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Paleoclimates and Provenance of Yolde Formation along Pantami Stream of the Gongola Sub Basin Northern Benue Trough, North East Nigeria.

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Abstract

The geochemical characterization of the Yolde Formation exposed along the Pantami stream section was undertaken to constrain provenance, paleoweathering intensity, depositional conditions, and tectonic setting. A total of eight (8) representative mudstone samples were systematically collected and subjected to whole-rock geochemical analysis. Major oxide ratios and selected trace element proxies were evaluated using established geochemical indices. The $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios range from 3.12 to 4.91, reflecting a relatively low compositional maturity and suggesting limited sedimentary recycling and textural immaturity of the detrital fraction. The $\text{Al}_2\text{O}_3/\text{TiO}_2$ ratios (5.25-8.69) indicate a dominant contribution from felsic to intermediate source rocks, consistent with derivation from continental crustal materials within the adjoining basement complexes. Paleoclimatic conditions inferred from Sr/Cu ratios (3.45-9.70) suggest deposition under predominantly arid climatic regimes, which likely influenced both sediment supply and diagenetic evolution. The Chemical Index of Weathering (CIW) values range from 84.80% to 93.36% (average = 89.01%), indicating intense chemical weathering within the source area, possibly under prolonged subaerial exposure and effective leaching of mobile cations. Redox-sensitive trace element ratios further constrain depositional conditions; Ni/Co values ranging from 0.24 to 1.44 (average = 0.57) are indicative of oxic depositional environments, suggesting well-oxygenated bottom waters during sediment accumulation. Tectonic discrimination based on SiO_2 versus $\text{K}_2\text{O}/\text{Na}_2\text{O}$ relationships places the Yolde Formation within a continental rift to passive margin transitional setting, consistent with the evolution of the Gongola Basin as part of the failed rift (aulacogen) system associated with the opening of the South Atlantic. Collectively, these geochemical signatures provide robust constraints on the provenance, paleoclimate, weathering intensity, and depositional framework of the Yolde Formation in the study area.

Keywords

Yolde Formation
Geochemistry
Provenance Analysis
Paleoweathering
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1. Introduction

The Benue Trough constitutes one of the seven recognized sedimentary basins in Nigeria and represents the most prominent structural and depositional feature influencing the Cretaceous geology of the country. With the exception of the Iullemeden Basin, most Nigerian sedimentary basins are genetically linked—directly or indirectly—to its tectonic evolution. The Benue Trough is an elongate intracontinental rift basin extending approximately 800 km in a NNE-SSW direction and averaging about 150 km in width (Obaje, 2009). It is widely interpreted as an aulacogen formed during the Cretaceous triple junction rifting, associated with the breakup of Gondwana. In this model, the trough represents a failed rift arm, while the two successful arms evolved into the South Atlantic Ocean and the Equatorial Atlantic fracture systems (Burke et al., 1971).

Geographically and structurally, the Benue Trough is subdivided into northern, central, and southern segments. Although these segments exhibit broadly correlatable tectonostratigraphic frameworks, variations in depositional timing render them partly diachronous. The Gongola Sub-basin, located within the Northern Benue Trough, comprises a well-defined stratigraphic succession including the continental Bima Formation, the transitional-marine Yolde Formation, the marine Pindiga Formation, the Campano-Maastrichtian deltaic Gombe Formation, and the overlying continental Keri-Keri Formation. The Yolde Formation, which constitutes the focus of this study, occupies the core of a gently folded anticlinorium and exhibits some

of the most laterally continuous and well-exposed sections within the basin. The most complete exposures occur northwest of Ruwan Kuka, where feldspathic sandstones are locally well indurated by siliceous cement, in contrast to their generally friable character elsewhere (Zaborski et al., 1997). Lithostratigraphically, the lower portion of the formation comprises interbedded sandstones and dark grey mudstones, commonly displaying desiccation cracks indicative of periodic subaerial exposure. The sandstones range from medium- to coarse-grained, frequently exhibiting trough cross-bedding and attaining thicknesses exceeding 5 m. Channel-fill sand bodies south of Kubtogana and west of Bangade attain thicknesses of up to 6 m and lateral extents exceeding 50 m. The upper part of the formation is characterized by regularly bedded sandstones intercalated with argillaceous units, bioturbation structures (e.g., *Planolites*), and calcareous sandstones. A distinctive horizon containing calcareous nodules (up to ~3 m in diameter) south of Titeba marks the transition to the overlying Pindiga Formation. Fossil assemblages, particularly bivalves, further support a marginal to shallow marine depositional setting (Reyment, 1965).

The study area is located along the Pantami stream within the Gongola Sub-basin of the Northern Benue Trough, geographically situated in Gombe State, northeastern Nigeria. It lies between latitudes 10°16'00"N and 10°17'30"N, and longitudes 11°08'00"E and 11°11'00"E. The area is readily accessible via major road networks within Gombe metropolis.

