VOL. 11 NO. 9,
FEBRUARY, 2026
E-ISSN 3026-958X
P-ISSN 3027-1169

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Science Innovation & Technology Research (JSITR)

X-Ray and Granulometric Analysis of Fluvial Sediment within the Gombe Sandstone Upper Benue Trough, Nigeria; Implication for Provenance, Paleoclimate, and Reservoir Quality Studies

Dahiru D. Muhammed[1]; Usman A. Usman[1]; Saidu Abdullahi[2]; Hamza S. Maina[1]; & Abdullahi S. Sa'ad[1]

[1]Department of Geology, University of Maiduguri. [2]Department of Geology, Federal University Gusau

Corresponding Author: saiduabdullahi@fugusau.edu.ng

DOI: https://doi.org/10.70382/ajsitr.v11i9.071

Abstract

X-Ray and Granulometric Analysis was carried out on the Gombe Sandstone sediment exposed at Gabukka River, within the Upper Benue Trough, northeastern Nigeria. The research aim is to evaluate provenance and depositional settings, paleoclimate, paleoweathering, and reservoir quality potential of Gombe Sandstone sediment deposited along Gabukka River. Twenty (20) sediment samples were analyzed using granulometry, X-ray diffraction (XRD), and X-ray fluorescence (XRF). The sediment samples are composed of poor to moderately sort very fine to coarse grained particles, with predominantly fine-skewed and platykurtic distributions reflecting fluctuating hydrodynamic conditions typical of fluvial–deltaic systems. Mineral distribution shows quartz as the dominant mineral (41–69 wt.%) with subordinate feldspar, muscovite, and minor clay minerals (kaolinite and chlorite), indicating moderate to high compositional maturity and derivation from felsic continental source area. Elemental oxide composition is dominated by SiO_2 (65.8–78.9 wt.%) followed by Al_2O_3, Fe_2O_3, K_2O, TiO_2, CaO, MnO, P_2O_5, and MgO in variable concentration. Bivariate analysis between SiO_2 and other oxides indicate quartz enrichment through hydraulic sorting and heavy mineral and clay concentration in finer facies. The different weathering indices and the present of kaolinite confirm the dominance of intense chemical weathering under warm, humid climatic conditions. The research work concludes that sedimentary deposits along Gabbuka River

are predominantly fluvial to fluvio–deltaic sediments deposited under oxidizing continental conditions. Reservoir potential is moderate to high, particularly within quartz-rich channel facies, but is locally reduced by clay enrichment and ferruginous cementation is anticipated.

Keywords: Gombe Sandstone; Gabukka River; X-ray diffraction (XRD); X-ray fluorescence (XRF); granulometric analysis; provenance; paleoweathering; fluvial–deltaic deposition.

Introduction

X-ray and granulometric analyses are widely recognized as effective tools in sedimentary rock studies because they provide reliable means of evaluating the textural, compositional, and diagenetic characteristics of sedimentary deposits and their applications in understanding provenance and reservoir quality. The integration of mineralogical and geochemical approaches remains critical in reconstructing basin evolution, tectonic setting, and sediment recycling processes (Taylor & McLennan, 1985; Guo et al., 2021; Omolaiye et al., 2024).

X-ray analysis utilizes mineralogical and elemental compositions in paleoenvironmental and diagenetic investigations. For example, elemental oxide compositions are commonly applied in determining provenance, tectonic setting, weathering intensity, redox conditions, paleoclimate, and diagenetic influences (Nesbitt & Young, 1982; Bhatia, 1983; Roser & Korsch, 1988; Cullers, 2000; Guo et al., 2021; Ameh et al., 2025). Likewise, clay mineral assemblages such as kaolinite, illite, smectite, and chlorite are widely used in paleoweathering, paleoclimate reconstruction, and reservoir quality evaluation (Moore & Reynolds, 1997; Worden & Burley, 2003; Zhou et al., 2018; Adeyemi & Oladunjoye, 2023; Irunkwor et al., 2025).

In the Upper Benue Trough, recent studies have shown that quartz abundance, feldspar alteration, and clay mineral distribution significantly influence diagenetic history and reservoir properties of Cretaceous sandstones (Adekeye et al., 2024; Ahmed et al., 2023; Abubakar et al., 2022). Furthermore, textural parameters such as mean grain size, sorting, skewness, and kurtosis remain essential in interpreting depositional energy conditions, sediment transport mechanisms, and basin hydrodynamics (Folk & Ward, 1957; Pettijohn et al., 1987; Syvitsky, 2007; Alabi et al., 2024). Recent integrated sedimentological–geochemical investigations have demonstrated the usefulness of granulometric indices in evaluating sediment maturity, mineral stability, post-depositional modification, and reservoir performance in both Nigerian and global sedimentary basins (Boggs, 2009; Abubakar et al., 2017; Falade et al., 2025; Adamu et al., 2024).

The Gombe Sandstone represents the youngest Cretaceous siliciclastic succession

within the Gongola Sub-basin of the Upper Benue Trough (Benkhelil, 1989; Nwajide, 2013). It unconformably overlies the Pindiga Formation and is overlain by the Kerri-Kerri Formation (Carter et al., 1963; Zaborski et al., 1997; Obaje, 2009). The formation comprises fine- to coarse-grained sandstones interbedded with siltstones, shales, clay lenses, and ironstone layers, and exhibits sedimentary structures such as cross-bedding, ripple lamination, and parallel bedding indicative of fluvial to marginal marine depositional systems (Nwajide, 2013; Adetunji et al., 2014; Ahmed et al., 2023).

Modern X-ray techniques now provide higher-resolution mineralogical and geochemical datasets for evaluating weathering indices (e.g., CIA, CIW), paleoclimate signatures, provenance discrimination diagrams, and tectonic setting interpretations (Nesbitt & Young, 1982; Cullers, 2000; Guo et al., 2021; Omolaiye et al., 2024; Ameh et al., 2025). Recent regional studies further suggest that Cretaceous sediments of the Upper Benue Trough were predominantly derived from felsic source terrains, experienced moderate to intense chemical weathering, and were deposited under passive margin to intracratonic tectonic regimes (Abubakar et al., 2022; Ahmed et al., 2023; Adekeye et al., 2024).

Although earlier investigations focused primarily on stratigraphy and sedimentology (Akaegbobi et al., 2005; Abubakar, 2006; Obaje, 2009), comparatively fewer studies have integrated mineralogical, geochemical, and granulometric datasets to comprehensively interpret provenance, diagenesis, paleoweathering intensity, paleoclimate, and tectonic setting within the Upper Benue Trough using modern analytical techniques (Adamu et al., 2024; Falade et al., 2025).

The present study focuses on the Gombe Sandstone deposit exposed along Gabukka River. By integrating field observations with mineralogical (XRD), geochemical (XRF), and granulometric datasets, this study aims to determine compositional parameters, evaluate provenance and depositional setting, assess reservoir quality potential, and interpret paleoweathering and paleoclimatic conditions within the Upper Benue Trough. The findings will contribute to sedimentary facies modelling and enhance petroleum exploration efforts in northeastern Nigeria (Abubakar et al., 2017; Ahmed et al., 2023; Adekeye et al., 2024).

The key objectives of this study are to: determine sediment textural parameters; characterize sediment mineralogy and geochemistry; evaluate provenance, reservoir potential, and depositional conditions; interpret paleoweathering and paleoclimatic condition s

PROBLEM STATEMENT

The **Gombe Sandstone** within the **Upper Benue Trough** represents an important Cretaceous sedimentary succession with significant implications for regional geology, paleoenvironmental reconstruction, and hydrocarbon reservoir evaluation. Despite its stratigraphic importance, detailed integrated mineralogical and geochemical studies of its fluvial facies remain limited, particularly in terms of quantitative X-ray diffraction (XRD), X-ray fluorescence (XRF), and granulometric analyses.

