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Geochemical Characterization and Provenance Studies of Gombe Formation, Gongola Sub-Basin, Northern Benue Trough, Nigeria

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Abstract

Major element geochemical analyses of the Gombe Formation in the Gongola Sub-basin, Northern Benue Trough, were conducted to determine the provenance, weathering intensity, compositional maturity, and tectonic setting of the sediments. The study was based on outcrop samples collected within Latitude 9°00′00″–10°30′00″N and Longitude 10°00′00″–11°30′00″E. A total of thirty-one (31) representative samples were collected and analyzed using X-ray Fluorescence (XRF) to determine the major oxide composition of the sediments. The XRF results identified SiO_2, Fe_2O_3, Al_2O_3, K_2O, TiO_2, MgO, P_2O_5, MnO, CaO, and NiO as the dominant major oxides. Binary geochemical discrimination diagrams based on the major oxide data were employed to classify the sandstones. The average Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA), and Chemical Index of Weathering (CIW) values of 79.76%, 64.81%, and 94.03%, respectively, indicate moderate to intense chemical weathering of the source rocks and/or weathering during sediment transport prior to deposition. The Index of Compositional Variability (ICV) values range from 0.32 to 33.47, with an average of 5.67, suggesting that the sediments are compositionally and chemically immature. Based on the $\log(Fe_2O_3/K_2O)$ versus $\log(SiO_2/Al_2O_3)$ discrimination plot, the sandstones were classified as wackes, arkose, lithic arenite, and sub-arkose, with minor iron-rich shale. Provenance discrimination diagrams indicate derivation predominantly from felsic and intermediate igneous provenances. Furthermore, the SiO_2 versus (Al_2O_3 + K_2O + Na_2O) plot suggests deposition under predominantly semi-arid to arid climatic conditions, reflecting the prevailing palaeoclimatic regime during sediment accumulation.

Keywords

X-ray fluorescence,
Felsic Igneous Provence,
Chemical Index of Alteration
Gombe Formation,
X-ray Fluorescence (XRF),
Major Element Geochemistry,
Provenance Analysis,
Tectonic Setting

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Introduction

Siliciclastic sediments are loose particles that originated from the weathering and erosion of pre-existing rocks which could be either igneous, metamorphic or sedimentary rocks. The geochemistry of clastic sediment has shown to reflect paleoenvironment of deposition, weathering condition, provenance, tectonic settings and climatic condition that existed during their deposition (Madukwe et al., 2014; Boboye et al., 2018).

The geochemical characterization of sediments ascertains the chemical composition of clastic sediments which are usually affected by hydraulic sizing, diagenesis, transportation and weathering activities (Taylor and McLennan, 1985; Wronkiewicz and Condie, 1987; Wronkiewicz and Condie, 1989). According to Bhatia and Crook, 1986; Das and Haake, 2003; Madukwe et al., 2014; the composition of sediments depends on the chemical composition of the source rock area and the tectonic setting of the depositional basins. Hence, composition of sediments has been used as subtle pointer for provenance, weathering conditions and the source of sediments (Roser and Korsch, 1986, 1988; Huntsman-Mapilaa et al., 2005; Madukwe et al., 2014).

This paper focused on geochemical characterization and provenance studies of Gombe Formation, using major oxides as proxies in determining their provenance and tectonic setting. Detail study on the geochemistry of the Gombe Formation is lacking in the literature. Notable research on geochemistry of Gombe Formation is that of Mohammed et al. (2018), but the research was limited to only mudstone within the Formation while the formation is said to consist of sandstone, siltstone, clay, mudstone and shale Zaborski et al. (1998).

The study area is in Gombe and its environs which falls within the Gombe Formation in the Gongola Sub-basin of Northern Benue Trough, Nigeria and is located within Latitude N9^0 00′ 00″ – N10^0 12′ 00″ and Longitude E10^0 00′ 00″ – E11^0 12′ 00″ which covers a total area of about 17742.24 Km^2(fig.1).