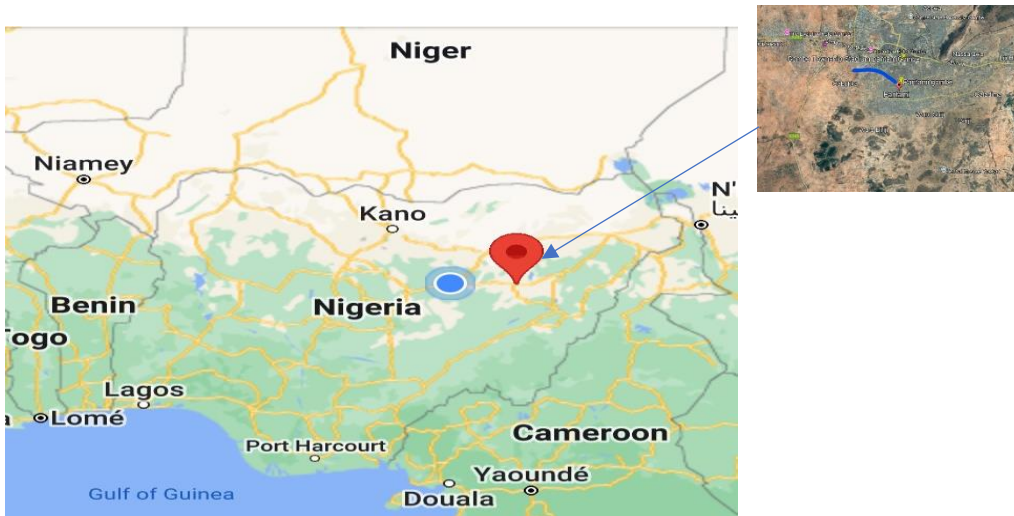


Figure 1: Google Image of the map of Nigeria showing the location of the study area

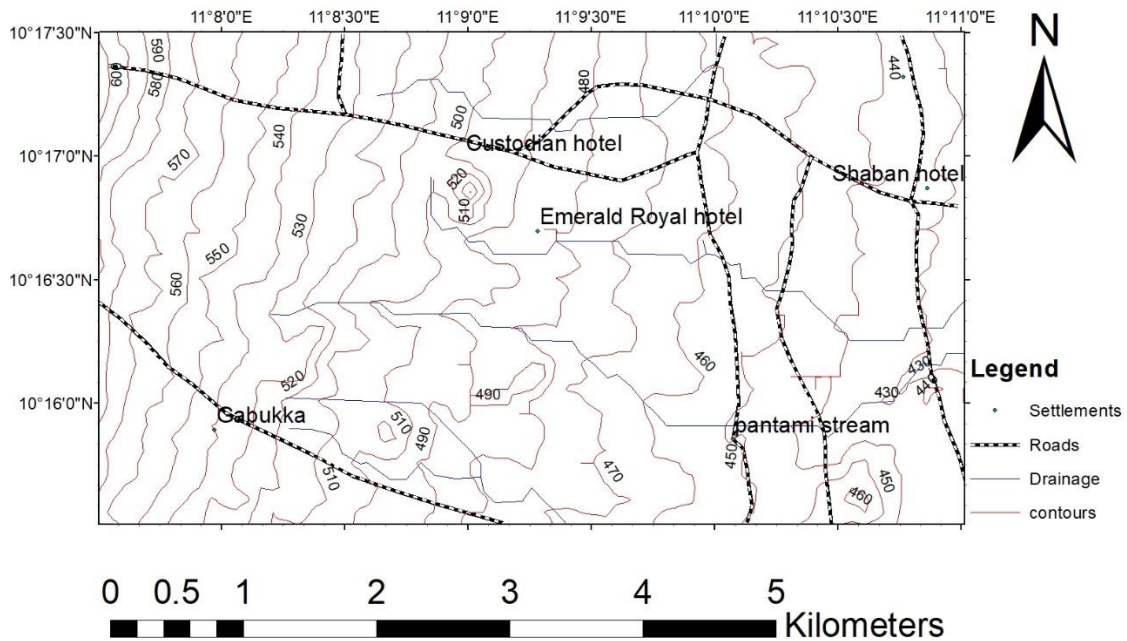


Figure 2: Topographic map showing the location of the study area and its environs.

The aim of this study is to reconstruct the paleoclimatic conditions and determine the provenance of sediments within the Yolde Formation in the Gongola Sub-basin of the Northern Benue Trough through detailed geochemical analysis. This involves the application of major and trace element geochemistry to elucidate source rock characteristics, weathering intensity, and depositional controls.

The specific objective of this research is to quantitatively characterize the geochemical composition of the Yolde Formation and utilize relevant geochemical proxies to evaluate the paleoenvironmental conditions prevailing during sediment deposition. This includes assessing paleoredox conditions, paleoweathering indices, and paleoclimatic indicators, with the goal of providing a comprehensive understanding of the sedimentary processes and tectono-sedimentary evolution of the study area.

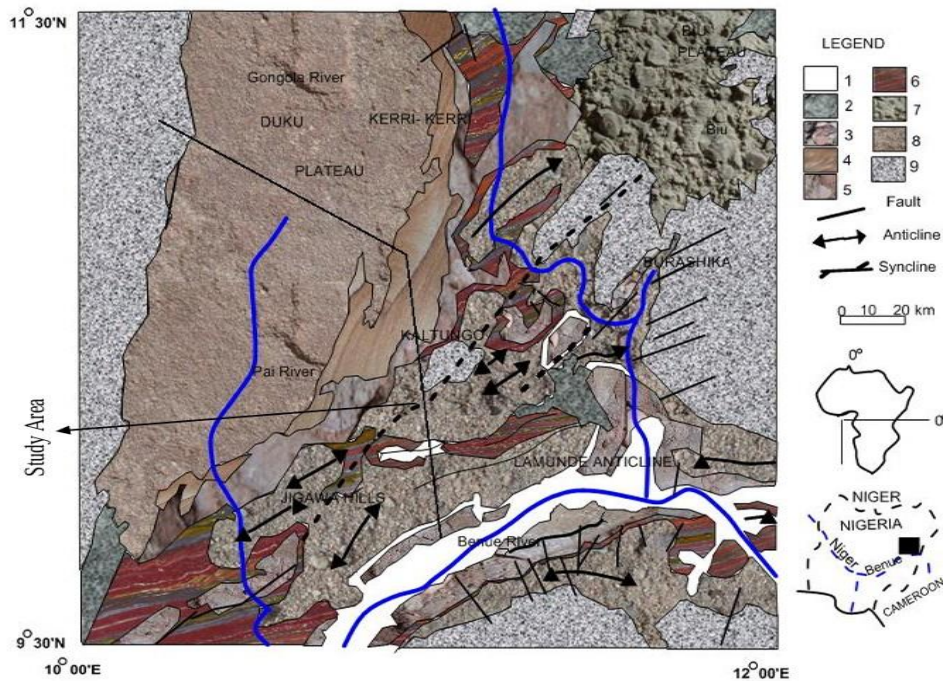


Figure 3: Geology of the Northern Benue Trough (Modified after Benkhilil 1989).

