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THE GEOCHEMISTRY OF VOLCANIC PLUGS INTRUDING SHALES OF THE PINDIGA FORMATION, GONGOLA SUB-BASIN, NORTHERN BENUE TROUGH, NIGERIA: IMPLICATIONS FOR PROVENANCE, WEATHERING, AND TECTONIC SETTING

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ABSTRACT

This study presents a geochemical investigation of volcanic plugs intruding the Cretaceous shales of the Pindiga Formation in the Gongola Sub-Basin, Northern Benue Trough, Nigeria. Eight representative samples comprising basalts (n = 4), shales (n = 3) and sandstone (n = 1) were analyzed for major oxides using wavelength-dispersive X-ray fluorescence (WD-XRF). Analytical accuracy was monitored using certified reference standards and analytical precision is better than ±5% for major oxides. The basaltic plugs plot within the sub-alkaline field on the TAS diagram and display a tholeiitic affinity on the AFM diagram. One basalt sample shows a peraluminous signature (A/CNK > 1), which may reflect assimilation of Al-rich country rocks during magma emplacement. Geochemical proxies suggest that the shales were predominantly derived from mafic igneous sources and are classified as Fe-shales. High Chemical Index of Alteration (CIA = 85.39–95.67) and low Index of Compositional Variability (ICV = 0.31–0.51) indicate intense chemical weathering under humid paleoclimatic conditions. Major-element tectonic discrimination diagrams suggest a tectonic setting consistent with an active continental margin, although interpretations are made cautiously due to the limited dataset and the known limitations of major-element proxies. The results provide new geochemical constraints on the relationship between Cenozoic magmatism and the Cretaceous sedimentary succession of the Gongola Sub-Basin.

Keywords: Benue Trough, Volcanic Plugs, Geochemistry, Provenance, Chemical Weathering, Tectonic Setting, Tholeiite, Fe-Shale

INTRODUCTION

The Benue Trough is a major intracontinental rift basin formed during the Early Cretaceous separation of the African and South American plates (Genik, 1993; Nwajide, 2013). Its northern extremity, the Gongola Sub-Basin, is characterized by thick sedimentary sequences and significant igneous activity, manifested as volcanic plugs, basaltic flows, and intrusive bodies (Benkhelil, 1989; Obaje et al., 2006). These volcanic features, part of the wider anorogenic magmatism associated with the Cameroon Volcanic Line, provide a critical window into the mantle dynamics and tectonic evolution of the region (Turner, 1978; Auwalu et al., 2023). Several tectonic models have been proposed for its evolution, including simple continental rifting, transtensional deformation, and plume-assisted magmatism associated with the Cameroon Volcanic Line (Stoneley, 1966; King, 1950; Grant, 1971; Olade, 1975; Benkhelil, 1989 and Guiraud and Maurin, 1992). Understanding the geochemical characteristics of intrusive volcanic bodies and their host sediments can provide important constraints on these models. Basaltic rocks originate from the upper mantle via partial melting and can erupt in diverse tectonic settings, including continental rifts, oceanic ridges, and subduction zones (Wilson, 1989; Winter, 2010). Discriminating between these settings is crucial for understanding the geodynamic history of a region. Furthermore, the geochemistry of sedimentary rocks, which are efficient integrators of source area composition, can be used to decipher provenance, weathering intensity, and the tectonic setting of the depositional basin (McLennan et al., 1993; Armstrong-Altrin et al., 2004).