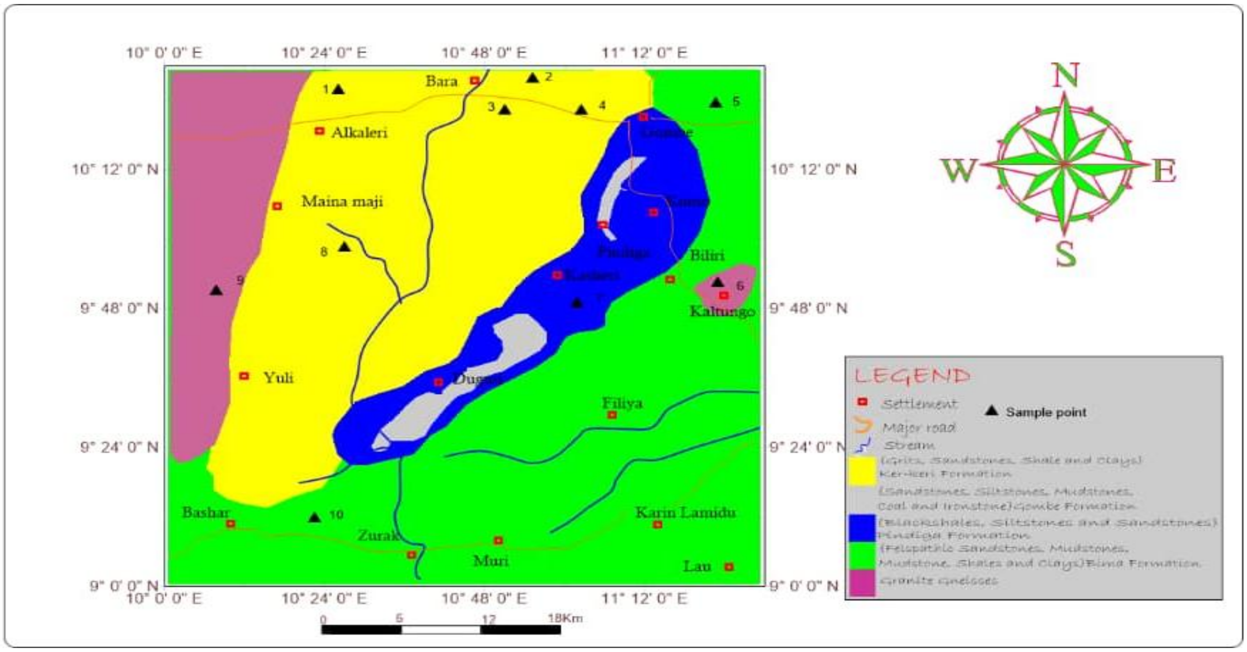

Figure 1: Location map of the study area

Geological Setting

The Benue Trough is trending NE- SW and has an aerial extend of about 1000 km in length and 150 km width. It was formed during the early Cretaceous rifting and strike slip movement of Central West African Basement (Benkhelil, 1989). Benue Trough is bounded by Niger-Delta Basin and by Chad Basin at its southern and Northern boundary respectively (Fig. 2) (Zaborski 1998). The trough is a sedimentary basin containing up to 6000 m of Cretaceous-Tertiary sediments associated with volcanic. The Benue Trough of Nigeria is part of the West and Central African Rift System (WCARS); formed during separation of the African and South American plates during the Early Cretaceous (Fitton, 1983; Genik, 1992). The Benue Trough is divided into Lower, Middle, and Upper (Fig.1) by Zaborski (1998) while Nwajide (2013) subdivided it into Southern, Central and Northern (this subdivision was used in this study). The Northern Benue Trough is made up of two major Sub-basins: the N-S trending Gongola Sub-basin and E-W trending Yola Sub-basin (Nwajide, 2013). The Geology and stratigraphy of Northern Benue Trough was described in detail by Carter el al. (1963), Offodile (1976), Benkhelil (1989), Zaborski et al. (1997), Abubakar (2006) and Tukur et al. (2015).

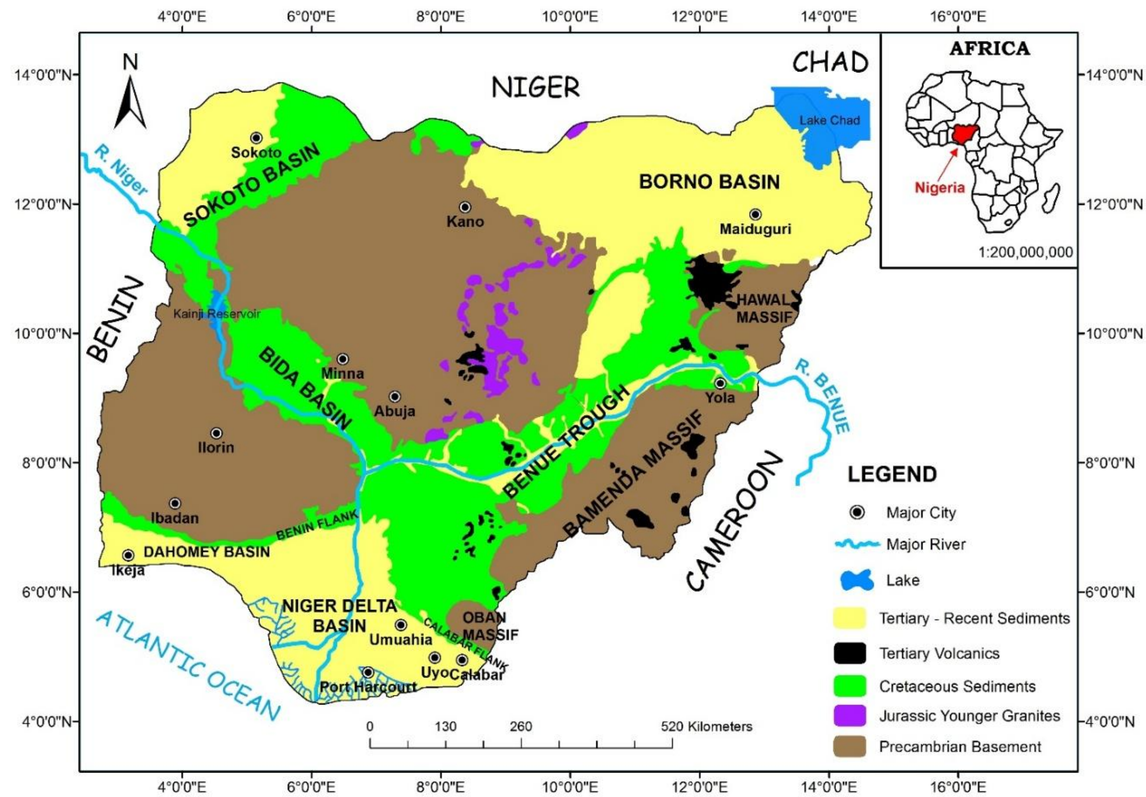

Figure 2: Map of Nigeria showing the major geological components; Basement, Younger Granites, and Sedimentary Basins (After Bata et al., 2017).

