Petrogenetic and Geotectonic Implications of Lokpa-Ukwu Pyroclastics in Southern Benue Trough, Nigeria.

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ABSTRACT

Pyroclastics form domal to lenticular relief structures within the Cretaceous sedimentary units in Lokpa-Ukwu area of the southern Benue Trough, Nigeria. Eleven rock samples of the pyroclastics were studied and interpreted on the basis of their petrography and whole-rock geochemistry in order to generate reliable interpretative model for their genetic and geodynamic history. Petrographic characterization shows that the rocks are composed of plagioclase (labradiorite and andesine), clinopyroxene (cpx) (augite), orthopyroxene (opx) (hypersthene), iron ores, olivine, nepheline and k-spar (in three samples), and quartz (in five samples).

Major element geochemistry indicates that the pyroclastics are deficient in CaO and MgO, high in Na_2O, TiO_2, and LOI, and low to high in K_2O and are mainly alkali rocks with some olivine tholeiites, and a wide range of SiO_2 contents (38.51-51.69%; av. 45.07%). The pyroclastics are opx- and cpx-normative with high normative plagioclase (44-66%; av. 53%). Trace element compositions indicate low contents of LILE, Zr, Ni, and Cr and high contents of HFSE, while the range of REE abundances and distinctive chondrite-normalized patterns define LREE enrichment and HREE depletion. The pyroclastics probably underwent fractional crystallization of olivine and cpx from a partial melt generated from the mantle due to hotspot activities underneath constructive plate margin. The magma was eventually modified by high-K alkaline chemistry, probably from the widening of the proto oceanic South Atlantic before a final emplacement as volcanics in a sediment-dominated continental rift setting.

(Keywords: geology, geochemistry, Cretaceous sedimentary formations)

INTRODUCTION

Lokpa-Ukwu is located within the Lower Benue Trough of Nigeria (Figure 1), and it accommodates discontinuous exposures of eroded volcanic and hyperbyssal features. The Benue Trough formed as a result of series of tectonism, accompanied by magmatism and repetitive sedimentation in the Cretaceous during the separation of South America from Africa. The determination of the source of the intruding magma and the history of the emplacement processes of the pyroclastics can be useful in the interpretation of the petrogenesis and geotectonics of the Benue Trough. To achieve this, therefore, sample analysis has been done in order to determine the character of the melting process of the intruding magma and how the magma was emplaced in southern Benue Trough since magmas can be characterized by their constituent immobile elements in rocks (O'Hara, 1965; Pearce and Cann, 1971; Floyd and Winchester, 1975; Wood *et al*. 1979). This study is essentially a support project to the ongoing research on magmatism and its relationship to the development of the Benue Trough.

FIELD CHARACTERISTICS AND GEOLOGIC SETTING

The southern Benue Trough is a segment of the failed arm of a triple junction, which accompanied the rifting that gave rise to the separation of South America from Africa, and the opening of South Atlantic Ocean in the Cretaceous times (Burke *et al.*, 1971; Fairhead and Okereke, 1987). Sediment thickness in the southern Benue Trough is estimated to be about 6,500 m, and this was generated by repetitive transgressive-regressive sedimentary cycles, which however suffered two deformations in the Cenomanian and Santonian along NE–SW axis.

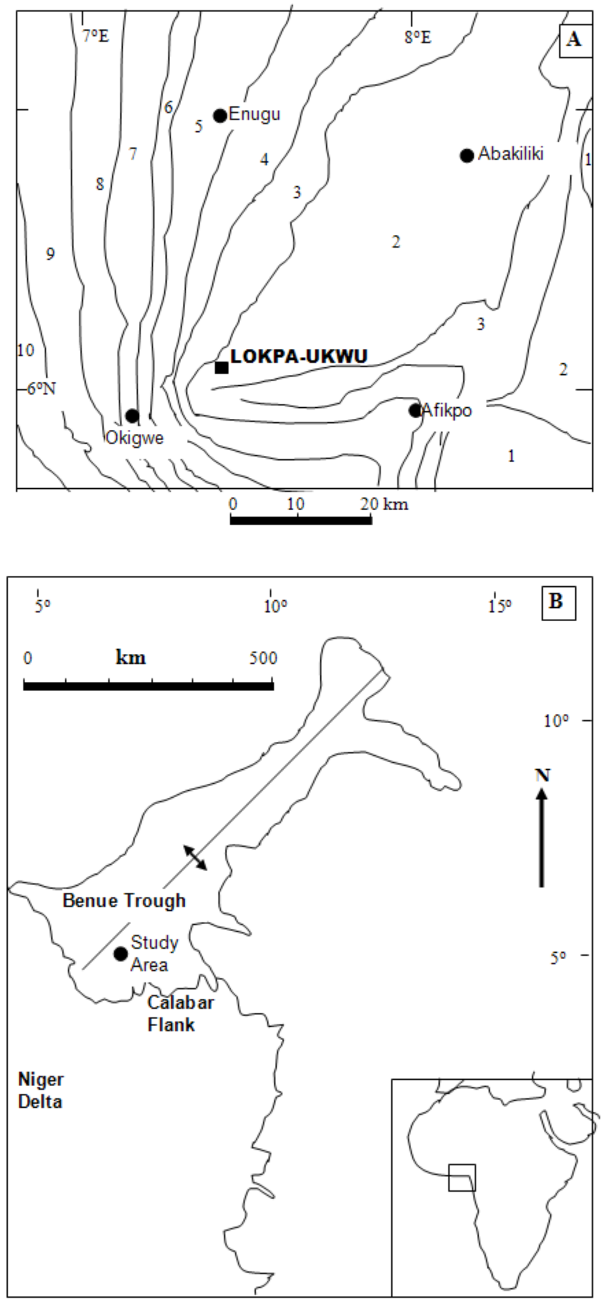

Figure 1: A) The Generalized Geological Map of Part of Southern Benue Trough, Nigeria, Showing Lokpa-Ukwu (study locality).
1 = Precambrian Oban Massif; 2 = Asu River Group (Albian); 3 = Ezeaku Fm (Turonian); 4 = Awgu Shale (Turonian); 5 = Nkporo/Enugu Shale (Campanian); 6 = Mamu Shale (Maastrichtian); 7 = Ajali sst (Maastrichtian); 8 = Nsukka Fm (Maastrichtian); 9 = Imo Shale (Palaeocene); 10 = Ameki Fm (Eocene).

