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## Chemostratigraphy and Paleoenvironmental Evolution of the Late Maastrichtian Gombe Formation Along Gabukka Stream Section, Gongola Sub-Basin Northern Benue Trough, Northeastern Nigeria

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### Abstract

The Late Maastrichtian sedimentary succession of the Gombe Formation in the Gongola Sub-basin of the Benue Trough preserves a high-resolution record of paleoenvironmental fluctuations immediately preceding the terminal Cretaceous. This study integrates chemostratigraphic analysis with paleoenvironmental reconstruction of the Gombe Formation exposed along the Gabukka Stream section, northeastern Nigeria. Systematic sampling of mudstone facies was conducted across measured stratigraphic intervals, and geochemical characterization was performed using X-ray fluorescence (XRF) to quantify major and trace element compositions. Key elemental ratios, including Ti/Al, K/Al, Si/Al, Fe/Mn, and Sr/Ca, were employed as proxies for detrital influx, sediment maturity, redox conditions, and marine influence. The results delineate three distinct chemostratigraphic zones characterized by systematic vertical geochemical variability. Elevated Ti/Al and K/Al ratios define intervals of intensified terrigenous input, likely linked to enhanced continental weathering and sediment supply. Conversely, fluctuations in Fe/Mn ratios indicate variable bottom-water redox conditions, reflecting shifts between relatively oxic and suboxic depositional environments. Trends in Sr/Ca ratios further suggest episodic marine incursions and variations in salinity regimes. Collectively, the geochemical signatures document a progressive paleoenvironmental transition from proximal, high-energy siliciclastic settings dominated by continental input to more distal, marine-influenced conditions during the Late Maastrichtian. This transition is consistent with regional transgressive trends recognized within the northern Benue Trough. The study refines the chemostratigraphic framework of the Gombe Formation and provides critical insights into sedimentary processes, basin dynamics, and paleoenvironmental evolution during the latest Cretaceous, with implications for regional stratigraphic correlation and basin analysis.

### Keywords

*Chemostratigraphy, Paleoenvironmental reconstruction, Gombe Formation, Gongola sub-basin, Benue Trough, Late Maastrichtian, Northeastern Nigeria*

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## Introduction

Sedimentary successions deposited within foreland and intracratonic basins during the Late Cretaceous Period provide important records of tectonic evolution, sea-level fluctuations, and paleoenvironmental changes associated with the final stages of the Cretaceous. These basins commonly accumulate thick clastic sequences that preserve detailed information on sediment provenance, depositional processes, and basin subsidence history. As a result, they represent valuable archives for reconstructing paleogeographic evolution and environmental dynamics during a time marked by significant global climatic and oceanographic changes. The integration of stratigraphic, sedimentological, and geochemical datasets has therefore become increasingly important for understanding the complex interactions between tectonics, sediment supply, and depositional environments in Late Cretaceous sedimentary basins.

In West Africa, one of the most prominent Cretaceous sedimentary basins is the Benue Trough, an elongated intracontinental rift basin that developed during the early stages of the opening of the South Atlantic Ocean. The trough extends across central Nigeria and is subdivided into several sub-basins, including the Gongola Sub-basin in the northeastern part of the basin. This sub-basin contains a well-preserved succession of Upper Cretaceous sedimentary formations that record the progressive evolution of depositional environments from marine to continental conditions during the Late Cretaceous.

Among these units, the Gombe Formation represents an important Late Maastrichtian

stratigraphic unit composed predominantly of sandstones, shales, and siltstones deposited in marginal marine to deltaic environments. The formation provides valuable insights into the depositional history and paleoenvironmental conditions that prevailed in the northern Benue Trough during the latest Cretaceous. Despite several sedimentological and stratigraphic studies conducted on the formation, detailed geochemical investigations aimed at establishing chemostratigraphic frameworks and reconstructing paleoenvironmental evolution remain relatively limited.

Therefore, this study focuses on the chemostratigraphic characterization of the Gombe Formation exposed along the Gabukka Stream section within the Gongola Sub-basin. By integrating lithostratigraphic observations with major elemental geochemical data, the study aims to establish chemostratigraphic zones and reconstruct the paleoenvironmental evolution of the depositional system during the Late Maastrichtian.

