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Geochemical constraints on the petrogenesis of the pyroclastic rocks in Abakaliki basin (Lower Benue Rift), Southeastern Nigeria

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A B S T R A C T

The pyroclastic rocks in the Cretaceous Abakaliki basin occur mostly as oval-shaped bodies, consisting of lithic/lava and vitric fragments. They are commonly characterized by parallel and cross laminations, as well contain xenoliths of shale, mudstone and siltstones from the older Asu River Group of Albian age. The rocks are basic to ultrabasic in composition, comprising altered alkali basalts, altered tuffs, minor lapillistones and agglomerates. The mineral compositions are characterized mainly by laths of calcic plagioclase, pyroxene (altered), altered olivines and opaques. Calcite, zeolite and quartz represent the secondary mineral constituents. Geochemically, two groups of volcaniclastic rocks, are distinguished: alkaline and tholeiitic rocks, both represented by fresh and altered rock samples. The older alkali basalts occur within the core of the Abakaliki anticlinorium while the younger tholeiites occur towards the periphery. Though most of the rocks are moderate to highly altered [Loss on ignition (LOI, 3.43–22.07 wt.%)], the use of immobile trace element such as Nb, Zr, Y, Hf, Ti, Ta and REEs reflect asthenospheric mantle source compositions. The rocks are enriched in incompatible elements and REEs ($\sum$REE = 87.98–281.0 ppm for alkaline and 69.45–287.99 ppm for tholeiites). The ratios of La/Yb_n are higher in the alkaline rocks ranging from 7.69 to 31.55 compared to the tholeiitic rocks which range from 4.4 to 16.89 and indicating the presence of garnet-bearing lherzolite in the source mantle. The spidergrams and REEs patterns along with Zr/Nb, Ba/Nb, Rb/Nb ratios suggest that the rocks were generated by a mantle plume from partial melting of mixed enriched mantle sources (HIMU, EMI and EMII) similar to the rocks of the south Atlantic Ocean such as St. Helena (alkaline rocks) and Ascension rocks (tholeiitic rocks). The rocks were formed in a within-plate setting of the intra-continental rift type similar to other igneous rocks in the Benue Rift and are not related to any subduction event as previously suggested.

1. Introduction

The Late Jurassic to Cretaceous Abakaliki basin is the southeastern Lower Benue Rift of Nigeria that represents the southern section of the intra-continental Benue Rift, also known as Benue Trough or Benue Aulacogen (Cratchley and Jones, 1965; Olade, 1975). The rift stretches northeastwards from the Gulf of Guinea to the northern parts of Cameroun is the failed arm of the South Atlantic - Gulf of Guinea - Benue triple junction, formed during the separation of South America from Africa at about 140 Ma (Berriasian times; Fig. 1) (Burke et al., 1971; Benkhelil, 1987; Popoff, 1990; Nürnberg and Müller, 1991; Coulon et al., 1996; Burke, 2001; Nwajide, 2013).

The study area consists of two magmatic centres in the Lower Benue Rift, namely: Abakaliki and Ejekwe-Wanikande districts (Fig. 2). The igneous rocks in the Lower Benue Rift are basic to intermediate igneous rocks comprising dolerites, basaltic sills, gabbros/microgabbros, alkali dioritic rocks, dolerites, nepheline syenites, trachytes, phonolites, phonotephrites, tephriphonolites, basaltic to trachybasaltic tuffs, and lapilli tuffs (Okezie, 1957; Obiora, 1994; Obiora and Umeji, 1995; Maluski et al., 1995; Coulon et al., 1996; Obiora and Charan, 2010, 2011; Chukwu and Obiora, 2014). The igneous rocks were emplaced within Late Aptian to Coniacian sedimentary rocks that experienced weak regional metamorphism (Obiora and Umeji, 2004). The pyroclastic rocks were believed to be of pre-Albian age (Uzuakpunwa, 1974; Olade, 1979); however, earlier work of McConnel (1949) reported the

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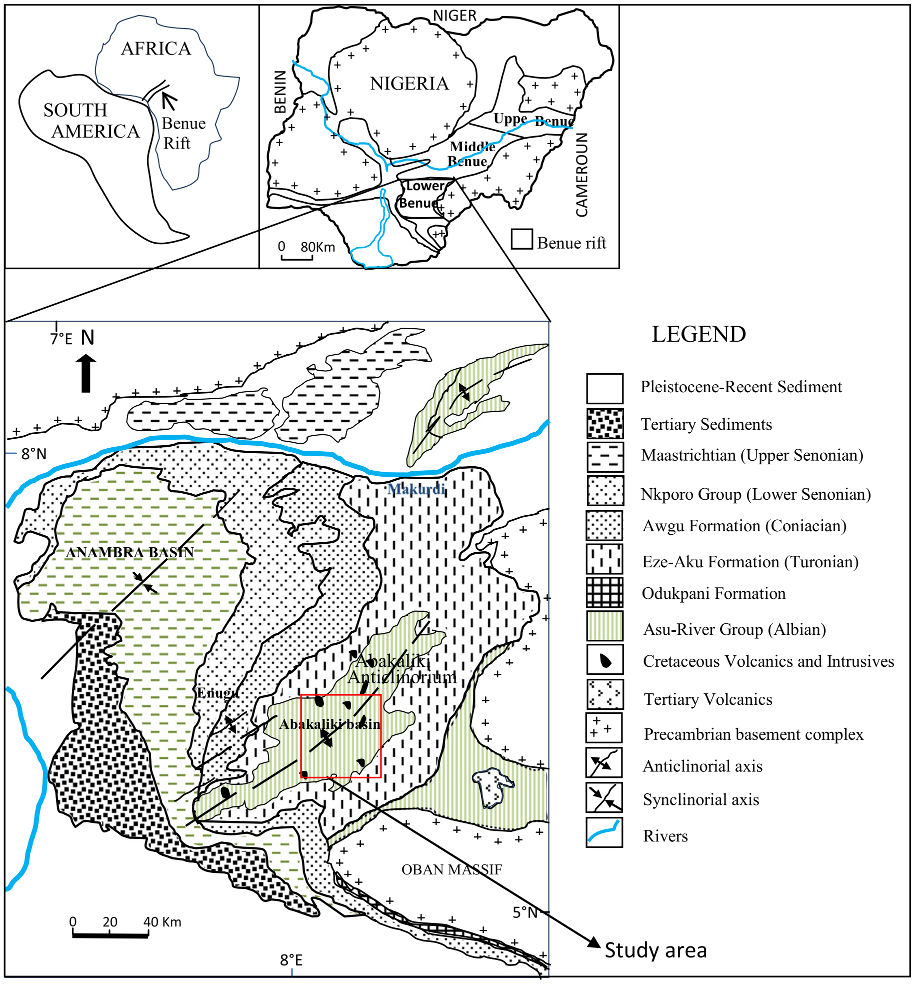


Fig. 1. Geological map of Southeastern Nigeria showing the study area.

same volcanic rocks were interstratified with Albian shales suggesting they were Albian in age. Farrington (1952) and Ojoh (1988, 1990) argued for a post-Albian age based on stratigraphic analysis and later supported by Maluski et al. (1995) and Coulon et al. (1996) who obtained an age of 103 ± 5 Ma using $^{39}Ar/^{40}Ar$ dating method on coherant rock types in the area. The emplacement of these pyroclastic rocks represent the final episode of the earliest magmatism that began at ca. 147 Ma in the northern part of the Benue Rift (Umeji and Caen-Vachette, 1983; Maluski et al., 1995; Coulon et al., 1996). As shown by Obiora and Charan (2010), pyroclastic deposits are well preserved in Abakaliki and Ejekwe-Wanikande districts than other areas of the Lower Benue Rift. Burke et al. (1972) used macroscopic observations to describe the pyroclastic rocks as andesite (a typical rock of subduction zone), thereby concluded that the Benue Trough had originated through subduction related activities. Olade (1979) described the Abakaliki pyroclastic rocks as alkali basalts reworked during marine transgression, while Hoque (1984) opined that the events of origin and evolution of the Benue Trough and the pyroclastic volcanism were independent events and not related.

After the work of Burke et al. (1972) on the pyroclastic rocks, works on the tectonic origin of the igneous rocks are scarce due to lack of geochemical data on these rocks. However, Coulon et al. (1996) attributed the magmatism in other parts of the Benue Rift to have originated from the St. Helena Plume. Recently, Obiora and Charan (2010, 2011) and Chukwu and Obiora (2014) show that the intrusive rocks from other parts of the Lower Benue Rift are predominantly alkaline, within-plate (intra-continental), similar to volcanic rocks on the East African Rift/Kenyan Rift. The pyroclastic rocks in Wanakom area (northeastern area of the Abakaliki anticlinorium) have not been reported in details.

In this paper, we report on the petrology and whole-rock geochemical data analysis of pyroclastic rocks in the region (Abakaliki and Wanakom areas); we use the new data to identify the nature of the volcanism and to constrain their petrogenesis and compare our results with data obtained from the other igneous rocks within the Lower Benue Rift.