ZABORSKI et al. (1998)		CARTER et al. (1963)		POPOFF et al. (1986)	
GONGOLA BASIN		ZAMBUK RIDGE	CHAD BASIN	GONGOLA TROUGH (Pindiga-Gombe) (Gongila-Gombe) Zambuk Ridge	
	PLEISTOCENE		Chad Formation	Chad Formation	PLEISTOCENE PLEIOCENE
	Kerri Kerri Formation		Kerri Kerri Formation	Kerri Kerri Formation	MIOCENE PALEOCENE
	Gombe Sandstones		Gombe Sandstones	Gombe Sandstones	MAASTRICHTIAN
Pindiga Formation	Fika Member		Pindiga Formation including Gulati sandstone	Fika Shales	CAMPANIAN
					SANTONIAN
					CONIACIAN
	Duhbulwa/Gulani Doba Fulani Member			Gongila Formation	M TURONIAN
	Kanawa Member				L
	Yolde Formation		Yolde Formation	Yolde Formation	U CENOMANIAN
	"Upper Bima Formation"		Bima Sandstones		M
BIMA GROUP	"Middle Bima Formation"		unconformity	Bima Sandstones	U ALBIAN
					L APTIAN
	"Lower Bima Formation"			unconformity	U JURASSIC
				v v v Volcanics v v v	
++ Crystalline basement ++	PRECAMBRIAN	++ Crystalline basement ++		++ Crystalline basement ++	PRECAMBRIAN

Figure 4: Lithostratigraphic subdivision of the Gongola Basin as proposed by Zaborski et al. (1998), Popoff et al. (1986) and Carter et al. (1963).

The geology and stratigraphy of the three sub-basin segments have been well described and documented (e.g. Obaje et al., 2006, Zaborski et al., 1997). The Northern Benue Trough is made up of two major sub-basins; the North-South trending Gongola sub-basin and the Geochemical analyses of Eight (8) fresh samples of mudstones were collected. The analysis was carried out at the Geochemical Laboratory of the Geology Department of Gombe State University using the Rigaku NEX DE EDXRF spectrometer. The method adopted for the sample preparation for XRF analysis of the major elements is outlined below:

- a. Samples were first grounded into a homogenous powder approximately 100-200 mesh. About 5g of each sample was weighed into 32 mm sample cups with a polypropylene X-ray film of 4 μm thickness and were hydraulically pressed.
- b. Sample heights were measured in millimeters and sample cups were capped. The EDXRF analysis was performed using a Rigaku NEX DE EDXRF spectrometer equipped with a fifteen-place sample changer with spin function using slow and steady spinning mode.
- c. EDXRF measurements were carried out under helium (He) atmosphere using a palladium (Pd) X-ray tube at a voltage of 60 kV and current 10 μA with 10 mm beam spot size, and silicon (Si) drift detector comprised of Peltier electronic circuit cooling system.
- d. Standardless calibration was employed using Fundamental Parameters (FP) methods software (Rigaku RPF-SQX) to allow for elemental quantification of completely unknown. The software can automatically estimate elemental concentration and provide appropriate corrections. Rigaku NEX DE EDXRF spectrometric analysis can be

East-West trending Yola Sub-basin. The study area falls within the Gongola Sub-basin of the Northern Benue Trough. The Gongola arm is made up of formations such as the Bima, Yolde, Pindiga, Gombe and Keri-Keri Formations.

employed to measure a wide range of atomic elements, from sodium (11) through uranium (92), while providing elemental detection limits from low parts-per-million (ppm) to high weight percent (%wt). The analytical uncertainties were generally within 0.1-1% (RSD).

4. RESULTS AND DISCUSSION

The mineralogical and chemical compositions of sediments are mainly controlled by the properties of the sedimentary environment.

Major element oxide geochemistry

The concentration of the major element oxides obtained include SiO_2 , Al_2O_3 , Fe_2O_3 , Na_2O , CaO , MgO , K_2O , P_2O_5 , TiO_2 , and MnO , the oxides average percentages and ranges are as follows:

SiO_2 values range from 54.2% - 67.8% with an average of 61.6%, Al_2O_3 ranges from 13.6%-17.4% with an average of 14.96%, Fe_2O_3 range from 5.55% -19.1% with an average of 10.66%, TiO_2 range from 1.75% - 2.76% with an average percentage of 2.16%, Na_2O values range from 0.32-0.51 and has an average percentage of 0.38%, CaO has a range of 0.98% -3.12% with an average percentage of 1.69%, K_2O has a range of 1.65% - 8.07% with an average of 6.19% , P_2O_5 values range from 1.38% - 1.55% with an average of 1.45% , MnO range from 0.014% -0.085% with an average of 10.66%, MgO has a range of 0.15% - 0.38% with an average 0.24%. The wide range of SiO_2 content may be due to effect of hydraulic sorting and slow deposition.

Table 1: Major oxides concentration values (wt %) of mudstone samples from the Yolde Formation along Pantami stream section.

