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Petrogenesis of Lava from Wainama West, Mount Oku (CVL): Source Characterization and Magma Evolution

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Abstract The Wainama West area belongs to the Cameroon volcanic Line (CVL). Three petrographic types of lavas are identified: basanites, trachytes and rhyolites. Basanites with porphyritic texture are made up of minerals: plagioclase, clinopyroxene, olivine phenocrysts and opaque minerals within a groundmass; trachytes with microlitic-porphyritic texture are composed of phenocrysts of sanidine, hornblende, plagioclases, pyroxene and opaque minerals enclosed in a fine groundmass showing a preferred orientation. Rhyolite shows a microlitic-porphyritic texture made up of quartz, sanidine and opaque minerals in the groundmass. According to their geochemical behaviour, major elements show an enrichment in SiO_2 (42.7–70.7 wt.%), Al_2O_3 (13.7–16.6 wt.%), Na_2O (2.3–6.3 wt.%), K_2O (1.3–4.9 wt.%) and an impoverishment in MgO (8.3–0.02 wt.%) and CaO (10.0–0.5 wt.%) from basanite to rhyolite. Some binary diagrams indicate a good correlation with some minor elements (Cr, Ba, Zr, Sr, Rb, and Nb) against SiO_2. REE patterns of the rocks are characterized by a negative anomaly in Eu ($0.3<Eu/Eu^*<0.4$) in basanite and weak negative anomaly in Eu ($0.1<Eu/Eu^*<0.2$) from trachytes to rhyolites, with parallel profiles. The Wainama West lavas are found to have originated from a single primary melt similar to that of OIB and the continental basalt but with slightly higher Nb/Ta content. From the Dy/Yb vs La/Yb diagrams, the major processes resulting to the generation of this primary melt is the partial melting of garnet peridotite, of the high degree (11-12%). The Wainama West alkali lavas were formed in intraplate setting of continental part of the CVL.

Keywords: *Wainama West, petrography, geochemistry, partial melting, garnet peridotite*

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1. Introduction

The Cameroon volcanic line (CVL) is one of the major tectono-magmatic features during the Cenozoic and Quaternary time in Africa [2,7,8,9]. The close to 2000 km long province is exposed in both oceanic and continental settings. The oceanic part of the CVL is composed of volcanic islands in the Gulf of Guinea: Pagalù, São Tomé, Príncipe, Bioko and seamounts (Figure 1). In the continental part, a series of grabens and horsts from Etinde and Mount Cameroon to Lake Chad ([6,11]) are occupied by volcanic fields, stratovolcanoes and plutonic–volcanic complexes [7]. This paper provides new investigations and analysis for the volcanic rocks in the Wainama West area, with the goal to clarify the origin of the lavas of Mount Oku in particular and the CVL in general.

2. Geological Setting

The study area is found on the western flank of Mount Oku which is part of the Oku volcanic group (OVG), situated between Babessi and Jakiri. It is located at latitude N06°3'0̍ - N06°4'0̍ and longitude E10°36'30̍ - E10°37'30̍ E. The OVG is a complex stratovolcanic edifice of 90 km across rising to a height of 3011m. About 2000m of lava pile have erupted here ranging from basalt through hawaite, mugearite to trachyte to rhyolites, high level intrusions and intercalated pyroclastics ([24,25]). Magmatic activity on this Mountain extends from 31My to present ([24]). Ancient lava of Mount Oku forms a bipolar series with alkaline basalt on the one hand, trachyte and rhyolite on the other hand. Recent volcanism formed craters and partially scoria cones, comprising many lakes like Nyos, Enep, Nyi, Wum and Oku [1]. According to [19], the oldest (24.79±0.11 My) felsic volcanism in the Western Cameroon Highland (WCH) occurred at Mount Oku. The enriched geochemical signatures (EM) of the Oku magmas derived from a sub-continental lithospheric mantle enriched in incompatible trace elements by ancient metasomatic processes [26].

3. Analytical Method

Thin sections of the representative rock samples were done in the Geotech Laboratories LtdVancouver Canada using conventional techniques. All rock samples were also coded and sent to ALS Chemex, South Africa for whole rock geochemistry. For the major elements, geochemical analyses, a prepared sample (0.200g) was added to lithium metaborate/lithium tetraborate flux (0.90g), mixed well and fused in a furnace at 1000°C. The resulting melt was then cooled and dissolved in 100ml of 4% HNO_3 / 2% HCl. This solution was then analyzed by ICP-AES and the results were corrected for spectral inter-element interferences. Oxide concentrations were calculated from the determined elemental concentration and the result was reported in that format. The oxides were calculated in percentages with an upper limit of 100 and a lower limit of 0.01. These oxides included Al_2O_3, BaO, CaO, Cr_2O_3, MgO, MnO, P_2O_5, K_2O, SiO_2, Na_2O, SrO and TiO_2. For samples that were high in sulphides, they were substituted with peroxide fusion in order to obtain better results. For the loss on ignition (LOI) values, the samples were decomposed in thermal decomposition furnace and the analytical method was gravimetric. A prepared sample (1.0g) was placed in an oven at 1000°C for an hour, cooled and then weighted. The percent loss on ignition was calculated from the difference in weight. For trace elements, the samples were decomposed by lithium borate fusion (FUS-LI01) and the analytical method used was ICP-MS. A prepared sample (0.200g) was added to lithium borate flux (0.90g), mixed well and fused in a furnace at 1000°C. The resulting melt was then cooled and dissolved in 100ml of 4% HNO_3/2% HCl solution. This solution was then analysed by ICP-MS. This analysis included both the REE and trace elements. Analytical uncertainties vary from 0.1% to 0.04% for major elements to 0.5% for trace elements and from 0.01 to 0.5ppm for REE.

