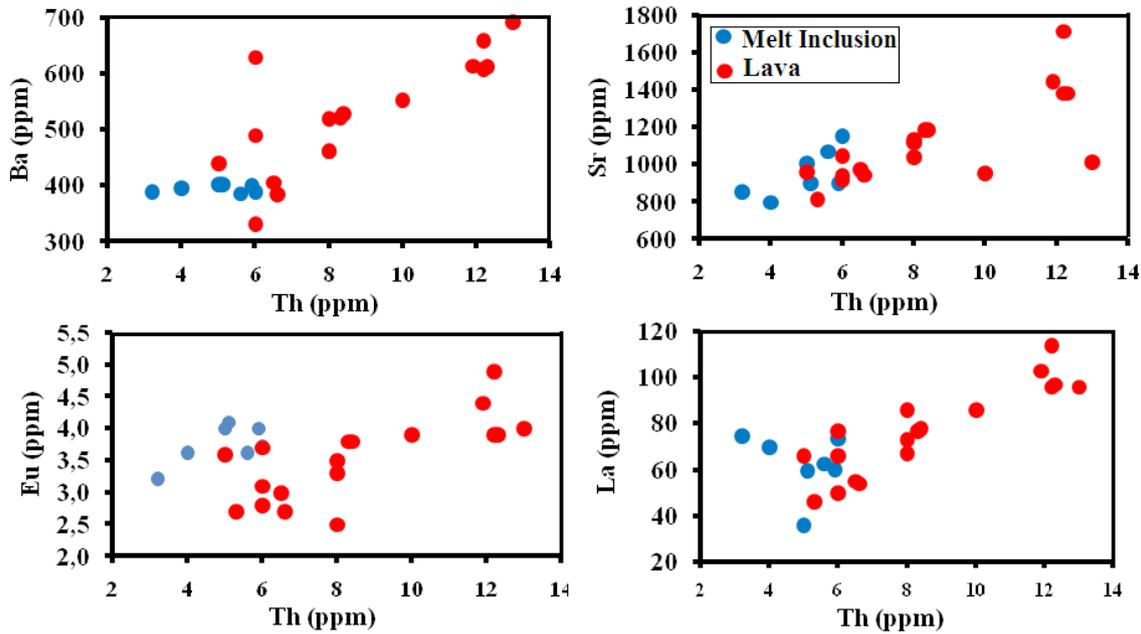


Figure 8. Evolution of Ba, La, Sr and Eu contents of melt inclusions versus Th, compared to those of the lavas from Mount Cameroon

However, the enrichment of the most incompatible elements varies greatly from one inclusion to another. Indeed, some inclusions show a less pronounced K anomaly, but are more enriched in Th, U, Nb and Ta. The spectra of the magmatic inclusions compared to that of lavas show profiles confirming an evolution from magmatic inclusions to lavas by fractional crystallization.

The negative K anomaly in inclusions is common in oceanic and continental alkali basalts of the Cameroon Volcanic Line. [41] show that the existence of this anomaly is due to the presence of a potassic residual phase in the mantle source.

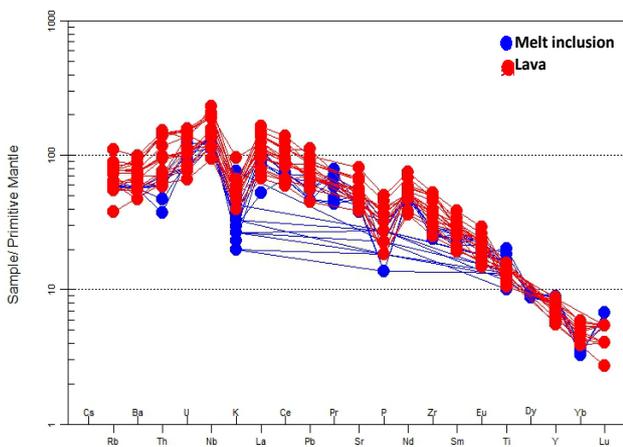


Figure 9. Multi element spider plot of melt inclusions and lavas from Mount Cameroon normalized to the primitive mantle [38]

Trace element concentrations are normalized to chondrite. The spectra show decreasing slopes from Light Rare Earth Elements to Heavy Rare Earth Elements (Figure 10). The parallelism between the REE spectra of inclusions and that of lava shows an important genetic link between them. They are characterized by an enrichment in LREE compared to HREE. However, this enrichment is slightly variable from basanitic to basaltic inclusions.