The Gongola Sub-Basin in the Northern Benue Trough contains numerous volcanic plugs that intrude the Cretaceous sedimentary sequence, particularly the Pindiga Formation. Previous studies have inferred the presence of subsurface intrusions in the Gongola Sub-Basin (Ofoegbu, 1986; Ajakaiye et al., 1986), and petrographic studies have described the volcanic rocks as porphyritic texture and suggested a possible wall rock interaction during emplacements (Adekeye and Ntekim, 2007; Auwalu et al., 2023), but detailed geochemical data integrating both the igneous bodies and the surrounding sedimentary rocks remain limited. Sedimentary rocks, especially shales, are valuable archives of source-area composition and weathering processes because they integrate geochemical signatures from large drainage basins. Similarly, basaltic rocks preserve information about mantle sources and tectonic environments (Abubakar et al., 2021; Hussain et al., 2021). Therefore, a combined geochemical study of volcanic plugs and host shales provides an opportunity to reconstruct both magmatic processes and sediment provenance within the basin. This study therefore aims to: Classify the volcanic plugs and determine their magmatic affinity, evaluate the provenance and weathering history of the host shales of the Pindiga Formation, and examine the tectonic implications of both igneous and sedimentary geochemical signatures within the Gongola Sub-Basin. Trace-element data were not available; this study relies primarily on major-element geochemistry. The limitations of major-element tectonic discrimination are acknowledged and interpretations are therefore considered preliminary.

Geological Setting

The Benue Trough is a NE-SW trending intracratonic rift basin that formed in the Early Cretaceous due to extensional forces accompanying the separation of the African and South American plates. It is subdivided into the Southern, Central, and Northern Benue Trough (Nwajide, 2013). The study area is located within the Gongola Sub-Basin of the Northern Benue Trough (Fig. 1a).

The basin is filled with up to 6000 m of Cretaceous to Cenozoic sediments, ranging from Albian to Maastrichtian in age. The stratigraphy begins with the continental Bima Sandstone, which is overlain by the marine shales and limestones of the Yolde, Pindiga, and Gongila Formations. The Cenozoic magmatic activity, represented by the volcanic plugs in this study, is related to the development of the Cameroon Volcanic Line (Benkhelil, 1989). The Pindiga Formation, the host rock for the intrusions (Fig. 1b), consists of dark-grey to black shales, siltstones, and thin limestone bands, deposited in a marine environment (Zaborski et al., 1997; Abubakar, 2014).

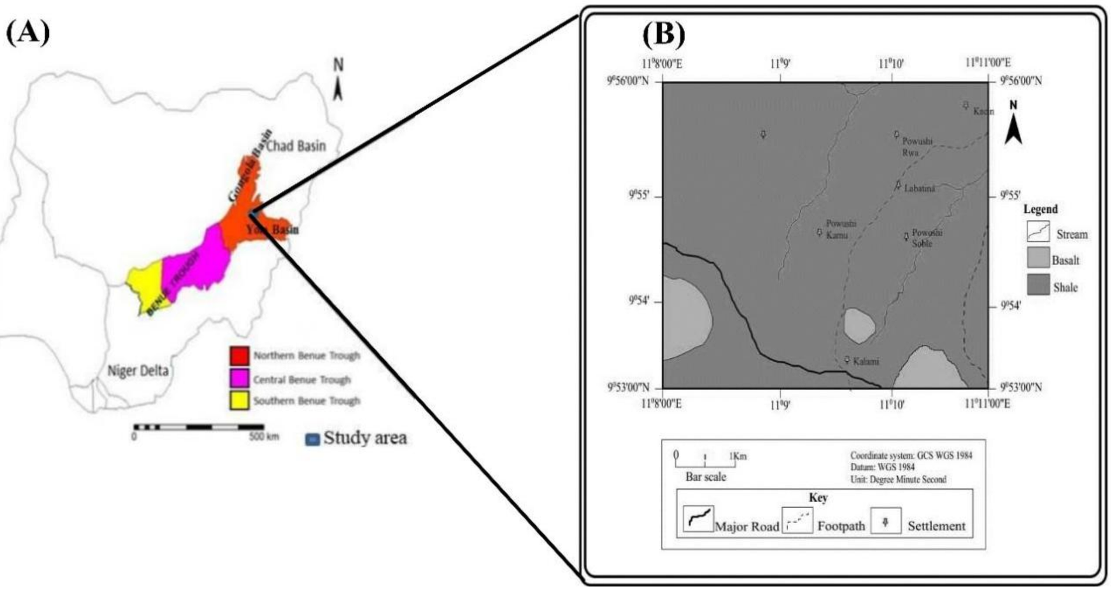

Figure 1: (A) Map of Nigeria Showing the Location of Gongola Sub-basin (after Nabage et al., 2024) (B) Geological Map of the Study Area (Modified from Auwalu et. al. 2023)

MATERIALS AND METHODS

Field Mapping and Sampling

Detailed field mapping was conducted using a compass traversing method. Traverse lines were established across the study area, and bearings were measured using a compass-clinometer while distances between locations were estimated using pacing and tape measurements. Structural data such as strike and dip of bedding planes, joints, and faults were recorded at each outcrop location. A total number of 8 representative samples of basaltic plugs (n=4), shales (n=3), and an indurated sandstone (n=1) were selected from the rock samples collected within the study area.