B) General Map of Western Africa Showing the Benue Trough of Nigeria and Study Area.

These deformations produced multiple folds and fractures parallel to the fold axis (Ofoegbu, 1985, Cratchley and Jones, 1965; Nwachukwu, 1972), and the Santonian deformation in particular produced the Abakaliki Anticlinorium with two synclinal basins (Anambra Basin and Afikpo Syncline) on its flanks (Kogbe, 1974), forming the main depocenters of the post-deformation era.

The deformation generated magmatic activities in the Asu River Group and Eze–Aku Formation (Okeke *et al.*, 1988, Hoque, 1984), and the link between the deformation and magmatism is apparent in the emplacement of the igneous rocks in southern Benue Trough along well-developed and steep anticlines (Farrington, 1952; Ofoegbu, 1985). However, these igneous activities, which are mainly intermediate to basic in composition, in the greater southern Benue Trough appear to have persisted from the activities associated with the separation of the South America from Africa in the Cretaceous to Tertiary times (Wright, 1976; Ofoegbu, 1985).

The geology and igneous activities in the Lower Benue Trough have been variously discussed by Reyment (1965), Short and Stauble (1967), Grant (1971), Freeth (1977, 1978a, 1978b, 1979, and 1990), Uzuakpunwa (1974), Olade (1979), Nwachukwu (1972), Fayose (1970), Offodile (1976), Petters (1978), Petters and Ekweozor (1982), Amajor (1987), Amajor and Ofoegbu (1988), Amajor *et al.* (1988), Okeke *et al.* (1988), Okereke (1988), Okereke and Ofoegbu (1990), Nwajide (1990), Ofoegbu and Odigi (1990), Ofoegbu and Onuoha (1990), Ogbukagu, I.K.N. and Akujieze, C.N. (1990), Uma and Onuoha (1990), Etuk *et al. 2008,* and Ukaegbu (2008).

The pyroclastics form domal to lenticular reliefs in the sedimentary terrain in Lokpa-Ukwu and are concordant to the axis of Abakiliki-Okigwe Anticlinorium in southern Benue Trough. Field relations in Lokpa-Ukwu consist of low-lying sedimentary sequences made up of shale of the Asu River Group (Albian), Nkporo Shale (Late Turonian), and Mamu Shale (Middle Maastritchian), with associated topographic highs of pyroclastics, basalts, and dolerites. One episode of basaltic magmatism can be recognized within the study area and this magmatism emplaced the ubiquitous but undeformed and unmetamorphosed pyroclastics. From the field relations, the deposition of the Nkporo Shale and Mamu Shale post-dates the emplacement of the pyroclastics.

SAMPLING TECHNIQUE AND METHODOLOGY

Eleven fresh samples of randomly distributed pyroclastics exposures representing spatial variations of the volcanics were collected from channels, quarry sites, and road cuts in the Lokpa-Ukwu area. Thin sections of the samples were prepared and described. The samples were also used for major, trace, and rare earth element analysis using ICP-MS technique at the Activation Laboratories, Ontario, Canada. The details of this technique are given in Thompson and Walsh (1983). Methods of interpretation of the chemical data employ mainly the use of graphs, elemental relationships and abundances in the earth crust.

PETROLOGY AND PETROGRAPHY

The pyroclastics are largely very fresh; very few are weathered, and they have fine texture. In thin-sections they consist mainly of felsic and femic components. Femic components include pyroxene, olivine, and iron ores, while felsic components are plagioclase, quartz, and k-spar. They are essentially composed of plagioclase of labradiorite and andesine compositions, cpx (augite), opx (hypersthene), olivine, iron ores, k-spar, nepheline and quartz). Some of the pyroclastics are quartz-normative, with quartz and pyroxene ranging from 0.84 to 8.33% and 7.88 to 22.76%, respectively. Normative diopside ranges from low to high.

GEOCHEMISTRY

Major Element Geochemistry and Normative Mineralogy: The major element results and molecular norms for the pyroclastics are presented in Table 1. The pyroclastics are characterized by SiO_2 contents of 38.51 to 51.69-wt%, with mainly low values ranging from 38.51 wt% to 46.43 wt%, except LKP 2 with high value of 51.69 wt%. Al_2O_3 contents of 13.73-16.75-wt% occur in two modes: moderate (13.88-13.88 wt%) and high (14.41 wt% to 16.75 wt %). Na_2O abundance levels range from low (1.63 to 1.81%) to very high (>3.0 %). Except for LKP 1, LKP 8 and LKP 11, K_2O contents are high and CaO contents low. Total iron is reported as Fe_2O_3. All samples have high TiO_2 and P_2O_5 contents. Very high LOI (4.5-13.22) are recorded in all the samples. On the SiO_2 vs (Na_2O+K_2O) binary diagram of Cox *et al.* (1979) the pyroclastics classify mainly as hawaiite (Figure 2).

They have major element chemical compositions similar to high-K_2O alkaline basalts as demonstrated by the plot of the samples in alkaline field on the Na_2O+K_2O vs SiO_2 binary diagram (Irvine and Baragar, 1971), alkalic field on the SiO_2 vs (Na_2O+K_2O) binary diagram (Middlemost, 1985) and calc-alkaline to tholeiitic fields on the AFM ternary discrimination diagram (Figures 3-5).

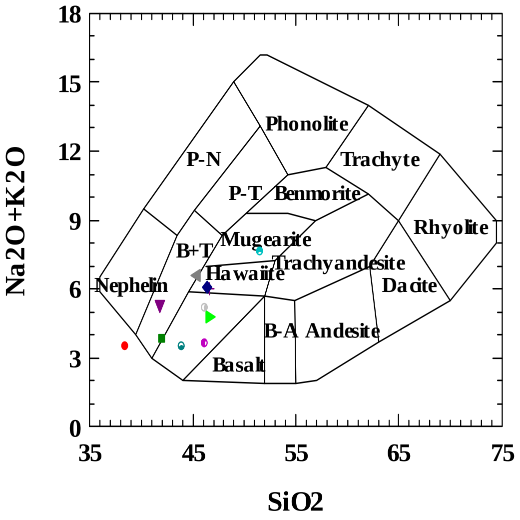

Figure 2: Na_2O+K_2O vs SiO_2 Binary Diagram Showing the Classification of the Pyroclastics as Hawaiites (after Cox *et al.* 1979).