Previous studies in the basin have largely emphasized stratigraphy and paleontology, with comparatively less focus on sediment texture, mineral composition, geochemical signatures,

and their combined implications for provenance, paleoclimate, paleoweathering intensity, and reservoir quality. This gap restricts comprehensive understanding of sediment source characteristics, depositional processes, and post-depositional modifications that control porosity, permeability, and overall reservoir performance.

Fluvial sandstones are especially sensitive to variations in hydrodynamic energy, source rock composition, tectonic setting, and climatic conditions. Without systematic granulometric, mineralogical, and geochemical characterization, interpretations of depositional environment and reservoir potential may remain speculative. Therefore, there is a need for an integrated study employing X-ray and granulometric analyses to evaluate sediment maturity, source terrain, paleoclimatic conditions, and implications for reservoir quality within the Gombe Sandstone succession.

General Objective

To evaluate the provenance, paleoclimate, depositional environment, and reservoir quality potential of fluvial sediments within the Gombe Sandstone using integrated X-ray and granulometric analyses.

Specific Objectives

- To determine the grain size distribution, sorting, skewness, and kurtosis of the fluvial sediments using granulometric techniques.
- To identify and quantify the mineralogical composition of the sediments using X-ray diffraction (XRD).
- To determine the major elemental oxide composition using X-ray fluorescence (XRF) analysis.
- To assess sediment maturity and provenance using mineralogical and geochemical indicators.
- To evaluate paleoweathering intensity and paleoclimatic conditions using established weathering indices and clay mineral assemblages.
- To interpret the depositional environment based on textural parameters and geochemical relationships.
- To assess the reservoir quality potential of the Gombe Sandstone with respect to mineral composition, clay content, and cementation trends.

Regional Stratigraphic Setting

The Gongola Arm forms the northeastern extension of the Upper Benue Trough and trends NE–SW as part of the roughly 1000-km-long Benue Rift System. It contains a thick upto 5km sequence of Cretaceous sediments that represent long-term subsidence and active sedimentation during early rifting (Carter et al., 1963; Popoff et al., 1986; Zaborski et al., 1997). The basin has experienced multiple episodes of tectonic wide structural evolution, resulting in partial folding, faulting, and fracturing of the sedimentary sequence that ultimately

affects subsurface heterogeneity. Stratigraphically, the Gongola Sub-basin comprises various successions of lithostratigraphic units deposited from the Aptian–Albian to the Paleogene.
The Bima Formation is the oldest basal sedimentary unit in the Upper Benue Trough. It lies unconformably on the Precambrian Basement Complex and consists of predominantly continental siliciclastic deposits. The Bima Formation is subdivided into three members namely, Lower Bima (B1), Middle Bima (B2), and Upper Bima (B3) (Carter et al., 1963; Allix, 1983; Guiraud, 1990; Zaborski et al., 1997). Lower Bima (B1) varies in thickness (0–1500 m) and is composed of poorly sorted, angular, arkosic sandstone, granulestones, and pebble conglomerates (Zarborski et al., 1997). The Middle Bima (B2) ranges between few metres to 400 m thick and is dominated by medium- to very coarse-grained feldspathic sandstones (Zarborski et al., 1997). Upper Bima (B3) is up to 600 m thick, it is consisting of well sorted medium- to coarse-grained sandstones. The B3 generally has a better reservoir potential within the Bima Formation (Zarborski et al., 1997).

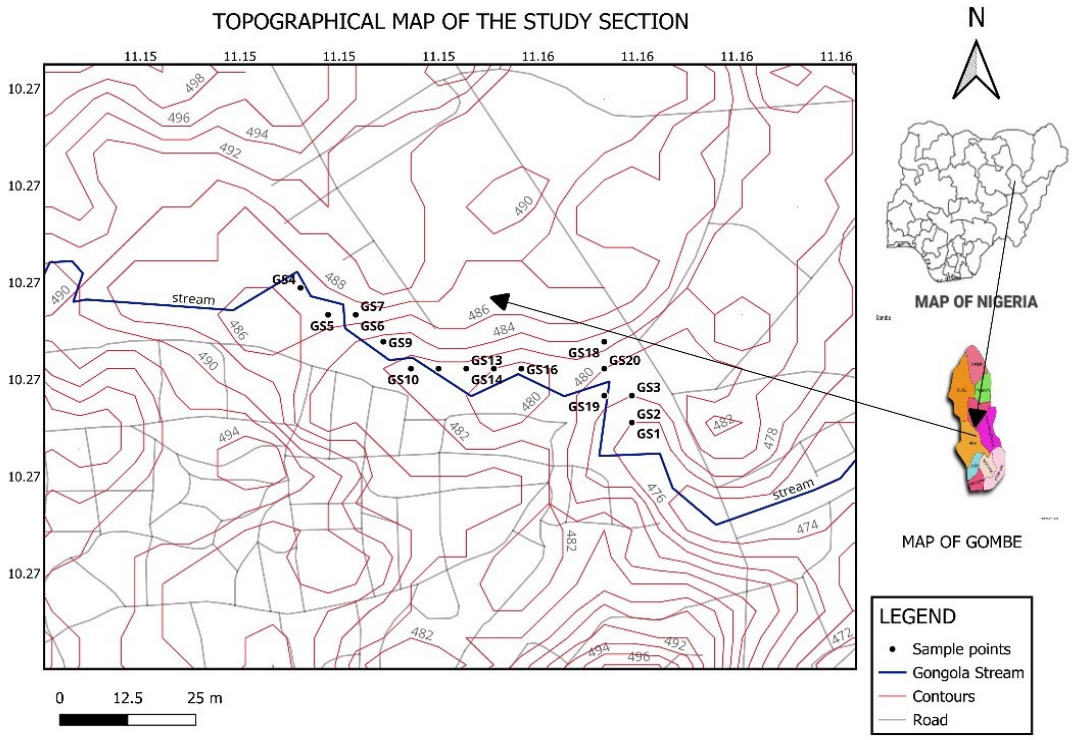


Figure 1: Topographic map of the study area showing the sampling points and location of Gabukka River within Gombe State, Northeastern Nigeria. (Source: Saidu Abdullahi 2026)

The Yolde Formation is Late Albian to Cenomanian in age, it conformably overlies the Bima Formation and marks a significant transition to marine sedimentation (Lawal, 1982; Allix, 1983; Zarborski et al., 1997; Dike, 2002). Yolde Formation is a fining upward sequence deposited in a series of transitional depositional environments, including deltaic, barrier-island, and lagoonal settings, the sequence comprises of interbedded coarse- to

fine-grained sandstones, shales, mudstones, and thin limestone beds (Carter et al., 1963; Shettima, 2005; Abubakar, 2006; Shettima et al., 2011). The formation shows moderate compositional maturity and sits along the flanks of anticlines in the Upper Benue Trough (Abubakar, 2006; Shettima et al., 2011). This highlights its susceptibility to structural evolution. Carter et al. (1963) and Falconer (1911) initially classified Yolde Formation as "passage beds," of significance stratigraphic importance.

The Pindiga Formation conformably overlies the Yolde Formation and represents a major marine sedimentary sequence deposited from the Turonian to Santonian periods. It consists of shales, limestones, marls, and sandstones subdivided into five key lithostratigraphic members: the Kanawa, Gulani, Deba-Fulani, Dumbulwa, and Fika members (Carter et al.,1963; Zaborski et al., 1997; Maigari, 2011).These members vary in thickness (generally 200–300 m for the sandstone-dominated units) and collectively represent both regressive and transgressive systems within the Upper Benue Trough. The Gulani Member is about 300 m and consists of thin-bedded coarse to very coarse pebbly sandstones interbedded with laminated mudstones, ripple-marks are very common and occasional desiccation cracks, (Zaborski et al; 1997). The Dumbulwa Member contains channel-filling, coarse, feldspathic, cross-bedded sandstones. The Deba-Fulani Member comprises of glauconitic and feldspathic calcareous sandstones, sandy limestone, shale, and fine cross-bedded units (Zaborski et al; 1997). Several reports show that the sand-rich units have a good reservoir potential, while the thick shale-dominated Fika Member as an effective seal (Du preez and Barbers, 1965; Poppof et al.,1986; Obaje et al., 1999). Overall, the Pindiga Formation experience a significant marine incursion into the Gongola Arm, with its members representing a mixture of marine, regressive, and shallow-water depositional environments.