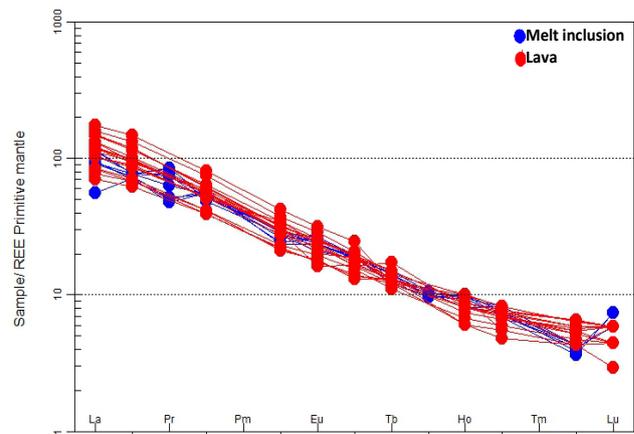


Figure 10. Chondrite-normalized Rare Earth Element spectra [42] of melt inclusions and lavas from Mount Cameroon

5. Discussion

5.1 Magma Evolution

In general, the main processes mentioned as the origin of magma diversity are fractional crystallization, partial melting, magma mixing and crustal contamination. One or more of these mechanisms may explain the compositional variations observed in the melt inclusions of Mount Cameroon.

5.1.1 Crustal Contamination

Melt inclusions show enrichment in Light Rare Earths and LILES (Figure. 10). This enrichment may be the result from crustal contamination. However, studying melt inclusions in relatively primitive olivines means that these liquids were trapped at the beginning of the fractional crystallization process and are therefore less likely to have been contaminated. In addition, the trapped liquids have relatively low silica contents, as the silica is enriched during a crustal contamination process. Nevertheless, the SiO₂ concentration range of melt inclusions is very wide (up to 51% by weight). This would indicate the absence of any contamination. This has already been discussed by [11,30].

It can therefore be concluded that the composition of the liquids trapped as melt inclusions in the most magnesian olivines of Mount Cameroon is not affected by the assimilation in the magmatic chamber.

5.1.2 Magmatic Evolution Process: Fractional Crystallization, Magma Mixing or Partial Melting

Sc contents do not show consistent variations with a fractional crystallization process (Figure 7). However, variations in Cr would show the influence of spinel, and

the negative correlation observed between silica and lanthanum (Figure 11), one of the incompatible elements, is contrary to an evolution mainly controlled by fractional crystallization. Ultimately, variations in the composition of melt inclusions cannot be explained essentially by a fractional crystallization process. Therefore, the processes of partial melting or magma mixing remain to be explored.

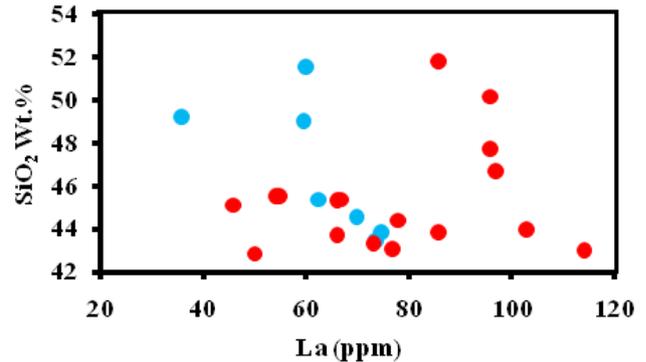


Figure 11. Evolution of SiO₂ concentrations as a function of the La content of melt inclusions. (Same legend as in Figure 8)

The differentiation between magma mixing or partial melting is by studying the relationship between two incompatible elements A and B but having different degrees of incompatibility “D” ($D_A < D_B < 1$) [43]. Indeed, in the case of a mixture, a linear correlation will always be obtained regardless of the sharing coefficients of the elements chosen. On the other hand, a melting process (at equilibrium or fractionated) will result in a straight line only if $D_A = D_B$ or if D_A and D_B are lower than the melting rate “F”; otherwise a curve will be [43], as in the example of the pair of elements La/Zr and Rb/Nb with $D_{La} < D_{Zr}$ and $D_{Rb} < D_{Nb}$) (Figure 12).