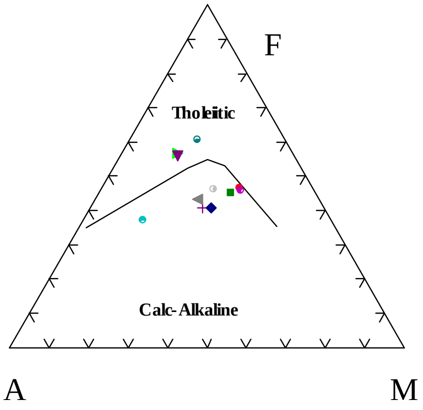

Figure 3: AFM Ternary Diagram (Irvine and Baragar, 1971), Showing that the Pyroclastics are mainly Alkaline, though Tholeiitic Features are Reflected in a few of the Samples.

Table 1: Major Element and CIPW Normative Mineral Compositions (in %) of the Pyroclastics in Lokpa-Ukwu, Southern Benue Trough.

Sample	LKP 1	LKP 2	LKP 3	LKP 4	LKP 5	LKP 6	LKP 7	LKP 8	LKP 9	LKP 10	LKP 11	AV.
Major Element Composition												
SiO_2	46.77	51.69	46.59	42.15	38.51	46.25	46.43	46.3	45.3	41.8	43.99	45.07
Al_2O_3	13.88	16.75	15.52	13.38	14.41	15.81	14.96	13.47	14.98	13.73	14.81	14.7
Fe_2O_{3T}	10.42	6.56	8.94	8.75	9.61	10.36	9.72	9.69	10.28	11.14	10.58	9.64
MnO	0.154	0.063	0.141	0.13	0.137	0.083	0.155	0.124	0.16	0.128	0.11	0.13
MgO	2.36	2.54	5.61	5.99	6.66	5.93	6.55	6.89	5.57	2.62	2.79	4.86
CaO	6.99	4.9	7.65	8.18	8.1	3.51	6.83	5.54	6.71	8.54	9.22	6.92
Na_2O	4.52	5.69	4.28	1.81	1.63	3.73	4.51	2.75	4.95	3.64	3.13	3.69
K_2O	0.25	1.87	1.75	1.94	1.83	1.4	1.58	0.78	1.66	1.59	0.3	1.36
TiO_2	2.603	3.436	3.241	2.912	3.249	2.738	3.156	2.715	3.776	2.992	2.769	3.053
P_2O_5	0.81	1.2	0.87	1.15	1.15	0.8	1.1	0.88	1.13	0.91	0.84	0.99
LOI	9.86	3.84	4.5	12.46	13.22	7.93	4.87	10.34	5.13	11.54	9.98	8.52
Total	98.62	98.54	99.1	98.86	100.7	98.54	99.87	99.48	99.65	98.61	98.53	99.12
K_2O/Na_2O	0.06	0.33	0.41	1.07	1.12	0.38	0.35	0.28	0.34	0.44	0.10	0.37
Na_2O/K_2O	18.08	3.04	2.45	0.93	0.89	2.66	2.85	3.53	2.98	2.29	10.43	2.71
CIPW norm												
Q	6.69	0.84		3.52		5.34		8.33			6.98	2.88
Or	1.67	11.68	10.94	13.28	12.69	9.14	9.84	5.18	10.39	10.80	2.00	8.87
Ab	43.04	50.78	34.21	17.71	16.15	34.79	37.09	26.07	34.81	34.41	29.88	32.63
An	18.95	15.43	18.96	26.18	31.13	14.04	16.72	24.76	14.52	18.83	28.74	20.75
Ne	-	-	2.19	-	-	-	1.64	-	5.12	0.49	-	0.86
C	-	-	-	-	-	3.85	-	-	-	-	-	0.35
Di_{Wo}	6.17	1.18	6.59	5.43	3.38	-	5.08	0.12	5.72	8.72	7.26	4.51
Di_{En}	5.32	1.01	5.68	4.68	2.91	-	4.38	0.10	4.93	7.52	6.25	3.89
Hy_{En}	1.33	5.69	-	12.65	13.07	16.36	-	19.22	-	-	1.62	6.36
Ol_{fo}	-	-	6.40	-	2.48	-	9.00	-	6.86	-	-	2.25
Mt	0.57	0.22	0.49	0.49	0.52	0.30	0.53	0.45	0.55	0.48	0.41	0.46
Hm	11.35	6.78	9.12	9.79	10.91	11.23	9.86	10.56	10.49	12.46	11.67	10.39
Ap	1.99	2.77	2.01	2.91	2.94	1.93	2.53	2.16	2.61	2.28	2.07	2.38

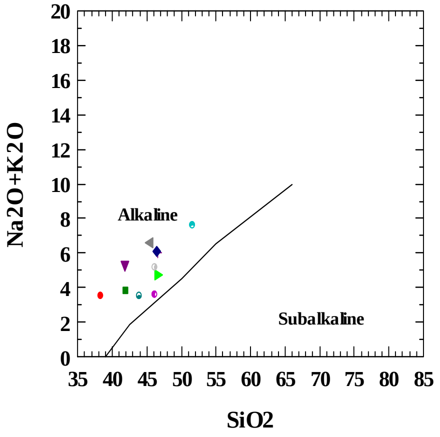

Figure 4: Na_2O+K_2O vs SiO_2 Binary Diagram (Irvine and Baragar, 1971), Showing the Plot of the Samples in Alkaline Field.

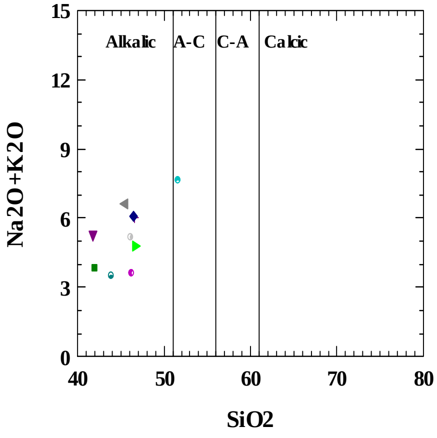

Figure 5: SiO_2 vs Na_2O+K_2O Binary Diagram (Middlemost, 1985), Showing that the Pyroclastics are Alkalic.