Geochemical Analysis

Rock samples were prepared for major element analysis following standard geochemical sample preparation procedures. Fresh and representative rock samples were first crushed and pulverized to a fine powder using an agate mortar and pestle to minimize contamination. The powdered material was then sieved to obtain a grain size fraction of approximately 100–200 mesh. Approximately 5 g of each powdered sample was accurately weighed and transferred into 32 mm diameter plastic sample cups. The base of each cup was lined with a 4 µm thick polypropylene X-ray film to support and contain the powdered material during analysis. The samples were subsequently compacted using a hydraulic press to obtain a stable and uniform sample surface, and the cups were sealed with plastic caps. Major element compositions were determined using wavelength-dispersive X-ray fluorescence (WD-XRF) spectrometry at the National Geosciences Research Laboratory, Kaduna, Nigeria. Analytical accuracy was monitored using certified reference materials, including USGS BHVO-2 reference standard and USGS AGV-2 reference standard. Analytical precision, evaluated through repeated measurements of standards and samples, was generally better than ±5% for major oxides.

Loss on ignition (LOI) was determined by heating approximately 1 g of powdered sample at 1000 °C for one hour to account for volatile components such as H_2O and CO_2. Analytical quality control was further assessed through duplicate analyses and procedural blanks. The results are presented in Table 1.

Data Processing

Geochemical classification and discrimination diagrams were generated. Pearson correlation coefficients were calculated using IBM SPSS (Version 20). Because of the small dataset and the compositional differences between igneous and sedimentary rocks, statistical analyses were conducted separately for basalts (n = 4) and shales (n = 3) to identify relationships between major oxides and infer controls.

Table 1: Major Oxide Geochemistry (wt.%) of Basalts, Shales, and Sandstone Samples

Oxide (wt%)	Shales			Basalts				Sandstone
Sample	AB2	AB11c	AB24	AB33	AB26	AB29	AB34	AB29b
SiO_2	60.43	70.04	64.96	59.05	45.36	43.33	44.26	70.22
Al_2O_3	22.10	18.78	19.00	18.60	20.66	17.56	19.06	16.76
Fe_2O_3	5.47	2.32	4.20	9.34	9.05	11.90	10.70	1.64
CaO	0.91	0.55	2.03	2.68	8.65	9.70	8.88	1.02
MgO	0.03	0.20	1.01	0.89	1.12	3.45	1.67	0.44
SO_3	0.11	0.08	0.12	0.28	0.09	0.14	0.12	0.11
K_2O	1.10	1.68	1.65	1.90	1.45	1.21	2.54	4.31
Na_2O	0.50	1.00	0.97	0.65	0.98	0.78	1.03	2.00
TiO_2	1.84	1.69	1.19	2.64	3.06	4.19	3.70	0.24
MnO	0.23	0.10	0.21	0.18	0.01	0.21	0.22	0.45
P_2O_5	ND	ND	0.08	0.20	1.04	1.02	0.61	0.05
LOI	6.01	2.12	2.89	1.10	2.33	3.42	4.11	1.20
Total	98.73	98.56	98.31	97.51	93.80	96.91	96.90	98.44
CaO/ Al_2O_3	0.04	0.03	0.11	0.14	0.42	0.55	0.47	0.06
Na_2O+K_2O	2.34	2.69	2.16	3.29	4.04	4.97	4.73	2.24
SiO_2/Al_2O_3	2.73	3.73	3.42	3.17	2.20	2.47	2.32	4.19
K_2O/Na_2O	0.16	0.24	0.24	0.27	0.21	0.17	0.36	0.62
CIA	94.97	95.67	85.39	83.22	67.87	56.79	63.90	89.77
ICV	0.41	0.31	0.51	0.89	1.16	1.17	1.14	0.35