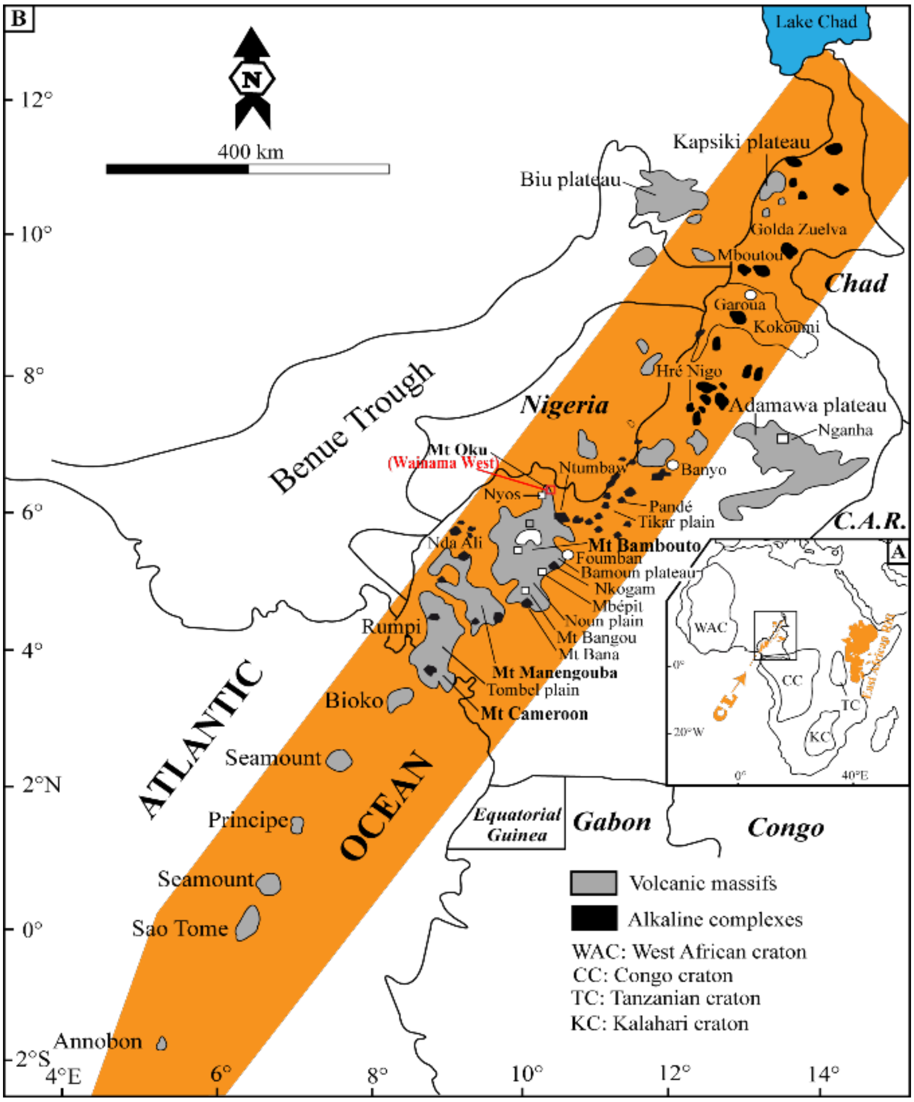

Figure 1. Location of the Wainama West area (the red square mark) along the Cameroon Volcanic Line (adapted after [13]). Location of seamounts after [4]. Inset bottom right is after [17]

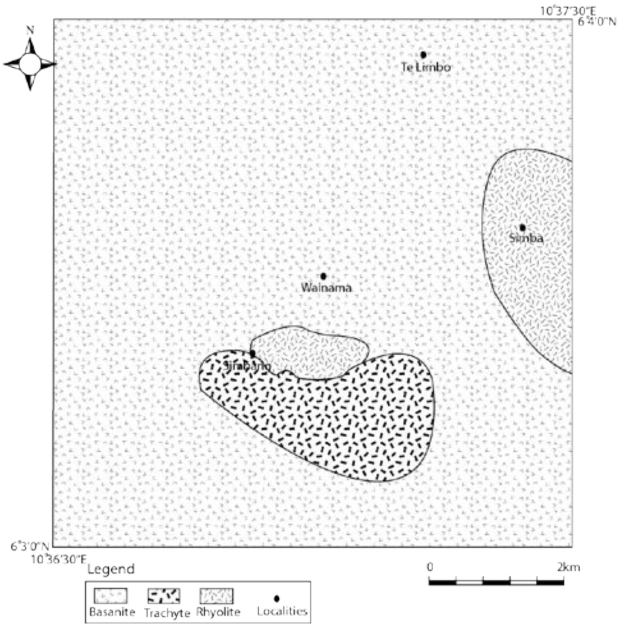

Figure 2. Geologic map of the Wainama West area

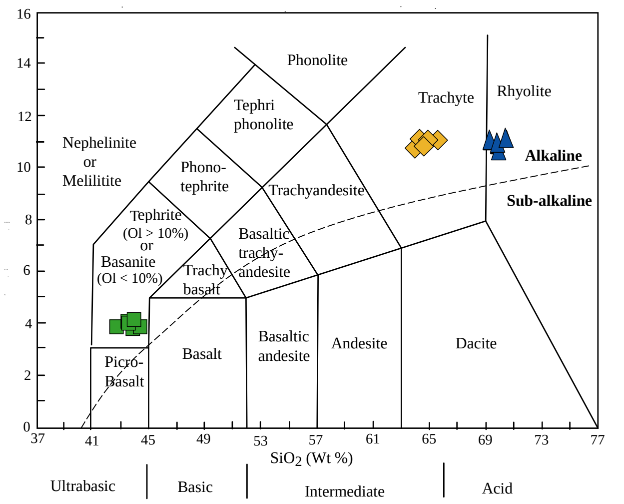

Figure 3. TAS diagrams of Wainama West lavas [18]. The curve with the broken lines is the limit of [14] saparating the alkaline series from the subalkaline series

4. Results

4.1. Petrography and Nomenclature

The different rock formations in the Wainama West area are illustrated on the geologic map (Figure 2). TAS diagram [18] shows that all the samples fall within the basanite, trachyte and rhyolite fields with alkaline affinities (Figure 3). Basanite presents a microlitic porphyritic texture and is characterized by the following minerals: Plagioclases (46%) which are euhedral to subhedral ranging from <0.4-7mm. Olivine (30%) crystals which are euhedral to anhedral, ranging from 0.08-0.5mm. Some olivine crystals present evidence of indingsitization. The opaque minerals (8%) occur as inclusions within olivine and clinopyroxene crystals. They are subhedral to anhedral in shape with sizes from 0.06-3.2mm. Clinopyroxenes (16%) are subhedral to anhedral with a size range of 0.5-1.1mm. Trachyte presents a microlitic porphyritic texture with mineral such as Sanidine (55%) with subhedral-euhedral shaped crystals. Their sizes range from 0.25-0.75mm. Plagioclases (28%) are both in the groundmass and phenocrysts. Opaque minerals (8%) are sub-rounded in shape and sometimes occur as inclusion in sanidine crystals. Clinopyroxenes (5%) are sub-euhedral with a size range between 1.5-4mm (Figure 4). Brown hornblendes (4%) occur in isolation and as inclusions in Sanidine. Rhyolite shows a microlithic-porphyritic texture with mineral such as Sanidines (60%) occur as euhedral or subhedral phenocrysts and also as microlites in the groundmass. Some large sanidine crystals contain inclusions of opaque minerals. Quartz (30%) occurs as sub-anhedral to anhedral phenocrysts and also in the groundmass. Groundmass (10%) contains micrograins of sanidine, opaque minerals and quartz (Figure 4).

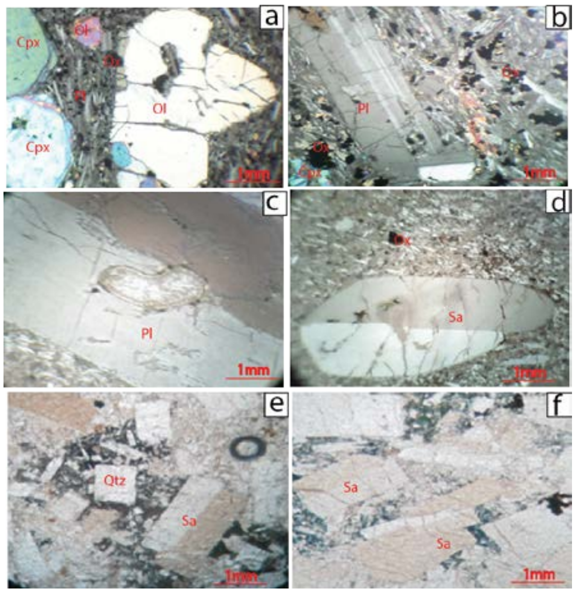

Figure 4. Photomicrograph of rocks from Wainama West: (a and b) basanite; (c and d) trachytes; (d and e) rhyolite. (Ol=Olivine, Sa=Sanidine, Cpx=Clinopyroxene, Pl=Plagioclase, Qtz=Quartz and Ox=Opaque minerals)