Oxides/Parameters	L1 (wt %)	L4 (wt %)	L10 (wt %)	L13 (wt %)	L16 (wt %)	L17 (wt %)	L18 (wt %)	L32 (wt %)	Average (wt %)	Range (wt %)
SiO ₂	54.20	59.30	62.20	62.30	67.80	66.10	61.00	60.20	61.64	54.20%-67.80%
Al ₂ O ₃	17.40	13.60	14.80	13.70	13.80	14.50	16.80	15.20	14.98	13.60%-17.40%
Fe ₂ O ₃	19.10	12.80	9.39	11.40	5.55	6.20	9.44	11.40	10.66	5.55% -19.10%
TiO ₂	2.10	1.81	1.97	2.28	2.19	2.76	2.40	1.75	2.16	1.75% - 2.76%
Na ₂ O	ND	0.51	0.32	0.34	ND	0.36	ND	ND	0.38	0.32%-0.51%
CaO	3.12	1.47	1.88	1.80	0.98	1.26	1.85	1.14	1.69	0.98% -3.12%
K ₂ O	1.65	8.07	6.78	5.52	7.26	6.44	5.95	7.82	6.19	1.65% - 8.07%
P ₂ O ₅	1.55	1.38	1.43	1.39	1.51	1.43	1.50	1.42	1.45	1.38% - 1.55%
MnO	0.02	0.01	0.09	0.05	0.03	0.05	0.02	0.06	0.04	0.01% -0.09%
MgO	0.30	0.22	0.24	0.38	0.15	0.22	0.23	0.20	0.24	0.15% - 0.38%

Geochemical classification of sediments was adopted from the geochemical classification diagrams of several authors (Pettijohn et al., 1972; Blatt et al., 1972; Herron, 1988; Lindsey, 1999), which shows the sampled sandstones are mainly Arkose.

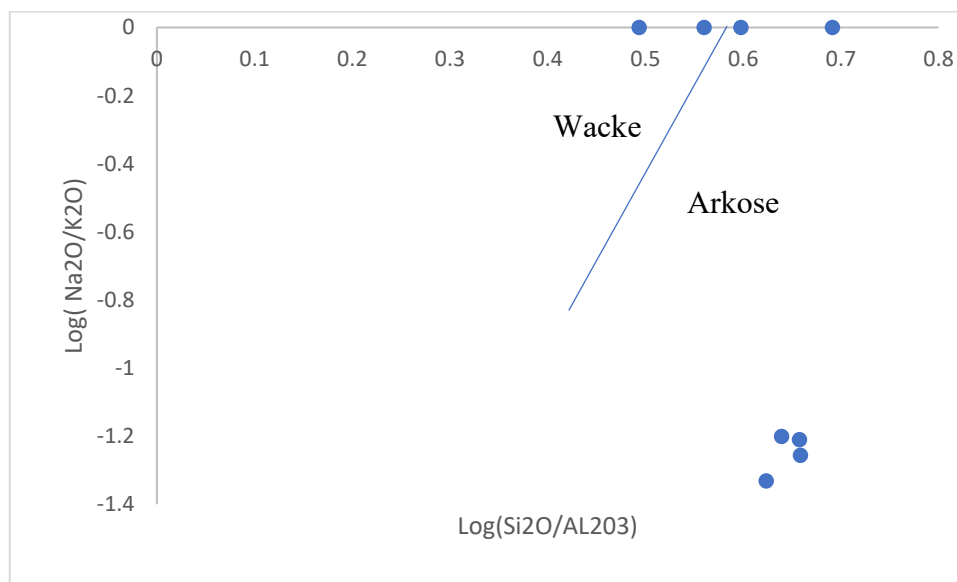


Figure 5: Chemical classification of samples based on Pettijohn schemes (1972).

Trace Element Geochemistry

The concentrations of the trace elements and their average values of mudstone sample from the Study area are presented in the table below.

Table 2: Minor and Trace Elements concentration values from Yolde the Formation along Pantami stream section.

Trace/Parameters	L1 (ppm)	L4 (ppm)	L10 (ppm)	L13 (ppm)	L16 (ppm)	L17 (ppm)	L18 (ppm)	L32 (ppm)	Average(ppm)	Range (ppm)
S	852	861	800	898	713	683	708	1160	834.375	683-1160
V	261	241	232	215	170	235	186	274	226.75	170-274
Cr	101	ND	75.2	73.2	62.8	155	112	65.1	92.04	62.80-155
Ni	71.5	38.40	58.20	61	52.90	67.60	91.90	59.20	62.59	38.40-91.90
Cu	108	62.9	75.3	93	61.6	69.9	121	72.5	83.03	61.60-121
Zn	273	126	103	245	71.2	140	204	93.6	156.98	71.20-273
Ga	102	58.1	71.3	48.3	33	53.8	83.9	63.7	64.26	33-102
As	ND	ND	ND	ND	ND	ND	27.6	ND	27.6	27.60
Kr	ND	ND	ND	ND	3.2	ND	ND	ND	3.2	3.20
Rb	187	429	355	386	332	344	384	432	356.13	187-432
Sr	638	610	527	424	429	424	418	491	495.13	418-638
Zr	871	1670	2210	1890	2100	1940	1640	1640	1745.13	871-2210
Y	61	107	112	122	71.4	178	124	98.3	109.21	61-124
Nb	104	75.2	61.6	63.2	30.7	57.3	92.4	73.5	69.74	30.70-104
Ag	ND	16.1	13.7	13.7	14	11.5	ND	14.1	13.85	11.50-16.10
Cd	ND	ND	ND	ND	ND	ND	ND	ND	0	ND
Sn	8.02	ND	ND	ND	ND	ND	ND	6.03	7.03	6.03-8.02
Ba	1090	2790	2670	2470	2210	2110	2080	2660	2260	1090-2790
Pb	84.10	77.20	96.40	65.60	58.90	59.50	27.70	85.20	69.33	27.70-96.40
La	169	175	184	144	ND	147	226	76.3	160.19	76.30-226
Ce	208	401	357	271	108	287	391	154	272.13	108-401
Pr	ND	ND	57.4	38.6	ND	27.8	79.3	ND	50.78	27.80-79.30

Nd	148	141	177	107	39.1	112	158	43	115.64	39.10-177
Dy	ND	ND	ND	ND	ND	ND	129	ND	129	129
Ac	29	24.3	ND	ND	ND	ND	59.3	31.7	36.08	24.30-59.30
Cl	349	401	355	580	708	486	344	677	487.5	344-708
Cr/V	0.39	0	0.32	0.34	0.37	0.66	0.60	0.24	0.37	0-0.66
Y/Ni	0.85	2.79	1.92	2	1.35	2.63	1.35	1.66	1.82	1.35-2.79
Sr /Cu	5.91	9.70	6.70	4.56	6.96	6.07	3.45	6.77	6.30	3.45-9.70

The figure above shows the high concentration of S, Sr, Zr, Cl and Ba with little or no Cd, Sn, Ag, Kr, As.