2. Field relationship of the pyroclastics

The outcrops of the pyroclastic rocks in the Abakaliki basin are concentrated around Abakaliki town and surrounding villages (southwestern parts of the map; Fig. 2) and extend to Ezekwe-Wanakom area (northeastern parts of the map) in Yala, Cross River State, Nigeria (Fig. 2). They form isolated hills within the eroded anticlinal structures around Abakaliki area. The pyroclastic rocks are hosted by the folded sequence of slaty shale and alternating sandy shale, siltstones, mudstones and occasional carbonate rocks [Aptian - Albian age, (Asu-River Group)] of shallow marine origin mostly around the centre of the tectonically formed Abakaliki anticlinorium. The extrusive rocks show sharp contacts with the host rocks without evidence of baking and contain angular to

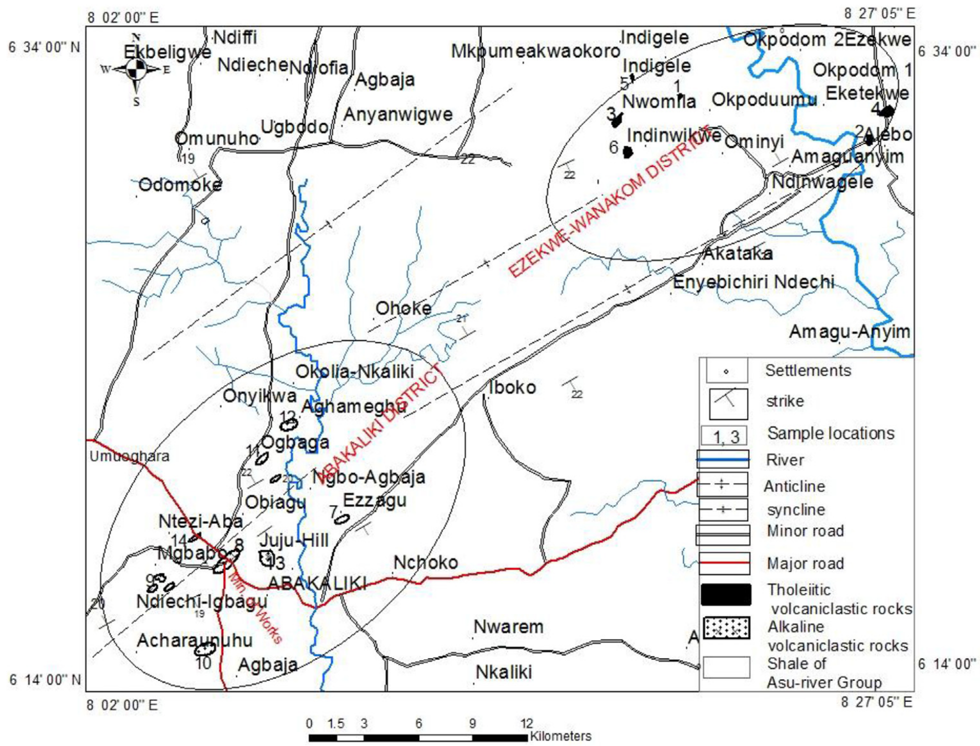


Fig. 2. Geological map of the study area, showing locations of the pyroclastic rocks in the Abakaliki and Ezekwe-Wanakom districts of the study area.

subangular xenoliths most probably from Albian rocks. These characteristics favour a late/post-Albian age for the volcaniclastic rocks. Towards the periphery of the anticlinorium, the pyroclastic deposits overlie unconformably Albian shales on weathered surfaces and flanked by the Turonian sequence of shale, sandstone and carbonaceous rocks (Eze-Aku Formation; Fig. 1). This suggests that the volcaniclastic rocks may be synchronous with the partly eroded Odukpani Formation (Cenomanian; Fig. 1) which directly overlies the Albian shales. Fourteen (14) bodies of the volcaniclastic rocks were mapped as shown in Fig. 2 and detailed description and locations presented in Table 1. The volcaniclastic rocks occur as small to large oval-shaped bodies trending NE – SW. The bodies range from about 10 m to 2 km long, 4 m to 450 m wide and exposed height of 3 m to 150 m, and are frequently exposed by quarry activities. The larger bodies occur mostly around Abakaliki town and its adjoining areas such as Locations 7, 8 and 13 see Table 1 and Fig. 2. The outcrop at Location 8 covers about 2 km long and 600 m wide, forming a ridge that stretches from the Old Ministry of Works through the Government House to Okpaugwu/New Layout, in Abakaliki town. The exact thickness of the volcaniclastic rocks is yet to be established, but a thickness of more than 140 m is exposed in the body in Location 7.

Field observations indicate that the common rocks are altered tuffs, lapillistones, and agglomerates. The altered tuffs are most widely distributed in the area (Table 1). The agglomerates do not occur as distinct bodies instead they occur together with the tuffs and lapillistones being concentrated in parts of the exposures, as observed in the Old Ministry of Works, Ezzagu (Sharon) and Onyikwa quarries (4.5 km northwest of Abakaliki). The tuffs are greyish/green ash-coloured, consisting of a coherent irregular fragment of fine lithic fragments and glass-shards. It also consists of occasional sub-angular xenoliths (3–7 cm) of metamorphosed argillaceous rocks mostly shale derived from the host Asu-River Group of Albian age. The angular to sub-angular nature of the xenoliths may suggest less reaction with the melt probably caused by rapid ascent. The tuffs exhibit structure (parallel and cross laminations) ranging from about 1 cm to 10 cm in thickness and this laminated unit represents the surge deposits. Some of the outcrops are graded and sorted, with a thickness of the graded units ranging from 1 cm to 5 cm. This unit could represent pyroclastic fall, while the other unit is poorly sorted and composed of compacted particles of tuffs and glass-shards units which represent the pyroclastic flow deposit. The unit that consists of larger blocks of breccia (5 cm–12 cm) and more xenoliths of angular to sub-angular argillaceous host rocks (1 cm–35 cm) and thicker compared to other units constitutes the agglomerates. They are dark-grey and consist of mainly more massive basaltic rocks in addition to its composition. Hoque (1984) also referred to the Abakaliki pyroclastic rocks (volcaniclastic rocks) as originated from pyroclastic fall, surge and flow. These units were observed at the Old Ministry of Works, Ezzagu (Sharon) and Onyikwa locations (see Fig. 3a–f). Volcanic bombs, of about 30–50 cm, which are basaltic in composition were also encountered around the Ezzagu and Old Ministry of Works quarries (Fig. 3f) and Ndiogogo, Wanakom area of the study area.

3. Petrographic characteristics of the rocks

Thin section studies show that the tuffs and agglomerates exposed around the core of the Abakaliki anticlinorium consist of plagioclase laths (labradorite in composition, some are altered to albite and sericite); clinopyroxene (replaced by uralite and chlorites), olivine (mostly replaced by iddingsite) and iron-oxides (magnetite) and sulphides (pyrite). These minerals occur in a matrix of scoriaceous vitric fragments that have been devitrified and form irregularly shaped glass-shards, giving the rocks a hypohyaline texture (Fig. 4a and b). Calcite, zeolite and quartz occur as

Table 1
Description of the sample locations in the study area.

Sample no.	Locations no.	Lat. and long.	Location name	Rock name
1AP	1	6°31′45″N	Nwomila, Wanakom	Tuff
1BP		8° 18′ 10″E	Nwomila, Wanakom	Tuff
2AP	2	6°31′01″N	Between Woleche ebo and Al Ebo 1., Wanakom	Tuff
2BP		8° 25′ 05″E	Between Woleche ebo and Al Ebo 1.	Tuff
3P	3	6°32′448″N	Ndiogogo 6, Wanakom	Volcanic Bomb
5P		8° 20′ 02″E	(Juvenile fragment), Niogogo Pyroclastic	Tuff
4P	4	6°32′00″N	Hand dug well wanakom Opp Court	Tuff
		8° 26′ 03″E		
6P	5	6°33′01″N	Ndingele, Wanakom	Tuff
		8° 18′ 15″E		
9P	6	6°31′10″N	Ndinwikwe, Wanakom	Tuff
		8° 18′ 35″E		
7AP	7	6°20′31″N	Sharon quarry, Abakaliki	Tuff
7BP		8° 08′ 42″E	Sharon quarry, Abakaliki	Tuff
7CP			Sharon quarry, Abakaliki	Agglomerate
8AP	8	6°18′57″N	Old min. of works Abakaliki (central part)	Tuff
		8° 05′ 56″E		
8BP		6°19′09.6″N	Old min. of works Abakaliki (southern part)	Lapillistone
		8° 05′ 48.9″E		
8CP		6°19′41.2″N	Old min. of works Abakaliki	Agglomerate
		8° 06′ 40.1″E		
10P	9	6°18′41″N	Ugwuokpu in Nkaliki	Tuff
		8° 04′ 53″E		
11AP		6°18′41″N	Ugwuokpu in Small Nkaleke 1	Tuff
11BP		8° 05′ 08″E	Ugwuokpu in Small Nkaleke 2	Tuff
12P	10	6°16′21″N	Inyimagu in Agbaja Pyroclastic	Tuff
		8° 05′ 56″E		
13P	11	6°23′36.2″N	Atang Onyikwa pyroclastic	Agglomerate
		8° 07′ 20.5″E		
14P	12	6°22′24.2″N	Onyikwa pyroclastic, Abakaliki	Lapillistone
		8° 07′ 03.7″E		
15AP	13	6°19′45.3″N	Juju hill pyroclastic leucocratic portion, Abakaliki	Tuff
15BP		8° 07′ 26.3″E	Juju hill pyroclastic (melanocratic portion)	Agglomerate
16P	14	6°20′48.5″N	Ameke-Aba (Mile 50), Abakaliki	Tuff
		8° 05′ 29.4″E		

amygdales and vein fillings. The tuff and agglomerates in Wanakom area in addition contain altered clino- and ortho-pyroxene (augite and hypersthene). They are also porphyritic with groundmass of the vitric component. The alteration products are calcite, sericite, chlorite and zeolite. Calcite and quartz also occur as cavity fillings.

4. Geochemistry

4.1. Analytical methods

Twenty-four representative rock samples were collected in two groups, the first group comprised of the least altered volcaniclastic rocks and the second group comprises the most altered volcaniclastics. The least altered samples were analyzed at the Activation Laboratories (ACTLABS) Ancaster, Ontario, Canada while the other rock samples were analyzed at the National Geophysical Research Institute, Hyderabad, India by the XRF for major-elements and ICP-MS for trace-elements. Roy et al. (2007) method of open acid digestion was used for sample preparation. 10 mL of the acid mixture (HF, HNO3, and $HClO_4$) in the ratio of 7:3:1 was added to 50 mg of powdered sample and heated on a hot plate (~150 °C) for 1 h to form crystal paste. Thereafter, 20 mL of 1:1 HNO_3 and distilled water was added and warmed (~70 °C) to dissolve the precipitate, after which 5 mL of 1 ppm ^{103}Rh was added as an internal standard. For more details, see the website http://www.actlabs.com.

4.2. Results

In the variation diagrams and other sections of this work, the volcaniclastic rocks were grouped into four units based on their field and chemical characteristics: the fresh tholeiitic volcaniclastic rocks (FTV), which represents the least altered tholeiitic rocks; the altered tholeiitic volcaniclastic rocks (ATV); the fresh alkali volcaniclastic rock (FAV) which represents the least altered alkali rocks; the altered alkali volcaniclastic rocks (AAV).