Stratigraphy

The stratigraphy of Upper Benue Trough (Gongola Sub-basin) have been discussed in some details by (Carter et al.,1963; Benkhelil, 1989; Popoff et al., 1986; Guiraud, 1993; Gebhardt, 1977; and Zaborski et al., 1998; Zaborski, 1998 and Nwajide 2013). The oldest sedimentary rock in the Northern Benue Trough is the Bima Group which overlies unconformable on the crystalline Basement rocks. The Bima Group is deposited under continental environment, Benkhelil (1989) and Zaborski, (1998) and it is Aptian – Albian in age. Guiraud (1990a; and 1990b) divided Bima into three as: Upper Bima Sandstone, Middle Bima Sandstone and Lower Bima Sandstone. The Cenomanian transitional-marine Yolde Formation overlies the Bima Group. According to Carter et al. (1963), the Yolde Formation was succeeded by the Cenomanian-Santonian marine Pindiga Formation. Carter et al. (1963) referred age- equivalent beds in Gongola Basin to the "Gongila Formation" which is made up of a lower limestone- shale member and an upper sandstone shale member, and to the "Fika Shales" for the overlying argillaceous beds. Zaborski et al. (1998) have characteristically described the Pindiga Formation to be best understood as consisting of five members: above, Fika Member, or "Fika Shales" of Carter et al. (1963), Dubuluwa Member, Deba Fulani Member, Gulani Member and Kanawa Member. The Campano-Maastrichtian Deltaic Gombe Formation overlies the Pindiga Formation and Tertiary Continental Keri-Keri Formation overlies the Gombe Formation (Fig. 3).

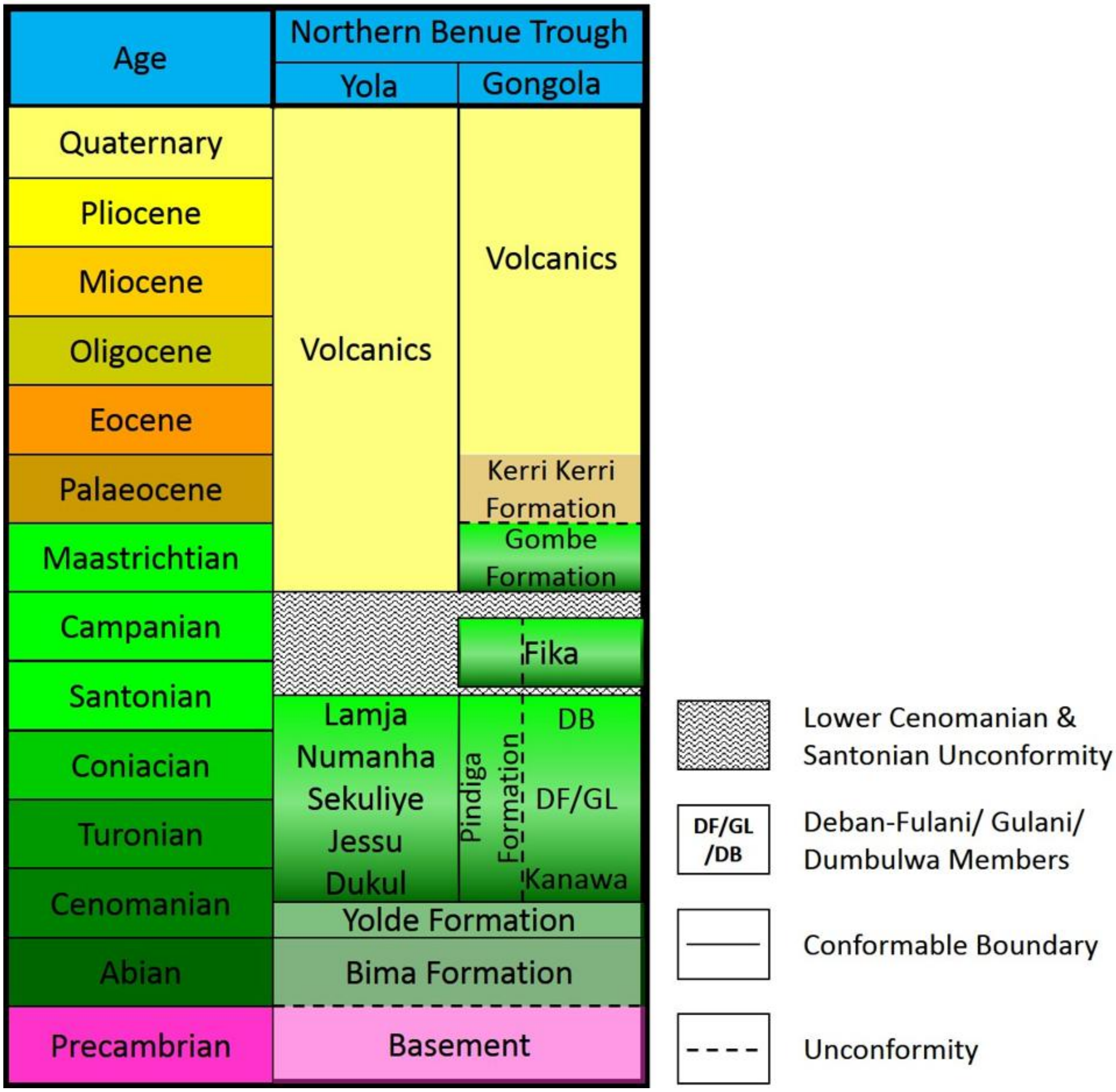

Figure 3: Stratigraphic successions in the Northern Benue Trough (after Bata et al., 2018)

Methodology

Thirty-one samples obtained during field work at Pantami and Wuro Briji stream channels were carefully analyzed using Energy Dispersive X-ray Fluorescence (EDXRF) for major oxides. Ten of the thirty-one samples were analyzed with EDXRF machine in Gombe State University Geochemical Laboratory and twenty-one (21) samples EDXRF Analysis were conducted at the National Steel Raw Materials Exploration Agency Laboratory (NSRMEAL), Kaduna, Nigeria. Samples were first grounded into a homogenous powder approximately 100-200 mesh, and then 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. 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. EDXRF measurements were carried out under helium (He) atmosphere using a palladium (Pd) X-ray tube at a voltage of 60 kV and current 10μA with 10 mm beam spot size, and silicon (Si) drift detector comprised of Peltier electronic circuit cooling system. 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.