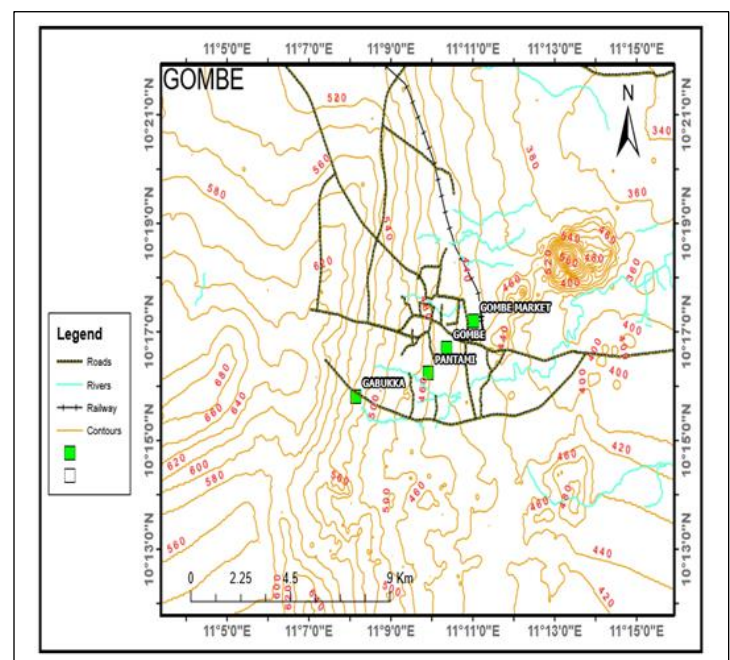


Figure 1: Map of the study area

## GEOLOGICAL SETTING

The Benue Trough of Nigeria is a rift basin in central West Africa that extends NNE-SSW for about 800 km in length and 150 km in width. The southern limit is the northern boundary of the Niger Delta while the northern limit is the southern boundary of Chad basin. The trough contains up to 6000m of Cretaceous-Tertiary sediments of which those predating the mid-Santonian have been compressionaly folded, faulted and uplifted in several places. Compressional folding during the mid-Santonian tectonic episode affected the whole of the Benue trough and was quite intense, producing over 100 anticlines and synclines (Benkhelil, 1989).

The Benue Trough is divided into Lower, Middle, and Upper by Cratchley & Jones (1965), Offodile (1976), Benkhelil (1982, 1989) and Zaborski et al., (1997) refined this classification. Nwajide (2013) subdivided it into Southern, Central and Northern. 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 Upper Benue Trough comprises the area extending from Bashar-Mutum Biyu line as far north as the "Dumbulwa-Bage high" which separate it from the Bornu Basin, (Zaborski et al., 1998). Early studies of the Upper Benue Trough and Southern Bornu Basin were carried out by Falconer (1911), Jones (1932). The basis for all later work was provided by Carter et al. (1963). The geology and stratigraphy of Northern Benue Trough was described in detail by Carter et al. (1963), Offodile (1976), Benkhelil (1989), Zaborski et al. (1997), Abubakar (2006) and Tukur et al. (2015).

The stratigraphic succession in the Gongola sub-basin of the Northern Benue Trough comprises the Aptian-Albian Continental Bima Formation, The Cenomanian transitional-marine Yolde Formation, the Cenomanian-Santonian marine Pindiga Formation, the Campano-Maastrichtian Deltaic Gombe Formation and Tertiary Continental Keri-Keri Formation.

The Gombe Formation is the youngest Cretaceous lithostratigraphic unit in the Gongola sub-basin of the northern Benue Trough, exposed around Gombe town. The type section is in the Kware/Pantami river area. It is a mainly continental siliciclastic succession consisting of sandstones, interbedded siltstones/shales, ironstones and occasional lignite/coal horizons. It typically reaches a few hundreds of metres in thickness at the type locality.

The formation was earlier recognized as Gombe grits and clay by Falconer (1911). Carter et al (1963) called them Gombe sandstone. It unconformably overlies the Pindiga formation and is Maastrichtian in age. The Gombe Formation is restricted to the Gombe western part of Gongola basin. It weathers to produce a ferruginous capping. This resistant material along with iron stone weathered out of the formation is responsible for the rugged and hilly topography characterizing much of its outcrops. In sub-crop, the Gombe Formation extends to the west beneath most of the Kerri-Kerri Basin (Dike 1993). Zaborski et al (1997) identified three (3) main lithofacies which may be considered as members: The prodeltaic facies, the bedded facies and the red sandstone facies

The Gombe Formation exhibits rapid lateral facies changes, variable thickness and local unconformities, producing correlation difficulties across outcrops and between wells (Shettima et al., 2020; Didi et al., 2025). Sequence-stratigraphic interpretations commonly place much of the Gombe into

regressive (high-stand/progradational) deltaic packages with episodic fluvial incision and local lowstand features; this architecture explains the prevalence of fining-upward channel fills, mouth-bar deposits and overbank facies in different parts of the basin (Odedede & Adaikpoh; Shettima et al., 2020).