The major elements oxides and trace elements concentrations in the 24 representative samples of the volcaniclastic rocks from the Abakaliki basin are presented in Table 2. The major element oxides were recalculated on a volatile −free basis because of high volatile and carbonates concentration of the rocks. The rocks generally show silica − undersaturation and wide variation in silica (SiO_2) content which range in composition from basic to intermediate (46.87−59.88 wt. %) in the least altered rocks which is confirmed using IgRoCS software of Verma and Rivera-Gómez (2013) and ultrabasic to basic (31.41−49.04 wt. %) in the altered rocks except sample 11BP (53.88 wt. %) of altered rocks which is intermediate in composition. The variations in SiO_2 could be attributed to the mobilization of elements (alteration nature of the rocks), but immobile elements characteristics suggest that some degree of differentiation played some roles. The least altered rocks (FTV and FAV) have a loss on ignition (LOI) ranging from 3.43 to 12.91 wt. % while the altered rocks (ATV and AAV) have higher LOI contents ranging from 11.01 to 22.07 wt. % is indicating excessive alteration. The altered rock samples also show a high concentration of CaO (7.04−32.36 wt. %), compare to the least altered rocks (0.13−10.96 wt. %) attributed to the formation of calcite crystals from the breakdown and replacement of calcic plagioclase, clinopyroxene and olivine and formation of calcite amygdales. MgO (4.62−11.26 wt. %, in the least altered rocks and 4.24−10.69 wt. %, in

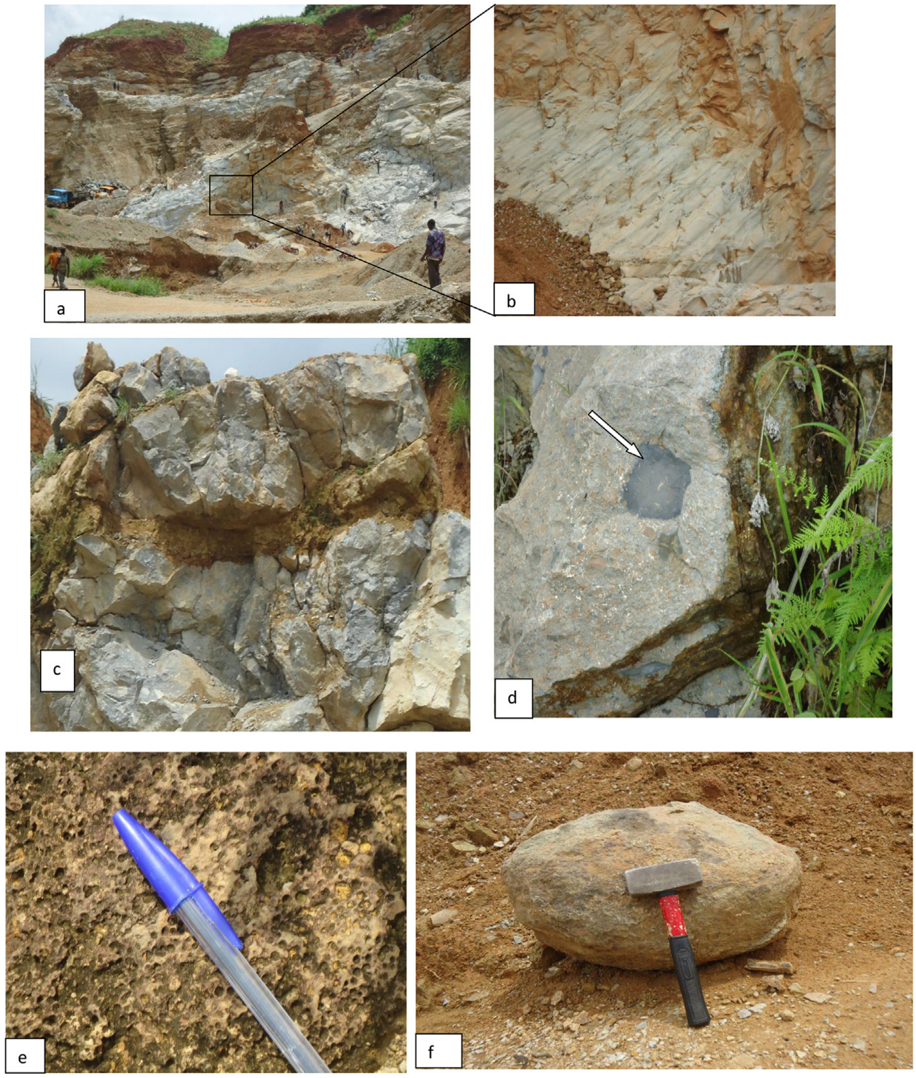


Fig. 3. Field photographs of structures in the volcaniclastic rocks showing (a), (b) Laminations of the tuffs from Ezzeagu (Sharon) Quarry (c) Poorly sorted section of the exposure (pyroclastic flow), Sharon Quarry (d) Shale xenolith, in lapillistones from Onyikwa, Abakaliki (e) Scoriaceous texture in the upper parts of the exposure in the Old Ministry of Works Quarry, Abakaliki. (f) Volcanic bomb from Ezzagu (Sharon) Quarry.

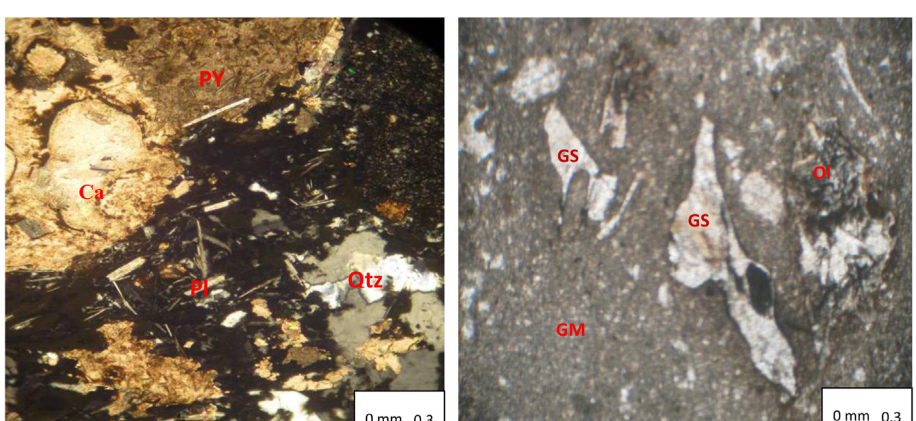


Fig. 4. Photomicrographs of volcaniclastic rocks showing the altered nature of the rocks (a) Micro laths of plagioclase and altered pyroxene (PY) in a glassy groundmass. Calcites occur as amygdules from Location 7 (b) phenocryst of irregular glass-shards (GS) and altered olivine (Ol) in groundmass (GM) of glassy components from location 8.

Table 2
Whole-rock major oxides (wt. %), trace elements (ppm), and rare earth elements (ppm) analysis of the study rocks.

	Fresh Tholeiitic volcanicalstic rocks (FTV)							Altered Tholeiitic volcaniclastic rocks (ATV)				
	1AP	2AP	2BP	3P	5P	6P	8AP	1BP	4P	8BP	9P	12P
SiO_2 (wt. %)	48.75	59.87	46.89	59.88	54.85	52.62	49.78	47.22	39.79	44.74	49.04	38.24
TiO_2	2.46	1.03	1.92	0.85	1.6	3.39	3.78	2.39	2.64	2.66	2.14	0.63
Al_2O_3	15.71	15.7	15.09	15.1	16.05	15.55	16.92	15.77	17.2	14.66	16.01	13.1
Fe_2O_3(t)	13.98	11.37	15.62	12.42	11.54	15.09	14.97	14.81	16.9	12.94	13	8.08
MnO	0.17	0.08	0.29	0.08	0.19	0.12	0.08	0.19	0.44	0.19	0.18	0.13
MgO	8.03	5.37	11.26	4.62	6.49	7.35	9.68	8.32	6.95	8.86	7.78	4.24
CaO	6.09	0.13	5.24	0.95	4.57	1.31	1.74	7.04	13.34	12.45	7.33	32.36
Na_2O	3.63	4.68	3.16	5.92	4.27	3.41	2.69	3.71	1.79	2.14	3.55	0.85
K_2O	0.13	1.67	0.28	0.1	0.06	0.33	0.01	0.11	0.44	0.81	0.55	2.21
P_2O_5	1.04	0.08	0.26	0.06	0.3	0.78	0.32	0.45	0.5	0.53	0.38	0.15
LOI	9.27	3.43	10.83	3.72	6.66	4.97	10.57	11.01	13.4	15.19	11.03	22.07
TOTAL	99.99	99.98	100.01	99.98	99.92	99.95	99.97	100.01	99.9	99.98	99.96	83.82
Sc (ppm)	20.48	16.68	21.71	9.82	16.03	22.83	19.48	21.47	24.58	20.13	18.42	11.6
Be	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
V	199.46	130	199.99	130.09	192	194.58	250.96	204.53	293.05	189.79	210.72	82.96
Cr	68.27	37.38	77.01	33.52	46.32	73.69	92.17	62.58	43.52	109.41	73.14	37.31
Co	36.84	24.06	43.68	25.8	28.58	47.04	42.19	37.66	33.65	31.1	32.46	13.905
Ni	24.64	9.94	32.32	9.66	14.59	30.63	39.55	25.25	21.63	28.79	23.63	10.59
Cu	50.62	29.82	51.54	18.91	28.49	66.47	69.85	57.12	67.98	52.41	44.37	21.35
Zn	29.94	31.3	29.86	22.15	27.19	40.91	36.01	31.37	33.42	30.59	34.95	31.39
Ga	21.57	24.76	21.92	22.11	23.2	21.64	21.07	20.65	24.01	15.34	19.36	20.6
Rb	2.94	26.42	4.12	1.72	1.37	9.46	0.57	2.21	12.81	14.57	8.52	65.65
Sr	320.24	166.56	171.54	77.43	207.33	351.07	507.56	314.08	158.96	287.73	367.74	442.67
Y	39.23	31.26	24.72	13.5	21.61	25.79	21.82	28.99	27.03	20.99	19.18	30.84
Zr	175.9	87.24	133.73	62.88	113.56	191.31	55.01	170.03	113.02	101.68	86.49	55.28
Nb	23.57	13.75	20.62	8.83	17.1	27.15	20.81	21.31	20.16	15.1	19	9.09
Sn	<1	<1	<1	<1	<1	<1	<1	<1	<1			
Cs	0.16	0.25	0.1	0.13	0.08	0.36	0.12	0.14	0.95	1.57	0.52	3.47
Ba	77.816	526.96	127.16	56.09	87.75	105.34	66.89	72.43	56.17	88.82	184.48	278.37
Hf	3.45	2.26	2.81	1.61	2.26	3.84	1.19	3.47	2.37	2.22	1.77	1.46
Ta	0.53	0.23	0.34	0.2	0.23	0.32	0.26	0.36	0.27	0.2	0.26	0.13
Pb	1.55	2.35	2.09	1.77	1.71	1.51	1.42	1.57	1.87	1.3	1.34	2.86
Th	2.06	8.34	3.15	6.18	3.04	1.39	0.79	2.22	1.02	0.46	1.48	6.05
U	0.26	0.58	0.32	0.32	0.24	0.2	0.08	0.24	0.15	0.08	0.17	0.42