4.2. Geochemistry

4.2.1. Major Elements

Results of the geochemical analysis for major elements are presented in Table 1. The major elements plotted against SiO_2 presents two trends (Figure 5). The increase of K_2O and Al_2O_3 is linked to increasing volume of modal plagioclase. The elements that show positive correlation indicated in (Figure 5) are Na_2O, which increases from basanite (ranging from 2.5%-2.56%) to trachyte (5.9 8%-6.33%) and K_2O with increasing trend from basanite (1.3%-1.48%) to rhyolite (4.66%-4.84%). The elements that show a negative correlation have a decreasing trend from basanite through trachyte to rhyolite. It can be seen that MgO in basanite ranges from 7.8%-8.255%, in rhyolite between 0.02%-0.08%. Its high deposition is linked to a crystallization of certain minerals like oxides which are encountered at varied proportions inside the lava and abundant in the basalt. Fe_2O_3 in basanite between 0.20%-1.83% and in rhyolites between 0.20%-0.50%.

This decrease indicates quick precipitation of ferro-titano oxide for lava of Wainama West. CaO in basanite ranges between 9.27%-10% and in rhyolite between 0.6%-0.72%. This decreasing evolution can be explained by the incorporation of Ca during the fractionation of clinopyroxene and plagioclase abundant in trachyte and rhyolite of Wainama West. P_2O_5 in basanite ranges between 0.76%-0.7% and in rhyolite between 1.15%-1.16%. This is probably the fractionation of apatite in basanite but was not seen in thin section.

Table 1. Geochemical Analysis of Major Elements (wt.%) and CIPW Norms of Wainama West Lava

	Basanite											
SAMPLE	W17	W18	W19	W20	W21	W22	W25	W26	W27	W28	W29	W30
SiO_2	43.4	42.7	44.3	43.4	43.3	43.2	43.9	43.6	43.2	43.9	43.2	43.2
Al_2O_3	14.2	14	14.5	14.2	14.2	14.2	14.4	14.3	14.1	14.4	14.2	14.2
Fe_2O_3	13.4	13.2	13.7	13.5	13.5	13.3	13.6	13.5	13.5	13.9	13.6	13.7
CaO	9.43	9.27	9.6	9.47	9.4	9.41	10	9.91	9.74	9.9	9.78	9.8
MgO	8.28	8.16	8.18	8	8.15	8.25	7.95	7.91	7.91	7.81	7.81	7.79
Na_2O	2.47	2.46	2.55	2.42	2.5	2.43	2.28	2.27	2.49	2.56	2.46	2.37
K_2O	1.27	1.26	1.3	1.29	1.26	1.26	1.42	1.43	1.42	1.48	1.44	1.46
Cr_2O_3	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.03	0.07
TiO_2	3.47	3.43	3.54	3.47	3.46	3.47	3.52	3.49	3.45	3.5	3.45	3.45
MnO	0.18	0.18	0.19	0.19	0.19	0.18	0.19	0.18	0.19	0.19	0.19	0.19
P_2O_5	0.77	0.76	0.79	0.77	0.77	0.76	0.77	0.77	0.76	0.79	0.77	0.77
SrO	0.1	0.1	0.1	0.1	0.1	0.1	0.12	0.13	0.11	0.11	0.11	0.11
BaO	0.05	0.05	0.06	0.06	0.05	0.06	0.06	0.05	0.05	0.06	0.05	0.05
LOI	2.75	2.6	2.73	2.76	2.65	2.71	2.24	2.31	1.51	1.48	1.66	1.92
Total	99.8	98.2	102	99.6	99.5	99.3	100	99.8	98.5	100	98.7	99
CIPW												
Quartz	-	-	-	-	-	-	-	-	-	-	-	-
Orthose	7.73	7.79	7.78	7.87	7.69	7.71	8.54	8.67	8.66	8.87	8.77	8.89
Albite	18.2	18	18.7	18.5	18.3	18.3	16.8	16.8	15.9	15.9	15.9	15.9
Anorthite	24.6	24.5	24.6	24.9	24.5	24.8	25.3	25.1	23.8	23.8	24	24.4
Acmite	-	-	-	-	-	-	-	-	-	-	-	-
Na metasilicate	-	-	-	-	-	-	-	-	-	-	-	-
Nepheline	1.8	2.05	1.7	1.42	1.92	1.63	1.54	1.57	3.14	3.32	3.03	2.59
Diopside	15.1	15.1	15.1	15.1	15.2	15	16.5	16.5	17.1	17.1	17.1	16.9
Hypersthene	-	-	-	-	-	-	-	-	-	-	-	-
Olivine	21.3	21.3	20.9	20.9	21.2	21.2	20.1	20	20.1	19.8	19.9	20.1
Magnetite	2.65	2.65	2.65	2.66	2.66	2.63	2.65	2.65	2.67	2.69	2.68	2.7
Ilmenite	6.79	6.81	6.81	6.81	6.79	6.83	6.81	6.8	6.76	6.74	6.76	6.75
Apatite	1.84	1.84	1.85	1.84	1.84	1.82	1.82	1.83	1.82	1.86	1.84	1.84
TOTAL	100	100	100	100	100	100	100	100	100	100	100	100
DI	**27.7**	**27.8**	**28.2**	**27.8**	**27.9**	**27.6**	**26.9**	**27.1**	**27.7**	**28**	**27.7**	**27.4**
	Trachyte						**Rhyolite**					
SAMPLE	W33	W34	W35	W36	W37	W38	W1	W2	W3	W4	W5	W6
SiO_2	66.2	66.2	66.5	65.6	65.7	64.9	68.6	68.9	69.8	69.9	70.7	69.4
Al_2O_3	13.8	13.8	13.8	13.7	13.7	13.5	16.6	16.5	15.8	15.8	15.9	15.8
Fe_2O_3	6.74	7.05	6.9	7.04	6.74	6.85	2.12	1.85	1.95	1.14	0.86	1.68
CaO	0.64	0.62	0.67	0.6	0.54	0.71	0.7	0.68	0.63	0.66	0.6	0.72
MgO	0.22	0.21	0.22	0.19	0.17	0.22	0.06	0.06	0.03	0.02	0.02	0.1
Na_2O	6.08	6.12	6.13	6.04	6.05	5.98	6.33	6.32	6.09	6.08	6.11	6.08
K_2O	4.85	4.91	4.9	4.83	4.84	4.77	4.84	4.83	4.72	4.66	4.73	4.67
Cr_2O_3	0.01	0.03	0.01	0.03	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
TiO_2	0.53	0.53	0.52	0.51	0.52	0.51	0.68	0.68	0.68	0.67	0.67	0.67
MnO	0.27	0.27	0.27	0.29	0.26	0.27	0.05	0.04	0.04	0.01	0.01	0.03
P_2O_5	0.05	0.05	0.05	0.05	0.05	0.05	0.15	0.15	0.16	0.16	0.15	0.15
SrO	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.03
BaO	0.02	0.02	0.02	0.02	0.03	0.02	0.09	0.08	0.08	0.08	0.08	0.08
LOI	1.55	1.49	1.87	1.66	1.49	1.75	1.68	1.57	1.55	1.27	1.18	1.58
Total	101	101	102	101	100	99.5	102	102	102	100	101	101
CIPW												
Quartz	9.87	9.36	9.69	9.45	9.96	9.56	11.4	12	14.8	15.7	16.2	14.6
Orthose	28.8	29.1	28.9	28.9	29	28.8	28.6	28.5	27.9	27.8	28	27.8
Albite	44	43.7	43.7	43.8	43.9	43.6	53.5	53.5	51.6	51.9	51.8	51.8
Anorthite	-	-	-	-	-	-	2.45	2.39	1.84	2.07	1.99	2.04
Acmite	3.67	3.82	3.73	3.85	3.7	3.79	-	-	-	-	-	-
Na metasilicate	0.84	0.89	0.91	0.81	0.89	0.9	-	-	-	-	-	-
Nepheline	-	-	-	-	-	-	-	-	-	-	-	-
Diopside	2.53	2.43	2.65	2.37	2.11	2.89	0.04	0.01	0.22	0.15	0.01	0.49
Hypersthene	9.19	9.64	9.32	9.79	9.37	9.38	1.75	1.41	1.35	0.31	0.03	1.05
Olivine	-	-	-	-	-	-	-	-	-	-	-	-
Magnetite	0	0	0	0	0	0	0.73	0.63	0.67	0.39	0.3	0.58
Ilmenite	1.01	1.01	0.99	0.98	1	0.99	1.29	1.29	1.29	1.28	1.28	1.28
Apatite	0.12	0.12	0.12	0.12	0.12	0.12	0.35	0.35	0.37	0.37	0.35	0.35
TOTAL	100	100	100	100	100	100	100	100	100	100	100	100
DI	**82.7**	**82.1**	**82.3**	**82.1**	**82.8**	**81.9**	**93.4**	**93.9**	**94.3**	**95.4**	**96.1**	**94.2**

