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Geochemical Pattern and the Evolution of the Mafic Rocks of Southwest Obudu Plateau, Bamenda Massif, Nigeria

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Authors' contributions

This work was carried out in collaboration between both authors. Author EEU designed the study, wrote the protocol and wrote the first draft of the manuscript. Author VUU managed the literature searches and data quality. Both authors read and approved the final manuscript.

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ABSTRACT

The mafic and ultramafic rocks of southwest Obudu, Nigeria are located within the Paleoproterozoic granulites facies rocks of the Bamenda Massif. These mafic and ultramafic rocks were not subjected to high level deformation and metamorphism which the surrounding rocks experienced. Since there are no pervasive signatures of the Pan-African Orogeny, these rocks were probably emplaced as later stage intrusive into these Pan-African rocks. The unmetamorphosed dolerite and diorite occur as boulders and veins cross-cutting the charnockitic rocks of Ukwortung and the environs. The ultramafic rock massively outcrops in Ukwortung and in other localities as mostly dykes in the granulite facies rocks. The Mg# (magnesian number) for the mafic and the ultramafic rocks of southwest Obudu, southeastern Nigeria are high (Mg# ranges from 19.95 to 65.15) and the FeO_T is equally high (FeO_T is 9.87–13.20). The Mg number of the ultramafic rock on the average is higher than those for partial melts from the lower crust (basaltic magma, Mg# <40) lower than

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values for Qingbulake intrusion in China (59–81) and those for metaperidotite in ophiolites (89 – 91), suggesting that its derivation was not directly from the partial melting of the lower crust. Its formation may have involved derivation interaction with mantle peridotite. However, the Mg numbers for the dolerites and the diorites are less than 40, lower than those of partial melts from the lower crust. This precludes their formation from interaction peridotite. The LILE and LREE enrichment, considerable depletion in HSFE with low La/Nb ratios are indicative of subduction related activities. The Zr/Y (>4) and Nb/Y (>2) are suggestive of materials derived from enriched mantle source which may have been metasomatised by slab melts during subduction/collision. Variable Ce/Y ratios, the elevated Sr/Nd ratios at low Th/Yb ratios reflect the addition of fluids from a subducting slab. However the low Th/Yb ratios of the mafic and ultramafic rocks preclude importance of sediment melts from the subducting slab. Therefore, hydrous melting of the metasomatised mantle material may have introduced significant LILE into the source.

Keywords: Bamenda; Obudu; mafic rocks; dolerites; diorites.

1. INTRODUCTION

The rugged terrain of Obudu Plateau is a continuation of the Bamenda Massif of Cameroon Republic into the south eastern Nigeria as the Precambrian Basement. The rocks constituting this basement complex in the Nigerian segment consist of migmatites, meta-peridotite, charnockitic gneisses and quartz rocks [1,2]. Granites, pegmatite, diorite, dolerite and quartzo-feldspathic veins occur as intrusive into the metamorphic rocks. The dolerites occur both as dykes and sills. [3] described these dolerites as olivine tholeiites. The diorites, dolerites and meta-ultramafic constitute the mafic rocks of the map area (Fig. 1). The granites vary in textures and mineralogy. At Okordem they are fine to medium grained with very weak foliation. In the Okure hills these granites are biotite granite and leucogranite in association with charnockites. The leucogranite is entirely devoid of ferromagnesian mineral but rather contains sporadic grains of post- tectonic garnet.

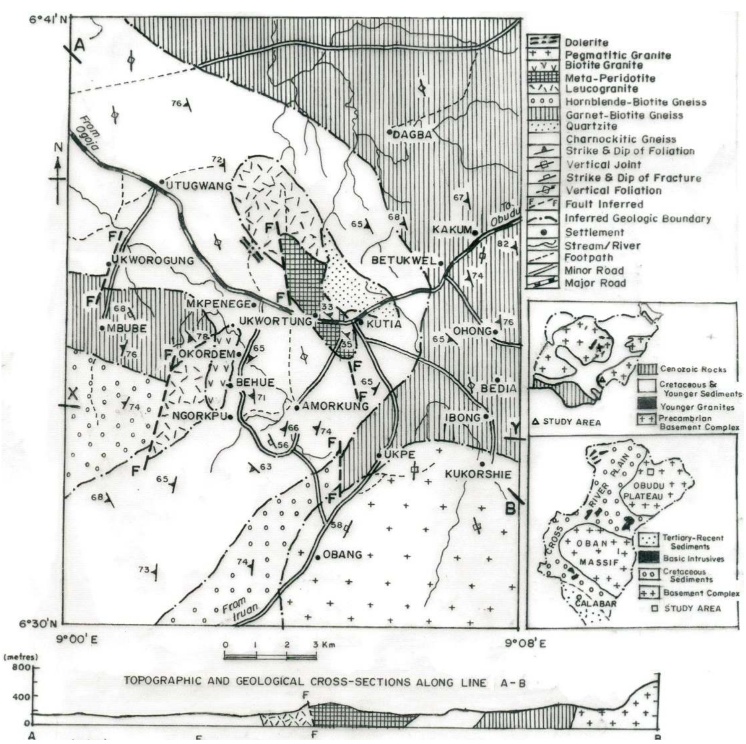

Fig. 1. Geologic map of the study area. In set: Generalized geologic map of Nigeria and Cross River State