RESULTS AND INTERPRETATION

The percentage abundance of major elements analyzed (Table 1) from the study area revealed different elemental composition of all the samples and it also indicates the heterogeneity of the sediment suite, provenance and paleoenvironment of deposition of the sediments. Variations in the chemical composition reflect changes in the mineralogical composition of the sediments.

The result showed that SiO_2 is the most abundant major oxides followed by Al_2O_3 and Fe_2O_3 with MgO being the least in occurrence due to its high mobility during weathering and transportation. SiO_2 abundance ranges from 15.06% to 85.1% with an average of 70.15%. This average value is higher than the value for upper Continental crust. Silica enrichment (table 1, 2 & 3) is a measure of sandstone maturity, and is a reflection of the time and intensity of weathering and destruction of other minerals especially the labile minerals during transportation (Lindsey, 1999). This high abundance of SiO_2 from the study areas also indicate the dominance of quartz grains in the clastic sediment with little influence from other detrital source which is also an indication of acidic plutonic igneous rock figure 4 and 5 (Boboye et al., 2018; Taylor and McLennan (1985). The variation of SiO_2 content is probably due to variation in grain size and diagenesis Madukwe and Obasi (2016).

Al_2O_3 ranged from 4.91 to 28.52 (average 15.6) and is due to weathering effect and Fe_2O_3 range from 0.01 to 16.24 (average 3.68). Table 1 also shows depletion of alkalis and alkaline earth metals which according to Cingolani et al. (2003) chemical alteration of rocks during weathering is the major cause of their depletion and preferential enrichment of Al_2O_3.

According to Herron (1988), terrigenous sediments can be classified by cross plotting the ratio of log (Fe_2O_3/K_2O) verse log (Si_2O_4/Al_2O_3). The thirty-one (31) samples analyzed from Gombe Formation revealed that three samples were shale, two samples were shale reach in Iron, fifteen samples were classified under wacke, sandstones that contain fifteen percent of mud or matrix. Seven samples failed within the Arkose, that is sandstone that contains ≥ 25 feldspar, two samples under litharenite and one sample as subarkose, this is sandstone that is neither arkose nor arenite and are made up of 5-25% feldspars. This classification further explains how the various beds within the formation varies in their composition and maturity; PettiJohn et al. (1972).