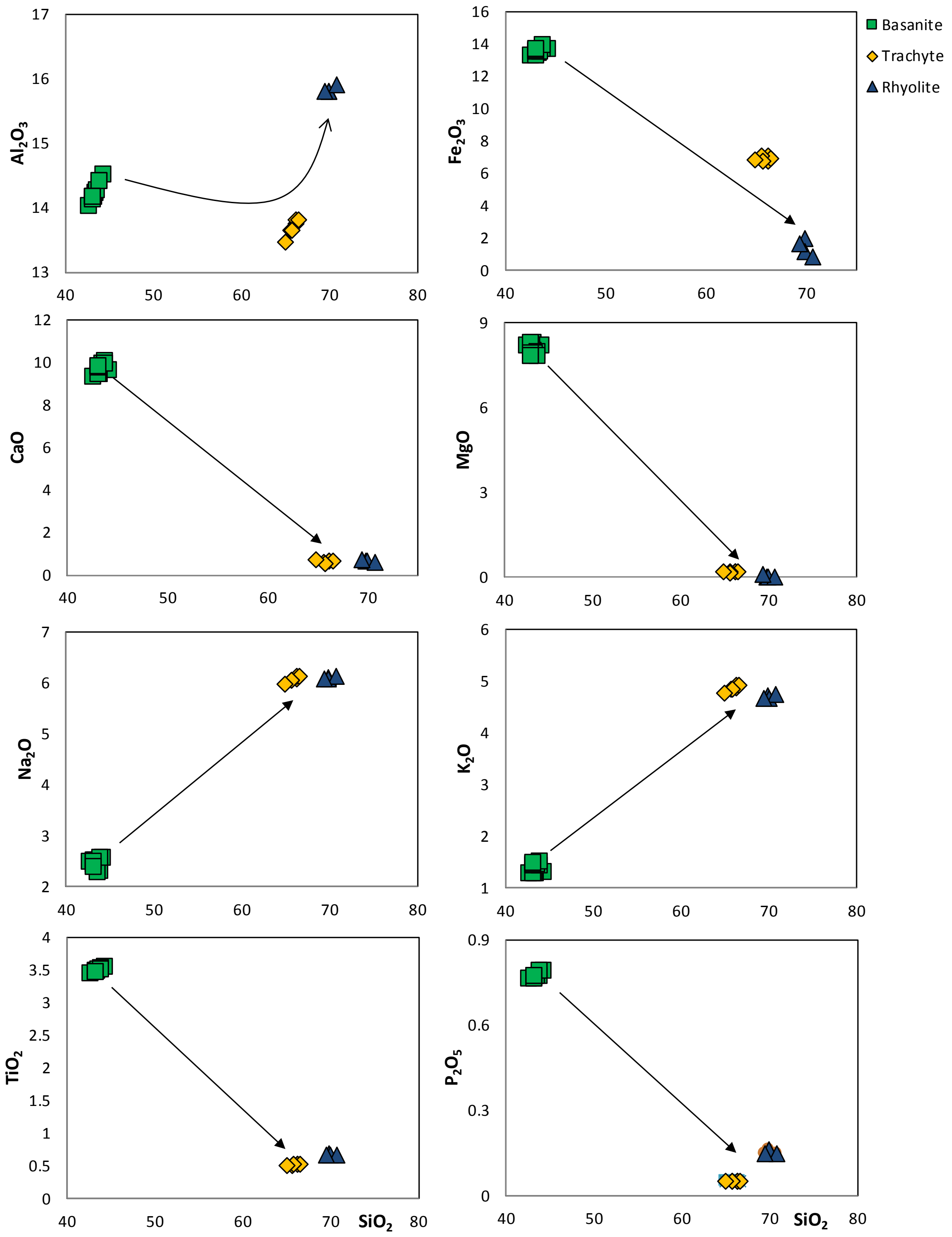

Figure 5. Evolution of Major elements versus SiO_2 of the Wainama West lava

4.2.2. Trace and Rare Earth Elements

Analyses of trace elements carried out on 24 elements are represented on Table 2. These elements follow same trend of evolution like major elements. The compatible elements present a high affinity for Fe-Mg minerals, with occurrence of olivine, pyroxene, spinel and magnetite [5]. The SiO_2 for compatible elements show a negative correlation all along the magmatic differentiation process for Sr and Cr (Figure 6). Sr content decreases during magmatic differentiation from 846-1115ppm in basanite to 219-244ppm in rhyolite; V presents a linear correlation and moderately decreases and varies from 266-276ppm in basanite to 5ppm in rhyolite; Cr presents a positive correlation and varies from 180-490ppm in basanite to 6ppm in rhyolites. Looking at the incompatible element versus SiO_2, it indicates positive correlation of Nb, Zr, and Rb with SiO_2.

The REE and multi elements results are presented in Table 2. The spectra of REE is normalised to Chondrite [20] (Figure 7). On the pattern, there is the enrichment of LREE (La, Ce, Nd, Sm) compared to the HREE (Gd, Dy, Er, Yb).

The multi-element spectra for the Wainama West lava represent a strong negative anomaly of Eu, Ba, and Sr and a positive anomaly of Nb, Ta, La, Zr, Hf, in both the trachytes and basanite (Figure 8). The trough at Sr is probably a consequence of low pressure plagioclase fractionation.