This Precambrian terrain was subjected to polyphase deformation and polymetamorphism during the Pan-African tectonothermal activities [4-6]. The structural imprint left on the rocks of the area are dominantly oriented from N - S to NE – SW and these define the prominent and pervasive Pan-African orogenic activities. The map area is mainly of high grade metamorphic terrain, attaining granulite facies metamorphism [6,7]. The geochemical characteristics of REE could be used to deduce the petrogenesis of the rocks of the region [7,8]. The rare-earth element abundance and their distribution patterns in the rock are products of the mineral phases and rock petrogenesis. This paper is aimed at utilizing the geochemical characteristics of the mafic rocks to derive the petrogenetic model, differentiation pattern and the metamorphic evolution of southwest Obudu Plateau.

2. METHODOLOGY

Representative rock samples from the map area (southwest Obudu Plateau) were pulverised at the Department of Geology, University of Calabar, Nigeria. The samples were analysed for their REE component using Inductively Coupled Plasma Mass Spectrometry (ICP-Ms) at the Activation Laboratories, Ontario, Canada. Approximately 30-gram sample was encapsulated and weighed in a polythene vial and an internal standard at a thermal neutron flux of 7×10^{12} $ncm^{-2}s^{-1}$. After seven-day decay, that was to allow ^{24}Na to decay, the samples were counted on a high purity Ge detector with a resolution better than1.7kw for the 1332 KeV Co 60. Using the flux wires, the decay corrected activities were compared to a calibration developed from multiple certified international reference materials. The standard present was only a check on accuracy of the analysis and was not used for calibration purposes. Samples were rechecked by re-measurement if element proportions vary from 10 to 30 per cent. This procedure is highlighted by [9] who however utilized the isotopes and gamma-ray energies processes employed by [10].

3. RESULTS AND DISCUSSION

3.1 Meta-ultramafic

This dark coloured rock outcrops at the Ukpe junction along Ogoja-Obudu road where it is highly weathered and serpentinized. Alteration of the amphibole to talc was observed in this weathered portion. Meta-ultramafic stretches from this junction into the Okure hills as a lensoidal body (Fig. 2). At Ukwortung, the rock is exposed as extensive outcrop with strong surface foliations (Fig. 3). Perforations on the surface of the outcrop at certain locations describing a kind of vesicular texture were observed (Fig. 3). The grain size increases up the hill, from medium to very coarse mid-way up the Okure hills. Prismatic hornblende ranging in size up to 3 – 4 mm imparts a glassy lustre and a linear fabric to the meta-ultramafic. These foliations are not very penetrative in this rock. The gneissic texture is very prominent in this very coarse-grained variety. The intrusive nature of this rock into the charnockitic gneisses is evident from the field relationship. The meta-ultramafic occurs as dykes in the charnockitic gneisses at some parts of Ukwortung and Okordem. Under the microscope the grains are mostly equigranular with olivine showing irregular characteristic fractures. Amphibole (hornblende) grains with prismatic cleavage occur in most thin sections (Fig. 4). Serpentinization has affected some of the grains as shown in the lower portion of Fig. 4. From the thin sections, stable assemblage and crystallization under aqueous condition are inferred from the euhedral hornblende and ubiquitous triple grain junctions. Specks of iron ore occur along with spinel crystals. In some sections, this iron specks as well as green symplectites (either serpentine or green amphibole) line these fractures.

3.2 Dolerite and Diorite

Diorite and dolerite occur as dykes and sills. The spatial distribution favour dolerites compared to diorite and the meta-ultramafic. The dolerite dykes are not restricted to any particular rock unit but occur as fine to medium-grained hyperbysal intrusive rocks. Dolerites were found to be concordant and discordant at different locations to the foliations of the host gneisses. At Ohong, dolerites are parallel to the foliations and have approximate width of 1.83 m and strike of 159°. In most other locations, the dolerite dykes are discordant to the foliation of the host gneiss. Dolerite dykes occur as swarm in the Okure hills towards the Okordem junction (Mkpenege) (Fig. 5). These swarms dissect the host rocks into discrete blocks and the dykes range in width from 4 to 58 cm. The dolerite dykes occurring close to the road cut at Ukwortung along Ogoja road strikes 086° with an average width of 15 cm. These discordant dykes making sharp contact with the host granulite facies rocks show slight displacement (Fig. 5).