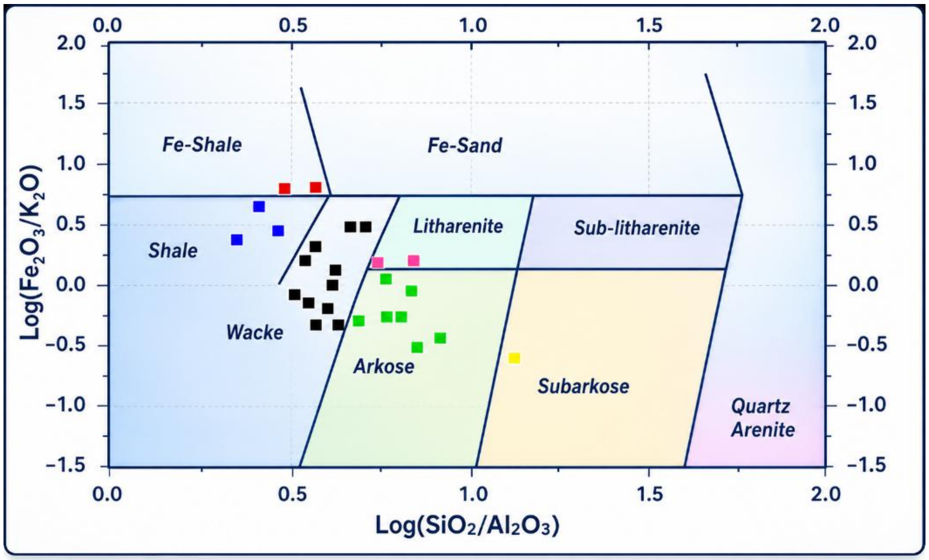

Figure 4: Chemica classification of sediments in the study area, Herron, 1988

Table1: XRF Results of Major oxides component (Wt %) of Gombe Formation

SAMPLE NO	LITHOLOGY	SiO2	Al2O3	Fe2O3	CaO	K2O	P2O3	MgO	TiO2	MnO	NiO
1	clay/gypsum	15.06	4.91	9.14	24.21	1.84	0.11	<0.001	0.57	<0.001	0.001
2	Sandstone	85.1	6.48	0.88	0.32	3.04	1.57	<0.001	2.17	0.02	0.001
3	Claystone	68.2	19.2	3.8	0.53	2.37	1.56	<0.001	3.6	0.06	0.004
4	Sandstone/Bio	67.05	18.57	2.45	1.54	3.12	0.07	<0.001	2.28	<0.001	0.1
5	Sandstone	75.13	15.58	1.88	0.5	3.25	<0.01	<0.001	1.93	<0.001	0.003
6	Sandstone	81.83	9.84	1.44	0.29	3.22	<0.01	<0.001	1.68	<0.001	0.001
7	Sandstone	78.1	12.2	1.75	0.51	2.88	1.65	<0.001	2.42	0.002	0.002
8	Sandstone	78	11.4	2.47	0.65	2.61	1.64	<0.001	2.63	0.02	0.003
9	Clay	63.9	21.6	6.1	0.757	2.23	1.57	0.07	3.18	0.07	0.007
10	Silty/Clay	74.15	15.65	3.76	0.73	1.32	<0.001	<0.001	2.05	<0.001	0.01
11	Sandstone	76.48	17.85	1.95	0.25	1.52	<0.001	<0.001	0.96	<0.001	0.01
12	Silty/Clay	77	13.6	3.07	0.5	2.33	1.91	<0.001	1.22	0.03	0.004
13	Sandstone	79.4	11	1.43	0.322	3.8	1.6	<0.001	1.98	0.02	0.002
14	Sandstone	73.12	19.39	1.71	0.3	3.22	<0.001	<0.001	1.29	<0.001	0.002
15	Sandstone	76.7	13.1	2.11	0.456	3.44	1.6	<0.001	2.03	0.02	0.004
16	Shale	65.61	19.81	1.43	0.3	1.63	<0.001	<0.001	1.47	<0.001	0.002
17	Shale	74.4	12.6	4.43	0.33	3.95	1.62	<0.001	2.05	0.04	0.004
18	Sandstone	80.2	11.3	2.13	0.79	1.4	1.85	<0.001	1.65	0.02	0.003
19	Silty/Clay	78.44	14.32	1.97	0.58	1.28	<0.001	<0.001	1.54	<0.001	0.003
20	Shale	68.11	20.43	3.07	0.46	3.76	<0.001	<0.001	2.59	<0.001	0.004
21	Sandstone	60.37	16.16	16.24	0.25	3.09	0.06	<0.001	1.99	<0.001	0.003
22	Shale	72.85	16.67	2.24	0.31	4.24	0.09	13.45	1.41	<0.001	0.003
23	Sandstone	66.88	12.87	2.82	0.28	1.01	0.18	0.99	1.27	<0.001	0.01
24	Sandstone	70.43	16.73	3.01	0.64	4.39	<0.001	<0.001	1.53	<0.01	0.002
25	Clay/sand	63.72	28.52	2.21	0.28	0.92	<0.001	<0.001	2.54	<0.01	0.003
26	Sandstone	71.95	19.27	1.53	0.36	0.75	<0.001	<0.001	1.05	<0.01	0.004
27	Shale	54.32	20.78	12.97	1.56	3	<0.001	<0.001	2.43	<0.01	0.004
28	Sandstone	70.89	16.72	3.55	0.58	3.51	0.02	<0.001	2.88	<0.01	0.004
29	Sandstone	73.97	15.72	0.01	0.26	5.42	<0.001	<0.001	1.1	<0.01	0.003
30	Sandstone	67.05	14.46	9.92	0.54	4.14	<0.001	<0.001	2.27	<0.01	0.002
31	Sandstone	66.26	16.84	2.54	1.26	3.79	<0.001	<0.001	1.21	<0.01	0.001
Average		70.15065	15.59903	3.677742	1.311129	2.789355	1.06875	4.5375	1.902258	0.032	0.003839

Table2: Ratios of Some Major Oxides and Values of CIA, PIA CIW and ICV calculated

N/S	Sample type	Al2O3/SiO2	SiO2/Al2O3	K2O/Al2O3	Al2O3/K2O	TiO2/Al2O3	Fe2O3/K2O	CIA	PIA	CIW	ICV	CIA/ICV
1	clay/gypsum	0.33	3.07	0.33	0.33	0.33	4.97	15.86	9.92	16.87	33.47	1
2	Sandstone	0.08	13.14	0.08	0.08	0.08	0.29	65.86	34.96	95.3	1.54	1.54
3	Claystone	0.29	3.56	0.29	0.29	0.29	1.61	86.88	76.16	97.32	4.52	4.52
4	Sandstone/Bio	0.28	3.62	0.28	0.28	0.28	0.79	79.94	66.51	92.35	4.12	4.12
5	Sandstone	0.21	4.83	0.21	0.21	0.21	0.58	80.61	63.79	96.9	2.51	2.51
6	Sandstone	0.13	8.32	0.13	0.13	0.13	0.45	73.71	49.59	97.14	1.91	1.91
7	Sandstone	0.16	6.41	0.16	0.16	0.16	0.61	78.26	59.79	95.99	2.46	2.46
8	Sandstone	0.15	6.85	0.15	0.15	0.15	0.95	77.77	59.96	94.61	3.36	3.36
9	Clay	0.34	2.96	0.34	0.34	0.34	2.74	87.86	78.79	96.62	7.08	7.08
10	Sand/Clay	0.22	4.74	0.22	0.22	0.22	2.85	88.42	80.97	95.55	4.63	4.63
11	Sandstone	0.24	4.29	0.24	0.24	0.24	1.29	90.98	83.24	98.62	2.26	2.26
12	Sand/Clay	0.18	5.67	0.18	0.18	0.18	1.32	82.78	68.6	96.46	3.66	3.66
13	Sandstone	0.14	7.22	0.14	0.14	0.14	0.38	72.75	47.62	97.16	1.94	1.94
14	Sandstone	0.27	3.78	0.27	0.27	0.27	0.54	84.64	70.59	98.48	2.08	2.08
15	Sandstone	0.18	5.86	0.18	0.18	0.18	0.62	77.08	56.84	96.64	2.73	2.73
16	Shale	0.31	3.32	0.31	0.31	0.31	0.88	91.13	83.63	98.51	0.44	0.44
17	Shale	0.17	5.91	0.17	0.17	0.17	1.13	74.65	51.25	97.45	4.93	4.93
18	Sandstone	0.15	7.1	0.15	0.15	0.15	1.53	83.77	73.39	93.47	3.07	3.07
19	Sand/Clay	0.19	5.48	0.19	0.19	0.19	1.54	88.51	80.6	96.11	2.66	2.66
20	Shale	0.3	3.34	0.3	0.3	0.3	0.82	82.89	67.63	97.8	3.66	3.66
21	Sandstone	0.27	3.74	0.27	0.27	0.27	5.26	82.88	67.03	98.48	16.62	16.62
22	Shale	0.23	4.38	0.23	0.23	0.23	0.53	78.56	58.58	98.18	2.64	2.64
23	Sandstone	0.2	5.2	0.2	0.2	0.2	2.8	90.89	83.76	97.88	16.65	16.65
24	Sandstone	0.24	4.21	0.24	0.24	0.24	0.69	76.89	56.71	96.32	4.74	4.74
25	Clay/sand	0.45	2.24	0.45	0.45	0.45	2.41	95.97	92.87	99.03	2.58	2.58
26	Sandstone	0.27	3.74	0.27	0.27	0.27	2.04	94.56	90.88	98.17	5.59	5.59
27	Shale	0.39	2.62	0.39	0.39	0.39	4.33	82.01	70.17	93.02	14.65	14.65
28	Sandstone	0.24	4.24	0.24	0.24	0.24	1.02	80.35	63.48	96.65	4.31	4.31
29	Sandstone	0.22	4.71	0.22	0.22	0.22	0.01	73.46	48.14	98.38	0.34	0.34
30	Sandstone	0.22	4.64	0.22	0.22	0.22	2.4	75.55	53.92	96.4	10.62	10.62
31	Sandstone	0.26	3.94	0.26	0.26	0.26	0.68	76.94	59.62	93.04	3.88	3.88