The Gombe Formation as described by Falconer (1911) is a sequence of sandstones, clays, and ironstone with ferruginous red top. Carter et al. (1963) also described it as sandstone, siltstone, shale, and ironstone assemblages deposited in a deltaic to estuarine settings, while Adeleye (1975) characterized it as a flaggy sandstones interbedded shale, with lignite layers, and lenticular ironstone bodies, that formed a gentle folding and minor reverse faulting. The sandstone bodies are moderately to well-sorted with variable grain sizes, making the unit one of the most promising reservoir intervals in the Upper Benue Trough. The formation belongs to Campanian–Maastrichtian group and represents the youngest Cretaceous unit in the Gongola Arm. This formation is restricted to the western Gongola Basin, extending westward beneath the Kerri-Kerri Basin.

The Kerri-Kerri Formation is a Paleogene continental sequence that unconformably overlies Cretaceous units in Upper Benue Trough, it extends beneath parts of the Chad Basin. The formation consists of medium- to coarse-grained sandstones, clayey grits with pebbly sandstones, and interbedded siltstone and clay. They are poorly to moderately sorted and often contain ferruginous cement, producing reddish-brown outcrops (Carter et al., 1963). Common sedimentary structures include trough and planar cross-bedding, ripple laminations, and

occasional channel fills, reflecting deposition in variable-energy continental environments such as fluvial (braided to meandering), lacustrine, and deltaic systems.

METHODOLOGY

Twenty representative samples (UMGS1–UMGS20) were collected at 20-meter intervals to capture adequate compositional variability within the study area. These samples were analyzed using granulometric and X-ray techniques to determine their textural, mineralogical, and elemental composition. All laboratory procedures were carried out following standardized analytical protocols.

Sieve Analysis

The set of equipment used for the grain size analysis include Endecotts EFL Mechanical Sieve Shaker, Set of ASTM E11 standard sieves, OHAUS Pioneer analytical balance, and Porcelain mortar and pestle. The Endecotts EFL mechanical sieve shaker operates by applying controlled vertical vibrations to a stacked series of sieves arranged in decreasing aperture size. As the sediment sample is shaken, particles are separated according to size; each grain is retained on the sieve whose mesh openings are smaller than the particle itself. Prior to sieve analysis, weathered surfaces were removed, after which the samples were dried, gently disaggregated, and weighed. Each sample was placed in a stack of ASTM-standard sieves (2 mm–63 μm) and processed using an Endecotts EFL mechanical sieve shaker for a fixed duration. The retained fractions on each sieve were weighed and converted to percentage values, which were then used to calculate grain-size parameters; mean size, sorting, skewness, and kurtosis, following the Folk and Ward (1957) method.

Geochemical Analysis

The samples were analyzed at Gombe State University using X-ray Fluorescence (XRF) to determine their elemental composition. Analysis was performed with an XRF spectrometer equipped with an X-ray tube, sample chamber, detector system, and software capable of both qualitative and quantitative assessment. A Rigaku NEX DE energy-dispersive XRF (EDXRF) spectrometer, fitted with a 15-position automated sample changer operating in a slow, continuous-spin mode, was used for geochemical analysis. Measurements were conducted under a helium atmosphere using a silicon drift detector, with a palladium X-ray tube set to 10 μA and 60 kV and a beam spot size of 10 mm.

For major and trace element analysis, samples were air-dried and mechanically crushed to produce a homogeneous fine powder (100–200 mesh). Approximately 5 g of each powdered sample was then weighed and placed into 32-mm plastic sample cups lined with 4 μm polypropylene X-ray film. The samples were hydraulically pressed for uniform compaction and securely sealed prior to analysis. A separate portion of each sample was further pulverized to <75 μm to improve homogeneity for pellet preparation. These finer powders were mixed with boric acid as a binder and pressed into stable pellets using a hydraulic press, after which

the pellets were stored labeled containers. This preparation enhances analytical precision and reproducibility. Element quantification was achieved using Rigaku RPFSQX software, which applies fundamental parameter (FP) based standardless calibration and automatically performs the necessary corrections. The Rigaku NEX DE system can detect elements from sodium (Z = 11) to uranium (Z = 92), with detection limits ranging from low parts per million (ppm) to high weight percent (wt.%). Analytical uncertainties typically fall within 0.1–1% relative standard deviation (RSD)

X-Ray Diffraction Analysis

The X-ray Diffraction (XRD) analysis was carried out to determine the mineralogical composition of the samples. Each sample was crushed into a fine powder and oven-dried at approximately 110 °C before being leveled on a sample holder. Prior to x-ray scanning, the instrument was calibrated using standard reference material, such as silicon, to ensure analytical accuracy. The XRD equipment operated with a Cu-anode tube generating Cu Kα radiation (λ = 1.5406 Å) at 40 kV and 30 mA, and scans were conducted across a 2θ range of 5°–70° with a 0.02° step size and a counting time of about one second per step. The resulting diffraction patterns were processed and compared with International Centre for Diffraction Data (ICDD) standards to identify mineral phases, and where necessary, quantitative analysis was undertaken using Rietveld refinement. All analytical procedures followed strict safety protocols to prevent X-ray exposure and sample contamination.

Textural Parameters

The grain-size data from sieve analysis were used to compute sediment textural parameters; mean grain size, sorting, skewness, and kurtosis. Using the Folk and Ward (1957) graphical method, these parameters are important in evaluating grain size distribution, textural maturity, river hydrodynamics, post-depositional processes and reservoir quality.

The mean grain size distribution ranges from coarse-grained (UMGS 2) to medium-grained (UMGS 1, UMGS 3–5), then dominantly fine to very fine-grained (UMGS 6–20) (Table 1). The strong shift toward fine to very fine sand reflects decreasing flow energy and a transition from higher-energy channel conditions (coarse–medium sand) to lower-energy like overbank (fine–very fine sand), a pattern typical of fluvial–deltaic systems. Most samples are moderately sorted, with others been poorly sorted (UMGS 1, UMGS 3–5, UMGS 11, UMGS 15, and UMGS 18). This variability suggests rapid deposition under fluctuating hydraulic conditions, consistent with channel and floodplain environments. The sediments are mainly fine-skewed, with some near-symmetrical and a few coarse-skewed distributions. Kurtosis values range from platykurtic to very platykurtic, with occasional mesokurtic and rare leptokurtic samples.

These grain size distributions reflect variable input from multiple sediment sources and significant sediment variation from coarse to fine-grained sediment. This variability reflects fluctuating depositional conditions from low-energy to high-energy regime typical of fluvial

and shallow-marine environments (Folk, 1980; Boggs, 1995; Nichols, 2009). Coarser samples represent high-energy channel deposit, while finer samples point to lower-energy floodplain or overbank deposits. Sorting ranges from moderate to poor, indicating episodic changes in flow conditions, a common phenomenon in fluvial sedimentation (Miall, 1996; Tucker, 2003). Skewness values show both fine- and coarse-skewed distributions, highlighting alternating low- and high-energy conditions. Kurtosis values range from platykurtic to leptokurtic, reflecting shifts between stable deposition and selective sorting. Collectively, the interpreted textural parameters indicate fluctuating hydrodynamic conditions with moderate sediment reworking prior to final deposition.