	Fresh Alkaline (FAV)								Altered Alkaline (AAV)				
	7AP	7BP	7CP	8CP	13P	14P	15AP	15BP	10P	11AP	11BP	16P	D.L
SiO_2 (wt. %)	46.87	50.71	48.81	58.92	48.13	48.68	49.15	58.84	35.07	31.41	53.88	46.32	0.01
TiO_2	2.84	3.23	2.22	1.98	2.34	2.9	2.52	2.22	2.8	3.74	1.51	2.76	0.001
Al_2O_3	15.36	17.58	14.24	11.64	16.51	16.54	17.18	14.51	12.48	16.12	15.34	17.1	0.01
Fe_2O_3(t)	14.68	12.21	10.37	9.4	11.23	11.99	11.84	8.94	12.72	14.14	10.61	8.45	0.01
MnO	0.12	0.05	0.16	0.13	0.16	0.15	0.13	0.13	0.22	0.24	0.13	0.16	0.001
MgO	11.24	10	10.34	7.74	6.58	9.42	8.69	4.5	10.74	10.69	5.84	10.45	0.01
CaO	6.08	1.89	8.35	6.21	10.96	5.23	5.52	7.1	22.07	19.62	9.08	8.16	0.01
Na_2O	2.36	3.85	4.23	3.46	2.97	4.66	4.4	2.37	1.77	1.35	2.03	5.85	0.01
K_2O	0.02	0.01	0.64	0.01	0.67	0.01	0.07	0.85	1.43	1.71	1.49	0.05	0.01
P_2O_5	0.4	0.43	0.59	0.45	0.49	0.4	0.48	0.51	0.67	0.99	0.05	0.69	0.01
LOI	5.4	7.06	12.91	10.06	12.17	10.32	8.75	9.18	21.81	19.66	12.87	15.14	
TOTAL	99.97	99.96	99.95	99.94	64.08	61.62	59.58	50.31	86.71	88.26	58.95	68.81	
Sc (ppm)	11.98	21	17	15	19	19	20	17	16.37	21.86	15.43	24	1
Be	<1	2	2	1	1	2	2	1	<1	<1	<1	1	1
V	239.46	254	175	159	204	226	211	195	210.42	275.91	171.87	235	5
Cr	95.77	270	380	270	190	270	260	210	114.76	122.82	69.33	230	20
Co	46.64	43	31	31	30	35	34	28	30.79	39.25	20.09	35	1
Ni	30.79	420	530	660	260	680	300	300	37.24	52.51	18.82	330	20
Cu	52.5	30	50	70	40	30	40	50	40.83	50.68	35.83	120	10
Zn	46.92	80	130	50	80	70	<30	90	27	35.65	35.8	50	30
Ga	22.61	21	15	13	18	17	19	17	13.36	17.39	12.01	16	1
Rb	0.3	1.99	8	<2	25	<2	2	37	21.9	30.07	33.53	<2	2
Sr	243.02	184	965	884	244	406	235	143	374.75	411.13	236.84	2856	2
Y	10.5	20	19	17	23	19	25	19	19.53	28.14	15.91	21	2
Zr	51.49	247	144	110	167	206	78	152	91.78	142.78	67.25	140	4
Nb	30.11	56	33	22	33	47	33	37	36.38	46.95	23.86	31	1
Sn	<1	<1	3	2	2	3	3	3				2	1
Cs	0.07	<0.5	<0.5	<0.5	1.5	<0.5	1	2.6	0.99	1.65	2.44	<0.5	0.5
Ba	52.08	32	380	45	107	24	45	218	161.88	223.4	230.96	115	3
Hf	0.92	5.2	3.1	2.5	3.8	4.3	1.9	3.5	1.58	2.41	1.2	3.2	0.2
Ta	0.13	3.5	2	1.3	2.1	2.9	2.6	2.3	0.19	0.44	0.22	2	0.1
Pb	3.53	4.9	6	25	8	7	4.9	7	1.6	1.67	1.68	4.9	1
Th	1.14	3.3	3.3	1.2	4.2	2.8	4.5	5.3	1.42	2.19	1.38	2.6	0.1
U	0.13	1.1	0.9	1.2	1	1	1.6	1.2	0.23	0.36	0.18	0.8	0.1

Table 2 (*continued*)

	Fresh Tholeiitic volcanicalstic rocks (FTV)							Altered Tholeiitic volcaniclastic rocks (ATV)				
	1AP	2AP	2BP	3P	5P	6P	8AP	1BP	4P	8BP	9P	12P
	Fresh Tholeiitic volcanicalstic rocks (FTV)							Altered Tholeiitic volcaniclastic rocks (ATV)				
	1AP	2AP	2BP	3P	5P	6P	8AP	1BP	4P	8BP	9P	12P
La	23.03	58.21	28.86	32.03	30.87	12.21	21.39	26.16	12.74	8.82	15.84	33.22
Ce	56.35	121.43	65.11	74.69	66.43	27.59	51.83	57.1	30.18	21.78	36	73.19
Pr	6.64	12.18	6.37	7.97	6.59	3.41	5.85	6.04	3.44	2.58	3.94	7.65
Nd	39.91	58.7	31.65	38.47	33.64	21.95	33.34	32.58	21.21	15.72	22.44	39.69
Sm	9.86	10.1	5.82	6.6	6.17	6.37	7.32	6.87	6.28	4.3	5.33	7.97
Eu	3.27	1.95	1.44	1.12	1.62	1.2	2.26	2.01	1.76	1.44	1.67	1.56
Gd	12.29	11.08	6.73	6.34	7.16	7.87	8.35	8.24	7.96	5.44	6.28	8.63
Tb	1.75	1.25	0.87	0.68	0.87	1.09	1.07	1.1	1.09	0.82	0.84	1.12
Dy	7.61	5.41	4.09	2.56	3.77	4.79	4.46	5.05	4.81	3.99	3.55	5
Ho	1.35	1.02	0.8	0.47	0.71	0.9	0.76	0.97	0.9	0.73	0.65	0.97
Er	3.54	3.2	2.46	1.55	2.23	2.5	1.97	2.87	2.59	1.93	1.83	3.06
Tm	0.5	0.48	0.39	0.23	0.31	0.36	0.24	0.44	0.36	0.28	0.25	0.45
Yb	2.44	2.6	2.02	1.36	1.78	1.99	1.08	2.35	1.99	1.42	1.33	2.34
Lu	0.36	0.38	0.3	0.22	0.26	0.29	0.15	0.35	0.29	0.2	0.2	0.33
∑ REE	168.9	287.99	156.91	174.29	162.41	92.52	140.07	152.13	95.6	69.45	100.15	185.18
∑LREE/∑HREE	4.55	10.25	7.8	11.91	8.41	3.61	6.62	6.025	3.69	3.59	5.59	7.38
La_N/Yb_N	6.78	16.06	10.25	16.89	12.44	4.4	14.21	7.98	4.59	4.46	8.54	10.18
Tb_N/Yb_N	3.26	2.19	1.96	2.27	2.22	2.49	4.5	2.13	2.49	2.62	2.87	2.18
Eu/Eu*	0.91	0.6	0.7	0.5	0.7	0.5	0.9	0.8	0.8	0.9	0.9	0.6
Mg#	50.56	45.69	56.23	39.82	50.05	46.47	53.52	50.03	42.28	54.96	51.62	48.34

	Fresh Alkaline (FAV)								Altered Alkaline (AAV)				
	7AP	7BP	7CP	8CP	13P	14P	15AP	15BP	10P	11AP	11BP	16P	D.L
La	28.59	37.1	24.1	15	28.9	23.5	38.7	34.8	29.97	35.28	58.63	22.5	0.1
Ce	64.84	78.3	51.4	33.1	61.3	51.4	80.8	72.3	64.21	77.55	123.4	48.2	0.1
Pr	6.75	9.06	6.07	4.06	7.11	6.09	9.22	8.14	6.66	8.14	12.23	5.75	0.05
Nd	35.43	36.7	25.7	17.6	29.3	26.3	37.4	32.7	34.91	43.84	59.53	25.5	0.1
Sm	6.36	7.3	5.6	4.2	6.2	5.7	7.6	6.6	6.63	8.83	8.58	5.6	0.1
Eu	1.65	2.09	1.83	1.39	1.82	1.72	2.14	1.85	2.01	2.78	1.91	1.98	0.05
Gd	6.99	6.2	5	4.4	5.8	5.2	6.7	5.3	7.66	10.42	8.93	5.4	0.1
Tb	0.74	0.9	0.8	0.7	0.8	0.8	1	0.8	0.93	1.28	0.86	0.8	0.1
Dy	2.6	4.7	4.1	3.5	4.5	3.9	5.4	4	3.87	5.31	2.86	4.5	0.1
Ho	0.41	0.8	0.7	0.6	0.9	0.7	1	0.7	0.64	0.94	0.52	0.8	0.1
Er	1.07	2.3	2	1.6	2.4	2	2.7	2	1.74	2.61	1.73	2.2	0.1
Tm	0.12	0.33	0.25	0.22	0.33	0.29	0.37	0.26	0.24	0.35	0.24	0.31	0.05
Yb	0.65	2	1.6	1.4	2.2	1.9	2.3	1.7	1.2	1.74	1.37	1.9	0.1
Lu	0.09	0.33	0.24	0.21	0.32	0.28	0.35	0.27	0.18	0.25	0.21	0.3	0.04
∑ REE	156.29	188.11	129.39	87.98	151.88	129.78	195.68	171.42	160.85	199.32	281	125.74	
∑LREE/∑HREE	11.21	9.59	7.68	5.86	7.69	7.49	8.76	10.28	8.65	7.58	15.69	6.63	
La_N/Yb_N	31.55	13.31	10.8	7.69	9.42	8.87	12.07	14.68	17.91	14.54	30.7	8.49	
Tb_N/Yb_N	5.17	2.05	2.27	2.27	1.65	1.91	1.98	2.13	3.52	3.34	2.85	1.91	
Eu/Eu*	0.8	0.9	1	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.7	1.1	
Mg#	57.71	59.35	63.99	59.47	51.07	58.35	56.66	47.3	60.09	57.39	49.52	68.79	