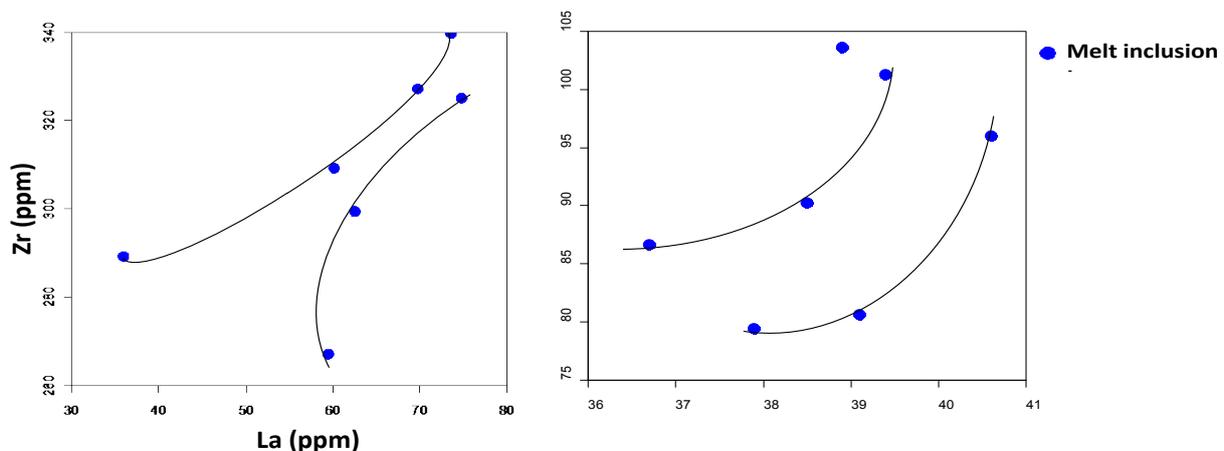


Figure 12. Evolution of Zr contents as a function of La, and Nb contents as a function of Rb of melt inclusions

The curves observed in Figure 12 above involve elements with different “D”. It is possible to compare the processes of partial melting and fractional crystallization in a C_A/C_B vs. C_A diagram where $D_A < D_B < 1$ [43]. In such a diagram, partial fusion results in a straight line passing through the origin, whereas fractional crystallization results in a straight line parallel to the abscissa axis [44,45]. In our case, we chose two Rare Earths, La and Yb with $D_{La} < D_{Yb}$, not only because of the constant order of incompatibility of the Rare Earths, but also because these two elements are incompatibles in most of the processes involved (Figure 13).

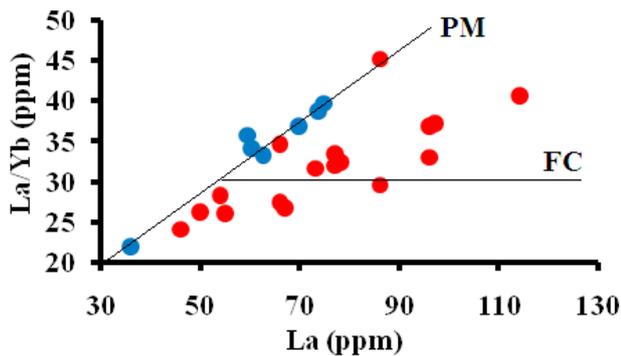


Figure 13. Evolution of the La/Yb ratio as a function of La; the line passing through the origin materialized by the melt inclusions shows an evolution by variation of the partial melting rate (PM), while the horizontal line materialized by the lavas of Mount Cameroon shows an evolution trend by fractional crystallization (FC). (Same legend as in Figure 8)

The compositions of the melt inclusions show that the lavas from Mount Cameroon are clearly more differentiated than the liquids trapped in the olivines. The relationship between lavas and melt inclusions is well illustrated by Figure 13. According to that diagram (Figure 13), inclusions evolve by partial melting while lavas evolve following both partial melting and fractional crystallization from a single source with varying degrees of partial fusion.