The Gombe Sandstone, reported as a Maastrichtian fluvial–deltaic deposit in the Gongola Basin, typifies the observed patterns in this study; where poorly to moderately sorted medium- to coarse-grained sands represent channel deposits and fine to very fine sands with fine-skewed and platykurtic distributions signify floodplain or overbank deposition (Carter et al., 1963; Zaborski et al., 1997). Overall, the grain size parameters show that the sediments are mainly fine to very fine-grained, moderately sorted, fine-skewed, and platykurtic. These features represent deposition under variable flow regimes involving both traction and suspension transport regime. The occurrence of poorly sorted and platykurtic samples also suggests mixing of grain populations and episodic sediment supply. Collectively, the interpretation suggest deposition in a fluvial environment with strong overbank influence, it is consistent with the reported fluvial–deltaic systems within the Gombe Sandstone (Carter et al., 1963; Zaborski et al., 1997).

Mineralogy

The mineralogical data from the XRD analysis of Gabukka River sediments within Gombe Sandstone show the occurrence of quartz, orthoclase feldspar, plagioclase feldspar, and muscovite, clay minerals; kaolinite and chlorite, all present in varying concentrations (Table 1 and Fig. 2). The abundance of quartz ranges from 41 wt% in UMGS 001 to 69 wt% in UMGS 004 with an average of 54 wt%. Orthoclase feldspar from 41 wt% in UMGS 017 to 16 wt% at UMGS 019 with an average of 26 wt% (Table 1). Plagioclase feldspar occurs with significantly lower abundance than orthoclase feldspar, ranging from 0.5 wt% in UMGS 017 to 23.5 wt% UMGS 019 with an average of 11 wt% (Table 1). Muscovite occurrence ranging from trace amounts (< 0.2) in UMGS 005 and UMGS 019, to 26 wt% in UMGS 009 with an average of 4.5 wt% (Table 1). Clay minerals occur generally low in the study area, except in UMGS 005 and UMGS 011 where kaolinite and chlorite abundance reaches 18.8 wt% and 10 wt% respectively.

The dominance of quartz in some selected samples, can be interpreted as high mineralogical maturity with sediment possibly derived from stable continental sources such as granite, the abundance of muscovite further supports a granitic provenance (Pettijohn et al., 1987; Morton & Hallsworth, 1999). The presence of feldspars (orthoclase and albite) in all samples (Table 1 and Fig. 2) indicate limited chemical weathering or relatively short transport history where

feldspar abundance is considerable high. Clay minerals, notably kaolinite and chlorite may suggest both depositional and diagenetic influences, with kaolinite pointing to intense weathering in humid climates and chlorite occurring as either detrital or diagenetic mineral (Chamley, 1989; Moore & Reynolds, 1997; Worden & Burley, 2003). Overall, the mineral assemblages of Gabukka River sediments show the dominance of siliciclastic sediments, derived from moderately to intensely weathered continental granitic and metamorphic source, and deposited in fluvial to a shallow marine environment.

Table 1; Results of integrated granulometric, major oxides geochemistry and bulk mineralogy analysis (Source: Field Data)

Sample ID	Quattz	Orthoclase	Albite	Muscovite	Kaolinite	Chlorite	MgO mass%	Al2O3 mass%	SiO2 mass%	P2O5 mass%	K2O mass%	CaO mass%	TiO2 mass%	MnO mass%	Fe2O3 mass%	Grain Size ϕ	Sorting	Skewness	Kurtosis
UMGS1	41	32.0	20.0	5.6	1.2	ND	0.122	18.0	69.3	1.78	1.77	0.95	2.25	0.05	5.43	1.24	1.10	0.24	1.29
UMGS2	50	29.0	16.0	5.4	1.8	ND	0.197	16.4	65.8	1.63	2.19	1.08	2.59	0.04	9.63	0.64	0.89	0.09	0.95
UMGS3	62	19.5	17.5	1.0	0.4	ND	0.141	15.5	70.9	1.66	2.64	0.77	2.67	0.09	5.12	1.20	1.16	0.26	1.08
UMGS4	69	25.0	3.0	1.8	0.5	ND	0.149	13.0	75.0	1.59	2.75	1.00	2.90	0.03	3.08	1.77	1.55	0.44	0.94
UMGS5	47	19.0	15.1	0.2	18.8	ND	0.108	14.0	72.0	1.46	2.88	1.16	3.31	0.08	4.40	1.93	1.38	0.15	1.10
UMGS6	60	25.0	10.4	2.4	2.0	ND	0.137	13.2	74.3	1.54	2.97	1.01	3.09	0.03	3.19	2.50	0.99	0.35	1.00
UMGS7	64	27.4	2.0	6.0	0.2	ND	0.053	12.9	77.4	1.61	2.69	0.49	2.35	0.02	2.06	3.03	0.80	-0.03	0.72
UMGS8	65	32.0	2.3	0.8	0.4	ND	0.066	12.3	75.9	1.53	3.73	0.42	2.53	0.03	2.92	3.60	0.86	-0.80	1.12
UMGS9	46	16.0	10.0	26.0	3.8	ND	0.043	11.8	77.5	1.55	2.77	0.33	3.16	0.02	2.27	2.97	0.82	0.24	0.63
UMGS10	45	18.2	4.0	10.1	23.0	ND	0.041	15.0	73.5	1.41	2.61	0.48	3.15	0.02	3.19	2.80	0.93	0.30	0.87
UMGS11	54	26.0	10.0	0.4	ND	10	0.054	11.7	75.9	1.24	2.70	0.38	4.16	0.03	3.17	2.93	1.03	-0.04	0.61
UMGS12	44	28.0	23.0	4.3	0.6	ND	0.100	10.7	78.7	1.49	3.24	0.37	3.25	0.02	1.71	2.73	0.73	0.44	0.68
UMGS13	54	36.0	4.0	4.3	2.0	ND	0.061	14.7	72.4	1.46	2.94	0.47	3.10	0.03	4.30	2.80	0.95	0.40	0.82
UMGS14	57	33.0	2.7	4.5	3.1	ND	0.057	13.0	74.8	1.48	2.86	0.39	2.55	0.03	4.29	2.61	0.93	0.81	0.53
UMGS15	58	34.0	5.0	2.0	1.1	ND	0.042	10.3	78.9	1.51	2.37	0.26	2.36	0.02	3.45	3.09	1.04	-0.25	0.64
UMGS16	49	33.0	14.0	4.9	ND	ND	0.013	14.2	73.2	1.68	2.28	0.40	2.22	0.03	5.52	2.37	0.90	0.36	2.41
UMGS17	58	41.0	0.5	0.3	ND	ND	0.068	15.0	73.8	1.75	1.27	0.15	1.95	0.02	4.29	3.27	0.88	-0.23	0.88
UMGS18	60	21.0	13.8	4.1	1.2	ND	0.022	15.4	73.7	1.69	1.53	0.54	1.86	0.06	4.83	2.53	1.30	-0.04	0.65
UMGS19	58	16.0	23.5	0.1	2.1	ND	0.011	12.2	76.4	1.36	1.96	0.39	4.35	0.1	2.67	3.15	0.85	-0.17	1.17
UMGS20	55	17.7	23.0	4.8	ND	ND	0.027	11.6	76.5	1.15	2.08	0.52	4.70	0.05	2.34	2.83	0.74	0.42	0.68

ND=Not detected

Geochemistry

Geochemical analysis for major oxide composition provides insights into the chemical characteristics, provenance, sediment sorting, mineralogy and catchment area, of the sediment samples. The results of the integrated granulometric, major oxides geochemistry and bulk mineralogy analysis are presented in Table 1.