Major element oxides were recalculated on a volatile −free basis, D.L = detection limit.

altered rocks) and $Fe_2O_{3(t)}$ (8.94–15.62 in the least altered rocks and 8.08–16.01 wt. % in altered rocks), results in Mg# (100 Mg/Mg + Fe) which ranges from 39.88 to 59.18 (42.40, average) in the FTV rocks, 46.02–59.17 (53.52, averages) in the ATV rocks, 49.87–67.57 (59.23, average) in the FAV rocks and 53.95–72.67 (63.69, average) in AAV rocks. High concentration of CaO (7.04–32.36 wt. % in ATV and 8.16 to 22.07 wt. % in AAV) compared to their respective high LOI (Table 2) in the tholeiites and alkaline rocks suggest addition of carbonate materials from surrounding carbonaceous sediments and breakdown of basic plagioclase as evidence in the occurrence of calcite and calcareous amygdules.

As a result of the altered nature of the volcaniclastic rocks as observed by the occurrence of secondary minerals such as calcite, chlorite, sericite and high LOI, mobile elements could be deceptive for petrogenetic interpretations. Previous studies such as those of Sayit and Goncouglu (2009) and Le Roex et al. (2010) indicated that some major elements (Si, Na, K, Ca and Mg), trace elements (Cs, Rb, Ba and Sr) and transition metals (Mn, Zn and Cu) can easily be mobilized by metasomatism, hydrothermal processes and metamorphism. In contrast, the high field strength elements (HFSE) (Zr, Y, Hf, Nb, Ti and Ta), REEs and transitional elements (V, Cr, Ni, Sc and Co), large ion lithophile elements (LILE) (Th) and Nd isotopic composition are relatively immobile under wide range of metamorphic conditions to the extent of medium grade and lower amphibolite facies, even sea floor alteration (Rollinson, 1993; Bienvenu et al., 1990). However, Cotton et al. (1995) and Patino et al. (2003) have observed that LREE can be mobilized in extreme conditions mostly in orogenic environments, which is not applicable in this study. To assess the reliability of the elements for petrogenetic interpretations, the correlation matrix of relatively immobile elements and some major element oxides in the volcaniclastic rocks were calculated in co-variance with Zr in different suites (table not given). The correlation matrix shows that Y, Nb, Hf, Ta, and P_2O_5 have good correlation, La, Ce, Tb, Dy, Yb, Lu, are Co are fairly correlated with Zr in the least altered tholeiitic rocks (FTV) while Ba, Nb, Hf, Ta, V, Co, Ni, Sr, Th, SiO_2, TiO_2, Na_2O, P_2O_5, MgO and K_2O have good correlation in the altered tholeiites (ATV). Least altered alkaline (FAV) rocks show good correlation in Nb, Hf, Ta, Yb, Lu and Ni while the altered alkaline rocks (AAV) show good correlation in Y, Nb, Hf, Ta, La, La, Ce, Nd, Dy, Yb, Lu, V, Cr, Co, Ni, Sr, Th,

SiO_2, TiO_2, P_2O_5 and MgO with Zr. This shows that these elements are least affected by alteration processes considering the altered nature of the rocks.

The volcaniclastic rocks in Abakaliki basin are basaltic in composition as indicated in Fig. 5. The samples of the FAV and AAV plot mostly in alkali basalt field while the samples of FTV and ATV except for three samples (6P, 8AP and 9P) fall in subalkaline (tholeiitic) basalt field on the Zr/Ti versus Nb/Y variation diagram of Winchester and Floyd (1977) modified by Pearce (1996). The three samples of the tholeiites in the alkaline field could be considered as transitional. From the variation diagram, it is clear that the fresh/altered alkali volcaniclastics (FAV/AAV) occur at the southwestern parts of the map which is the central parts of the Abakaliki anticlinorium while the fresh/altered tholeiitic volcaniclasts, (FTV/ATV) occur around Ezekwe-Wanakom area northeastern parts of the anticlinorium except rock samples 8AP, 8BP and 12P which occur in the southwestern parts (see Fig. 2).

The primitive mantle-normalized incompatible trace elements patterns indicate that the volcaniclastic rocks are generally enriched in incompatible elements. The patterns are grouped into two types based on their magma characteristics. The first type consists of samples of the alkaline (FAV and AAV) while the second type consists of samples of the tholeiites (FTV and ATV). These patterns generally show absence of Nb-Ta anomaly which demonstrated a typical example of anorogenic setting. The first type (Fig. 6a) shows depletion in Rb, K, Sr and Hf and enrichment peak at Nb-Ta, except four samples (7AP, 10P, 11AP and 11BP) which show depletion in Ta similar to the tholeiites (Fig. 6b). The second type (Fig. 6b) shows depletion in Rb, Ta, K, P, Hf, mildly Sr and Ti and spike in Nb. The depletion/enrichment of the mobile large ion lithophile elements (LILE) Rb, Ba, K and Sr could be attributed to the effect of alteration especially in the altered rocks (ATV and AAV), but their behavior in FTV and FAV rocks are primarily related to their source characteristics. Rb easily substitutes for K in amphiboles in basaltic melts (Green, 1980), the depletion of Rb and K in the FTV and FAV rocks suggest the presence of amphiboles (hornblende) in the source. The depletion of K is also related to the

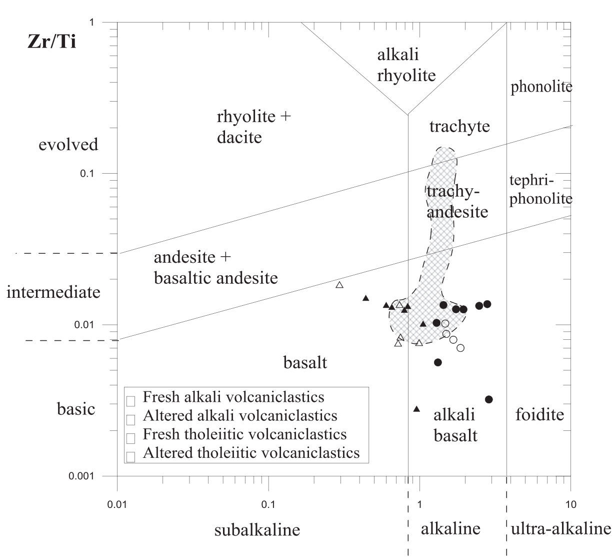


Fig. 5. Plot of Zr/Ti vs Nb/Y diagram of Winchester and Floyd (1977) with fields modified by Pearce (1982) for the discrimination of different magma series and their differential products compared with rocks from southern Lower Benue Rift. Shaded circles represent the FAV; open circles represent AAV, shaded triangles represent FTV while open triangles represent ATV. Data of rocks from southern Lower Benue Rift are from Chukwu and Obiora (2014). (Symbols are the same in all the figures).

formation of leucites in the early stage of the melt crystallization but may have been replaced by analcite which is easily broken down under weathering condition (Green, 1980). The depletion of Sr, P and Ti in the FTV and FAV shows substantial fractionation or accumulation of plagioclase, apatite and titano-magnetite, respectively in the basalts. The enrichment in Sr (three samples of group two) shows the presence of plagioclase in the melt while the depletion of Hf and Ta reflects fractionation of zircon, sphene and ilmenite. The different patterns of the rocks in the units indicate magma of different genetic origin and magma mixing. Fig. 6c and d shows comparison of the alkaline and tholeiitic rocks with the St. Helena basalts and Ascension basalts respectively and alkaline and tholeiitic rocks from Southern parts of the Lower Benue rift.

The chondrite-normalized patterns are fractionated (Fig. 7) and show enrichment in the light rare-earth elements (LREEs) relative to the heavy rare-earth elements (HREEs) suggesting the presence of residual garnet in the source. The patterns are grouped into two; the first group (Fig. 7a) which represents the alkaline rocks (FAV and AAV) shows no Eu anomaly while the second group indicates mild negative Eu anomalies for the tholeiitic rocks (FTV and ATV; Fig. 7b). The mild negative Eu anomalies in the tholeiitic rocks (FTV and ATV) are reflected in their Eu/Eu* ratios which range from 0.5 to 0.9 compared to the absence of Eu anomalies in the alkaline rocks (FAV and AAV) in which the Eu/Eu* ratios ranging from 0.9 to 1.1. The FAV and AAV rocks show higher ratios of the LREEs to HREEs compared to the FTV and ATV rocks. This is reflected in values of $(La/Yb)_n$ which are higher in FAV (7.69–31.55), and AAV (8.49–30.7) compared to lower ratios in FTV (4.4–16.89) and ATV (4.46–10.18).

5. Discussion

5.1. Alteration effects of the pyroclastic rocks

The volcaniclastic rocks in Abakaliki basin is a product of subaerial falls of submarine explosions deposited above wave during the Upper Albian (103 ± 5 Ma) (Ojoh, 1990; Maluski et al., 1995). The existence of structures such as parallel/cross laminations and bedding/graded bedding in the volcaniclastic rocks do not represent a reworking of the pyroclastic rocks by epiclastic processes or related to marine sedimentation as earlier suggested by Olade (1979) and thereby wrongly attributed the alterations in the rocks to shallow marine transgressions. The structures in the volcaniclastic rocks are products of explosive volcanism, in the form of pyroclastic ash fall, flow and surge deposits in interlayered in a complex fashion with each other (Best and Christiansen, 2001) in the study area as stated in Section 2. Hoque (1984) also supported the notion of magmatic processes for the volcaniclastic rocks. The presence of angular to sub-angular argillaceous fragments (xenoliths) of the host rocks in the volcaniclastic rocks further indicates that the volcanic activities which produced the volcaniclastic rocks postdated sediment deposition in the area. Recent exposed quarry faces in the areas around the centre of the Abakaliki anticlinorium (Sharon quarry, Old Ministry of Works and Onyikwa market quarries), enables clearer observations of structures in these rocks.