Table 2. Selected Trace elements (concentration in ppm) for Wainama West lava

	Basanite											
SAMPLE	W17	W18	W19	W20	W21	W22	W25	W26	W27	W28	W29	W30
Ba	469	460	482	488	465	480	479	472	471	471	469	471
Ce	90,5	90	91,7	89,2	90,2	90,1	90,4	90,2	89,7	91,2	90,3	89,8
Cr	420	430	410	420	428	420	420	420	420	452	420	490
Cs	0,28	0,25	0,24	0,31	0,24	0,29	0,27	0,18	0,21	0,2	0,23	0,19
Dy	5,76	5,66	5,48	5,77	5,69	5,71	5,29	5,4	5,71	5,7	5,57	5,68
Eu	3,07	3,16	3,06	3,15	3,1	2,98	2,95	3,16	3,06	3,06	2,98	3,1
Ga	23,1	22,4	22	20,8	20,9	21	21,2	21,9	21,2	21,2	21	21,1
Gd	7,85	7,94	7,83	8,06	8	8,08	8,18	7,74	7,73	8,06	7,69	8,04
Hf	5,5	5,5	5,7	5,5	5,5	5,5	5,6	5,5	5,3	5,7	5,5	5,6
Ho	0,98	1,04	1	1,07	1	1,01	1,06	1,02	0,99	1,01	1,01	0,95
La	43,1	42,5	43,8	42,4	42,6	43	42,3	42,8	42,3	43,4	43,1	42,3
Lu	0,26	0,26	0,27	0,26	0,28	0,28	0,27	0,27	0,26	0,3	0,25	0,28
Nb	58,5	58,3	59,3	57,5	57,6	58,1	57,8	57,6	57,8	58,5	57,6	57,8
Nd	45,6	45,8	46	44,9	45,4	45,2	45,6	45,8	44,3	45,8	46.1	44,5
Rb	25,8	25,4	25,5	27	25,6	27,1	29,2	26,8	25,6	27	26,4	26,9
Sm	8,94	9,08	9,05	9,1	9,49	9,11	9,23	9,33	9	9,47	9,39	9,45
Sn	2	2	2	2	1	2	2	2	2	1	2	2
Sr	858	846	869	868	848	871	1030	1115	959	941	938	973
Ta	3,5	3,4	3,5	3,4	3,3	3,3	3,4	3,4	3,4	3,4	3,4	3,4
Tb	1,12	1,06	1,13	1,13	1,16	1,09	1,11	1,11	1,1	1,14	1,09	1,1
Th	4,02	3,93	4,01	3,98	4,12	4,05	4	4	4,09	3,97	3,94	4
Tm	0,3	0,32	0,34	0,32	0,35	0,33	0,35	0,33	0,34	0,33	0,32	0,29
U	1,15	1,07	1,21	1,11	1,08	1,12	1,11	1,08	1,08	1,13	1,07	1,01
V	273	271	274	267	266	273	276	275	266	268	270	269
W	1	1	1	1	1	1	1	1	1	1	1	1
Y	25,1	25,3	25,8	24,9	24,9	25,4	25,2	25,1	24,9	25,2	25,2	25,1
Yb	1,91	2,01	2,1	1,99	1,91	2,03	1,98	1,93	1,91	1,93	1,93	2,01
Zr	243	240	246	240	239	242	239	241	239	243	241	240
	Trachyte						**Rhyolite**					
SAMPLE	W33	W34	W35	W36	W37	W38	W1	W2	W3	W4	W5	W6
Ba	185,5	213	160,5	209	223	157,5	738	721	687	717	699	723
Ce	404	359	381	399	396	367	248	275	273	288	318	259
Cr	10	12	10	220	10	11	13	10	10	11	10	12
Cs	0,12	0,12	0,15	0,12	0,13	0,14	0,12	0,14	0,14	0,15	0,14	0,14
Dy	20,7	18,1	19,65	20,2	20,4	19,3	13,8	15,4	19,75	17,55	19,45	14,95
Eu	3,08	2,65	2,98	3,01	3,14	2,74	3,82	3,89	4,25	4,11	4,15	3,82
Ga	41,3	42,8	42	42	42,9	42	37,5	37,9	37,1	37,9	37,8	36,9
Gd	23,3	20	22,2	22,4	22,1	20	15,6	17,45	20,3	20,2	23,6	16,75
Hf	35,3	35,6	35,3	34,7	35,5	35,2	24,6	24,3	25,1	24,7	24,4	25,1
Ho	4,07	3,45	3,96	3,95	4,01	3,74	2,81	3,07	3,92	3,43	3,97	2,92
La	204	175	191,5	198,5	204	179	125	144	151	164	197	137,5
Lu	1,45	1,36	1,45	1,49	1,46	1,42	1,02	1,15	1,46	1,13	1,26	1,02
Nb	267	270	270	261	270	266	181	183	188	185	187	178
Nd	156,5	136	151,5	156,5	154,5	141	102	113	122,5	124,5	142	107
Rb	114	115	116	113,5	116,5	114,5	93	93,5	93,7	91,8	93,5	92
Sm	28,3	24,5	27,6	27,7	27,8	26,6	18,8	20,8	23,6	21,7	25	19
Sn	11	10	10	10	11	11	8	7	7	7	7	7
Sr	23,9	28,8	20,8	21,8	24	23,8	242	236	219	239	223	244
Ta	15,5	15,7	15,5	15,2	15,6	15,5	11,2	11,6	11,2	11,2	11,3	11,2
Tb	3,68	3,2	3,58	3,58	3,72	3,39	2,39	2,75	3,43	3,02	3,57	2,7
Th	23,4	23,4	23,3	23,1	23,2	23,2	16,35	16,8	16,55	16,25	15,7	16,1
Tm	1,59	1,43	1,58	1,55	1,55	1,48	1,08	1,19	1,52	1,29	1,46	1,07
U	5,88	5,44	6,16	6,02	6,31	5,83	4,05	4,42	4,25	4,56	4,59	4,14
V	5	5	5	5	5	5	5	5	5	5	5	5
W	1	2	2	2	1	1	3	3	3	3	3	3
Y	101,5	89,1	102	101,5	104	94,5	75,6	81,3	98,7	103	119	90
Yb	10,35	8,89	9,72	9,9	10,15	9,58	6,95	7,69	9,89	7,95	8,39	7,14
Zr	1600	1610	1595	1570	1610	1590	1140	1145	1160	1145	1125	1135