Rare Earth Element Geochemistry: The REE abundances of the samples are presented in Table 2 and their chondrite-normalized patterns (Haskin *et al.* 1968) are illustrated in Figure 6. One basic pattern of REE abundances is identifiable in the samples. The different samples show a general uniformity in their near straight REE pattern with slight positive Eu anomalies. The average REE abundances of the pyroclastics are about 2 times higher than the normal abundances in similar rocks (30-125 ppm) (Haskin and Schmitt, 1967), (110-115 ppm) (Beka and Ukaegbu, 2006), and average values for Lower crust (Taylor and McLennan, 1985).

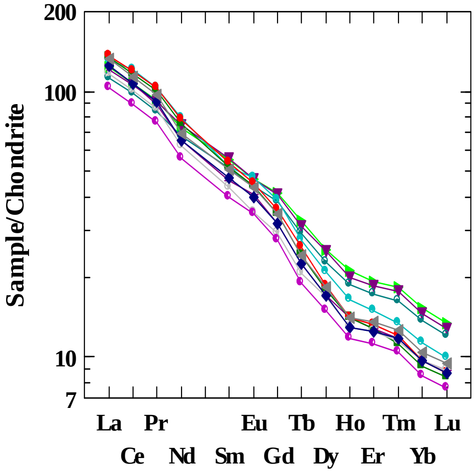

Figure 6: REE Chondrite-Normalized Patterns (Haskin *et al*., 1968), Showing Enriched LREE and Sloping Patterns Indicating Some Level of Fractionation of the Pyroclastics.

All the pyroclastics show narrow variability in Eu/Eu* (0.248-0.368). The main REE patterns are characterized by enrichment in LREE, and depletion in HREE, relative enrichment in the middle REE; thus giving rise to sloping REE patterns, which impact on the pyroclastics a character that suggests some level of fractionation. This is also demonstrated by Ce_N/Yb_N ratios, which range mostly from 27.11 to 48.07 with average of 37.53 due to LREE enrichment.

Trace Element Geochemistry: The abundances in the samples are presented in Table 3 and illustrated in Figures 7, 8, and 10-16. The trace element compositions of the pyroclastics show variable ranges, which, however, lie within the compositions for basic rocks. The pyroclastics show low contents of the relatively immobile elements (Zr, Nb, Ni, and Cr), low contents of large cations (Cs, Rb, Pb, Ba, Sr, and Eu), and high concentrations of highly charged cations (Th, U, Hf, and Sn). The contents of the ferromagnesian elements are fairly high as indicated by high ratios of Ni/Co and low ratios of V/Ni. In general, the base metals (Pb, Zn, and Cu) show limited variations.

Elemental ratios of Th/U, Rb/Sr, Ba/Nb, Rb/Zr, Hf/Ta, and Ba/Ta (Table 3) are low. The multi-element patterns, normalized to continental crust and oceanic crust show enrichment of the HFSE relative to the LILE, and the consistency of the HFSE and irregularity in the pattern of concentrations of LILE (Figures 7 and 8).

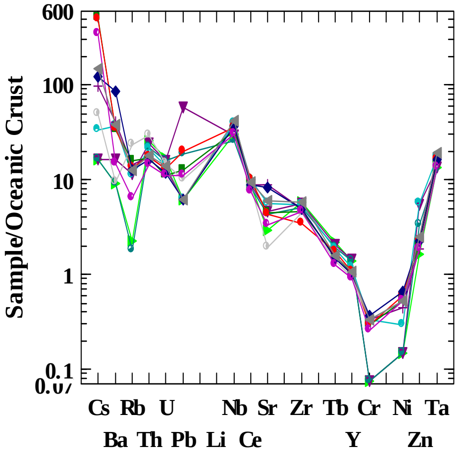

Figure 7: Oceanic Crust-normalized Multi-Element Diagram of the Pyroclastics, Showing Low Contents of Cr, Ni, and LILE, and High Contents of HFSE.

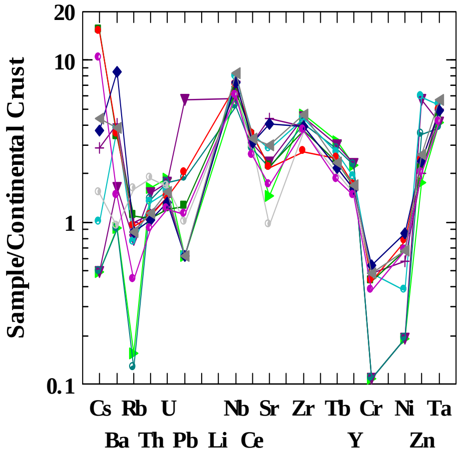

Figure 8: Continental Crust-Normalized Multi-Element Diagram of the Pyroclastics, Showing High Contents of HFSE, Lack of Consistency in the Behavior of LILE and Low Contents of Cr and Ni.

Table 2: Rare Earth Element Compositions (in ppm) of the Pyroclastics from Lokpa-Ukwu, Southern Benue Trough.

Element	LKP 1	LKP 2	LKP 3	LKP 4	LKP 5	LKP 6	LKP 7	LKP 8	LKP 9	LKP 10	LKP 11	AV.
La	45.5	48.2	46.1	49.2	49.9	42.8	46	38	48.8	44.4	41.3	45.47
Ce	103	115	102	112	114	96.9	103	85.4	109	101	93.9	103.2
Pr	12.7	14.2	12.3	13.8	14.1	11.8	12.6	10.5	13.3	12.6	11.6	12.68
Nd	52.1	56.2	46.3	53.5	55.5	44.1	46.7	39.6	49.4	52.8	48.4	49.51
Sm	12.8	12.9	10.7	12.1	12.4	10.1	10.9	9.2	11.7	13	11.9	11.61
Eu	4.07	4.13	3.58	3.84	3.94	3.05	3.49	3	3.8	4.06	3.82	3.71
Gd	12.7	11.9	9.7	10.6	11	9	9.8	8.4	10.6	12.6	11.8	10.74
Tb	1.9	1.6	1.3	1.4	1.5	1.2	1.3	1.1	1.4	1.8	1.7	1.47
Dy	9.7	8	6.5	6.8	7.1	6.4	6.5	5.7	7	9.5	8.7	7.45
Ho	1.8	1.4	1.2	1.2	1.2	1.1	1.1	1	1.2	1.7	1.6	1.32
Er	4.8	3.7	3.2	3.2	3.3	3.1	3.1	2.8	3.4	4.6	4.3	3.59
Tm	0.65	0.48	0.42	0.4	0.43	0.41	0.42	0.37	0.45	0.63	0.58	0.48
Yb	3.8	2.8	2.4	2.3	2.4	2.4	2.4	2.1	2.6	3.6	3.4	2.75
Lu	0.51	0.38	0.34	0.32	0.33	0.34	0.33	0.29	0.36	0.49	0.46	0.38
ΣREE	266.03	280.89	246.04	270.66	277.1	232.7	247.64	207.46	263.01	262.78	243.46	254.36
LREE	226.1	246.5	217.4	240.6	245.9	205.7	219.2	182.7	232.2	223.8	207.1	222.47
La/Yb	11.97	17.21	19.21	21.39	20.79	17.83	19.17	18.10	18.77	12.33	12.15	16.53
La/Sm	3.55	3.74	4.31	4.07	4.02	4.24	4.22	4.13	4.17	3.42	3.47	3.92
Ce/Yb	27.11	41.07	42.50	48.70	47.50	40.38	42.92	40.67	41.92	28.06	27.62	37.53
Eu/Eu*	0.248	0.262	0.308	0.297	0.286	0.368	0.319	0.365	0.290	0.254	0.264	0.291