The volcaniclastic rocks which are among the initial magmatic phase at ca. 147-106 Ma (Maluski et al., 1995; Coulon et al., 1996) in the Benue Rift, constitute part of the oldest rocks in the Lower Benue Rift. Hence, the post-magmatic effects on the rocks in a tropical environment most probably caused the breakdown of plagioclase and the dissociation of carbon dioxides from carbonated pore fluids contributing to the alteration process in the rocks as evidenced by the formation of secondary minerals (chlorite, calcites and zeolites) in the rocks. Though high concentrations of LOI also attest the excessive alterations, Hikov (2013), has shown that the presence of sulphide minerals especially pyrites can

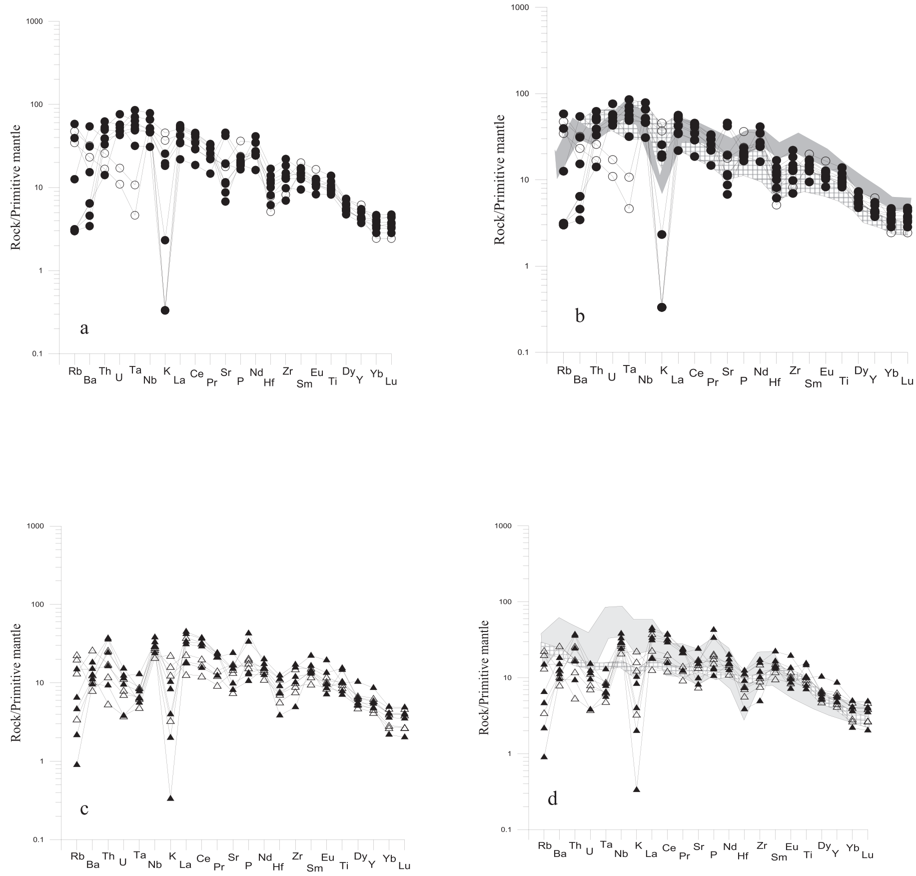


Fig. 6. Primitive mantle-normalized diagrams of the volcaniclastic rock samples. Normalized values are after Sun and McDonough (1989). (a) Tholeiitic rocks, with strong depletions in Rb, Ta, K and Hf (b) Alkaline rocks, with strong depletions in Rb, K, Sr and Hf and three samples showing enrichments in Sr (c) Tholeiitic rocks of the Abakaliki basin compared with basalts from Ascension (light ash shade) and tholeiitic rocks from the Lower Benue Rift (crosshatch) (d) Alkaline rocks compared with basalts from St Helena (ash shade) and alkaline rocks from Lower Benue Rift (crosshatch). Data for the Ascension basalts and St Helena basalts are from Weaver et al. (1987), Lower Benue Rift data from Chukwu and Obiora (2014).

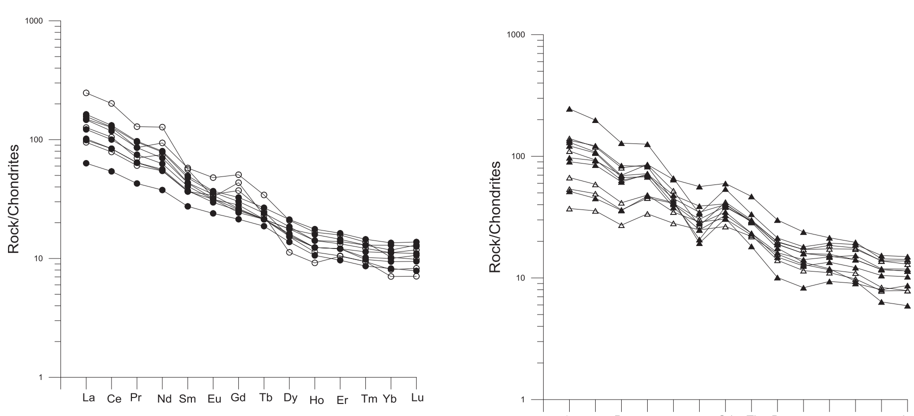


Fig. 7. Chondrite-normalized REE Diagrams showing fractionated Pattern and Enrichment in LREE. Normalized values are after Sun and McDonough (1989). (a) REE diagram showing mild negative Eu anomaly (mostly tholeiites) (b) REE diagram showing no Eu anomaly (alkalines).

influence the degree of LOI in rock. Therefore, LOI >3 wt. %, especially in the fresh samples (FTV and FAV) in the Abakaliki basin, could be due to sulphides (pyrite) in the rocks. Element mobility in the rocks can also be seen in non-correlation of LILE elements (Ba, Rb, K and Sr), La, Sm, V, Cr, Co, SiO_2, Na_2O and K_2O in the correlation matrices against Zr (not shown) although some of the elements behavior especially in the less altered rocks (FTV and FAV) are related to mineralogical fractionation. The altered rock samples (ATV and AAV) that show low $SiO_2 < 40$ wt. %, and high Al_2O_3, $Fe_2O_{3(tot)}$, TiO_2 and MnO are characterized by the presence of chlorite. The excess alteration of the volcaniclastic rocks is attributed also to diagenetic processes and chemical weathering in such calcareous sediments which liberates carbonates in the form of calcites. The interaction in the carbonated fluids may also have resulted in the mobilization of some of the LIL elements (Rb, K and P) and Sr in the ATV and AAV rocks seen in the spidergrams (Fig. 6).

5.2. Magma type and source region

The bimodal compositions of the volcaniclastic rocks in Abakaliki basin indicate that they originate from two magma types. The alkaline basalts occur predominantly around the central parts of the Abakaliki anticlinorium (Abakaliki area), while the tholeiitic basalts occur around the northeastern periphery of the anticlinorium (Ezekwe-Wanakom area), and northeastern parts of the map (Fig. 2). Although, most of the rocks, exhibit some degree of alteration as discussed earlier, immobile incompatible elements such as Zr, Y, Nb, Ti, Ta and Hf and their ratios can be used reliably to infer mantle conditions. The two magma types are obvious in the variation diagram of Zr/Ti versus Nb/Y diagram of Winchester and Floyd (1977), modified by Pearce (1996; Fig. 5). The alkaline rocks (FAV and AAV) show a higher enrichment in the incompatible elements and have higher La/Sm_n ratios of 2.31–4.41 and La/Yb_n that range from 7.69 to 31.55 compared to the tholeiitic rocks. The tholeiitic rocks (FTV and ATV) have low La/Sm_n ratio that ranges from 1.24 to 3.72 and La/Yb_n that ranges from 4.4 to 16.89. These significant variations in the rations of the incompatible elements show that alkaline rocks are highly silica undersaturated compared to tholeiites in ocean island basalts and show also the presence of residual garnet in the sources of the rocks. Conversely, the alkaline rocks show lower ratios of Zr/Nb: 1.71 to 5.06 and Y/Nb: 0.35 to 0.77 when compared with the tholeiites which have higher values of Zr/Nb: 4.55 to 7.98 and Y/Nb: 1.0 to 3.39, except sample 8AP (FAV; transitional tholeiite) which has low Zr/Nb ratio of 2.64. These ratios show that the alkaline and tholeiites are not products of depleted MORB rather, are a product of intra-plate magmatism derived from a geochemically enriched mantle source. Hofmann et al. (1986) and Burianek et al. (2008) have shown that most mantle rocks have Ce/Pb values of ~25 in contrast to crustal originated rocks which have Ce/Pb less than 5. The alkaline rocks have an average Ce/Pb ratio of 22.31; whereas the tholeiites have an average Ce/Pb ratio of 31.39 allowing us to infer a mantle origin for these rocks. The mild negative Eu anomalies suggest plagioclase fractionation in the tholeiitic rocks. The enrichment in incompatible elements (Fig. 6) and high LREEs relative to HREEs in these rocks as shown by La/Yb_n indicate garnet-bearing source because HREEs have strong partitioning affinity into garnet. The low ratio of Tb/Yb_n 1.65 to 5.17 in the alkaline rocks and 1.95 to 4.5 in the tholeiitic rocks also reflect garnet-bearing lherzolite source (Sayit and Goncouglu, 2009). These suggest upper mantle region for the volcaniclastic rocks generation because residual melt containing garnet indicates a depth of about 80 km (Wilson, 1989), which shows that the magma is generated most probably within the asthenosphere. Rocks of similar compositions and predominant alkalinity have been accounted for in Upper and Lower Benue Rift (Coulon et al., 1996; Obiora and Charan, 2010; Chukwu and Obiora, 2014). In Fig. 8, the alkaline rocks show low ratio of $Y/Nb < 1$ and low $Zr/Nb < 5$, comparable to well-known alkaline rocks of the South Atlantic Ocean islands basalts (SOIB) such as St. Helena, Tristan da Cunha and Gough while the tholeiitic rocks show intermediate ratio of Y/Nb and Zr/Nb, comparable to the tholeiitic rocks of Ascension and Meteor Rise (Shona ridge) of SOIB (Le Roex et al., 2010). The Mg# for the FTV rocks range from 39.88 to 59.18 (average of 42.40), and ranges from 46.02 to 59.17 (average of 53.52) in the ATV rocks, and from 49.87 to 62.01 (average of 58.04) in the FAV rocks, and from 53.95 to 65.95 (average of 60.69) in the AAV rocks. The Mg# ratios indicate that these rocks do not represent primary magma, but were likely derived from a primary magma by fractionation. However, two samples 7CP and 16P of