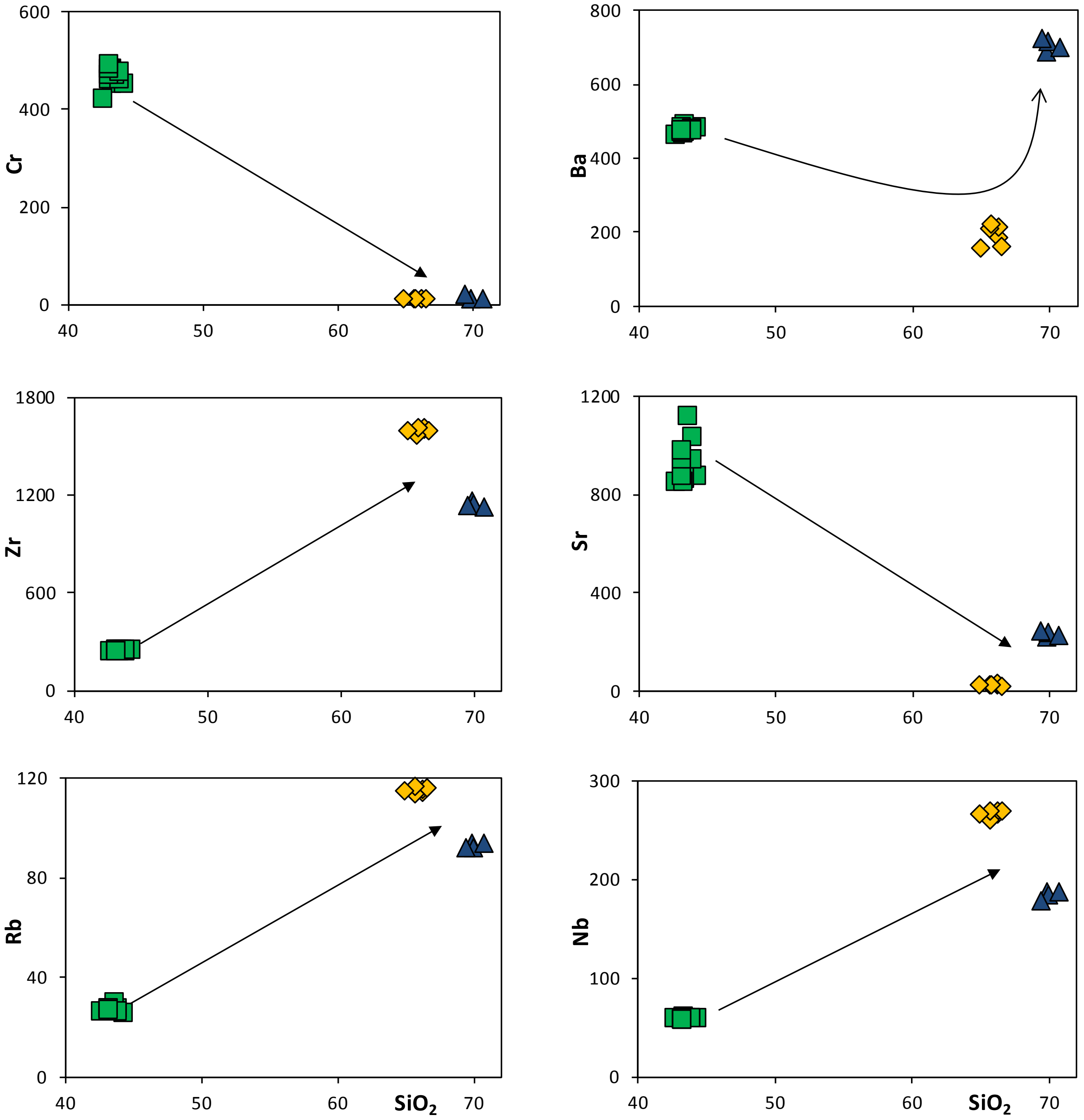

Figure 6. Binary diagrams for some compatible and incompatible elements against SiO_2. Symbols as for the Figure 5

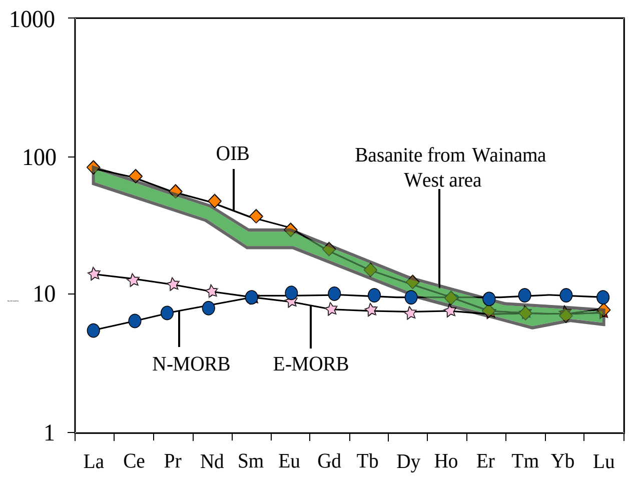

Figure 7. REE spectra of the Wainama West lava normalised with Chondrite [20]. Symbols as for the Figure 5 (OIB= Ocean Island Basalt, N-MORB= normalised-mid ocean ridge basalt, E-MORB= enriched-mid ocean ridge basalt

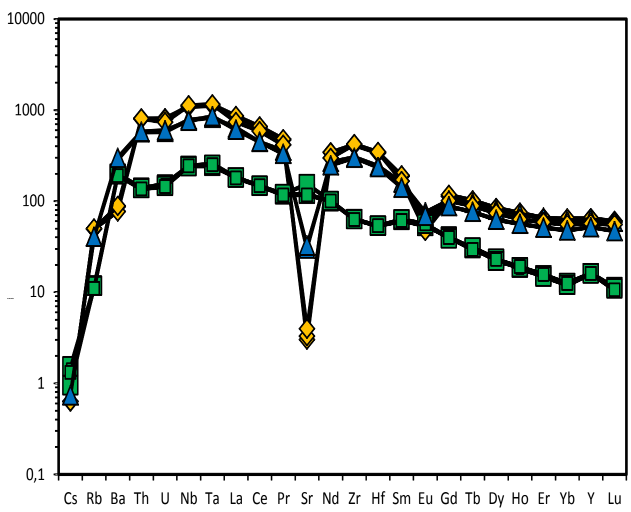

Figure 8. Primitive mantle normalised spider diagram of trace elements of the Wainama West lava [35]. Symbols as for the Figure 5

5. Interpretation and Discussion

5.1. Magma Generation

The major and trace elements distribution shows that the dominant process for the generation of rhyolitic and trachytic lavas from the basanite parental melt is fractional crystallisation. The fractionating phases are olivine, clinopyroxene, plagioclase (Figure 9), ferro-titano oxide and apatite as indicated by a continuous decrease in CaO, Fe_2O_3, TiO_2, P_2O_5, MgO, with a corresponding increase in Al_2O_3, Na_2O, K_2O (Figure 10). A binary diagram of the oxides against SiO_2 indicates a decrease in MgO and is interpreted as a continuous fractionation of olivine from basanite through trachyte to rhyolite. A decrease in CaO indicates fractionation of clinopyroxene. Petrographically, basanite contain more pyroxene than trachyte and rhyolite, which is an evidence of differentiation through fractional crystallization. The dispersion of Fe_2O_3, TiO_2, V and P_2O_5 is clear in all petrographic types and explains fractionation of ferrotitano-oxide and apatite. The content of K_2O, Na_2O, and Al_2O_3 shows a lesser evolution which is very different. This is explained by non-crystallisation of alkaline feldspars in the mafic rocks. The study of trace elements shows that olivine and clinopyroxene preferentially incorporates Co and Ni, ferro-titano oxide fractionate V, apatite fractionates intermediary elements like Y, Co, Ni, the plagioclases fractionate Sr, Ba, Eu and to a lesser degree La.