PETROGENETIC AND GEOTECTONIC MODELLING

Petrogenesis: Petrology and major element geochemistry indicate that partial melting and fractional crystallization of mantle rich in olivine, clinopyroxene, and plagioclase generated the magma. The mineral paragenesis of plagioclase + pyroxene + olivine, of the pyroclastics is typical of high temperature condition.

The high content of plagioclase and the pattern of fractionation of plagioclase appear to control the evolution of the igneous activities. Also high normative average content (58.62%) of plagioclase suggests that the pyroclastics may have contained a significant amount of cumulate plagioclase. Strong enrichment in plagioclase cumulates is confirmed by the ratios of La/Yb (6.84-7.67) and Ce/Yb (14.60-16.23). Additionally, the significant slight Eu anomaly supported by low ratios of Eu/Eu* (0.248-0.368) suggest that plagioclase is of cumulate origin. This probably represents an important factor in the evolution of these pyroclastics.

The narrow range in the concentrations of the major elements, indicates homogeneity in source material, with minimal contamination during limited differentiation. The pyroclastics may have been modified by crystallization of olivine, orthopyroxene and anorthite, and addition of potash. The magma was probably basaltic (volcanic) materials with alkaline affinities. Thus, the pyroclastics appear to represent high-K_2O basalts. The high mean values of the K_2O and alkalis indicate a secondary feature taking into account the emplacement of the pyroclastics in a sedimentary terrain, which was probably a source of alkali-rich medium during the intrusion.

Table 3: Trace Element Compositions (in ppm) of the Pyroclastics from Lokpa-Ukwu, Southern Benue Trough.

Sample	LKP 1	LKP 2	LKP 3	LKP 4	LKP 5	LKP 6	LKP 7	LKP 8	LKP 9	LKP 10	LKP 11	AV.
Sc	14	16	17	16	17	16	16	16	19	16	17	16.36
Be	3	2	3	3	3	3	3	3	3	3	3	2.92
V	150	184	201	166	178	177	203	175	240	189	174	185.18
Ba	230	933	1010	843	868	234	2143	366	959	405	225	746.91
Sr	382	731	1136	577	567	251	1060	441	786	609	562	645.64
Y	45	38	32	33	34	30	32	29	34	46	45	36.18
Zr	460	439	394	369	273	362	393	368	467	447	409	398.27
Cr	19.99	90	90	80	80	90	100	70	90	19.99	19.99	68.18
Co	18	17	25	26	29	30	29	28	29	23	20	24.91
Ni	19.99	40	60	70	80	70	90	70	70	19.99	19.99	55.45
Cu	30	30	60	30	40	10	70	80	50	380	280	96.36
Zn	140	470	160	170	190	160	190	160	210	460	280	235.45
Ga	24	16	20	19	20	24	19	18	21	25	23	20.82
Ge	1	1	1	2	2	1	1	1	1	1	1	1.18
As	4.99	4.99	10	4.99	4.99	4.99	4.99	4.99	4.99	50	4.99	9.54
Rb	5	24	32	35	30	51	28	14	28	25	4	25.09
Nb	67	86	82	71	78	67	81	66	92	64	57	73.73
Mo	3	1.99	3	3	3	1.99	4	1.99	3	3	2	2.72
Ag	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49
In	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Sn	6	3	6	4	6	3	13	9	4	17	12	7.55
Sb	0.49	0.49	0.49	0.49	1.9	0.49	0.49	0.49	0.49	0.49	0.49	0.62
Cs	0.49	1	2.9	15.2	14.9	1.5	3.7	10.3	4.4	0.49	0.49	5.03
Hf	12.4	10.6	10.2	9.2	9.6	9	9.5	8.1	11	11.3	10.2	10.1
Ta	4.1	5.3	5	4.4	4.9	4.2	4.9	4.1	5.7	4.1	3.8	4.59
W	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Tl	0.09	0.1	0.09	0.2	0.2	0.2	0.09	0.09	0.09	0.09	0.09	0.12
Pb	4.99	4.99	4.99	10	16	8	4.99	9	4.99	46	15	11.72
Bi	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Th	5.7	4.6	3.9	3.7	3.8	6.5	3.6	3.2	4	5.3	4.8	4.46
U	1.7	1.4	1.3	1.1	1.3	1.5	1.2	1.1	1.4	1.6	1.6	1.38
Rb/Ba	0.02	0.03	0.03	0.04	0.03	0.22	0.01	0.04	0.03	0.06	0.02	0.03
Ba/Nb	3.43	10.85	12.32	11.87	11.13	3.49	26.46	5.55	10.42	6.33	3.95	10.13
Ba/Ta	56.10	176.04	202.00	191.59	177.14	55.71	437.35	89.27	168.25	98.78	59.21	162.73
Rb/Zr	0.01	0.05	0.08	0.09	0.11	0.14	0.07	0.04	0.06	0.06	0.01	0.06
Rb/Sr	0.01	0.03	0.03	0.06	0.05	0.20	0.03	0.03	0.04	0.04	0.01	0.04
Th/U	3.35	3.29	3.00	3.36	2.92	4.33	3.00	2.91	2.86	3.31	3.00	3.23
Hf/Ta	3.02	2.0	2.04	2.09	1.96	2.14	1.94	1.98	1.93	2.76	2.68	2.20

However, the range of the major elements suggests that the pyroclastics were not substantially affected by chemical mobility. The concentration of Cu does not suggest that leaching of Cu from most of the pyroclastics occurred, thus indicating that hydrothermal alterations in the pyroclastics must have been minimal. Burke *et al.* (1971), Amajor and Ofoegbu (1988), Amajor *et al.* (1988), Okeke *et al*. (1988), and Onwualu-John and Ukaegbu (in press) had described alkali-rich rocks elsewhere in the Benue Trough. The igneous rocks in southern Benue Trough appear to have genetic and/or tectonic links.