Fig. 2. Outcrop of meta-ultramafic rock at Ukwortung, Southeastern Nigeria occurring as a lensoidal body

Fig. 3. Outcrop of meta-ultramafic rock at Ukwortung, Southeastern Nigeria

Fig. 4. Photomicrograph of meta-ultramafic rock showing pyroxene, hornblende and iron ore grains

Fig. 5. Swarm of dolerite dykes intruding the leucogranite near Okordem junction Southwest of Obudu Plateau

Amygdaloidal texture with calcite dust and finely divided micaceous fillings occupy the vesicles in Ukwortung dolerites. These dolerites also contain pyritic phenocrysts as was observed along Ibong – Kukorshie road. Diorite dyke was observed at the land slide site at Ukpe with a strike of 160^o and has a width range of 60–72 cm. Also occurring within the same environment, the deep green coloured diorite has a width of 5.62 m and strikes 138°. At Ukwortung, Ukpe and Ogban areas, diorite occurs as boulders. At Kutia, this rock shows very coarse texture. In thin section, the dolerites vary in texture from porphyritic, fine to medium grained. Cluster and interlocking plagioclase and olivine grains constitute the phenocrysts (Fig. 6). Deformation structures were observed on the plagioclase grains. Fracturing of the grains and shearing of the twin lamellae lend credence to forceful emplacement of the magma along a restricted environment. The modal proportion of the major mineral constituents of the dolerite include plagioclase of labradorite composition (An_{56}) 45%, pyroxene (augite) 29% and olivine 13%. Accessory minerals are biotite, hornblende, calcite, quartz, opaque and sericite depending on the locality. Diorite on the other hand shows very coarse texture and the grains are inequigranular. The lath-like plagioclase crystals tend to fence other grains (Fig. 7). The plagioclase phenocrysts show no particular orientation but are often clustered forming interlocking crystals.

Sub-ophitic texture was observed in some sections. Major minerals include plagioclase (oligoclase), clinopyroxene and olivine. Quartz occurs in negligible amount.

3.3 Geochemistry: Major Element Data

The results of the major element composition and CIPW normative analyses are as presented in Table 1. The total oxides range in values from 98.84 to 99.97 wt. %. Whole rock analysis of the meta-ultramafic rock of the study area revealed that it is low in SiO_2 (43.30–44.45 wt. %). TiO_2 (0.68-0.72 wt. %), P_2O_5 = 0.09, Na_2O (0.43–0.44 wt. %), K_2O (0.10–0.15 wt. %) and (Na_2O + K_2O) are equally very low. This low K_2O content suggests that the rock belongs to the low- K tholeiitic suite [11]. Al_2O_3 varies from 6.68–6.84 wt. %. This rock contains high proportion of MgO (24.11–24.56 wt. %). The FeO_T ranges from 13.09 to 13.20 wt. % and A/CNK < 1. The meta–ultramafic rock is primitive in composition with Mg# 64.81–65.15. These values falls within the range of those from the Qingbulake intrusion in China (59–81, [12]); but lower than those of metaperidotite in ophiolites (89–91, [13] and [14]). These probably point to the intrusion not being a direct crystallization of primitive magma but may have underwent a certain degree of differentiation and evolution [12]. The normative anorthite (16.58–16.72) is in consonance with high normative olivine (35.48–42.26) and diopside (14.13–14.65) < normative hypersthene (18.69–23.52).

In binary plot of TiO_2 against Zr the rocks plots in the mafic – ultramfic field (Fig. 8), the dolerites from the study area show a narrow range of SiO_2 (50.96 – 52.40 wt. %). The high Al_2O_3, 14.79 wt. % on the average and CaO with range 8.35–8.52 wt. %, low TiO_2 P_2O_5 and high Na_2O/K_2O ratios (3.87–4.49) are probably products of plagioclase accumulation. The MgO indicate a range of 5.14–6.08 wt. % with moderately high Mg# (27.90–33.05), Na_2O + K_2O (4.35–4.85 wt. %) and A/CNK ~ 1.20.

In the SiO_2 – FeOt/MgO binary plot, the dolerites occupy the tholeiite field along with the diorite (Fig. 9). Diorite samples from the area Southwest of Obudu Plateau, Nigeria have a narrow SiO_2 (56.27–57.24 wt. %) range. This SiO_2 values are higher than those of the meta-ultramafic and dolerite samples from the same area. The TiO_2 < 1 on the average and the P_2O_5 are quite low. The Na_2O/K_2O (1.56–1.62) ratios are lower than same ratios for dolerites and meta-ultramafics from the same area. A/CNK or ASI is slightly greater than a unity, and K_2O < Na_2O. Mg# (19.95–25.72) is lower than the values for the dolerites. FeO_T has a range of values of 9.87–11.09. There is absence of normative olivine and higher proportion of normative albite over anorthite. The higher proportion of normative orthoclase (12.49–14.14) and lower normative Di (3.17–3.47) are indications that this rock is more fractionated than both dolerites and meta-ultramafics.