The geochemistry of Gombe Sandstone River sediment shows a SiO_2 concentration ranges between 78.9 wt % to 65.8 wt% with an average of 74.3 wt % (Table 1). Al_2O_3 concentration varies from 10.3 wt% - 18.00 wt% with an average of 13.5 wt %. CaO ranged between 0.15 wt % and 1.16 wt % with average value of 0.56 wt %, K_2O values range from 1.27 wt % to 3.33 wt % with average of 2.51 wt %. P_2O_5 varies from 1.78 wt % to 1.15 wt % with an average of 1.52 wt %. MgO varying from 0.19 wt% to 0.01 wt% averaging 0.07 wt %, while MnO ranged from 0.09 to 0.02 wt% with an average of 0.04 wt %. TiO_2 ranges between 4.7 wt% to

1.86 wt%, averaging 2.93 wt%. Fe_2O_3 ranges from 9.63 wt % to 1.71 wt % with an average of 3.89 wt %.

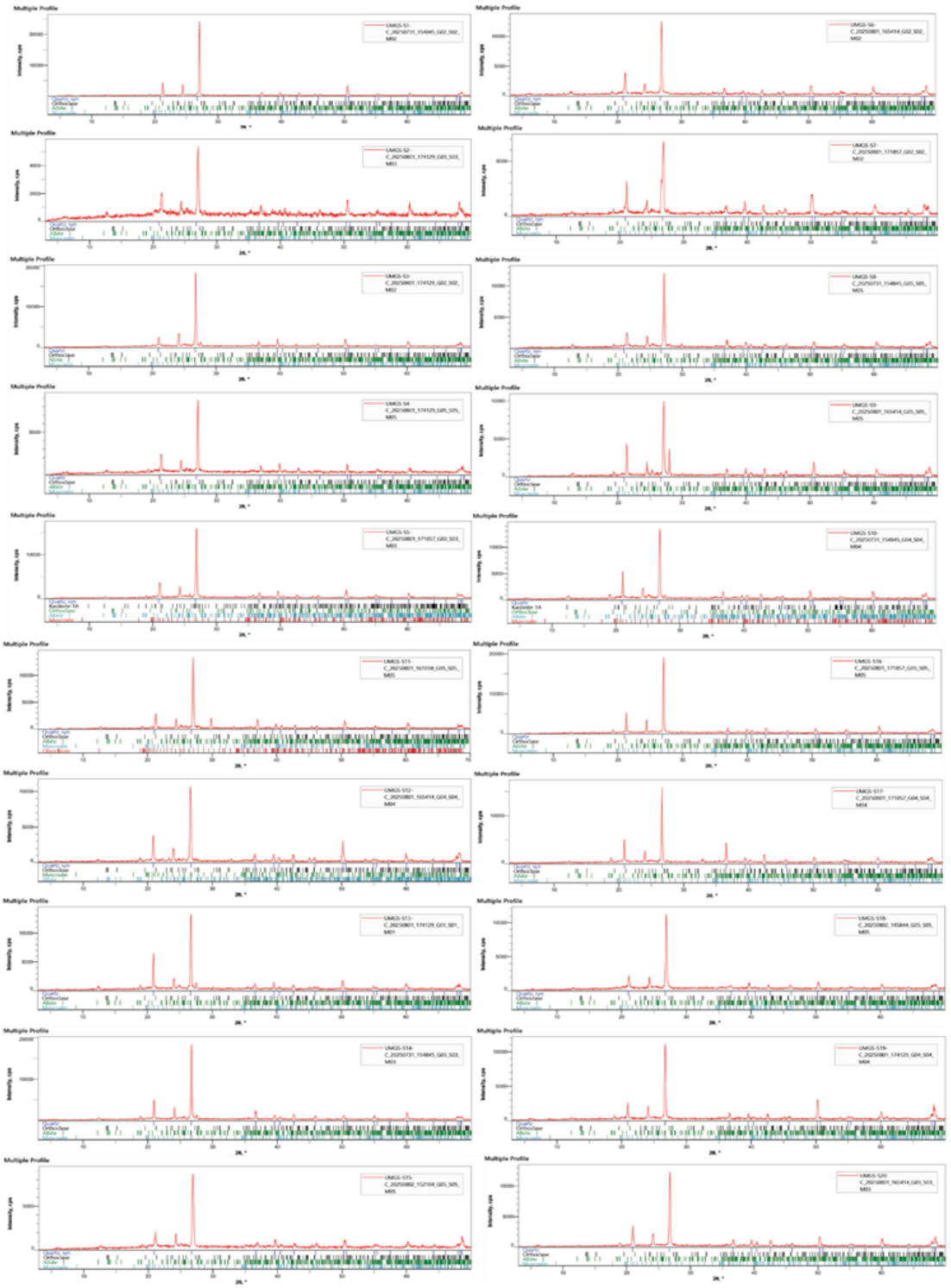


Figure 2: XRD Diffractographs of all the twenty (20) sediment samples.(Source Field Data)

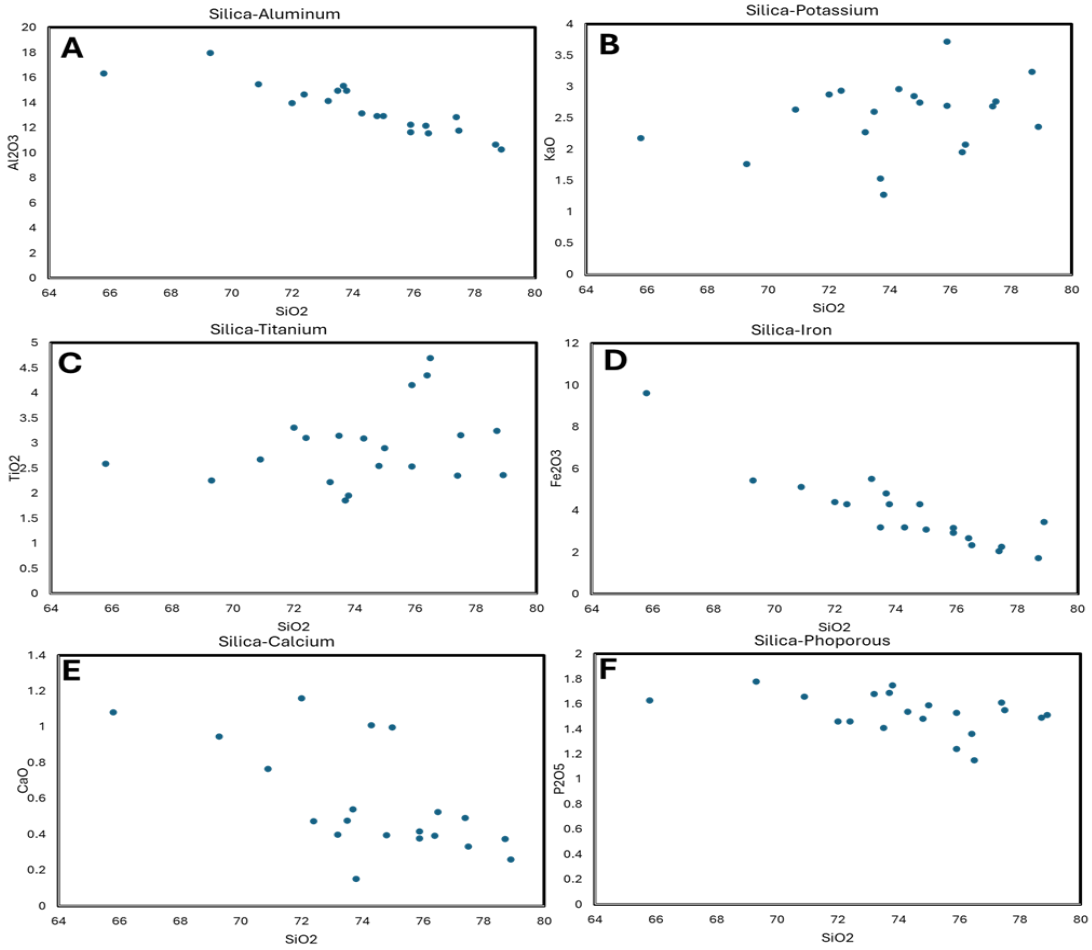
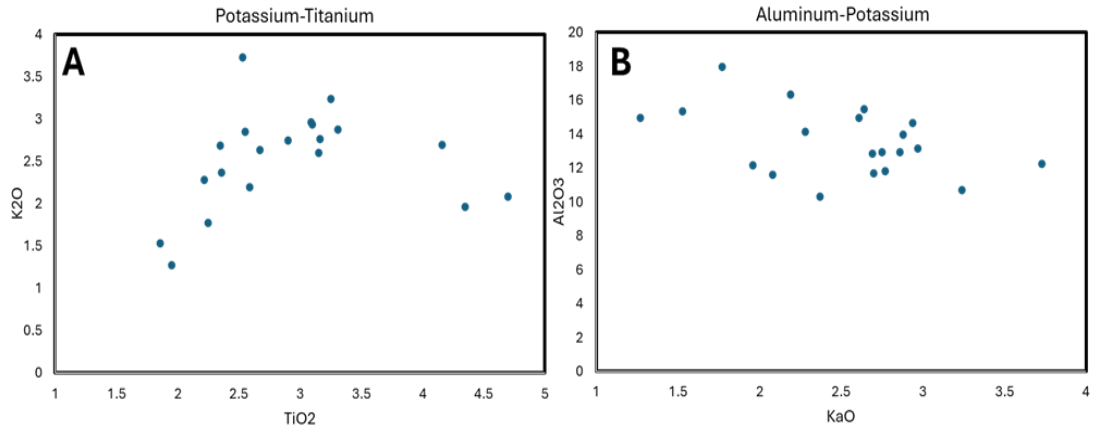