The particularly low MgO suggests that these samples might not contain a significant component of liquidus olivine and orthopyroxene. The behavior of the concentrations of major elements therefore indicates differentials in their level of fractionation of olivine and pyroxene during evolution from a single source. The volcanics apparently do not represent one phase of wholesome crystallization and differentiation; batch melting and crystallization appear to have been prevalent, given the elemental spread.

Langmuir *et al*. (1977) had pointed out that REE ratios during fractional melting are a function of the quantum of melts added to the system. The ratios of such parameters as La/Yb (6.84-7.67) and Ce/Yb (14.60-16.23) suggest primary melts. Langmuir *et al.* (Op. cit) suggested that the total abundances and ratios of incompatible REE in magma from a given source depend on the type of melting, and that each increment of melt inherits very different REE ratios during fractional melting. The position of the trend is such that the samples with highest Ce/Yb represent the more evolved magma compositions. This evolutionary pattern can be interpreted to result from progressive partial melting and controlled depletion of a single mantle source region*.* The more SiO_2-rich rocks represent more evolved products of this process, with increasing plagioclase fractionation.

The uniformity in the distribution of the elements, and the fact that the elements show a variety of important low ratios suggest the nature of the magmatic processes that produced the pyroclastics. For instance, the results of the analyses show that low contents of Cr, Ni, and LILE, and a range of REE abundances and distinctive patterns of sloping patterns with slight positive Eu anomalies characterize the pyroclastics. These patterns indicate liquids generated by some degree of partial melting and fractional crystallization of magma rich in ferromagnesian minerals and plagioclase, probably of mantle origin. Also, the low ratios of Th/U (1.28-5.43) suggest mantle source, while limited magmatic differentiation of the pyroclastics is suggested by the low Rb/Sr (0.03-0.07).

The low Ni and Cr contents do not necessarily suggest that the magma fractionated strongly because the positive correlation between Ni and Cr is an indication of their occurrence in liquidus phase. It is apparent that the low contents of Ni, Co, and Cr in the rocks indicate source characteristics and some degree of fractionation of olivine and clinopyroxene. Also, low contents of trivalent ferromagnesian elements such as Sc and V and high La/Yb ratios of the samples suggest clinopyroxene fractionation. Similarly the REE patterns of the pyroclastics with approximately parallel trends are consistent with plagioclase and clinopyroxene fractionation. The possible pattern therefore would be olivine depletion and a compensational increase in the abundance of the pyroxenes in the more evolved volcanic components. This is expected during crystal fractionation if the source material is adequately enriched in the relevant compositions.

The narrow range of the concentrations of incompatible elements such as Zn and Ni indicates homogeneity in incompatible elements in source material. The various REE profiles of the pyroclastics, therefore, represent the primary patterns, which suggest that basaltic magmas were derived from sources with similar REE concentrations and ratios within the same area. Also the abundances of LREE are generally similar, precluding derivation from a multiple magma chamber. However, the slight compositional differences between the REE may imply E-type MORB produced by slight variations in the degrees of partial melting from a single mantle source (Panjasawatwong *et al.* 2006).

Similarly, the similar abundances of LREE in the rocks, suggests a pattern of magmatic evolution from mantle to crustal compositions from a single source during ascent, involving some kind of crustal input. The low ratios of Rb/Sr and Th/U appear to further suggest that the volcanics are of mantle origin. Parental magma to the pyroclastics may have followed a single fractional crystallization path controlled by batch melting and scaled fractionation of olivine and clinopyroxene during magma ascent.

Geotectonics: Volcanic rocks, especially basalts, exhibit specific chemical features for specific tectonic environments (Pearce and Cann 1973; Wood et al. 1979). They are known to be associated with divergent plate margins (ocean floor basalts, OFB), convergent plate margins (volcanic arc basalts, VAB), within plate of oceanic margin (oceanic island basalts, OIB), and within plate of continental crust (continental basalts) (Pearce and Cann, 1973). However, basalts with similar chemistry may be produced in different tectonic regimes since their compositions also reflect the nature of the particular mantle and the melting processes operating (Floyd, 1982).

The REE patterns of the samples of the pyroclastics reflect melts from same source and, of course, mineralogy but they have inherited individual identities and characters during differentiation in the same tectonic setting. The normalized multi-element distribution patterns of the rocks of the volcanics (Figures 7 and 8) show that the alkaline suites have low LILE (Ba, Sr, and Pb) and high HFSE (Nb, Ta, Zr, and Hf) contents, which are characteristic of ocean floor series and spreading centers. They show varying enrichment of the incompatible nature of the elements from right to left.

Geochemical values of immobile trace elements (Ti, Zr, Y, Hf, Th, Ta, and Nb) and low ratios of Ba/Nb (9-23) and Ba/Ta (130-327) suggest that the protolith was emplaced as volcanics in a spreading boundary, such as mid-oceanic ridge and WPB setting. Also the affinity to spreading centers is confirmed by very low ratios of Ba/Nb (3-26; av.10) and Ba/Ta (56-437; av. 162).

Furthermore, rock samples show consistent plots in ocean floor basalts (OFB) (divergent) setting on the FeOt-MgO- Al_2O_3, Ti-Cr, Ti/100-Zr-Y*3 and V vs. Ti/1000 variation diagrams (Figures 9-12). On the other hand, plots on the Nb*2-Zr/4-Y, Zr vs. Zr/Y, Hf/3-Th-Ta, and Hf/3-Th-Nb/16 variation diagrams (Figures 13-16) suggest emplacement in within-plate-basalts (divergent) setting.