NB: ND means Not Detected

Paleo-environment condition.

Table 3: Ratios of Some parameters calculated from the major oxides concentration values from the Yolde Formation along Pantami stream section.

Oxides/parameters	L1 (wt %)	L4 (wt %)	L10 (wt %)	L13 (wt %)	L16 (wt %)	L17 (wt %)	L18 (wt %)	L32 (wt %)	Average (wt %)	Range (wt %)
K_2O / Al_2O_3	0.10	0.59	0.46	0.40	0.53	0.44	0.35	0.51	0.42	0.35 - 0.59
K_2O / Na_2O	0	15.89	21.46	16.24	0	18.04	0	0	8.95	0-21.46
SiO_2 / Al_2O_3	3.12	4.36	4.20	4.55	4.91	4.56	3.63	3.96	4.16	3.12-4.91
Al_2O_3 / TiO_2	8.29	7.51	7.51	6.01	6.30	5.25	7	8.69	7.07	5.25-8.69
CIA	577	1104.80	997.60	866	924.1	905.70	880	996	906.40	577-1104.80
CIW	84.80	87.30	87.08	86.50	93.36	89.97	90.08	93.02	89.01	84.80-93.36
ICV	24.3	23.2	18.7	19.1	14.1	14.7	17.6	20.7	19.1	14.1-24.3
Log (Na ₂ O/K ₂ O)	0	-1.20	-1.33	-1.21	0	-1.26	0	0	-0.62	-1.33-0
Log (Si ₂ O/AL ₂ O ₃)	0.49	0.64	0.62	0.66	0.69	0.66	0.56	0.60	0.62	0.49-0.69

Paleoclimate during sedimentation

Based on the methodology established by **Suttner and Dutta (1986)**, the bivariate plot is a geochemical tool used to determine the **paleoclimate** (humid vs. arid) and **chemical maturity** of sedimentary rocks particularly sandstones. Humid sediments plot in regions with lower $SiO_2/(Al+K+Na)$ ratios (due to intense weathering removing alumina). Arid/Semi-arid sediments plot in regions with higher $SiO_2/(Al+K+Na)$ ratios (less intense weathering). The plot shows the sample fall under arid climatic zone.

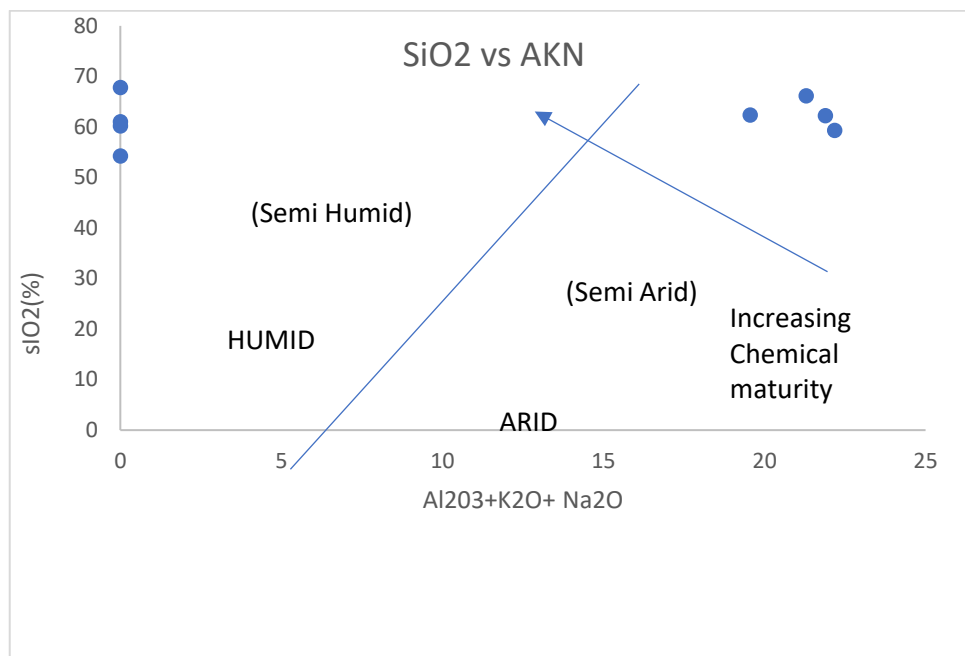


Figure 6: Chemical maturity and paleoclimate of the samples expressed by bivariate plot of SiO_2 versus $\text{Al}_2\text{O}_3 + \text{K}_2\text{O} + \text{Na}_2\text{O}$ (After Suttner & Dutta, 1986).

The Sr/Cu ratios have been employed by many researchers to interpret the paleoclimatic conditions under which terrigenous sediments were deposited (e.g., Akkoca et al., 2019; Gabriel et al., 2019; Li et al., 2020; Liu & Zhou, 2007; Moradi et al., 2016). Liu and Zhou (2007) indicate that low values of Sr/Cu ratios ranging from 1.3 to 5.0 are related to humid climatic conditions, whereas high values ranging from 5.0 to 10 indicate arid climatic conditions and greater than 10 indicate a hot and arid climate.