5.1.3 Estimation of the Degree of Melting and Identification of the Petrogenetic Model

The rare earth spectra of the Mount Cameroon melt inclusions and lavas show a high enrichment of Light Rare Earths compared to Heavy Rare Earths (Figure 10). [46] said that enrichment may be explained by two main hypotheses:

- (1) Either the magmatic source is enriched in incompatible elements and the melting rate is relatively high;
- (2) or the source is depleted and partial melting occurs

at a low rate.

It is possible to estimate the variation in the melting rate of a homogeneous source between a liquid with the lowest melting rate (F1) and a liquid with the highest melting rate (F2). The equilibrium partial melting equation defined by [47] is considered for a highly incompatible element A and is obtained for F1 and F2:

$$CA1 = \frac{CoA}{F1.(1-D)-D} \quad (1)$$

$$CA2 = \frac{CoA}{F2.(1-D)-D} \quad (2)$$

or $D \ll 1$, thus negligible in each equation, and so the following equation is:

$$\frac{CA1}{CA2} = \frac{FA1}{FA2} \quad (3)$$

In the case of this study, Figure 8 shows that highly incompatible elements such as Ba, La or Th indicate that the degree of partial melting increases by a factor of 0.2 to 2.

The Ce/Y and Zr/Nb ratios in Figure 14 are used to estimate the partial melting degrees of the mantle and to determine the nature of the source. The diagram shows the relationship between source composition and degree of partial melting. The melt inclusions of Mount Cameroon lie between the enriched garnet lherzolite and depleted garnet lherzolite curves. Magmas under Mount Cameroon would be generated at different partial melting rates ranging from 0.2 to 2% (Figure 14). This diagram shows, the presence of garnet in the source of the lava from Mount Cameroon, suggesting a deep depth [48] for the magma origin.

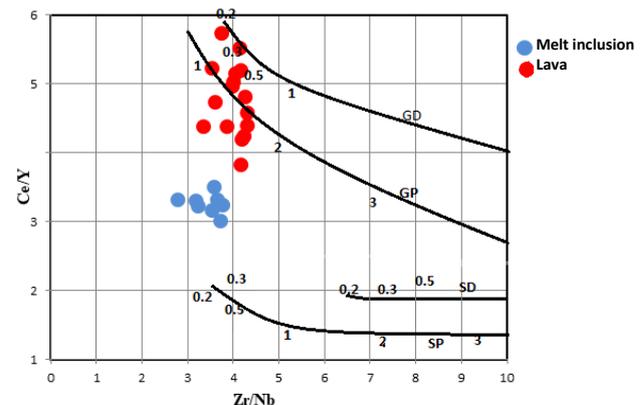


Figure 14. Ce/Y vs Zr/Nb diagram by [48] of the partial melting and mantle source melting rates applied to melt inclusions on Mount Cameroon. GD= depleted garnet lherzolite; GP= Primitive Garnet Lherzolite; SD= depleted spinel lherzolite; SP= primitive spinel lherzolite

Furthermore the work of [54] demonstrated from the study of trace elements and rare earths in the basic rocks of the volcanoes of the continental part of the Cameroon

Line that the products emitted have characteristics of OIBs and come from the partial melting of the ascending mantle in the asthenosphere. As far as rare earths (incompatible elements) are concerned, it is recognized that the melting of a stabilized mantle in the garnet domain produces alkaline basaltic magmas whose rare earth spectra are depleted in heavy rare earths compared to light rare earths because the former are retained in the solid residue with which they are highly compatible (stronger “affinity” of heavy rare earths for garnets which are not very fusible).

5.2 Petrogenesis of Primitive Trapped Liquids

In the previous paragraphs, it is shown that liquids trapped as melt inclusions result from the partial melting of an homogeneous source, with variable melting rates; the compositional “anomalies” highlighted in the multi-element spectra can therefore be interpreted as characteristics of this mantelic source.