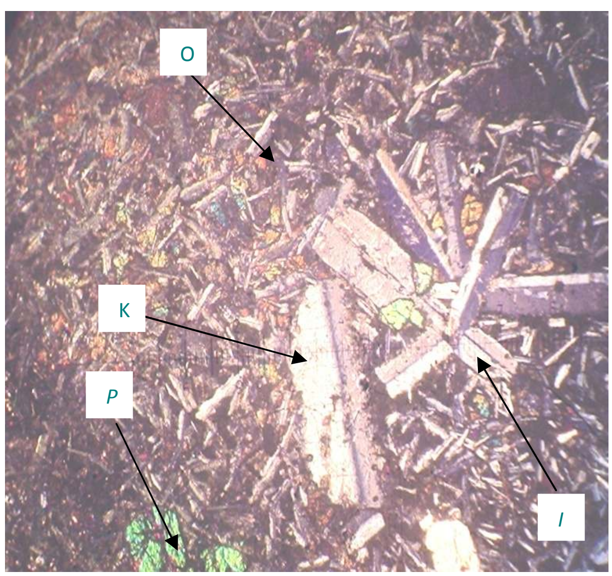

Fig. 6. Cluster and interlocking plagioclase phenocrysts in the dolerite dyke of Southwest, Obudu area

X40 (cross polarized light) (K = plagioclase; O = olivine; P = pyroxene; I = interlocking plagioclase grains)

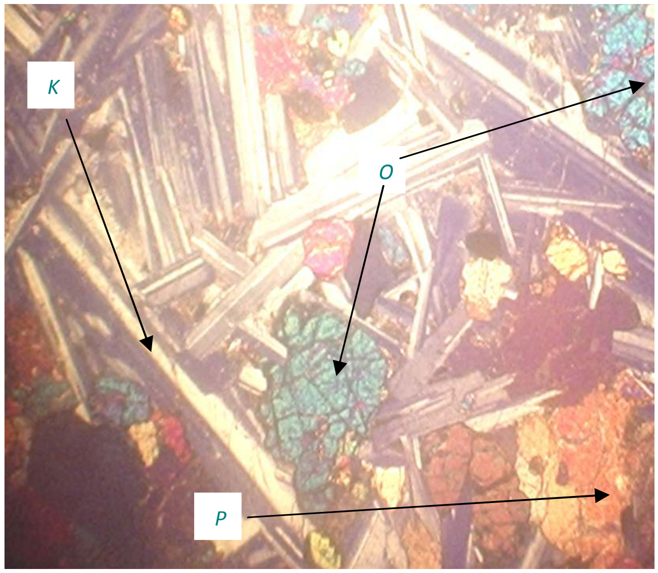

Fig. 7. Diorite from Kutia showing very coarse porphyritic texture
X40 (cross polarized light). (K = plagioclase; O = olivine; P = pyroxene)

Table 1. Major element composition and CIPW norm values of basic and mafic rocks from southwest of Obudu Plateau, Nigeria

Major elements	1	2	3	4	5	6	7	8	9	10
SiO_2	44.45	43.60	43.40	52.40	51.81	50.96	51.95	56.82	57.24	56.27
TiO_2	0.71	0.72	0.68	1.80	1.78	1.81	1.89	0.72	0.78	1.25
Al_2O_3	6.84	6.76	6.68	14.87	14.88	14.75	14.65	16.24	15.75	15.42
Fe_2O_3	1.33	1.36	1.33	2.87	2.90	2.78	2.80	2.62	2.39	2.33
FeO	12.00	11.92	11.89	9.55	9.66	9.27	9.33	8.73	7.96	7.77
MnO	0.17	0.18	0.18	0.135	0.122	0.134	0.17	0.15	0.16	0.19
MgO	24.11	24.56	24.5	6.08	5.68	5.81	5.14	2.85	3.5	2.46
CaO	6.97	6.81	6.81	8.40	8.35	8.52	8.74	5.54	5.12	6.94
Na_2O	0.43	0.44	0.44	3.64	3.06	3.55	3.86	3.29	3.48	3.68
K_2O	0.15	0.10	0.10	0.82	0.79	0.80	0.86	2.09	2.15	2.36
P_2O_5	0.08	0.09	0.09	0.26	0.22	0.24	0.06	0.02	0.09	0.08
LOI	2.73	2.74	2.74	0.31	0.33	0.82	0.43	0.65	0.78	0.96
Total	99.97	99.28	98.84	99.14	99.58	99.44	99.79	99.72	99.87	99.71
ACNK	0.88	0.91	0.87	1.20	1.22	1.20	1.09	1.49	1.47	1.19
Na_2O/K_2O	2.87	2.44	2.44	4.44	3.87	4.44	4.49	1.57	1.62	1.56
$Na_2O + K_2O$	0.58	0.54	0.54	4.46	4.85	4.35	4.72	5.38	6.63	6.04
Mg#	64.81	65.15	64.99	27.9	31.64	33.05	30.25	20.45	25.72	19.95
	CIPW -norm values									
Q(s)										
Or	0.62	0.61	0.91	3.06	4.72	4.8	4.91	12.49	12.9	14.14
Ab	3.87	3.85	3.73	30.62	26.13	30.44	31.5	28.09	29.84	31.5
An	16.58	16.72	16.72	22.57	24.76	22.24	19.39	23.57	21.27	18.78
Di	14.43	14.13	14.65	14.36	14.15	15.86	12.48	3.47	3.33	3.17
Hy	18.69	20.93	23.52	21.81	21.54	16.45	11.84	20.15	20.47	20.33
Ol	42.26	38.69	35.48			2.90	10.59			
Mt	2.01	3.45	3.43	3.31	3.39	3.28	3.16	2.86	2.65	3.42
Il	1.34	1.42	1.39	3.40	3.42	3.49	3.47	1.38	1.50	2.41
Ap	0.20	0.20	0.18	0.57		0.53	2.68	0.04	0.20	0.18