The values of Sr/Cu of Yolde Mudstone of the study area range from 3.45 to 9.70 with an average of 6.30, which shows deposition under arid climatic conditions.

Maturity

Potter (1978) stated that maturity of sandstones can be reflected by the $\text{SiO}_2/\text{Al}_2\text{O}_3$ index. High ratios indicate mineralogically mature (quartzose, rounded) samples, while low ratios represent chemically immature samples. Maturity is reflected best

in quartz, As the percentage of quartz increases the mineralogical maturity also increases. $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios of clastic rocks are sensitive to sediment recycling and weathering process and can be used as an indicator of sediment maturity. With increasing sediment maturity, quartz survives preferentially to feldspars, mafic minerals and lithics (Roser and Korsch, 1986; Roser et al., 1996).

Average $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios in unaltered igneous rocks range from ~ 3.0 (basic rocks) to ~ 5.0 (acidic rocks). Values of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio > 5.0 in sandstones are an indication of progressive maturity (Roser et al., 1996). Low values of $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios and low values of $\text{K}_2\text{O}/\text{Na}_2\text{O}$ together indicate mineralogically immature sediment.

The Yolde sediments have $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratios of between 3.12- 4.91 (average = 4.16), these values are an indication of an intermediate rock and low $\text{K}_2\text{O}/\text{Na}_2\text{O}$ indicate

mineralogically immature with little clay. $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (alkali content) is a measure of the feldspar content and also applicable for index of chemical maturity. For Yolde samples, the alkali content is between 0-21.46; this value shows a little number of feldspars and thus indicating low degree of maturation (Pettijohn et al., 1972; Roser and Korsch, 1986; Fedo et al., 1995; Paikaray et al., 2008). An approach towards assessing detrital mineralogy is to use the Index of Compositional Variability (Cox et al., 1995). The Index of Compositional Variability (ICV) is defined as:

$$\text{ICV} = (\text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{CaO} + \text{MgO} + \text{TiO}_2) / \text{Al}_2\text{O}_3$$

More matured sandstone with mostly clay minerals displays lower ICV values that are less than 1.0 and such sandstones are derived from cratonic environment (Cox et al., 1995). The results of the Index of Compositional Variability range between 14.10-24.29 for

Yolde formation suggesting that sediments are compositionally immature and sourced from non-cratonic setting.

Provenance

Major and minor oxides are used in provenance studies (e.g. Taylor and McLennan, 1985; Condie et al., 1992; Cullers, 1995; Armstrong-Altrin et al., 2004). According to McLennan et al., (1993), major elements provide information on both the rock composition of the provenance and the effects of sedimentary processes, such as weathering and sorting. These elucidates on the attributes of the source rocks and providing definite patterns of sedimentary history (Dickinson, 1985, 1988). The bivariate plot of Na_2O - K_2O shows that the samples are quartz-intermediate and quartz-rich, which suggests that they may be of felsic origin.

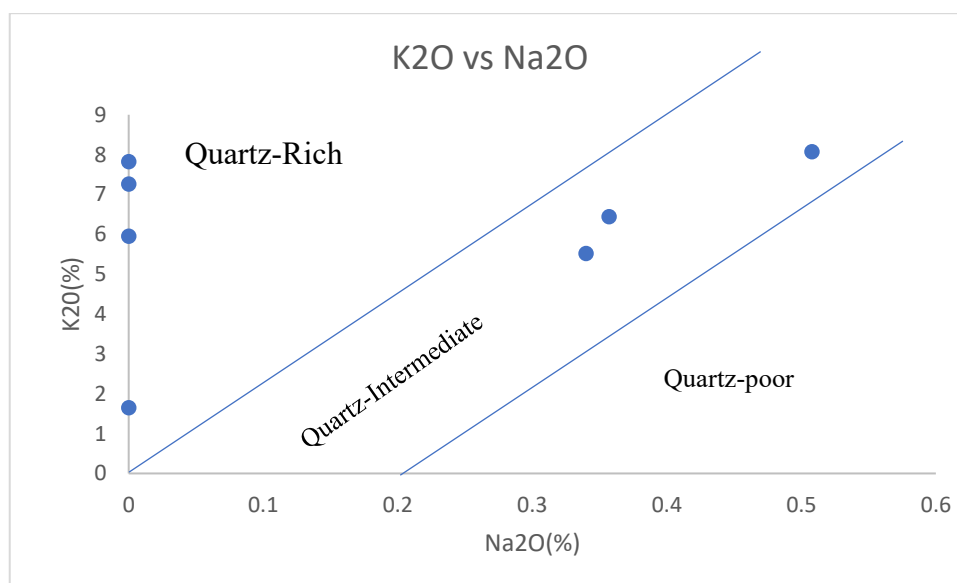


Figure 7: Bivariate plot of Na_2O versus K_2O of the studied sediments showing quartz content after Crook (1974).

The concentration of zircon is used to characterize the nature and composition of source rock (Hayashi et al., 1997; Paikaray et al., 2008). Hayashi, et al. (1997) stated that the TiO_2/Zr ratios are so much supportive to distinguish among three different source rock types, i.e., felsic, intermediate and mafic. The TiO_2 versus Zr plot (Fig 15) shows the Yolde sediments plotting in intermediate field.