Comparison with Different Mantle

The spectra of the Mount Cameroon melt inclusions are characteristic of continental intra-plate basalts^[10,42]. The isotopic compositions of intra-plate basalts show a strong heterogeneity of their mantle source composition^[49]. Systematic isotope studies of these intra-plate basalts reveal several distinct poles of the mantle source^[39]. These poles represent different enriched mantle reservoirs which, by mixing, define the entire compositional spectrum of intraplate basalts. Thus, in addition to the Depleted Mantle (DMM), three other reservoirs have been identified, EM1, EM2 and HIMU^[39,49] (Figure 15).

Each of the above-mentioned mantle reservoirs has its own signature of incompatible elements. It is therefore interesting to compare the composition of the samples in this study with those of basalts representative of these different reservoirs.

The enrichment of incompatible elements in the studied samples relative to the MORBs, which would indicate an enriched mantle source relative to the upper mantle source of the Mid-Oceanic Ridge Basalts (Figure 15).

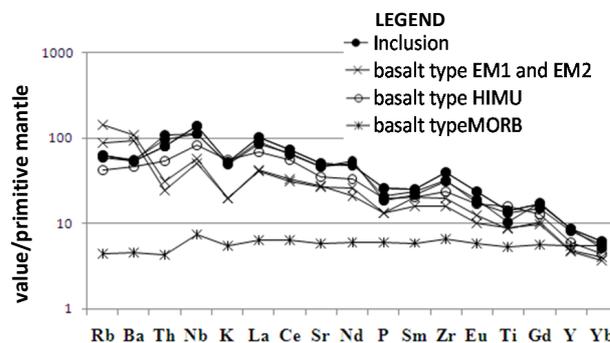


Figure 15. Multi-element Spectra of the melt inclusions of Mount Cameroon, normalized to the primitive mantle^[50] compared to those of representative basalts of different mantle reservoirs

Melts inclusions show the characteristic depletion in LILE (Rb, Ba and K) of HIMU-type basalts and their spectra are very close to those of HIMU-type basalts. In addition, the multi-element spectra show a progressive enrichment from Yb to Nb (the highest enrichment is attributed to Nb) followed by a slight decrease from Nb to Rb. This character is indeed a fundamental property of alkaline basalts of the HIMU type in which elements such as Ba and Rb are less enriched than Nb^[51]. This is in accordance with the available isotope data on Mount Cameroon basalts^[30]. Measurements of these isotope ratios $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ are respectively between 0.703198 - 0.703579 and 0.512735 - 0.512858. For the isotope ratios $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, the values are 20.2130, 15.6594 and 40.1075, respectively^[30]. The values of these isotope ratios of the lava from Mount Cameroon as well as those of all the lava from the Cameroon Volcanic Line^[52], confirm the hypothesis of the HIMU type mantelic source.

6. Conclusion

This study determine the nature, evolution and specificities of the magmatic liquids trapped in early minerals from Mount Cameroon, and compare them with emitted lavas. The liquids trapped are the original primitive lava which gave birth to basaltic lavas hosts emitted during volcanic eruptions. Major elements of melt inclusions, trapped in the most magnesian olivines (Mg#84-86) of Mount Cameroon has revealed original “primitive” liquids of basanite and alkali basalt type. The original primitive lavas did not undergo the process of evolution by fractional crystallization, but fundamentally (or exclusively) underwent the process of partial melting. The evolution of emitted lava was governed by both partial melting and fractional crystallization, the last process playing the ma-

major role. Variations in trace element contents in basaltic lavas results from evolution by fractional crystallization, but in trapped liquids, it directly reflect the partial melting rate of a homogeneous mantle source.

Enrichment of Light Rare Earth Element as well as depletion in Heavy Rare Earth Element in the Mount Cameroon inclusions are compatible with their derivation from a low degree of partial melting of a mantelic source where garnet is the residual phase. The “primitive” liquids and lavas of Mount Cameroon represent a co-genetic sequence formed by varying degrees of partial fusion from a source considered to be homogeneous. The primitive liquids trapped in inclusions of Mount Cameroon lavas, would have come from a deeper magma chamber surely in the asthenospheric mantle; and the lava emitted could have originated from a shallower magmatic chamber of the lithospheric mantle.

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