Note: ND = Not Detected; CIA = Chemical Index of Alteration; ICV = Index of Compositional Variability

RESULTS AND DISCUSSION

Major Element Geochemistry of Basalts

Although the dataset is limited (n = 8), the results provide preliminary insights into the geochemical characteristics of the volcanic plugs and host sediments. The basaltic samples (AB26, AB29, AB33, AB34) show a restricted range in SiO_2 (43.33 – 45.36 wt. %) and are characterized by high Fe_2O_3 (9.05 – 11.90 wt.%), CaO (8.65 – 9.70 wt.%), and TiO_2 (3.06 – 4.19 wt.%) contents, consistent with a mafic composition. On the total alkali-silica (TAS) diagram (Le Bas et al., 1986), all samples plot within the sub-alkaline basalt field (Fig. 3). The AFM diagram (Irvine and Baragar, 1971) confirms their sub-alkaline nature and classifies them as tholeiitic, characterized by iron enrichment (Fig. 4).

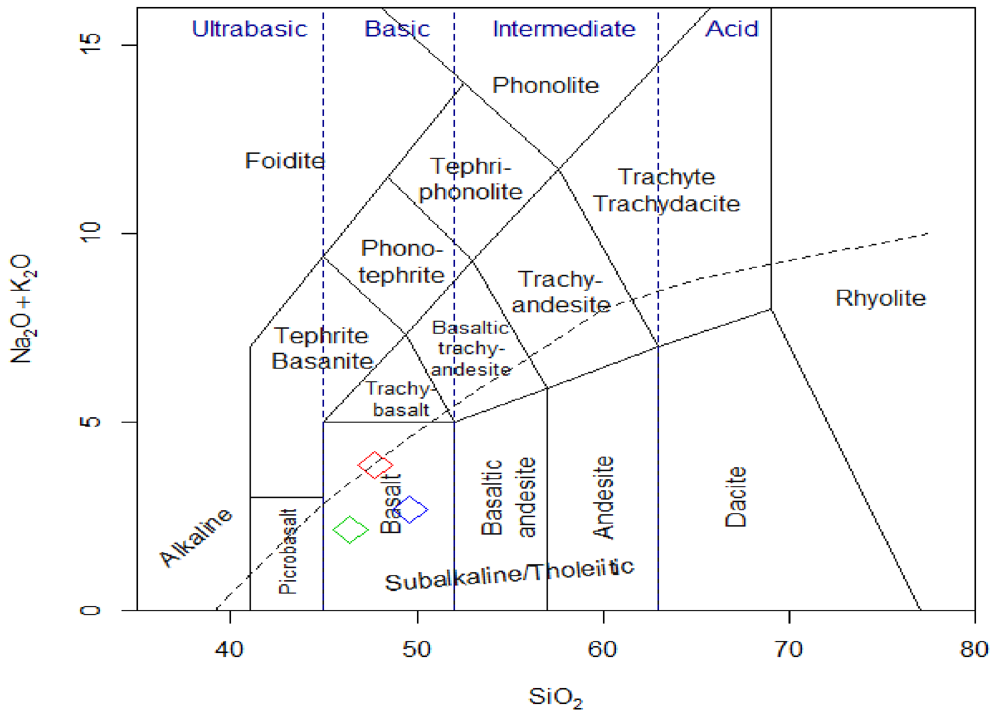

Figure 3: Plot of Na_2O+K_2O Versus SiO_2 Showing the Type of Basaltic Rock after (Le Bas et al. 1986)