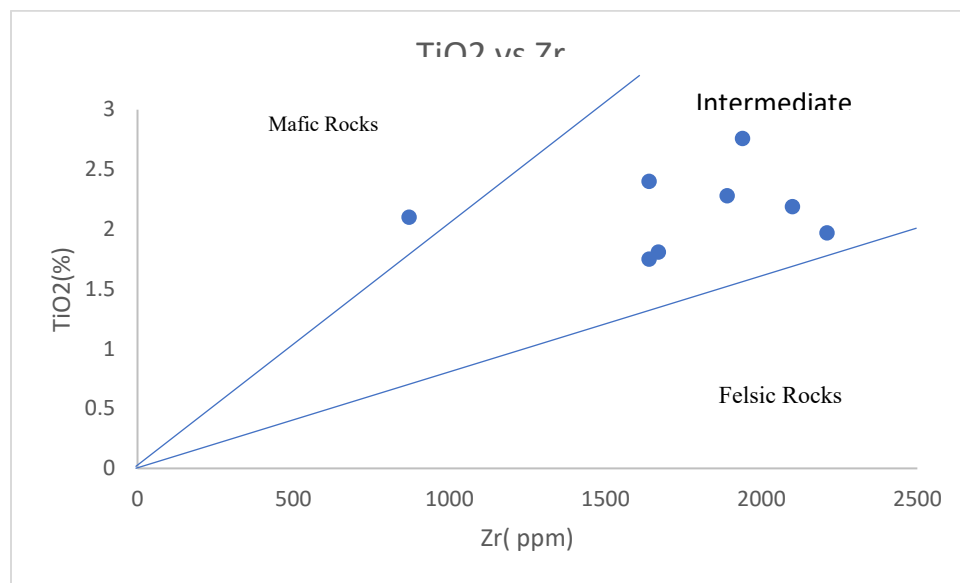


Figure 8: TiO₂-Zr plot for the sediments (Hayashi et al 1997).

The Al₂O₃/ TiO₂ ratio is broadly used to characterize the nature of provenance materials (Akkoca et al., 2019; Gabriel et al., 2019; Hayashi et al., 1997; Tawfik et al., 2017). Felsic igneous rocks display a ratio of 3-8; whereas, ratios of 8-21 and 21-70 are recorded for intermediate and Mafic igneous rocks, respectively (Gabriel et al., 2019). The Al₂O₃/ TiO₂ ratio of the study area varies from 5.25-8.69, indicating derivation from Felsic to intermediate igneous rocks

Redox conditions

U, Th, V, Cr, Ni, Co, Cu, and Zn elements are redox-sensitive and provide reconstructions of oxygen conditions in sedimentary environments (Martinez-Ruiz et al., 2015). Geochemical parameters such as authigenic U, Th/U, Ni/ Co, V/Cr, and Cu/Zn are very helpful for determining paleoredox conditions during sediment deposition (Wignall and Myers, 1988; Tribouillard et al., 2006; Yang et al., 2011; Rimmer, 2004; Mir, 2015).

The Ni/Co ratio is also used as a redox indicator (Dypvik, 1984). It is proposed that

Ni/Co ratios of <5 indicate oxic environments, while a ratio of >5 proposes suboxic and anoxic environments (Jones and Manning, 1994). The Ni/ Co ratio of the Yolde formation is below 5 indicating an oxic environment.

Paleo-weathering

Weathering indices are useful to measure the degree of weathering of the terrestrial rocks from which sediment grains are derived. Chemical weathering indices are commonly used in recent and old weathering profile studies (Kirschbaum et al., 2005; Goldberg and Humayun, 2010). Previous work on clastic sedimentary rocks shows that their chemical composition is mainly dependent on the composition and the weathering conditions at the source rock area (Nesbitt and Young, 1989; Nesbitt et al., 1996). Nesbitt and Young (1982) were of the opinion that evaluation of the degree of chemical weathering/alteration of the sediments' source rocks can be determined by calculating the Chemical Index of Alteration (CIA), where CIA = molar (Al₂O₃/[Al₂O₃+CaO* +Na₂O+K₂O]).

This index works correctly when Ca, Na, and K decrease as the intensity of weathering increases (Duzgoren-Aydin *et al.*, 2002). In the equation given above, CaO* is the amount of CaO incorporated in the silicate fraction of the studied sandstone samples (Fedo *et al.*, 1995). The asterisk in CaO* means the CaO value has been corrected for non-silicate like carbonates and phosphates. Correction for CaO from carbonate contribution was not done for the studied sandstone samples since there was no CO₂ data. Consequently, to compute for CaO* from the silicate fraction, the assumption proposed by Bock *et al.* (1998) was adopted.

In this regard, CaO values were accepted only if $\text{CaO} \leq \text{Na}_2\text{O}$; accordingly, when $\text{CaO} > \text{Na}_2\text{O}$, it was assumed that the concentration of CaO equals that of Na₂O (Bock *et al.*, 1998). This procedure provides measure of the ratio of the secondary aluminous mineral to feldspar, and forms a basis for the measure of intensity of weathering (Elzien *et al.*, 2014). The Chemical Index of Weathering (CIW) proposed by Harnois, (1988) is similar to the CIA except for the exclusion of K₂O in the equation: $\text{CIW} = \text{molar} (\text{Al}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O}))$. The CIA and CIW are interpreted in similar way with values of 50 for un-weathered upper continental crust Approximately 100 for

highly weathered materials, with complete removal of alkali and alkaline-earth elements (McLennan *et al.*, 1983; McLennan, 1993; Mongelli *et al.*, 1996). Low CIA values (i.e. 50 or less) also might reflect cool and / or arid conditions (Fedo *et al.*, 1995). For Yolde samples, the CIW ranged between 84.80% and 93.36% (Average = 89.01%), indicating high degree of weathering of the source materials.

Tectonic setting

The major and trace element compositions of clastic sedimentary rocks have been broadly used to identify tectonic settings of the source rocks in a catchment area (Bhatia and Crook, 1986; Roser and Korsch, 1986; Armstrong-Altrin, 2015). Tectonic setting interpretations were carried out using the SiO₂ vs. K₂O/Na₂O diagram of Roser and Korsch (1986). Roser & Korsch (1986) classify the tectonic settings into oceanic island arc, active continental margin, and passive margin, while Verma and Armstrong-Altrin (2013) recognized three main tectonic settings: island or continental arc, continental rift, and collision. On the Roser and Korsch (1986) diagram, In the SiO₂-K₂O/Na₂O diagram, the representative samples from Yolde formation plot within the PM (Passive Margin).