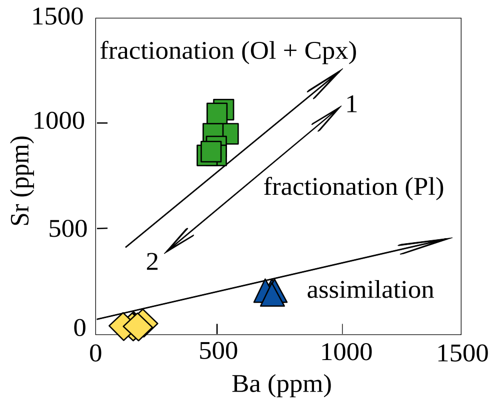

Figure 9. Sr vs Ba diagram for Wainama West lava; fractionation and assimilation shown after [10] modified. Symbols as for the Figure 5

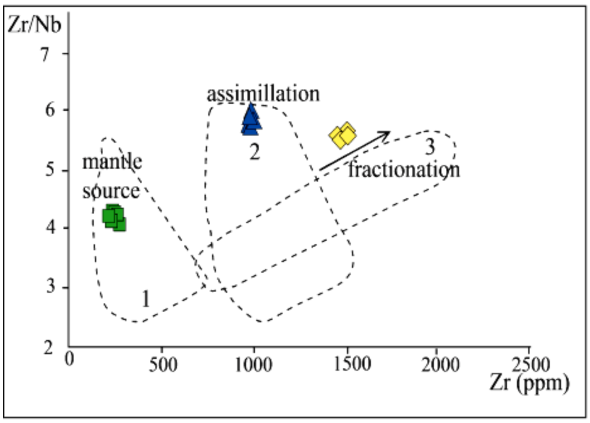

Figure 10. Zr/Nb diagram of Wainama West lavas. Dashed lines show fields of rocks of Meidob Hills, sudan (after [10] modified) indicating a mantle source of mafic rocks (1) or assimilation for rhyolite; the trend of fractionation is outlined (3). Symbols as for the Figure 5

These results permit us to interpret the principal variations in trace elements. The first evolutionary series is marked by a decrease in transition elements fractionated by olivine and clinopyroxene (Sr, Cr,) and after V to separate the ferro-titano oxide. The rest of the other elements have an incompatible behaviour. A decrease in the concentration of Eu and Sr in trachyte is due to fractionation of plagioclase (Figure 8). Generally, in the lava studied, we observe enrichment in LREE as compared to HREE. This suggests presence of residual garnet in the source during partial melting. An evidence that the rocks are coming from processes of fractional crystallisation. Removal of feldspar from a felsic rock (rhyolite) by crystal fractionation or the partial melting of a rock in which feldspar is retained in the source will give rise to a negative anomaly in the melt. Generally, multi-element spectra have negative anomalies in Ba, Eu, and Sr, in trachyte and rhyolite suggesting fractionation of plagioclases and positive anomalies in, Nb, La, Zr and Dy.

5.2. Mantle Source Characteristic

The Dy/Yb versus La/Yb diagram (Figure 11) indicates the melting of garnet and spinel peridotite based on the compatibility of Yb and incompatibility of La in garnet and different rate and fraction of La/Yb and Dy/Yb ratios during the melting stages in the garnet stability field. The study of the discrimination diagram between melting of garnet and spinel peridotite shows that the basanitic magma of the Wainama West area is formed from the partial melting of garnet peridotite. The trend of the basanitic lava of this area falls within the high degrees (11-12%) of partial melting of a garnet rich peridotite compared to the low degree partial melting of Mount Cameroon (8-10%), but and both fall mainly around the 2% partial melting curve [27,38].

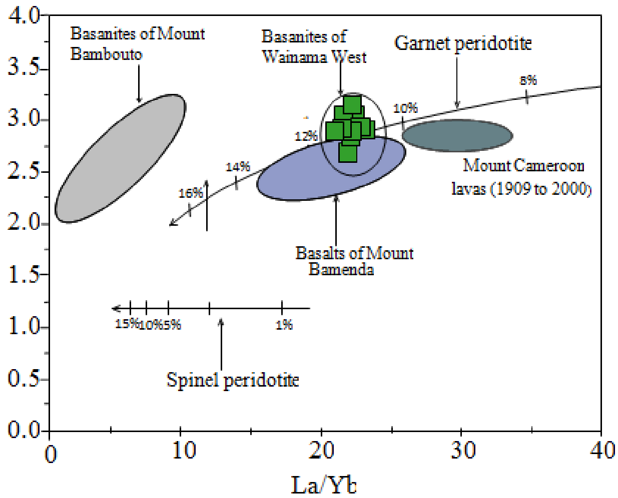

Figure 11. The Dy/Yb vs La/Yb diagram. Melt curves for garnet peridotite and spinel peridotite are from [3]. Mount Bambouto from Nkouathio (2006), Mount Bamenda from [16], Mount Cameroun from [34]. Symbols as for the Figure 5

5.3. Contamination and Assimilation Plots

The Zr/Nb diagram indicates assimilation for benmoreitic trachyte pumice and lava, [10] (Figure 10). The lava of Wainama West has high Ba concentrations in rhyolite and trachyte with exceptions in samples W33 (185.5ppm) and W35 (160.5ppm) and low Sr concentrations decreasing from the rhyolite to basalt. This is explained by the partial assimilation of the magma by the country rocks. The fractionation of olivine and pyroxene clearly increases Sr and Ba content of the residual liquid. The Zr\Nb Vs Zr diagram (Figure 10) argues for more assimilation in rhyolite which has a high Zr\Nb ratio of 6.4 and 6.0 for Zr content range of 1125 and 1145ppm. In contrast, the trachyte samples display considerably higher Zr values of 1570 and 1610ppm, clearly indicating a fractional process.

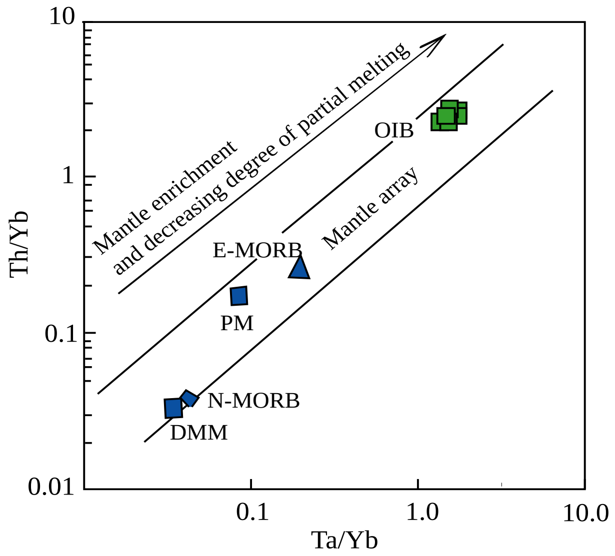

Figure 12. The Ta/Yb vs Th/Yb diagram. Symbols as for the Figure 5

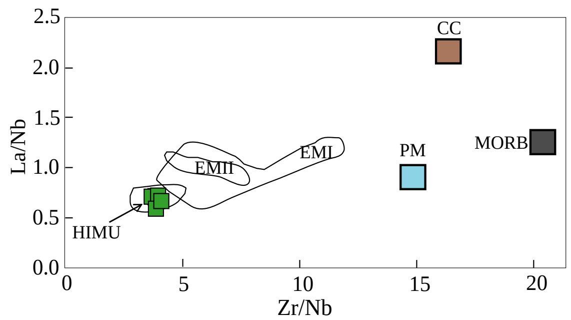

Figure 13. Zr/Nb vs La/Nb diagram of Wainama West area. Comparison with major reservoirs (OIB) oceanic island basalts; (MORB) mid-oceanic ridge basalts; (PM) primitive mantle; mantle poles HIMU (high $^{238}U/^{204}Pb$ ratio), EMI and EMII (enriched); (EMI) enriched mantle I, (EMII) enriched mantle II. (CC) continental crust The data (MORB, PM, C.C, HIMU, EMI, EMII) are from Weaver (1991). Symbols as for the Figure 5