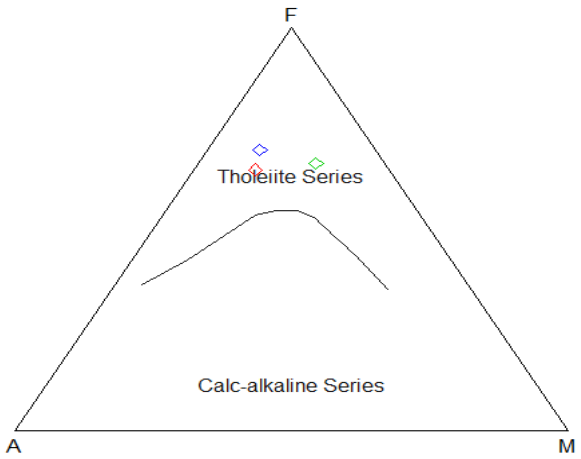

Figure 4: Plot of Oxide of Alkalis (A), Iron (F), and Magnesium (M) Showing the Series of Magma after (irvine and Baragar 1971)

Aluminum Saturation index on the A/CNK vs. A/NK diagram (Shand, 1943) shows that sample AB26 is peraluminous (A/CNK > 1), while samples AB29 and AB34 are metaluminous (A/CNK < 1) (Fig. 5). The peraluminosity in sample AB26 is atypical for basalts and may reflect assimilation of Al-rich shale from the Pindiga Formation during magma ascent and emplacement, although further isotopic or trace-element data would be required to confirm this interpretation.

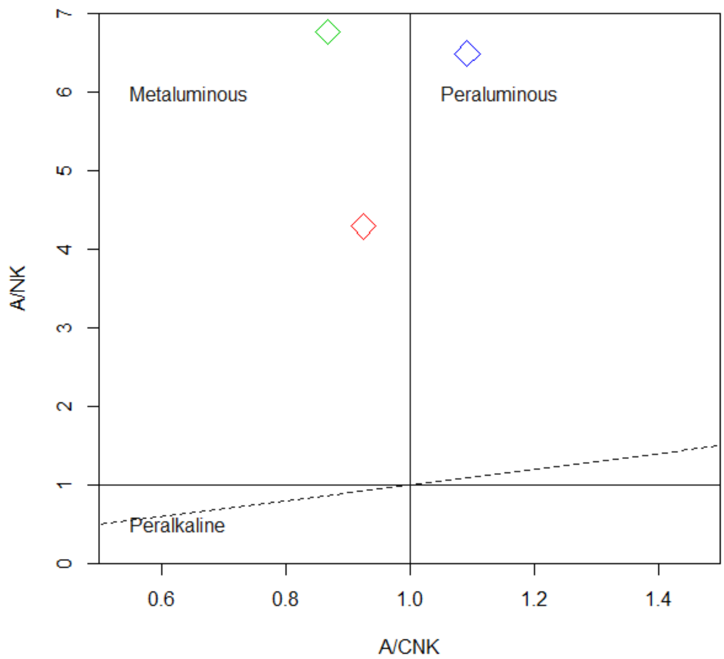

Figure 5: Plot of Al_2O_3 ($Na_2O + K_2O$) and Al_2O_3 ($CaO + Na_2O + K_2O$) Showing Alumina Saturation after (Shand, 1943)

Major Element Geochemistry of Sedimentary Rocks

The shale samples (AB2, AB11c, AB24) have high SiO_2 (60.43 – 70.04 wt. %) and Al_2O_3 (18.78 – 22.10 wt. %) contents. The sandstone (AB29b) is highly siliceous (70.22 wt. % SiO_2). The log(SiO_2/Al_2O_3) vs. log(Fe_2O_3/K_2O) diagram (Herron, 1988), the shale samples plotted primarily within the shale to Fe-shale field, indicating high iron content consistent with a mafic igneous provenance (Fig. 6). The sandstone falls in the lithic wacke field.

Weathering and Maturity of the sedimentary rocks in the study area, the shales exhibit high Chemical Index of Alteration (CIA) values (85.39 – 95.67) (Table 1), indicating intense chemical weathering in the source area under a humid paleoclimate (Nesbitt and Young, 1982). Their low Index of Compositional Variability (ICV) values (0.31 – 0.51) (Table 1) indicate compositionally mature sediments dominated by clay minerals (Cox et al., 1995). The black shale (AB24) shows a slightly lower CIA and higher ICV, suggesting a less weathered source component or proximity to volcanic input (Fig. 7). High CIA values may reflect intense chemical weathering in the source region, although sediment recycling and compositional inheritance from previously weathered source rocks may also contribute to elevated CIA values.