1 - 3 Meta-ultramafic; 4 - 7 = dolerite and 8 - 10 Diorite from the study area

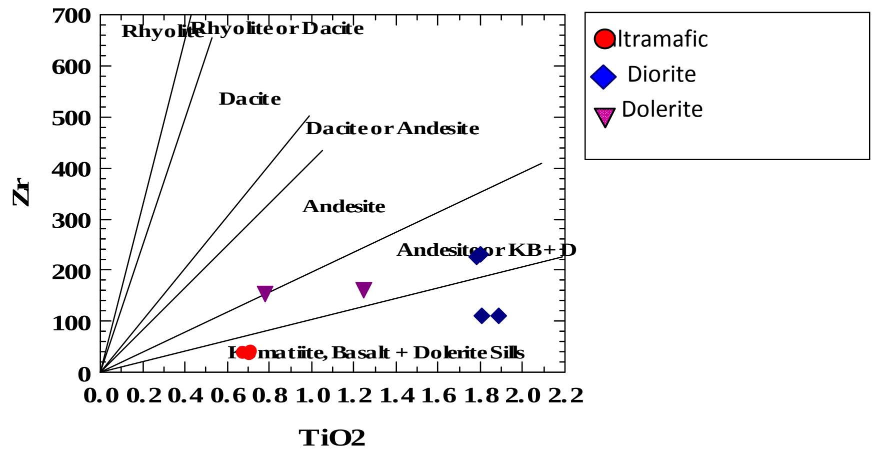

Fig. 8. Classification of the mafic and meta-ultramafic rocks on Zr – TiO_2 (after Winchester and Floyd, [15])

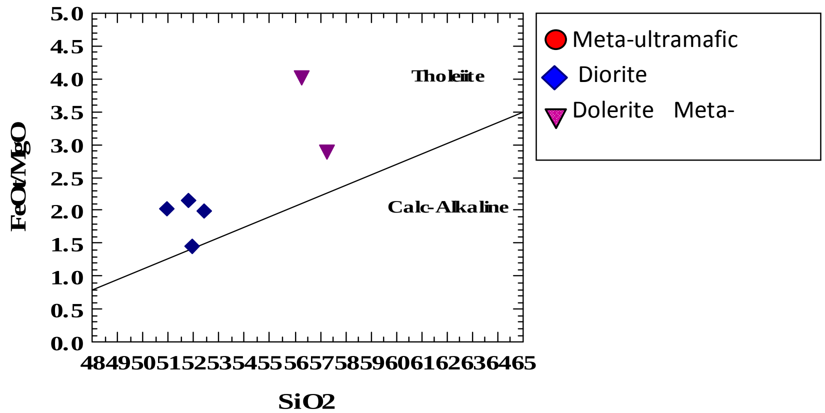

Fig. 9. Binary plot of SiO_2 against FeO_t/MgO for mafics rocks from the area SW Obudu, Bamenda Massif (after Miyashiro [16])

The trace elements analysis and their ratios for the mafic rocks from the area southwest of Obudu Plateau are presented in Table 2. The mafic rocks of southwest Obudu show slight variation in the trace and rare-earth element proportion. The meta-ultramafic show high concentration in elements like Cr (2045–2060 ppm), Ni (1056–1072 ppm), Cu (366–373 ppm) and W(215–311 ppm), but are low in the concentration of Ba, Nb, Ta, Cs, U and the rare-earths. The dolerites and the diorites are equally enriched in such elements as Ba (1020–1117) for the diorite and Ba (345–643) for dolerite. These mafic rocks equally show high concentration of such elements as Sr, Zr, V and Zn but are low in TiO_2 (0.68–1.89). The mafic rocks show variation in the total REE contents. For the meta-ultramafite, ∑REE values range between 29.39 and 32.39 with average value of 30.77. The dolerite has ∑REE values of 92.50–138.44 with average of 123.31. Diorite on the other hand has ∑REE average values ranging from 53.99 to 69.61.