Table 3: Minimum, Highest and Average values of Major Oxides and Ratios of Some Oxides

MO	Minimum	Maximum	Average
SiO_2	15.01	85.1	20.15
Al_2O_3	4.91	28.52	15.6
Fe_2O_3	0.01	16.24	3.68
CaO	0.25	24.21	1.31
K_2O	0.75	5.42	2.29
P_2O_5	<0.001	1.91	1.07
MgO	<0.001	4.54	2.27
MnO	<0.001	0.07	0.032
TiO_2	0.57	3.6	1.9
NiO	0.001	0.01	0.003
TiO_2/Al_2O_3	0.053	0.33	0.13
SiO_2/Al_2O_3	2.23	13.13	4.93
Fe_2O_3/K_2O	0.0018	5.25	1.54
Al_2O_3/K_2O	2.13	31	7.48

Maturity and Climatic Conditions During Sedimentation

The SiO_2/Al_2O_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; Madukwe et al., 2014). Average SiO_2/Al_2O_3 ratios in unaltered igneous rocks range from ~ 3.0 (basic rocks) to ~ 5.0 (acidic rocks). Values of SiO_2/Al_2O_3 ratio > 5.0 in sandstones are an indication of progressive maturity (Roser et al., 1996). The SiO_2/Al_2O_3 ratios of the sediments studied revealed that the ratio values vary from 2.23 to 13.13 (average = 4.93) table 2 and 3. The SiO_2/Al_2O_3 ratios in sandstones were higher than those in the clay or shale. The sandstones have minimum SiO_2/Al_2O_3 ratio of approximately 3 and maximum SiO_2/Al_2O_3 ratio value of approximately 13. The values for SiO_2 /Al_2O_3 ratio for the sediments are appreciably high indicating that the areas have been heavily weathered (Roser and Korsch, 1986; Roser et al., 1996). Figure 5 indicates that majority of the sandstones tends towards increasing chemical maturity because they formed under Arid to semi-arid conditions. Sandstones usually contain clay minerals growing on the surface of the grains or lining and sometimes filling the pore spaces. The high values given from the ratio of SiO_2 /Al_2O_3 indicates that all the samples have low degree of clay. The higher the SiO_2 content the lower the degree of clay (Prothero, 2004).

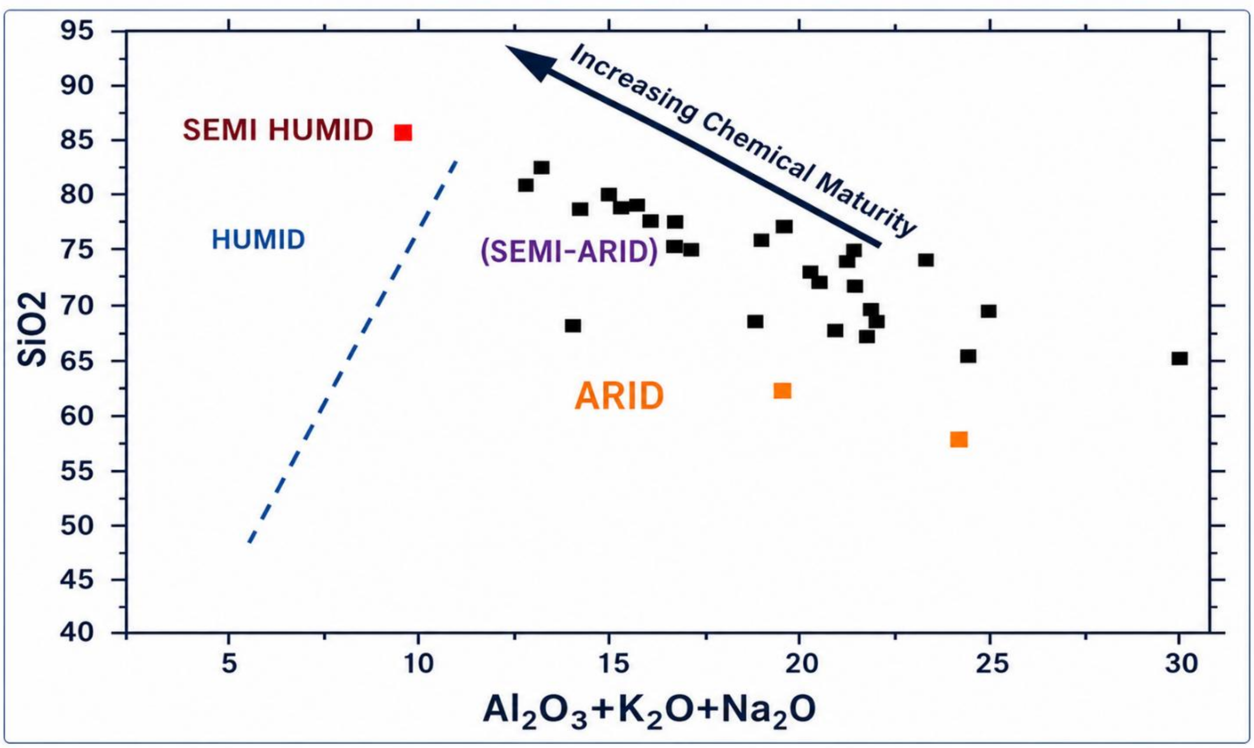

Figure 5: Chemical maturity of Gombe Sandstone from Suttner and Dutta, 1986

Source Area Weathering

According to Nesbitt and Young (1982) and Fedo et. al. (1995) , there are four different means by which alteration of sedimentary rocks can be studied. The four parameters used for the estimation of the degree of chemical weathering in the study areas include; Chemical Index of Alteration CIA), Plagioclase index of Alteration (PIA), Index of Compositional Variability (ICV) and Chemical Index of Weathering (CIW) in obtaining CIA, PIA, ICV and CIW, table 2.