Figure 3: Bivariate plots showing correlation of major oxides against SiO_2. (Source: Field Data)

Bivariate analysis conducted on the major oxides indicates that SiO_2 shows negative to weak correlation with K_2O and negative correlation with Al_2O_3, Fe_2O_3, K_2O, MgO, CaO, P_2O_5 and TiO_2 (Fig. 3). TiO_2 shows strong and positive association with Al_2O_3 and Fe_2O_3 and weak to moderate positive correlation with K_2O and MgO and weak or somewhat poor relation with CaO and P_2O_5 (Fig. 4). Al_2O_3 and K_2O exhibit a moderate to strong positive correlation (Fig. X). The positive correlation between Al_2O_3 and K_2O is because both oxides are derived from feldspar and clay minerals common in siliciclastic deposits such as the Gombe Sandstone. In contrast, SiO_2 typically reflecting quartz content shows a negative correlation with Al_2O_3 and K_2O, this pattern indicates that quartz-rich, mature fluvial channel sandstones contain lower amounts of clay, feldspar, and potassium. This observed oxides covariance can be attributed mineralogical sorting during sediment transport, where increasing quartz content dilutes aluminosilicate minerals. SiO_2 displaying a negative correlation with Fe_2O_3 and TiO_2, also reflects decrease in concentrations of iron bearing and heavy mineral phases due to dilution and hydraulic sorting as quartz increases. Geochemically, this separates quartz rich channel

sands from finer, clay or heavy mineral rich overbank deposits in Gombe Sandstone. TiO_2 enrichment is therefore associated with heavy mineral lags or clay rich beds ((Taylor & McLennan, 1985; McLennan et al., 1993; Cullers, 2000). Additionally, SiO_2 shows negative correlations with CaO and P_2O_5 because both CaO (either from calcite, Ca-rich plagioclase, and fossil fragments) and P_2O_5 (typically apatite) become more concentrated when quartz content decreases. This pattern also reaffirms mineral sorting during transport and minor contributions from accessory or biogenic minerals. Overall, the negative correlation between SiO_2 and oxides such as TiO_2, CaO, and P_2O_5 reflects quartz dilution associated with fluvial processes. High SiO_2 concentrations reflects the abundance of matured quartz-rich channel sand deposits with low amounts of clay, feldspar, heavy minerals, and carbonates. In contrast, lower SiO_2 samples enriched in Al_2O_3, K_2O, Fe_2O_3, and TiO_2, reflects clay-rich, feldspar-rich, or heavy-mineral-rich overbank and floodplain deposits formed under lower-energy conditions.

Titanium is primarily hosted by phyllosilicate minerals such as mica (Condie et al., 1992) and heavy minerals such as rutile and ilmenite (oxides), due to its relative immobility during sedimentary processes, it serves as a reliable indicator of provenance (McLennan et al., 1993). The strong positive correlation between TiO_2 and Al_2O_3 (Fig. 4) reflects enrichment in fine-grained clays or less matured lithic grain of mica. The TiO_2 and Fe_2O_3 relationship (Fig. 4) also shows a broadly similar and relatable trend. K_2O, mainly from K-feldspar and illite, shows a weak to moderate positive relationship with TiO_2, suggesting moderate sediment immaturity and a felsic provenance. MgO contribution is minimally in this study, whereas the weak TiO_2–CaO relationship indicates that carbonate input is unrelated to heavy-mineral distribution. In the Gombe Sandstone, quartz-rich channel sands occur alongside clay-rich overbank deposits and minor heavy-mineral accumulations, as earlier indicated by grain size and mineralogy data. The TiO_2, Al_2O_3, and Fe_2O_3 associations reflect detrital heavy-mineral enrichment in finer sediments and the effects of mechanical sorting, since these oxides exhibit negative correlation with SiO_2. Overall, TiO_2 serves as an immobile tracer linked with clay and heavy-mineral content and supports interpretation of a felsic to intermediate provenance within a siliciclastic fluvial–deltaic system.



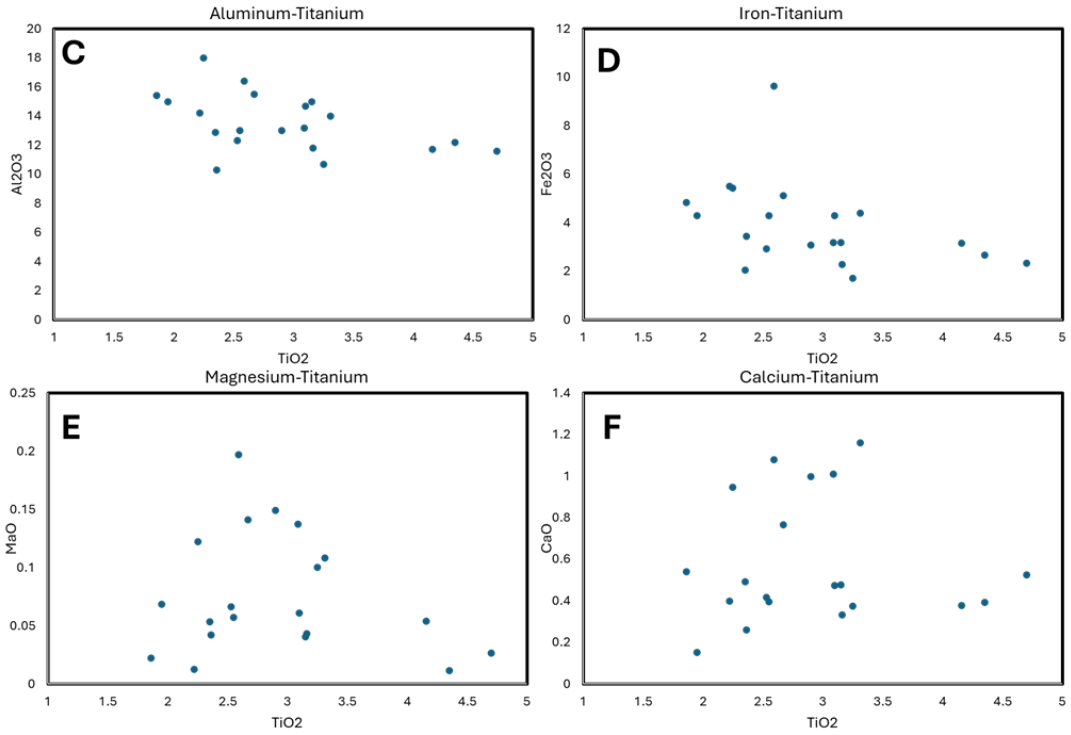


Figure 4 Bivariate plots showing correlation between major oxides.(Source Field Data)