On the discrimination plot Zr – TiO_2 of [12], meta-ultramafic and dolerite plot in the field of mafic – ultramafic rocks. The diorite exhibit a higher concentration of Zr compared to meta–ultramafic and the dolerites confirming higher fractionation than other mafic rocks of the area (Fig. 8).

On the Ti - Zr - Y diagram after [17], these rocks plot in the field of within plate basalts. This meta-ultramafic rock shows no arc affinity but the dolerite show calc – alkaline affinity by plotting at the boundary region. The Ti–Zr-Sr discrimination diagram (Fig. 10) show the meta-ultramafic being of ocean floor basaltic magma type whereas dolerite and diorite both plot in the IAB and CAB fields respectively. The arc characteristic is strongly exhibited by both dolerite and diorite as they both plot in the magmatic arc field of Hf-Th-Nb diagram of [18]. The meta-ultramafic is in the Within Plate Basalt and E-MORB field (Fig. 11).

Table 2. Trace element composition of mafic rocks from Southwest of Obudu Plateau, Nigeria

Trace elements	1	2	3	4	5	6	7	8	9	10
Ba	6	9	7	472	643	345	365	1109	1020	1117
Rb	1.86	0.96	1.96	48	46	20	24	133	145	132
Sr	70	67	72	574	569	455	443	442	439	439
Y	9	7	8	< 1	< 1	24	23	20	18	21
Zr	35	38	33	232	226	111	112	158	154	160
Nb	4	6	7	3	4	17	16	13	12	14
Th	0.3	0.4	0.2	21	20	1.7	1.5	3.1	3	3.3
Pb	4.95	3.98	5.89	32	34	4.99	4.97	56	57	54
Ga	9	11	7	29	32	23	21	32	30	32
Zn	70	76	68	47	49	87	85	176	178	177
Cu	373	381	366	< 10	< 8	42	33	22	20	23
Ni	1060	1072	1056	< 20	< 23	47	46	315	313	318
V	166	144	162	156	153	156	153	318	320	316
Cr	2060	2045	2056	6	< 18	187	182	83	85	86
Hf	1	1.3	0.9	< 1	6.4	3.73	3.16	3.96	3.9	3.88
Cs	0.88	1	< 4	1	< 1	0.96	0.5	13.02	12.87	13
Sc	27	31	25	21	20	18.1	19	25	26	27
Ta	0.7	0.6	0.8	1.8	2.3	1.4	1.98	1.18	1.2	1.19
Co	126	124	128	104	106	86	84	27.86	30	27.55
Li	< 0.1	< 0.1	< 0.1	1	1.4	1.3	1.2	1.3	1.42	1.46
Be	0.89	0.96	0.86	0.8	0.83	2	2	3.54	4.8	5.11
U	0.99	0.98	0.96	< 4	< 0.52	0.5	0.7	2.4	26	25
W	215	311	220	279	274	102	86	57	0.02	0.03
Mo	1.97	0.98.	1.97	4.99	1.96	1.98	1.97	tr	Tr	tr
As	< 5	< 4	< 5	< 4	Tr	Tr	tr	tr	Tr	tr
Ti	< 0.1	< 0.1	< 0.1	0.2	0.21	0.22	0.2	tr	0.11	tr
La	3.8	4	3.7	23.8	24.5	21.66	16.5	5.81	4.32	4.62
Ce	10.4	10.6	10.3	51.3	50.8	44.6	34.2	18.1	11.21	12.43
Pr	1.43	1.46	1.41	6.2	6	5.89	3.98	3.63	2.41	3.08
Nd	6.6	6.7	6.5	27.9	27.4	28.1	17.5	13.12	10.21	12.4
Sm	1.6	1.8	1.5	7	6.95	6.83	4.4	4.2	3.55	4.15
Eu	0.54	0.56	0.53	2.46	2.41	2.58	1.65	1.54	1.36	1.48
Gd	1.7	1.8	1.6	7	6.92	6.85	4.6	5.26	4.58	5.09
Tb	0.3	0.7	0.2	1.1	0.96	0.98	0.8	1.1	0.87	0.89
Dy	1.7	1.9	1.6	5.6	6.1	5.8	4.2	6.71	6.33	6.56
Ho	0.3	0.4	0.2	1	0.99	1.2	0.7	1.52	1.27	1.46
Er	1	1.1	0.9	2.6	2.57	2.64	2	4.11	3.66	4.35
Tm	0.15	0.2	0.13	0.33	0.45	0.38	0.26	0.58	0.62	0.66
Yb	0.9	1	0.7	1.9	1.87	2	1.5	3.4	2.98	3.28
Lu	0.14	0.15	0.13	0.25	0.31	0.27	0.22	0.53	0.62	0.65
∑ LREE	23.83	24.58	56.71	116.2	109.92	107.08	76.58	44.86	31.7	36.68
∑HREE	6.19	7.25	2.86	19.98	20.17	20.12	14.28	23.21	20.93	22.94
Ba/Nb	1.50	1.50	1.00	157	161	20.29	22.81	85.31	85.00	79.79
Zr/Ba	5.83	4.22	4.71	0.49	0.35	0.32	0.31	0.14	0.15	0.14
La/Nb	0.95	0.67	0.53	0.13	0.16	0.79	0.79	0.45	0.36	0.33
Ce/Pb	2.1	2.66	1.75	1.6	1.49	9.1	6.88	0.32	0.2	0.23
Sm/Hf	1.60	1.39	1.67	>7	1.09	1.83	1.39	1.06	0.91	1.07
Rb/Cs	2.11	0.96	<0.70	48	> 46	20.83	48.00	10.22	11.27	10.15
Zr/Y	0.26	0.18	0.24	0.004	0.004	0.22	0.21	0.13	0.12	0.13