The CIA, PIA and ICV values range from 15.86% – 95.97%, 9.92% - 92.87% and 0.32 % - 33.47% with an average value of 79.75%, 64.81% and 5.66% respectively (Table 4). These values are variable and may be as a result of multiple provenances for the sediments which have variable proportion of source area weathering and related process or may be due to low concentration of the alkaline and alkaline earth elements. Nevertheless, most of the samples display CIA, PIA and ICV values greater than 70% (Table 2 and Table 4) indicating moderate to high (intensive) weathering either at the source or during transport before deposition these values were compared with that of Chemical Index of Weathering values in table 2. The results further confirmed that the rocks are highly weathered as the CIW values for the 31 samples were almost reaching 100%, Okon et al. (2017). Increase in chemical weathering results in increase of chemical index of alteration values, approximately 50 for unweathered feldspar rich rocks to values approximately 100 for highly weathered kaolinite- or gibbsite- rich sediments Okon et al. (2017).

Index of compositional variability (ICV) is applied in assessing detrital mineralogy and the ratio of K_2O/Al_2O_3 (Cox et al., 1995). ICV is defined as: $(Fe_2O_3+Na_2O+CaO+MgO+TiO_2)/Al_2O_3$. 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). According to the results of the Index of Compositional Variability, all of the samples have values greater than 1 with the exception of sample with serial number 16 and 29(table2 and 4) which show lower values of ICV 0.44 and 0.34 respectively. This showed that the two samples are mineralogically mature and the remaining 29 samples are considered mineralogically immature.

Table 4: Summary of source area weathering for the study area

Indices		Standard (%)	Study Area (%)	Interpretation
CIA	Range	75 -100	15.86 – 95.97	
	Mean		79.75516	Highly weathered
PIA	Range	75 -100	9.92 – 92.87	
	Mean		64.80613	Moderate weathering
CIW	Range	75 -100	16.87 – 99.03	
	Mean		94.02903	Highly weathered
ICV	Range	75 -100	0.32 – 33.47	ICV<1 – mature sst ICV> 1. Immature
	Mean		5.666129	

Provenance and Tectonic Setting

The following authors (Blatt *et al.*, 1980; Bhatia, 1983; Bhatia and Crook, 1986; Roser and Korsch, 1986 & 1988) have correlated geochemistry of sandstones to specific tectonic environment. The discriminant function plot of Roser and Korsch (1988) defined four (4) main provenances: mafic igneous provenance; intermediate igneous provenance; felsic igneous provenance; and quartzose sedimentary provenance (Figure 6).

The Gombe sandstone plots show that most of the sample's plot within the felsic igneous provenance field with few samples plotted within the intermediate igneous provenance field while only one sample failed within the Quartzose sedimentary provenance, this suggests that the sediments were derived from a silica high crystalline (plutonic-metamorphic) terrain with a lesser intermediate-acid volcanic component. This also may indicate a large input of clastic materials from rifted continental margins.

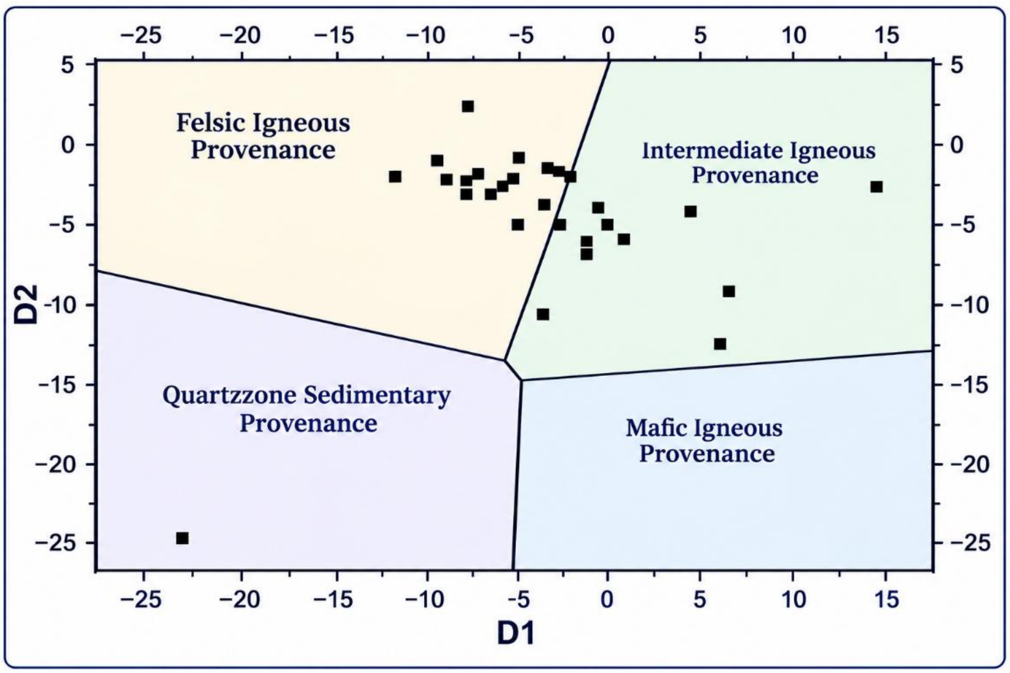

Figure 6: Discriminant function diagram using major elements for the provenance signatures of Gombe Formation (After Roser and Korsch, 1988) D1= Discriminant Function one (1), D2= Discriminant Function Two (2)

Geochemistry of sandstone is an invaluable tool for discriminating tectonic settings (Rozer and Korsch 1986, Bhatia 1983, Mclennan et al 1993, Armstrong-Altrin et al., 2005). The discriminant diagram by Bhatia (1983, Madukwe et al., 2014) was carried out to further determine the tectonic setting of the basin. The result indicated that most of the rocks were classified under active continental margin and passive continental margin while few other samples were classified under continental arc and oceanic arc.