The negative to weak correlations between SiO_2 and K_2O, Al_2O_3, Fe_2O_3, MgO, CaO, P_2O_5, and TiO_2, suggest quartz enrichment through mechanical sorting (Kampunzu et al., 2005). The Gombe Sandstone as widely reported, is a fluvial–deltaic siliciclastic deposits (Carter et al., 1963; Guiraud, 1990) composed of quartz-rich channel sandstones, siltstone and shale interbeds, minor ferruginous cement, and occasional feldspathic material. The geochemical patterns show that high SiO_2 values reflect quartz-rich, matured channel sandstones where other oxides in lesser concentration are diluted through sediment sorting. It also shows that SiO_2 is hosted quartz-dominated component, displaying inverse correlations with Al_2O_3, Fe_2O_3, K_2O, MgO, CaO, P_2O_5, and TiO_2 as a result of dilution during sedimentary maturation. In contrast, TiO_2 exhibits positive correlations with Al_2O_3 and Fe_2O_3, reflecting their association in fine grained enrichment. Samples with high SiO_2 represent high-energy, quartz-dominated channel deposits, while samples with lower SiO_2 and higher TiO_2, Al_2O_3, Fe_2O_3, and K_2O indicate clay- or heavy-mineral-rich facies typical of lower-energy floodplain environments. The positive relationships among TiO_2, Al_2O_3, and K_2O point to a felsic to intermediate source area, and the overall geochemical trends align with hydraulic sorting during fluvial transport in fluvial–deltaic siliciclastic systems. Collectively, these geochemical patterns are characteristic of mineralogical sorting and provenance influences within a fluvial–deltaic siliciclastic system such as the Gombe Sandstone, where quartz-rich channel sands are distinctly different from overbank deposits enriched in clay and heavy minerals. This is

consistent with established geochemical models for siliciclastic basins (Taylor & McLennan, 1985; Roser & Korsch, 1988).

Paleoclimate

The distribution of mineral assemblages and elemental compositions provide valuable information on paleoenvironmental conditions, since it is controlled by both climate and diagenetic processes. (Westermann et al., 2013). Consequently, it is essential to assess potential diagenetic overprints on clay minerals before drawing paleoenvironmental conclusions. Authigenic clay minerals typically develop during burial diagenesis, where increasing temperature and pressure promote the transformation of smectite to illite and chlorite, along with the development of mixed-layer clays (smectite–chlorite) (Godet et al., 2008). However, the analyzed samples lack illite, and mixed-layer clays, but present selective chlorite occurrence. This can be interpreted as negligible diagenetic alteration and thus suggest the dominance of primary environmental processes in sediment record. This enhances reliability of clay minerals particularly kaolinite and chlorite as paleoclimatic indicators. Kaolinite is the most dominant clay mineral in the samples, occurring alongside significantly low amount of chlorite, it serves as a robust proxy for paleoclimate studies (Chamley, 1989; Ruffell et al., 2002; Raucsik and Varga, 2008; Sheldon and Tabor, 2009). Kaolinite formation is associated with warm, humid (tropical to sub-tropical) paleoclimatic environments. The presence of kaolinite therefore suggests that the Gombe Sandstone experienced a humid tropical paleoclimate with strong weathering and leaching in the source area that readily supported the development of kaolinite. The dominance of kaolinite within the Gombe Sandstone has been widely reported as evidence of strong chemical weathering under warm, humid climatic conditions (Singer, 1984; Shettima et al., 2012; Bolarinwa et al., 2019; Bello et al., 2023; Ayinla et al., 2017; Abdulkarim et al., 2024; Idris et al., 2025).

Paleoweathering Indices

The weathering indices (chemical index of alteration-CIA, chemical index of weathering-CIW and plagioclase index of alteration-PIA) were calculated following the methods developed by Nesbitt and Young (1982) and Fedo et al. (1995). All major oxide values were first converted to molar proportions. Based on the average major oxide composition ($Al_2O_3 \approx 13.5$ wt.%, CaO ≈ 0.56 wt.%, $K_2O \approx 2.51$ wt.%, with low MgO and negligible carbonate content), the calculated weathering indices are: CIA = 70–82, CIW = 80–92, and PIA = 75–88. CIA values of 70–82 represent moderate to strong chemical weathering, these high CIA values therefore indicate substantial feldspar alteration and the leaching of mobile cations (Ca, Na, K) (Nesbitt & Young, 1982; McLennan, 1993). The CIW values of 80–92 indicate heavy removal of Ca and Na from plagioclase, thus reflecting significant plagioclase alteration, while the PIA values of 75–88 further suggest extensive plagioclase alteration and subsequent clay formation, particularly authigenic kaolinite (Nesbitt & Young, 1982; Nesbitt & Young, 1989; Fedo et al., 1995). These findings are consistent with the evidence from X-ray results; presence

kaolinite, depletion of alkali and alkaline-earth elements, quartz enrichment, compositional maturity, and a felsic continental source (Nesbitt & Young, 1982; McLennan, 1993; Fedo et al., 1995; Taylor & McLennan, 1985). The weathering indices indicate that the rock units were subjected to intense chemical weathering under warm, humid climatic conditions prior to deposition. The high weathering indices also imply sediment recycling and prolonged subaerial exposure within a stable continental setting, aligning with established interpretations of source-rock alteration and tectonic framework (Nesbitt & Young, 1982; McLennan, 1993; Fedo et al., 1995).

Reservoir potential

It is widely established that integrating granulometric, mineralogical, and XRF data is useful in understanding the controls on sediment composition, provenance, paleoclimate, and reservoir potential of sandstone deposits. Granulometric results show that the sandstones are predominantly fine- to coarse-grained with moderate grain sorting, reflecting relatively high-energy depositional conditions capable of transporting cleaner and relatively uniform sands. These textural attributes generally promote good porosity and permeability and facilitate fluid flow by minimizing the abundance of pore occluding matrix (Beard & Weyl, 1973; Bloch et al., 2002; Worden & Burley, 2003). Near-symmetrical skewness and mesokurtic to leptokurtic kurtosis values further suggest a higher possibility of having uniform grain packing and reduced abundance of finer materials. Thereby, enhancing the reservoir potential of Gombe sandstone by preserving the primary intergranular porosity (Folk & Ward, 1957; Tucker, 2003).

Mineralogical analysis reveals the dominance of quartz with subordinate feldspar and muscovite. This composition reflects nearly well matured sediments with high mechanical stability, reducing the likelihood of compaction-induced porosity loss (Pettijohn et al., 1987; Boggs, 1995; Folk, 1980). Quartz-rich zones can retain primary porosity more effectively than areas enriched in feldspar or lithic components due to their high resistance to chemical weathering (Pettijohn et al., 1987; Boggs, 2009; Worden & Burley, 2003). However, the variability in quartz distribution reveals heterogeneity across the sandstone body, quartz-rich zones exhibit higher reservoir quality due to stronger grain frameworks and reduced cementation, while zones with abundant feldspars and clays are regarded as poor for reservoir quality (Pettijohn et al., 1987; Bloch et al., 2002; Worden & Burley, 2003; Bjørlykke, 2010).