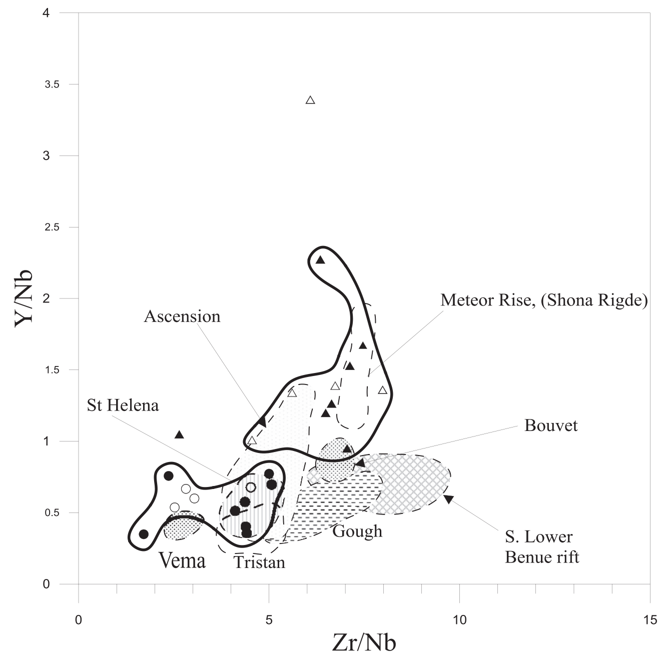


Fig. 8. Plots of incompatible ratios of Y/Nb versus Zr/Nb diagram for the volcaniclastic rocks in Abakaliki basin and compared with rocks from southern Atlantic Ocean (St Helena, Ascension, Vema, Tristan da Cunha, Gough, Bouvet and Meteor rise) and Lower Benue Rift. Data for Southern Atlantic Ocean basalts are from Le Roex et al. (2010), and data for Lower Benue rocks are from Obiora and Charan (2011) and Chukwu and Obiora (2014).

alkaline rocks (FAV and AAV respectively) yielded high Mg# (>66) which suggests they represent primitive magmas; although there is evidence for MgO loss as a result of olivine decomposition to iddingsite during alterations. Furthermore, high concentrations of Ni (>300 ppm) indicate parental magmas from peridotite mantle source (Green, 1980). The concentrations of Ni in some of the alkaline rocks (samples 7BP, 7CP, 8CP, 14P and 16P) range from 330 to 680 ppm; indicate also that they represent primary magmas.

HFS elements such as Nb are depleted in the lithospheric mantle or in a melt which has interacted with crustal materials relative to the LREE (La). Therefore, variations in La/Nb ratio is attributed to metasomatic enrichment. High Nb/La ratio (approx. >1) show OIB like asthenospheric mantle source for basaltic magma and the lower ratio (approx. < 0.5) show a lithospheric mantle source (Abdel-Fattah et al., 2004). The ratios of Nb/La (0.97, average), in the tholeiitic rocks (FTV and ATV) and 1.23 average, in the alkaline rocks (FAV and AAV), the spidergrams (Fig. 6c and d) and REEs pattern indicate ocean island basalt asthenospheric mantle source. Furthermore, the average ratios of Zr/Nb, Ba/Nb, Rb/Nb and Th/Nb (Table 3) in the tholeiitic rocks (6.22, 9.8, 1.02 and 0.22 respectively) and alkaline rocks (3.69, 4.12, 0.39 and 0.08 respectively) show that the tholeiitic rocks are similar to an enriched mantle source reservoir (EMI and EMII) while the alkaline rocks display ratios similar to the HIMU reservoir (Weaver, 1991; Table 3). These observations indicate that the Abakaliki basin is composed predominantly of alkaline rocks generated by a mantle plume similar to one which gave rise to the alkaline rocks of St. Helena basalts. The tholeiitic rocks in the northeastern of the anticlinorium were generated in an environment similar to the Ascension island in mid-oceanic ridge by their proximity to the South Atlantic rocks and chemical compositions. The oldest rock along the St. Helena chain is 82 Ma (O'Connor and Le Roex, 1992) while the ascension is 1–1.5 Ma (Harris et al., 1982).

The plume-related source for the pyroclastic rocks from the

Table 3
Variation intervals and mean values of some incompatible trace element ratios for the tholeiitic and alkaline rocks from the Abakaliki basin, compared with various mantle sources.

	This study				OIB			N-MORN	
	Tholeiites		Alkaline		HIMU	EMI	EMII	DM	PM
	Range	Mean	Range	Mean	Mean	Mean	Mean	Mean	Mean
Zr/Nb	2.64–7.98	6.22	1.71–5.06	3.69	4.1	6.9	6.1	30	14.8
La/Nb	0.45–4.23	1.7	0.5–2.46	0.94	0.72	0.94	0.98	1.07	0.94
Ba/Nb	2.79–38.32	9.8	0.51–11.52	4.12	5.6	13.2	9.7	4.03	9
Rb/Nb	0.03–7.22	1.02	0.01–1.41	0.39	0.37	1.01	0.73	0.36	0.91
Th/Nb	0.03–0.7	0.22	0.04–0.14	0.08	0.09	0.112	0.134	0.07	0.117
Th/La	0.04–0.19	0.11	0.02–0.15	0.09	0.12	0.115	0.137	0.07	0.125
Ba/La	1.75–11.65	5.87	0.86–15	4.53	7.8	14.1	8.2	4	9.6

Data source: OIB (HMU, EMI, EMII), Depleted mantle (DM), primodial mantle (PM) and mid-oceanic ridge basalt (N-MORB) are from Weaver (1991).

Abakaliki basin is also shown in Fig. 9 Zr/Y versus Nb/Y log-log diagram of Fitton et al. (1997) where the rocks plot mostly within the field of Icelandic plume array "tramline". The ΔNb line in the diagram separate plume from non-plume basaltic sources and basalts plotting below the ΔNb line are derived from shallow depleted source (DM) or are derived from subduction zones or plume melts contaminated by continental crust/sub-continental lithosphere. All the rock samples (FTV, ATV, FAV and AAV) plot above the ΔNb line in mantle plume field towards the recycled components (REC) within the OIB source. Fig. 9 confirms the heterogeneous recycled mantle source comprising of recycled subducted ocean crust (HIMU), lower continental (CC; EMI) and upper CC or marine sediment (EMII; Zindler and Hart, 1986). The heterogeneity in the plume source is also shown by the variable Nb/Y or vertical trend of the plotted samples (Fig. 9). So far, the volcaniclastic rocks from Abakaliki basin in this study have not shown evidence of N-MORB or depleted mantle source, though Coulon et al. (1996) reported of minor N-MORB in Upper Benue Rift volcanic rocks.

The occurrence of the two magma types (alkaline and tholeiitic rocks) from different and heterogeneous sources for the pyroclastic rocks of the Abakaliki basin is also apparent from the shapes of the REEs (Fig. 7) and the spidergrams (Fig. 6c and d) that are similar to those of St. Helena and Ascension OIBs respectively. The alkaline rocks (samples 7AP, 10P, 11AP and 11BP) which exhibit similar pattern as the tholeiites show mixing of the heterogeneous sources in the mantle. The existence of two magma type is in accord with the findings of Coulon et al. (1996) in northern and southern Benue Rift.

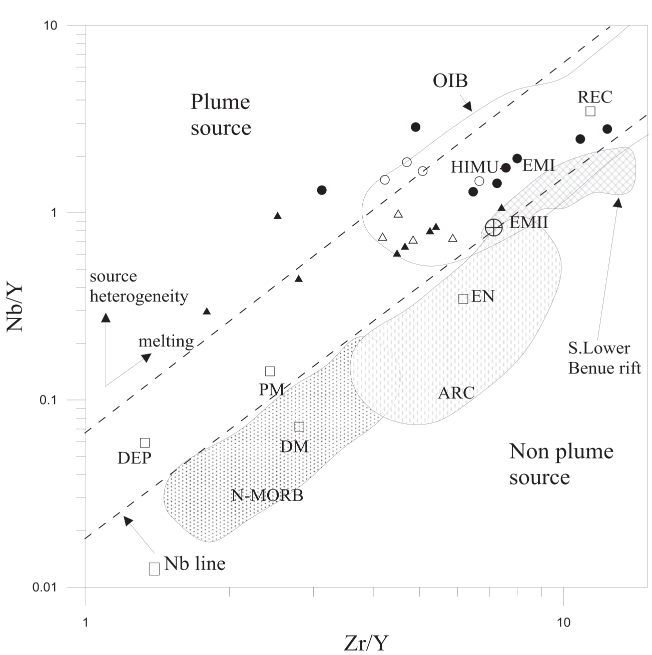


Fig. 9. Plots of the volcaniclastic rocks from the Abakaliki basin in Nb/Y versus Zr/Y log-log diagram after Fitton et al. (1997) for discrimination of plume and non-plume rocks. The rocks plots within the tramlines defined by the Icelandic mantle plume lavas. The rocks from another part of Lower Benue (Chukwu and Obiora, 2014) also plotted in a similar array. PM, Primitive mantle, DM, depleted mantle, EN, enriched components and REC, recycled components.