1 - 3 Meta-ultramafic; 4 - 7 = dolerite and 8 - 10 Diorite from the study area

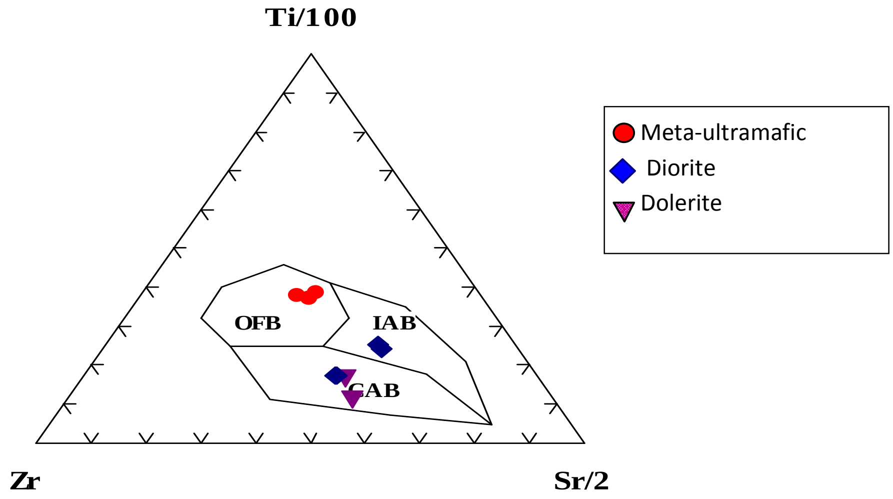

Fig. 10. Discrimination diagram Ti – Zr – Sr for the mafic rocks from SW Obudu, Bamenda Massif (after Pearce and Cann [17])

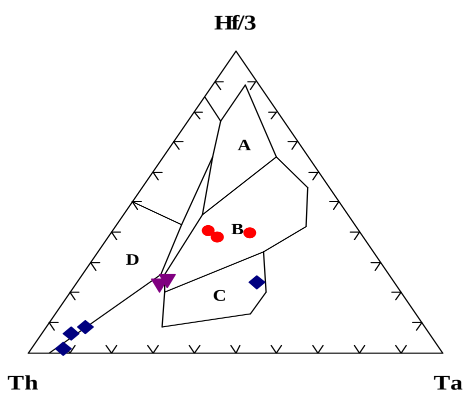

Fig. 11. Tectonic plots of Hf – Th – Nb for the mafic and meta-ultramafic rocks of the area: A= N-type MORB; B=E-type MORB & Tholeiitic WPB (within plate basalts; C= Akaline WPB and WPB and differentiates; D= destructive plate-margin basalts and differentiates (after Pearce and Cann [17])

In the primitive mantle normalized trace element diagram for mafic rocks of the area (Fig. 12), the meta-ultramafic rocks show enrichment in Pb, Cs and Ta. Ba is slightly depleted as well as Y. However, Rb, Th, Nb, Ce, Sr, Zr and Tb are fairly uniform. Ga content in the mafic and meta-ultramafic have higher values than the value (Ga ≈ 4ppm) of [19] for the primitive mantle. Magma source is probably due to partial melting of the lithospheric mantle enriched in Ga.

The mafic rocks of southwest Obudu Plateau show enrichment in HREE and depletion LREE. Positive anomalies are slightly shown by Pr, Tm. Whereas Ce, Ho and Yb define negative anomalies (Fig. 13).