The behavior of many of the elements supports mantle as well as crustal affinities. Association with both the mantle and crust suggests deep source, probably the mantle, and differentiation of the magma as it ascended into the crust with which it interacted. The initiation and termination of the eruption in divergent settings indicate that the magmatic activities were generated from a common source. Thus, the final emplacement of the pyroclastics in a continental setting is suggestive of a prolonged divergent activity initiated at great depth. The magma traced and utilized the rift until the last batch completely solidified as pyroclastics on the continent.

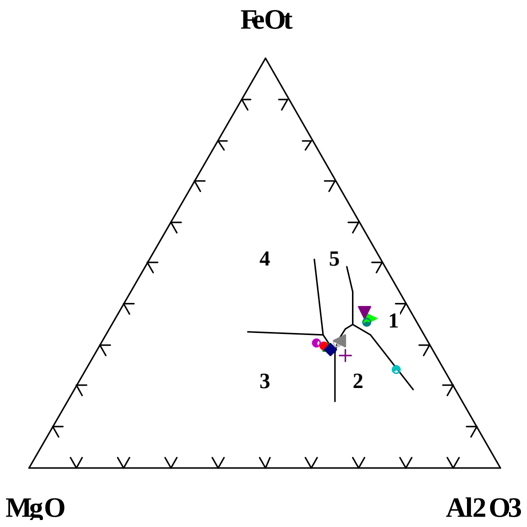

Figure 9: FeOt-MgO-Al_2O_3 Ternary Diagram Showing the Plot of the Pyroclastics in the Field of Spreading Centers and Mid-Ocean Ridge Ocean Floor Basalts (after Pearce *et al.* 1977).
1 = Spreading Centres, Island Basalt; 2 = Orogenic (Island Arc and Continental Margin) Basalt; 3 Mid-Ocean Ridge and Ocean Floor Basalt; 4 = Ocean Island Basalt; 5 = Continental basalt.

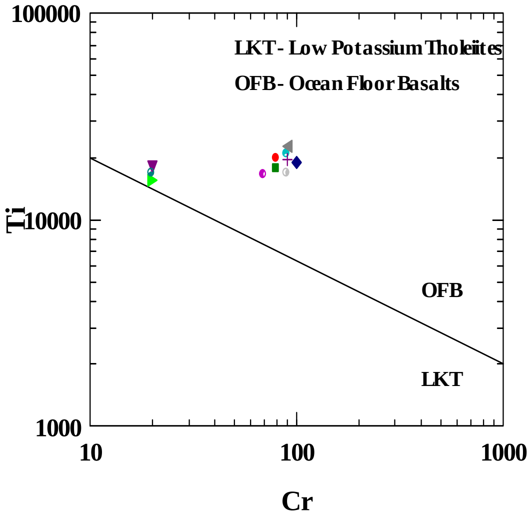

Figure 10: Ti vs Cr Binary Diagram Showing the Plot of the Pyroclastics in the Field of Ocean Floor Basalts (after Pearce, 1975).

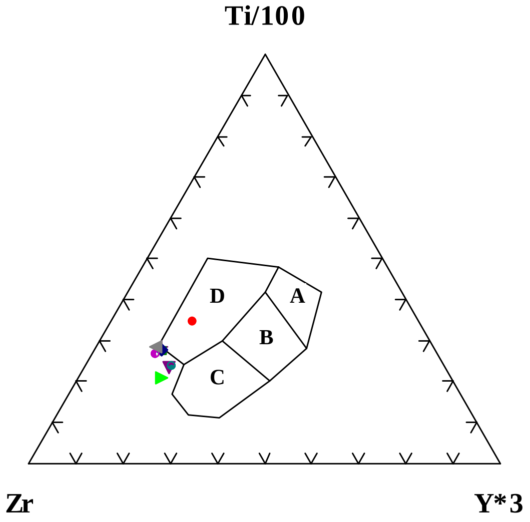

Figure 11: Ti/100 – Zr – Y*3 Ternary Diagram Showing the Plot of the Pyroclastics within Ocean Floor Basalt Field (after Pearce and Cann, 1973).
A,B, for LKT; A,C. for CAB; B, C for OFB.

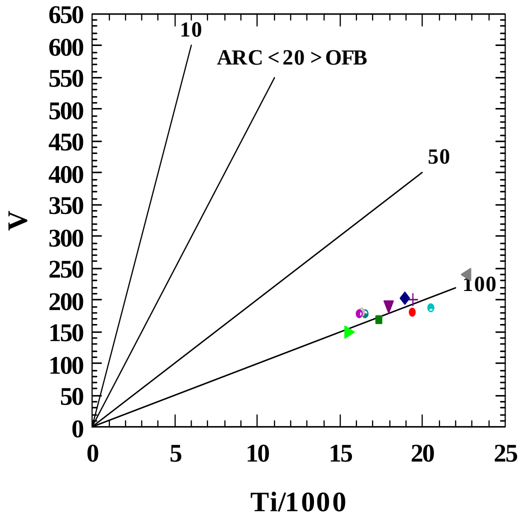

Figure 12: Ti/100 vs V Binary Diagram Showing the Plot of the Samples within Ocean Floor Basalt Field (after Shervais, 1982).

The chemical evidence of eruption on oceanic environment suggests that these pyroclastics consist of MORBs (Panjasawatwong et al. 2006). Whether the volcanics are erupted at normal ridge segments (N-type MORB) or tectonically anomalous ridge segments (such as hotspot or E-type MORB can be deduced from their ratios of La/Ta, Rb/Sr, Th/U and Hf/Ta (Wood *et al.* 1979).

The values of the ratios for N-type MORB are La/Ta (~15), Rb/Sr (~0.01), Th/U (~2), and Hf/Ta (>7), and La/Ta (~10), Rb/Sr (~0.04), Th/U (~4), and Hf/Ta (<7 but >2) for E-type MORB. The pyroclastics classify as E-type MORB type from the ratios of Rb/Sr (0.04), Th/U (3.23), and Hf/Ta (*2.35-2.88*) in the samples (Table 2). Also the Hf/Ta ratios (*2.36-2.88*) for the pyroclastics further buttress the fact that the pyroclastics have affinity with E-type MORB (Wood *et al*. 1979).