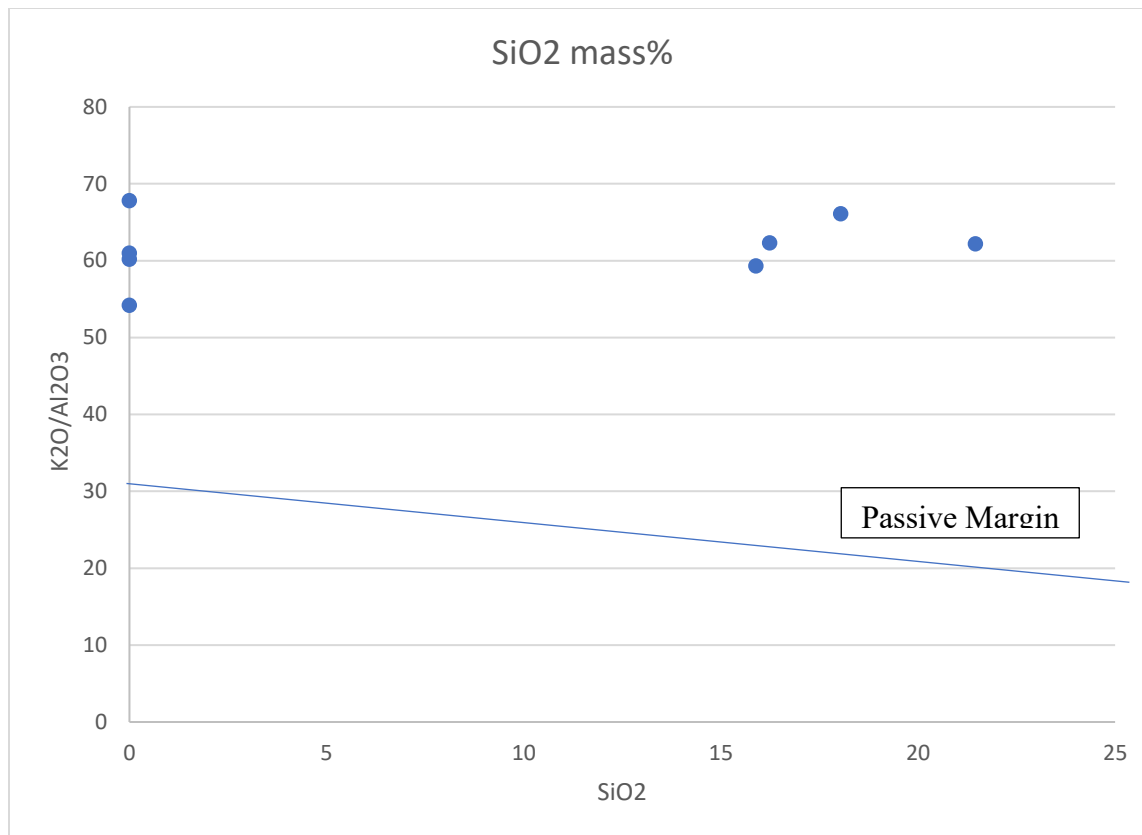


Figure 9: Bivariate plot of SiO_2 versus $\text{K}_2\text{O}/\text{Na}_2\text{O}$ indicating tectonic setting discrimination diagram Source; (Roser & Korsch, 1986)

5 CONCLUSIONS

Following a detailed geochemical investigation of mudstone units of the Yolde Formation exposed along the Pantami stream section, the following conclusions are established:

1. Major oxide geochemistry indicates that SiO_2 constitutes the dominant component, reflecting the silica-rich nature of the sediments, whereas MnO occurs in the lowest concentrations. The average $\text{K}_2\text{O}/\text{Al}_2\text{O}_3$ ratio of 0.424 suggests a paucity of K-feldspar within the mudstone matrix, consistent with limited feldspathic input or advanced weathering. Conversely, relatively higher $\text{K}_2\text{O}/\text{Na}_2\text{O}$ ratios indicate a greater contribution from plagioclase

relative to alkali feldspar, supporting a mixed but feldspar-lean detrital assemblage.

2. Integrated major and trace element geochemical signatures indicate that the mudstones were derived predominantly from intermediate to felsic source terrains. This compositional framework is consistent with sediments classified within arkosic to wacke compositional fields, reflecting moderate compositional maturity and a mixed provenance signature typical of continental crustal sources.

3. Provenance discrimination suggests that the source materials are largely of intermediate affinity, with significant input from felsic lithologies. The elevated silica content is primarily attributed to detrital quartz enrichment. Furthermore, geochemical indices indicate that the source area experienced intense chemical weathering, leading to the depletion of labile components and enrichment of resistant phases such as quartz.
4. Paleoclimatic and paleo-redox proxies indicate that deposition occurred under predominantly arid climatic conditions within an oxic depositional environment. This interpretation is supported by diagnostic elemental ratios (e.g., Sr/Cu and Ni/Co), which reflect limited organic preservation and well-oxygenated bottom-water conditions during sediment accumulation.
5. The mudstones are geochemically classified as texturally immature, despite evidence of advanced chemical weathering. This apparent paradox suggests rapid erosion and deposition from proximal sources, with insufficient time for sedimentary reworking and compositional stabilization.
6. Tectonic discrimination diagrams constrain the depositional setting to a continental rift to passive margin transitional regime, consistent with the evolutionary framework of the Gongola Basin within the broader Benue Trough. This tectonic setting reflects sedimentation within a failed

rift (aulacogen) associated with the opening of the South Atlantic.

Overall, the geochemical dataset provides a coherent interpretation of provenance, weathering intensity, depositional conditions, and tectonic evolution of the Yolde Formation within the study area.

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