5.3. Partial melting

The alkaline and tholeiitic rocks in the Abakaliki basin are characterized by a common linear trend of the rock samples that is almost parallel to the ΔNb trend (Fig. 9) which suggests partial melting of a garnet enriched mantle source (Fitton et al., 1997; Revillon et al., 2000; Viruete et al., 2009). Maluski et al. (1995) and Coulon et al. (1996) considered that only the ca. 146-106 Ma alkaline rocks in the Benue Rift were derived by a Mantle Plume process while the younger tholeiitic rocks formed by the transfer of heat from underlying lithosphere to the subcontinental lithosphere. However, we observed in this study that the generation of the alkaline and tholeiitic rocks in the Abakaliki basin, which exposes the initial magmatism, in Lower Benue Rift was dependent on different degrees of partial melting resulting from pressure changes. The alkaline rocks in the central Abakaliki anticlinorium were derived from their source due to low degrees of partial melting at higher pressure, unlike the tholeiitic rocks on the periphery of the anticlinorium which were derived due to high degrees of partial melting at lower pressures (Keppie et al., 1997). This also indicates that the central part of the Abakaliki anticlinorium which is constituted mainly by alkaline rocks with primitive magma compositions represents an older member of the rocks compared to tholeiites in the peripheral parts which developed later by further rifting. Furthermore, the plume model of Best and Christiansen (2001) stated that the degree of magma generation is lower in thicker a lithosphere compared to thin lithosphere. This suggests that oceanic islands on thicker lithosphere away from the Mid-oceanic ridge axis (such as St. Helena, Azores, Tristan da Cunha, Gough and Shona) are predominantly composed of alkaline basaltic rocks because of low degrees of partial melting. However, areas closer to the Mid-oceanic ridge axis such as Iceland, Ascension, Grand Canary and the Bouvet islands are characterized by tholeiitic rocks. This suggest that rocks from the present work and other rocks around the Lower Benue Rift that are predominantly alkaline in composition with minor tholeiites are not the product of mid-oceanic ridge magmatism but formed from a thicker lithosphere and do not compare to basalts from Iceland and Ascension islands. The minor associated tholeiitic rocks are products of further rifting of the underlying lithosphere which increases the rate of partial melting within the same thickened lithosphere.

5.4. Tectonic setting

The geochemical plots of the volcaniclastic rocks from the Abakaliki basin in various discriminating diagrams that use immobile HFSEs (Fig. 10a–c) indicate that the volcanic rocks are within-plate alkaline and tholeiitic basalts (WPB). On the Zr-Ti-Y diagram of Pearce and Cann (1973), the rocks also plot in the field of WPB (Fig. 10a). The FAV and AAV rocks and the FTV and ATV rocks similarly plot in the same tectonic field setting on the Zr-Nb-Y and the Ti/Y versus Nb/Y diagrams of Meschede (1986) and Pearce (1982), respectively (Fig. 10b and c). The within-plate alkaline rocks are exposed mostly towards Abakaliki town while the tholeiitic rocks outcrop around Ezekwe-Wanakom areas in the northeastern part of the Abakaliki basin. Three rock samples in Fig. 10c exhibit transitional tholeiitic compositions. The results from this study allow us to modify the classifications by Wright (1968), Burke et al. (1971) and Burke et al. (1972) of these pyroclastics as andesitic in composition and of calc-alkaline affinity, suggesting a short-lived subduction event in the Benue rift; rather the rocks are a product of within-plate volcanism. The use of the less mobile elements and plotting unaltered volcaniclastic rocks in the newly developed tectonic discriminant function, DF1-DF2 diagrams (Fig. 11a and b) of Verma and Agrawal (2011) and Verma and Verma (2013) in this work indicate that the pyroclastic rocks from the Abakaliki basin are a product of within-plate (plume) intra-continental rifting-related environment. In this respect, these rocks are similar to the St Helena and the East African rift system rocks, which is in line with the views of Olade (1979); Hoque (1984); Obiora and Charan (2010, 2011) and Chukwu and Obiora (2014).

6. Conclusions

(i) Field observations, petrographic and geochemical data indicate that the pyroclastic rocks in the Abakaliki basin comprise primarily altered tuffs, lapillistones and agglomerates of basaltic composition.

(ii) Immobile elements characteristics and REEs of the volcaniclastic rocks indicate that they are composed of alkaline and tholeiitic rocks. The ratios of some HFSEs show that the alkaline rocks are associated with a fertile region in an asthenospheric HIMU mantle source similar to St. Helena rocks while the tholeiites are mostly related to EMI and EMII sources similar to the Ascension tholeiites.

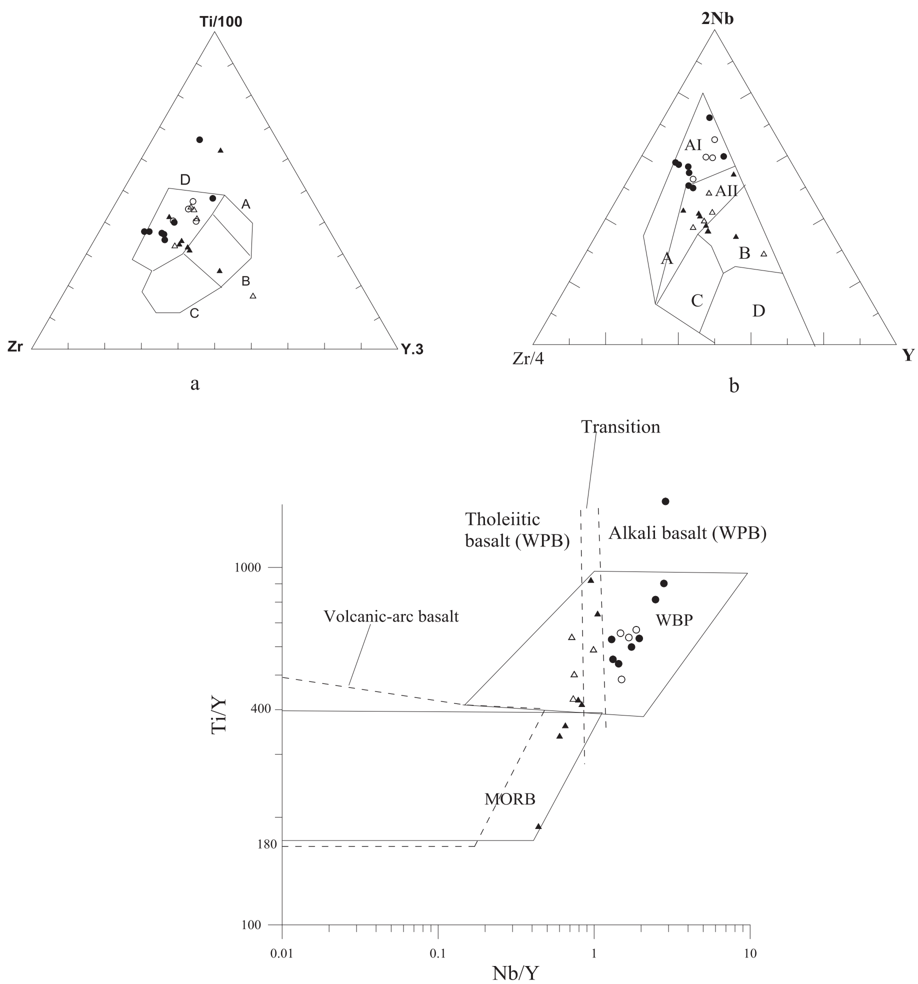
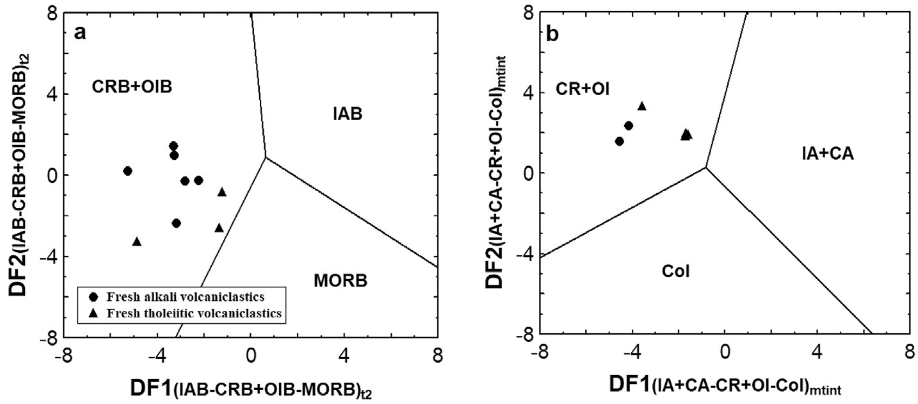


Fig. 10. a: Plots of the volcaniclastic rocks in Zr-Ti-Y diagram of Pearce and Cann (1973). D = within plate basalts (OIB and Continental basalts), A = Island-arc tholeiites, C = calc-alkaline basalts, B = MORB, island-arc tholeiites and calc-alkali basalts. b: Plots of the volcaniclastic rocks in Zr-Nb-Y diagram of Meschede (1986). AI = within plate alkaline basalts, AII = within-plate alkaline basalts and within-plate tholeiites, B = E-type MORB, C = within-plate tholeiites and volcanic arc basalts, D = N-type MORB and volcanic arc basalts. c: Plot of the volcaniclastic rocks in Ti/Y versus Nb/Y diagram of Pearce (1982).



a b

Fig. 11. a: Application of log–ratio transformed immobile trace element–based discriminant function DF1–DF2 discrimination diagrams (see the subscript t2 in all these diagrams; Verma and Agrawal, 2011) for basic rock samples from the Abakaliki basin. The four fields that can be identified are: IAB–island (and continental) arc basic rocks; CRB–continental rift basic rocks; OIB–ocean island basic rocks; MORB–mid-ocean ridge basalt; CRB + OIB– within-plate (see more detail in Verma, 2017). b: Application of major element based multidimensional diagrams (see the subscript "mint" in all these diagrams) for intermediate rocks of Verma and Verma (2013) for the discrimination of island-arc (IA), continental-arc (CA), within-plate (CR + OI), and collisional (Col) tectonic settings (see more detail in Verma et al., 2015; Verma, 2017).

(iii) The Nb/Y versus Zr/Y and multi-element diagrams suggests that the rocks formed through the melting of heterogeneous mantle source regions by an Icelandic type plume similar to the plume that generated most seamounts around the South Atlantic Ocean about 82 Ma.

(iv) The alkaline rocks at the central parts of the Abakaliki anticlinorium constitute the older rock suites while the tholeiites at the periphery constitute the younger rock suites in the basin. This work has further shown that the pyroclastic rocks are not andesites but were product of within-plate tectonic setting similar to the rocks of East-African rift system. The findings are consistent with the results obtained by Coulon et al. (1996) on the igneous rocks from other parts of the Benue Rift.

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