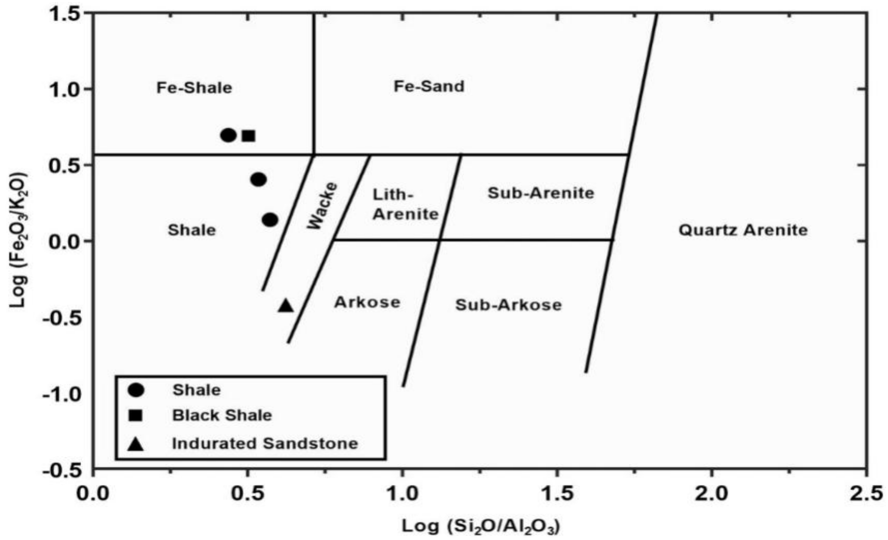

Figure 6: Geochemical Classification of Sedimentary Rocks in the Study Area (after Herron, 1988)

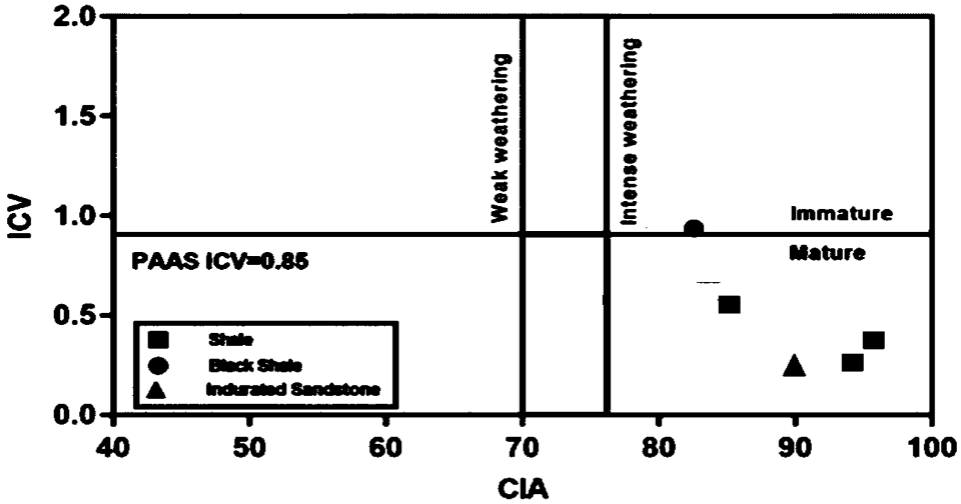

Figure 7: Maturity and Weathering of Sedimentary Rocks in the Study Area (after Long et al., 2012)

Tectonic Setting

The tectonic discrimination diagram (Roser and Korsch, 1986) plots all sedimentary samples within the Active Continental Margin field (Fig. 8).

The sub-alkaline tholeiitic character of the basalts is typical of magmatism associated with continental rift settings. This convergence of evidence from both igneous and sedimentary geochemistry strongly supports an active continental rift setting for the basin.