5.4. Petrogenesis

Several authors have shown a similarity between multi-element spectra of lava along the CVL ([9,13-22]). This similarity is equally observed in the Wainama West area. In effect lava of this area show spectra enriched in LREE and in incompatible elements. The REE and Trace elements spectra of this area, as well as that along the CVL, are similar in the OIB spectra. The ratio of trace incompatible elements compared to others of the CVL shows that it presents an OIB signature (Figure 12) with variable participation of HIMU components (Figure 13). However, the Zr/Hf and Nb/Ta ratio diagram (Figure 14) shows that the Wainama West mantle source is similar to those of the continental basalts, OIB, OVG and the Kenya rift. The elemental ratios like Nb/Ta and Zr/Hf have been very useful in finger printing the source of the volcanic rocks of the study area. The Zr/Hf ratios of the study area have values similar to those of the OIBs, whereas Nb/Ta ratios tend to be higher. The Zr/Hf ratio ranges from 42.7 to 47.1 with an average of 44.9 and the Nb/Ta ratio range from 16.5 to 17.6 with an average of 17.05. The above values are respectively above and in the range of the OIB. (OIB: Nb/Ta=15.9- 0.6, Zr/Hf =35.5-45.5) [28]. This indicates a slight Nb excess in basanite but assuming similar degree of partial melting. However, the Nb/Ta ratio is slightly higher than the range obtained for the continental part of the CVL (Nb/Ta=11.19-14.77) ([15,23,27,36]) but it is within the Tibesti volcano range (Nb/Ta=11.19-17.49) [12], Oku volcanic group and Kenya rift. Finally, [39] used the slightly higher Nb/Ta and average Zr/Hf ratio as evidence of derivation from distinct liquid relative to the others although sharing a common source region. This difference is only controlled by fractional crystallization.

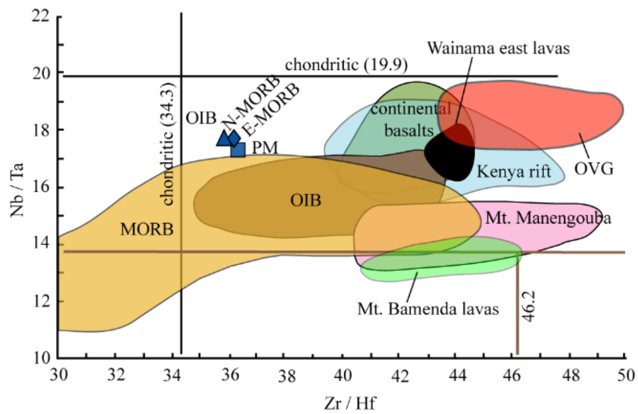

Figure 14. Zr/Hf vs. Nb/Ta diagram. PM, N-MORB, EMORB, and OIB from [35]; chondritic values from [21]; MORB, OIB, and continental basalts fields after [28]; Kenya rift field drawn with the data of [31,32] and [29], Mount Manengouba from [30], Mount Bamenda from [16].

5.5. Geotectonic Context

The combined study of the petrology and geochemistry reveal that the lava of Wainama West area is of the within plate volcanic setting. From the Ta/Yb vs Th/Ta plot, the rocks samples fall in the Within Plate Basalt (WPB) (Figure 15A). The Ta/Hf vs Th/Hf plot indicates the rock samples fall in the Within Plate Volcanin Zone (WPVZ) (Figure 15B).

5.6. Comparing the Wainama West Lava and others along the CVL

The general volcanic situation and the chemical composition of the lavas of the study area are similar to others along the CVL. Wainama West lava fall within the alkaline series which is concordant to those of the volcanic massif of Adamawa, Mount Cameroon which constitutes a weakly alkaline series [37], those of Tombel graben are mildly alkaline [27], Mount Manengouba belongs to the sodic alkaline series [30], Mount Bamenda also has an alkaline affinity [16] and Mount Oku [25]. This confirms the fact that majority of the rocks along the CVL are alkaline in nature.

The lava of Wainama West, Mount Bamenda, Mount Oku and Mount Cameroon has the same origin (mantle source). Comparing the source of the volcanic rocks of Wainama West and that of the OIB and MORB, the source has the same origin as that of the OIB (Figure 12, Figure 13). The Zr/Hf ratio average falls within the range of OIB while Nb/Ta ratio is slightly higher than the OIB parts of the CVL but is within the Tibesti volcano, Oku volcanic group, and Kenya rift.

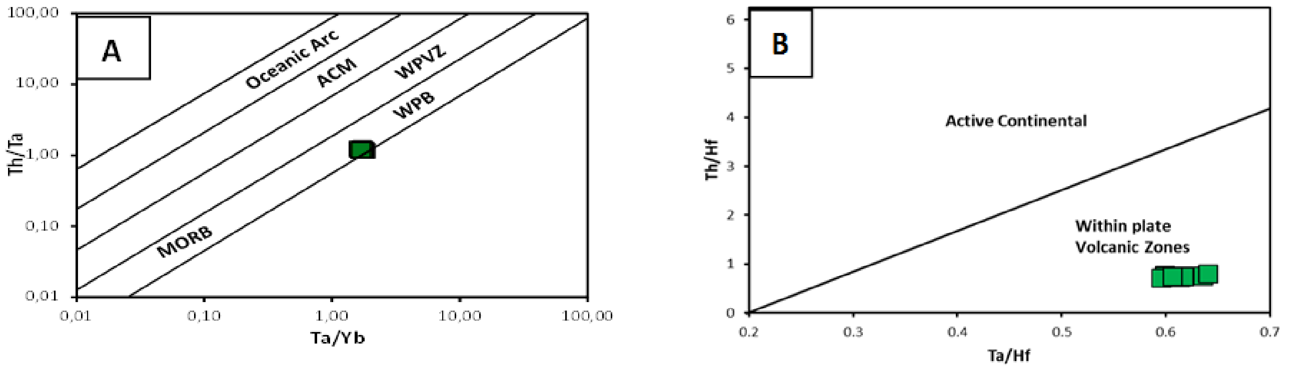

Figure 15. Diagrams showing the geotectonic context of the Wainama West lava (A) Ta/Yb vs Th/Ta plot, (B) Ta/Hf vs Th/Hf plot [33]. Symbols as for the Figure 5

6. Conclusion

Rocks and lava of the Wainama West area are made up of basanite, trachyte and rhyolite. This volcanic series is strongly differentiated and evolves from alkali basalts to rhyolites with a Daly gap. Their geochemical behaviour show an enrichment in SiO_2, Al_2O_3, Na_2O, K_2O and an impoverishment in MgO and CaO. A good correlation exists between some minor elements (U, Nb, Ta, La, Zr, Hf, Yb, Rb, Y) with that of DI. The principal differentiation mechanism of the Wainama West lava is fractional crystallisation, marked by a progressive decrease in MgO and CaO content and an increase in Na_2O and K_2O content. The principal phases that fractionate are ferro-titano oxide, olivine, clinopyroxene and plagioclases, with fractionation of olivine and clinopyroxene appearing at the beginning of the differentiation. Eu and Sr indicate a negative anomaly in trachyte and rhyolite. The negative anomaly of Eu and Sr in trachyte and rhyolite indicates plagioclase fractionation. The lavas of the Wainama area are of the alkaline series, originate from the mantle and has same source as those of the OIB with HIMU signatures. The geodynamic context of the lavas of the Wainama West fall within plate volcanic setting, Within Plate Basalt (WPB) and Within Plate Volcanic Zone (WPVZ).

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