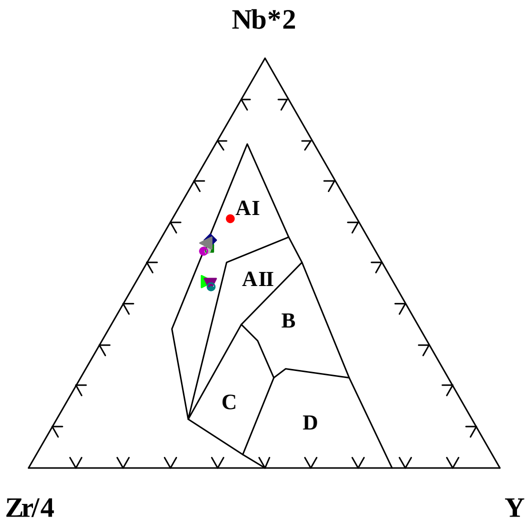

Figure 13: Nb*2 – Zr/4-Y Ternary Diagram Showing the Plot of the Pyroclastics in the Field of Within Plate Basalts (after Meschede, 1986).
AI-AII = Within Plate Basalt; B = P-MORB; C-D = Volcanic Arc Basalt; D = N-MORB.

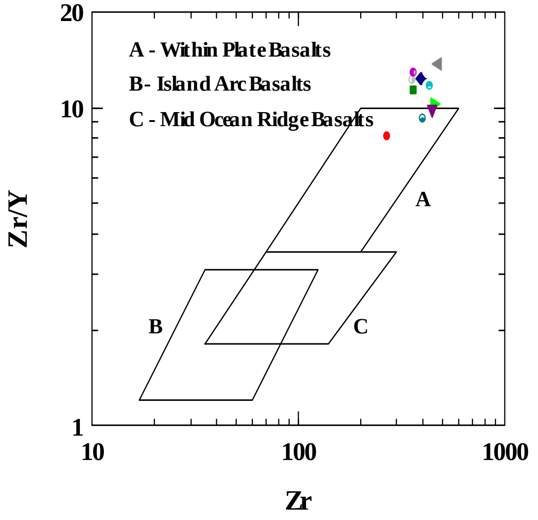

Figure 14: Zr vs Zr/Y Binary Diagram Showing the Plot of the Samples in Within Plate Basalt Field (after Pearce and Norry, 1979).

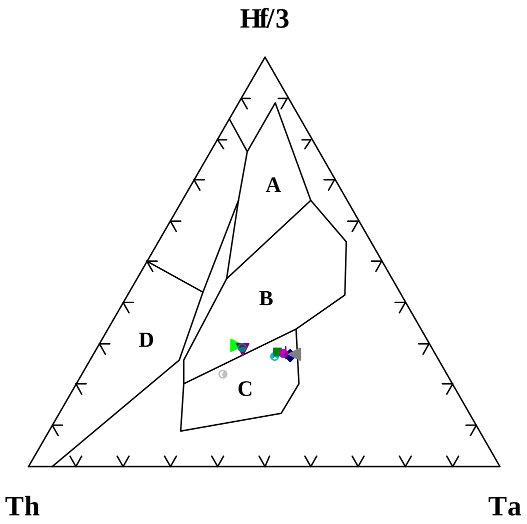

Figure 15: Hf/3-Th-Ta Ternary Diagram Showing the Plot of the Pyroclastics in Within Plate Basalt Field (after Wood 1980).
Fields: A = N-MORB; B = Enriched MORB and Within Plate Basalts; C= Alkaline Basalt WPB & differentiates; D = destructive plate margin basalt and differentiates.

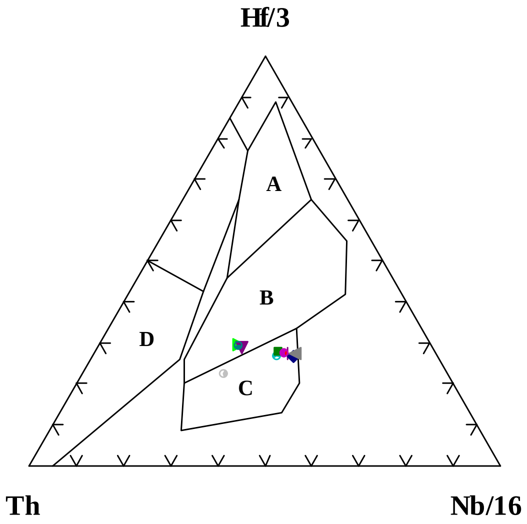

Figure 16: Hf/3 –Th-Nb/16 Ternary Diagram Showing the Plot of the Samples in Within Plate Basalt Field (after Wood, 1980).
Fields: A =N-MORB; B = Enriched MORB and Within Plate Tholeiites; C = Within Plate Basalts and Differentiates; D = Destructive Plate.

The pyroclastics appear to be ocean floor and continental rift volcanic piles dominated by alkaline magmatism during the development of a proto-sea in the South Atlantic. The plot of most samples in the field of ocean floor basalt and within plate basalt is consistent with their compositions and therefore, depicts their tectonic setting (Grant *et al*. 1972). It is apparent the ocean floor affinity is related to the initial magmatic source, while the continental affinity characterizes a later emplacement in a sediment-dominated spreading environment. In other words, their intrusion was initiated beneath seafloor spreading centers and later migrated to a continental spreading setting. From the discussions above, the likely petrogenetic and geotectonic model is that these pyroclastics constitute alkaline volcanism emplaced in a seafloor spreading setting and subsequently rested on a continental rift setting.

CONCLUSION

The petrographic and major element geochemistry of pyroclastics from southern Benue Trough suggest that they represent high-K_2O alkaline basalts, which resulted from the fractionation of the ferromagnesian mineral and plagioclase from a common magma source. Similarly, the trace and rare earth element compositions of the pyroclastics suggest that the rocks have undergone different degrees of plagioclase fractionation. Such element pattern characterizes magma resulting from partial melting, fractional crystallization and differentiation above mantle source. Thus, the basaltic pile underwent systematic evolution from lowermost basalts of alkaline affinity in the ocean floor setting until a final emplacement in a continental rift setting. The eruption through ocean floor basalts (OFB) setting with limited evolution in spreading centers probably took place during the development of a proto-sea in the South Atlantic.

This study has therefore shown that alkaline volcanism was generated from seafloor spreading setting and that the volcanism eventually extended to continental rift setting when drifting and supply of magma continued from depth under the Benue Trough.

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