Overall, the Gombe Sandstone in Gabukka demonstrates significant but variable reservoir potential, with the most favorable sites occurring where quartz is dominant with minimal aluminosilicate minerals and reservoir quality degrading depositional condition and diagenetic alteration is least expected. Reservoir potential is controlled by the interplay between primary depositional features, especially grain size and sorting and secondary diagenetic modifications such as compaction, cementation, and dissolution (Schmidt & McDonald, 1979; Worden & Burley, 2003; Bjørlykke, 2010). Additionally, these results confirm that the Gombe Sandstone exhibits textural maturity and compositional prowess favourable for reservoir quality

enhancement. The medium to coarse grained sediments and relatively good sorting enhance porosity and permeability, while the consistent grain-size distribution across samples suggests stable depositional energy and uniform sediment supply within the area (Beard & Weyl, 1973; Pettijohn et al., 1987; Bjørlykke, 2010).

Provenance and Depositional settings

Quartz is the principal mineral in the Gombe Sandstone, accompanied by lesser amounts of orthoclase, albite, and muscovite. This mineral assemblage indicates a stable felsic plutonic source, such as granite or gneiss, and reflects a high degree of mineralogical maturity (Blatt et al., 1980; Pettijohn, 1987; Boggs, 2009). Geochemical results further show that the sandstone is compositionally mature and highly enriched in quartz, as demonstrated by elevated SiO_2 values (65.8–78.9 wt.%). These characteristics support derivation from felsic continental rocks and imply repeated sediment reworking. The moderate Al_2O_3 contents (10.3–18 wt.%) correspond to feldspar and clay minerals, indicating partial feldspar alteration and moderate chemical weathering typical of fluvial–deltaic depositional systems.

Integrating the mineralogical data with grain-size characteristics such as sorting, skewness, and mean size has justifiable establish that the sediments were deposited in a fluvial to fluvio-deltaic environment, governed by shifting flow regime associated with fluvial settings (Miall, 1996; Nichols, 2009). The dominance of quartz, together with lesser amounts of feldspar, points to a granitic provenance. The occurrence of feldspar and Fe-bearing aluminosilicates like chlorite and muscovite supported with variable Fe_2O_3 values (1.71–9.63 wt.%) which point to localized ferruginization and variable oxidation levels, reflects oxidizing subaerial conditions typical of continental fluvio-deltaic setting (Pettijohn, 1987; Boggs, 2009; Tucker, 2001). Extremely low CaO and MgO concentrations further indicate minimal carbonate or dolomite cementation, reinforcing the predominantly continental deposition.

The sandstone deposit at Gabbuka River indicates deposition under variable flow conditions within a fluvial system. This interpretation is consistent with wider reports that classified the Gombe Formation as a Late Cretaceous continental to marginal-marine deposit in the Upper Benue Trough (Zaborski et al., 1997; Obaje, 2009). The distribution of major oxides further supports this interpretation, showing deposition in oxidizing, relatively high-energy fluvial environments, where reservoir quality is largely controlled by quartz enrichment, minimal carbonate cementation, and spatially variable cementing materials.

Conclusions

Integrating granulometric, mineralogical, and geochemical data of Gombe Sandstone exposed at Gabukka River, within the Upper Benue Trough, is useful in understanding sediment depositional evolution, provenance, paleoclimate, and reservoir potential.

Grain-size distribution varies greatly from fine- to coarse-grained sandstones with moderate to poor sorting, fine-skewness, and platykurtic curves, reflecting deposition under fluctuating hydrodynamic conditions typical of fluvial systems.

Mineralogical composition is dominated by quartz with feldspars, muscovite, kaolinite and chlorite indicating moderate to high compositional maturity and derivation from felsic continental source rocks.

Major oxide geochemistry shows abundance of SiO_2 and moderate Al_2O_3 contents, Fe_2O_3, K_2O, MnO, P_2O_5, CaO and MgO and confirms quartz enrichment through hydraulic sorting and support a predominantly continental depositional setting.

The high weathering indices couple with occurrence of kaolinite suggests the dominance of intense chemical weathering under warm, humid Late Cretaceous climatic conditions, with limited burial diagenetic overprint.

Reservoir potential ranges from moderate to good and reservoir quality is still within the realm of depositional influences.

Overall, the Gombe Sandstone represents a quartz-rich fluvial–deltaic siliciclastic system derived from felsic continental sources, with reservoir heterogeneity primarily governed by depositional facies architecture and mineralogical maturity.

References

Abdulkarim, S. I., Maigari, A. S., Haruna, A. I., Samaila, N. K., Nnakenyi, N. I., Mohammed, M., & Kariya, I. I. (2024). Paleoenvironmental interpretation of the Upper Cretaceous and Tertiary sedimentary deposits in the Gongola Sub-Basin, Upper Benue Trough, NE Nigeria. *FUDMA Journal of Sciences, 8*(3), 154–162.

Abubakar, M. B., Dike, E. F. C., & Ojo, O. J. (2022). Provenance and tectonic setting of Cretaceous sediments in the Upper Benue Trough, northeastern Nigeria: Evidence from integrated geochemical datasets. *Journal of African Earth Sciences, 188*, 104472.

Adekeye, O. A., Ahmed, H. A., & Yusuf, A. S. (2024). Mineralogical controls on diagenesis and reservoir quality of Upper Cretaceous sandstones, Gongola Sub-Basin, Nigeria. *Marine and Petroleum Geology, 160*, 106743.

Adeyemi, G. O., & Oladunjoye, M. A. (2023). Clay mineral assemblages and paleoweathering signatures of Cretaceous sandstones in a tropical basin setting, Nigeria. *Sedimentary Geology, 452*, 106389.

Ahmed, H. A., Abubakar, M. B., & Shettima, A. (2023). Geochemical constraints on provenance and depositional setting of Campano-Maastrichtian Gombe Sandstone, Northern Benue Trough. *Journal of African Earth Sciences, 197*, 104798.

Bello, A. M., Usman, M. B., Ismail, M. A., Mukkafa, S., Abubakar, U., Kwami, I. A., & Chiroma, L. U. (2023). Linking diagenesis and reservoir quality to depositional facies in marginal to shallow marine sequence: An example from the Campano-Maastrichtian Gombe Sandstone, Northern Benue Trough, NE Nigeria. *Marine and Petroleum Geology, 155*, 106386.

Falade, A. O., Oni, T. E., & Olorunsola, O. S. (2025). Integrated geochemical and mineralogical evaluation of sandstone reservoirs in a basement-influenced sedimentary basin. *Discover Geoscience, 3*(1), Article 212.

Guo, X., Zhang, L., Wang, Y., & Li, J. (2021). Diagenetic evolution of clay minerals and its impact on reservoir quality in clastic sedimentary basins. *Sedimentary Geology, 417*, 105874.

Idris, M. D., Yandoka, B. M. S., Ayuba, M. K., & Abdullahi, I. M. (2025). Biostratigraphy, thermal maturity and paleoenvironment of the basal part of Gombe Formation from Gongola Sub-Basin, Northern Benue Trough, Northeastern Nigeria. *Journal of Science Research and Reviews, 2*(4), 65–78.

Irunkwor, T. C., Molua, C. O., Okobia, C., & Eze, C. N. (2025). Clay mineral transformation, weathering indices and implications for reservoir quality in tropical sedimentary basins. *Discover Geoscience, 3*(1), Article 256.

Omolaiye, G. E., Oniyangi, A. K., & Issa, T. A. (2024). Integrated mineralogical and geochemical investigation of subsurface sediments for foundation and reservoir characterization. *Discover Geoscience, 2*(1), Article 103.

Zhou, X., Li, Z., & Sun, W. (2022). Clay mineral diagenesis and its influence on reservoir quality evolution in clastic sedimentary systems. *Marine and Petroleum Geology, 138*, 105567