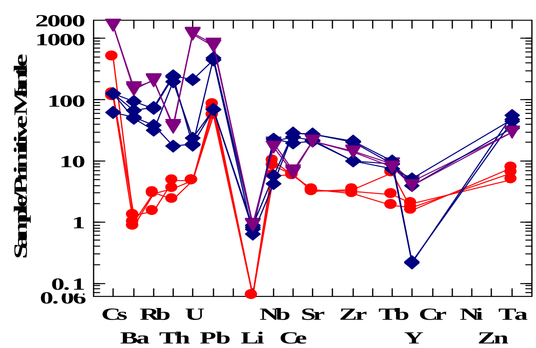

Fig. 12. Primitive mantle normalized trace element diagram for the mafic rocks of the map area

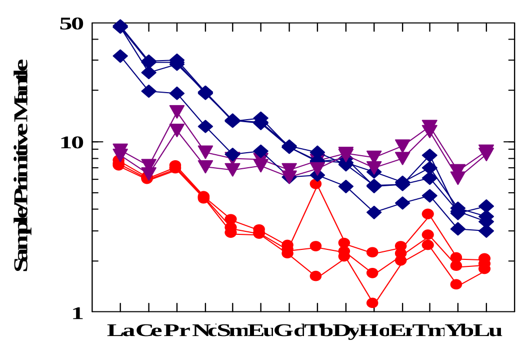

Fig. 13. Primitive mantle normalized rare earth element diagram for the mafic rocks of the map area

3.4 Petrogenetic and Tectonic Significance

The meta-ultramafic is low in SiO_2 (43–44 wt. %) without normative quartz and normative Or <1 [20]. The relatively high MgO contents ranging from 24 to 25 wt. %, their high compatible element contents (Ni = 1056–1072 ppm, Co = 124–128 ppm and Cr = 2045–2060 ppm) indicate that this rock was derived from a near primitive magma and not from evolved magma [21].

The trace and rare-earth (REE) patterns seem to be similar for the mafic rocks from southwest Obudu Plateau, a possible comagmatic genesis for these rocks could be deduced. These intrusive rocks are low in Ti, Zr and Nb; rich in LREE and depleted in HSFE (e.g. Y, Nb, Zr) with ratios of Ce/Pb = 0.23–9.10, La/Nb = 0.13–0.97. These low ratios might indicate mantle metasomatism and /or small degree of partial melting [13]. Th/Yb and La/Yb values ranges are 0.85 – 3.01 and 1.41–13.10 respectively. The mafic rocks of southwest Obudu, Nigeria display enrichment in LILE and LREE but with considerable depletion in HSFE. The mantle source for these mafic rocks, especially the closely related dolerite and meta-ultramafic cannot be ruled out. The low HREE, Y and Zr suggest partial melting of the upper mantle source with residual garnet [22]. Sm/Hf average values for meta-ultramafic and dolerite are 1.55 and 2.83 respectively. These values are greater than that for the primitive mantle (1.43; [13]). This probably is an indication of fractionation of hafnium from samarium during magma generation. Ce/Pb ratios for meta-ultramafic ranges between 1.75 and 2.64; that of dolerite (1.49 – 9.10) and diorite (0.20 – 0.32). Variation may probably indicate certain level of fractionation [19]. Zr/Ba ratios for the ultramafic and dolerite far exceed 0.2 but the values for diorite are less. The values exceeding 0.2 are indicative of magma derived from the asthenosphere (or mixed by asthenosphere materials, [23]). The low values according to these workers, for dolerite could be as a result of the magma being derived from lithospheric mantle. All the Zr/Y ratios are low for all the rocks, <1. Rb/Cs values for these rocks are much lower than the value for oceanic basalt and primitive mantle as proposed by [19]. The mafic rocks from SW Obudu, Nigeria may have been derived from an enriched mantle by partial melting. The granitoids associated with these mafic rocks have been dated Paleoproterozoic (2061.4±0.4 Ma,) and Mesoproterozoic (1548.8±0.5 Ma), [24]. These ages are much older than those ascribed by [25] to the meta-ultramafic (811.6±1.1 Ma). These granitoids were emplaced in active arc environment and a probable later collision activity [26] which probably culminated in subduction related activities earlier mentioned. The ultramafic rocks in the Obudu area could likely be tectonic slices of the upper mantle just like the Mallam Tanko serpentinites of [27]. They are very likely remnants of ophiolites caught in the suture zones [28] yet to be properly defined in this environment. The meta-ultramafic rock may likely be associated with the closing phase of the Mesoproterozoic orogenic cycle which may have produced a setting for the magmatism that resulted in the leucogranitic and the meta-ultramafic rocks of this area [24].

4. CONCLUSION

On the basis of geochemical data, the mafic rocks of southwest Obudu, Nigeria display signatures from which the following conclusions could be reached:

- i) The meta-ultramafic rock is a derivative of a near primary magma and probably not from an evolved magma. These mafic rocks occur as veins in some localities in the Proterozoic rocks of the area, indicating they intruded the later in their semi-molten state. The rocks were approximately coeval with the Proterozoic rocks.
- ii) The mantle source for these mafic rocks, particularly the closely related dolerite and meta-ultramafic cannot be ruled out.
- iii) The diorite being more fractionated very likely is a product of an evolved magma and may be unrelated to the other mafic rocks of the area. The area probably experienced more than one episode of magmatic activity.
- iv) The meta-ultramafic rock probably is associated with closing phase of the Mesoproterozoic orogenic cycle that produced magmatism which gave rise to the leucocratic rocks.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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