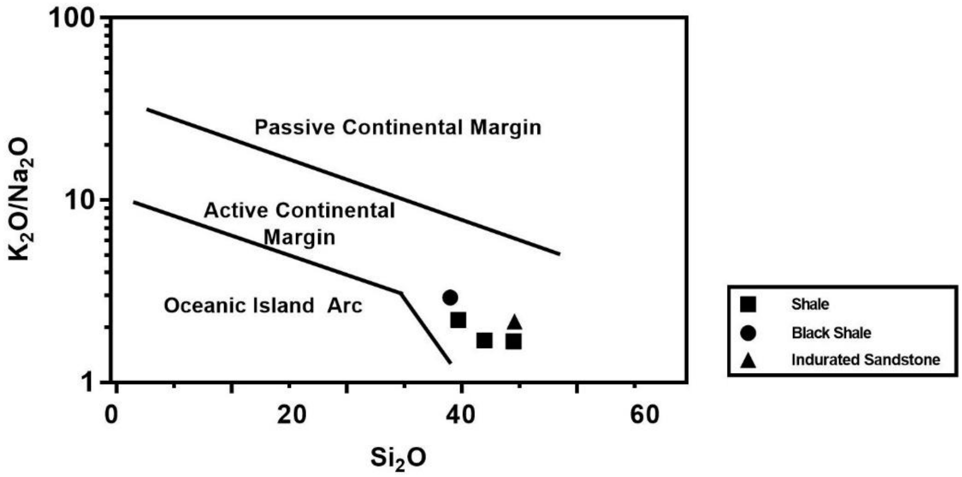

Figure 8: Tectonic Setting of Sedimentary Rocks in the Study Area (after Roser and Korsch, 1986)

Pearson Correlation Analysis

The correlation matrix (Table 2), SiO_2 shows strong negative correlations with Fe_2O_3 (r = -0.933), TiO_2 (r = -0.923), CaO (r = -0.961), and P_2O_5 (r = -0.912), confirming its dilution by mafic minerals and apatite. Al_2O_3 shows no strong positive correlation with K_2O, suggesting a significant portion is presented in detrital, non-clay minerals like feldspars, supporting a first-cycle igneous provenance. The strong positive correlation between Fe_2O_3 and TiO_2 (r = 0.948) may indicates their co-occurrence in ferromagnesian minerals.

Table 2: Two-tailed Pearson Correlation Matrix for Major Oxides

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	TiO_2	MnO	P_2O_5
SiO_2	1										
Al_2O_3	-.174	1									
Fe_2O_3	-.933**	.087	1								
CaO	-.961**	-.042	.861**	1							
MgO	-.748*	-.382	.763*	.819*	1						
SO_3	-.060	-.201	.395	-.037	.138	1					
K_2O	.369	-.621	-.412	-.224	-.224	-.032	1				
Na_2O	.374	-.636	-.513	-.165	-.160	-.321	.914**	1			
TiO_2	-.923**	.116	.948**	.872**	.761*	.201	-.512	-.551	1		
MnO	.395	-.520	-.364	-.344	-.076	.068	.752*	.616	-.501	1	
P_2O_5	-.912**	-.018	.799*	.959**	.782*	-.066	-.281	-.152	.813*	-.429	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The coexistence of Cenozoic volcanic plugs with Cretaceous marine sediments suggests that magmatism post-dated the main phase of sedimentation in the Gongola Sub-Basin. Intrusion of basaltic magma into relatively mature shale sequences indicates that magmatic activity occurred after significant chemical weathering had already affected the sediment source regions. This relationship highlights the complex interaction between post-sedimentary magmatism and earlier depositional processes within the Benue Trough system.

CONCLUSION

This study provides new geochemical insights into volcanic plugs intruding the Pindiga Formation in the Gongola Sub-Basin. The basalts display sub-alkaline tholeiitic characteristics, suggesting mantle-derived magmatism associated with regional tectonic activity. Host shales are classified as Fe-shales derived from mafic igneous sources and record intense chemical weathering under humid paleoclimatic conditions. Although interpretations are limited by the small sample set and the reliance on major-element geochemistry, the results suggest a tectonic environment consistent with an active continental margin during basin evolution. The study highlights the importance of integrating igneous and sedimentary geochemistry in reconstructing the geological evolution of the Northern Benue Trough.

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