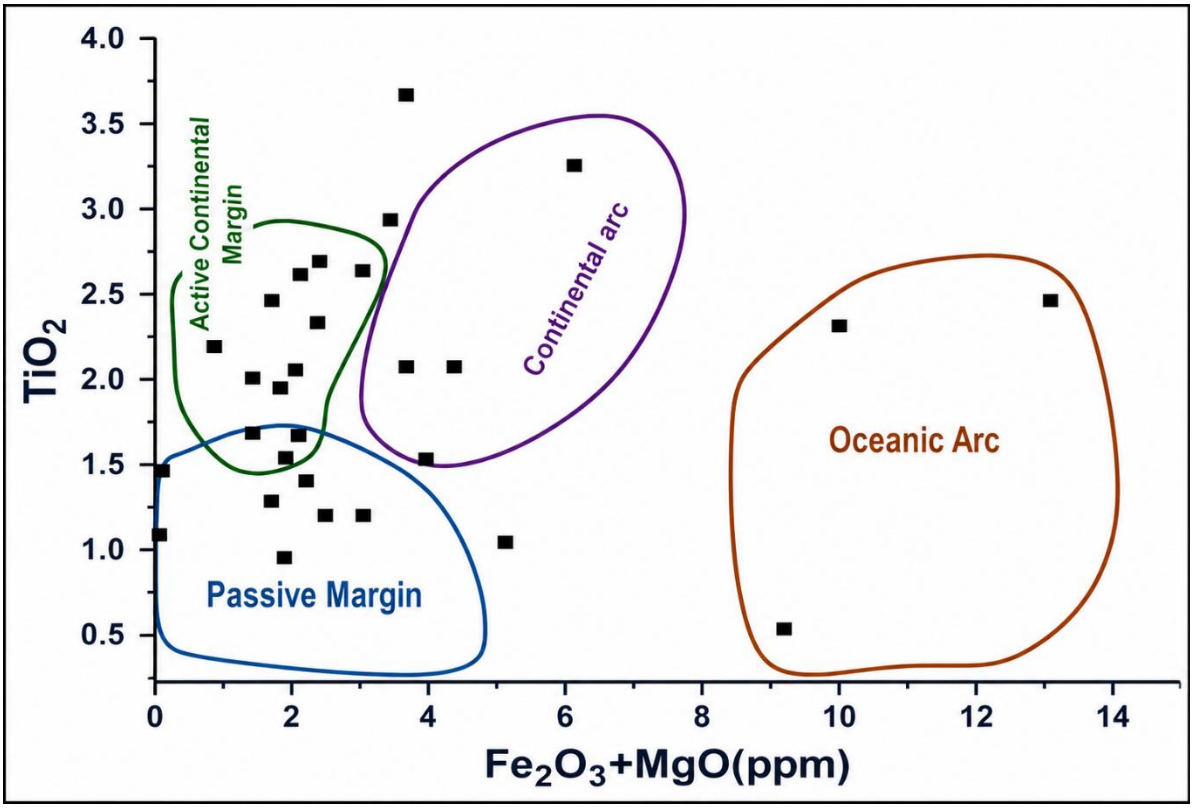

Figure 7: Figure. 4: Discrimination Diagram Bhatia (1983)

Conclusion

Major element geochemical characterization of the Gombe Formation has provided important insights into the provenance, weathering history, compositional maturity, and depositional environment of the sediments. The geochemical discrimination diagrams classify the sandstones predominantly as wackes and arkose, with subordinate lithic arenite and sub-arkose, indicating sediments that are generally texturally and compositionally immature and were deposited before extensive sedimentary reworking.

The provenance discrimination plots reveal that the detrital materials were derived predominantly from felsic igneous rocks, with minor contributions from intermediate igneous sources, reflecting erosion of continental crustal terrains.

Weathering indices, including the Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA), and Chemical Index of Weathering (CIW), indicate that the source rocks experienced moderate to intense chemical weathering prior to deposition. In addition, the generally high Al_2O_3/TiO_2 ratios, coupled with low MgO concentrations, further support a predominantly felsic parent rock composition. The relatively high Index of Compositional Variability (ICV) values confirm that the sediments remained chemically and mineralogically immature, suggesting rapid erosion, short transport distances, and limited recycling before final deposition.

Palaeoclimatic interpretation based on the SiO_2 versus (Al_2O_3 + K_2O + Na_2O) discrimination diagram indicates that sediment generation and deposition occurred predominantly under semi-arid to arid climatic conditions, although evidence of moderate to intense chemical weathering suggests prolonged weathering of the source terrain prior to transport. Furthermore, tectonic discrimination diagrams indicate deposition within active continental margin and passive margin settings, implying sediment supply from evolving continental crust influenced by both tectonic uplift and stable cratonic environments.

Overall, the geochemical signatures demonstrate that the Gombe Formation records sediments derived predominantly from felsic continental sources, subjected to significant chemical weathering, deposited under semi-arid to arid palaeoclimatic conditions, and accumulated in active and passive continental margin tectonic settings. These findings contribute to a better understanding of the sedimentary evolution and palaeogeographic history of the Gombe Formation within the Gongola Sub-basin of the Northern Benue Trough.

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