Age	Gongola Arm	Yola Arm	Paleoenvironment	
Tertiary	Kerri - Kerri Formation		Continental (Fluvial / Lacustrine)	
Maastrichtian	Gombe Sandstone	Erosion?	Continental (Lacustrine / Deltaic)	
Companian				
Santonian	Pindiga Formation	Lamja	Marine (Offshore / Estuarine)	
Coniacian		Numanha		
Turonian		Sekuliye		
		Jessu		
	Kanawa	Dukkul		
Cenomanian	Yolde Formation		Transitional	
Albian and older	Upper Bima Sandstone Member		Braided	Continental
	Lower Bima Sandstone Member		Alluvial/Braided Lacustrine	
Precambrian	Basement Complex		Igneous/Metamorphic	

Figure 2: Stratigraphic successions of the Northern Benue Trough, Nigeria (modified from Abubakar 2006; Tukur et al 2015)

**Methodology**

Topographic and geologic map of Gombe town and environ were utilized to identify areas with well-exposed outcrops of the Gombe Formation as part of the fieldwork exercise. Along these well exposed outcrops identified, lithostratigraphic sections of this formation outcropping around Gabukka stream, were systematically logged to record data on lithologic variations, colour, texture, bed geometry, sedimentary structures and fossil content. These observations were made while traversing along foot paths, stream channels and other paths forming the access route in

the study area. Representative samples from the Gombe Formation were carefully collected and labelled accordingly

Geochemical analysis was conducted on seven (7) representative mudstone samples collected. 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 millimetres 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. Standard less 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.

### Geochemical Data Treatment

#### Normalization and Ratios

To minimize the effect of detrital dilution and grain size variations, geochemical ratios were employed. Al<sub>2</sub>O<sub>3</sub> was used as a normalization factor because of its association with fine-grained aluminosilicates and relative immobility during diagenesis. Element Al<sub>2</sub>O<sub>3</sub> ratios were computed for both major and trace elements.

### Enrichment Factor (EF) Calculations

Two levels of enrichment factor analysis were undertaken:

#### 1. Formation Mean Normalized EF

Chemozones were delineated using enrichment factors relative to the formation mean. Samples were normalized using the immobile element Zr. Redox-sensitive elements (V, Ni, Zn, Cr) showed distinct vertical enrichment patterns that permitted subdivision into CZ-1 (base), CZ-2 (middle), and CZ-3 (top).

The enrichment factor for each element was calculated using the formula:

$$EF_{x, formation} = \frac{\left(\frac{x}{Al}\right)_{sample}}{\left(\frac{x}{Al}\right)_{formation\ mean}}$$

Where;

$\left(\frac{x}{Al}\right)_{sample}$  is concentration of the element of interest

$\left(\frac{x}{Al}\right)_{formation\ mean}$  is concentration of reference element Al, wherein elements were categorized as enriched (EF > 1) or depleted (EF < 1) based on their calculated values facilitating an understanding of elemental distribution patterns.

#### 2. Upper Continental Crust (UCC) Normalized EF

Using Upper Continental Crust (UCC) values (Rudnick & Gao, 2003), (Table 1) enrichment factors were recalculated

Table 1: Upper Continental Crust (UCC) values from Rudnick & Gao (2003, revised)

Element/Oxide	Unit symbols	Concentration (%)
SiO <sub>2</sub>	%	66.62
Al <sub>2</sub> O <sub>3</sub>	%	15.40
Fe <sub>2</sub> O <sub>3</sub>	%	4.97
TiO <sub>2</sub>	%	0.64
K <sub>2</sub> O	%	2.80
V	Ppm	97
Cr	Ppm	92
Ni	Ppm	47
Zn	Ppm	67
Zr	Ppm	193

The enrichment factor for each element was calculated using the formula:

$$EF_{x, formation} = \frac{\left(\frac{x}{Al}\right)_{sample}}{\left(\frac{x}{Al}\right)_{UCC}}$$

Where;

$\left(\frac{x}{Al}\right)_{sample}$  is concentration of the element of interest

$\left(\frac{x}{Al}\right)_{UCC}$  is concentration of UCC

wherein elements were categorized as enriched ( $EF > 1.3$ ) or depleted ( $EF < 0.7$ ) based on their calculated values facilitating an understanding of elemental distribution patterns. Values  $> 3$  suggest strong paleo environmental control, often linked to redox conditions and organic matter preservation.

## RESULTS AND DISCUSSION

### Major Element Geochemistry

The XRF analysis of the Gombe Formation mudstones shows systematic variations in major oxides (wt.%). The dominant oxides include  $SiO_2$ ,  $Al_2O_3$ ,  $Fe_2O_3$ ,  $TiO_2$ , and  $K_2O$ , with variable contributions from  $CaO$ ,  $MgO$ ,  $MnO$ , and  $P_2O_5$ .

Table 2: Result of major oxides of mudstone samples from Gombe Formation

Oxides	$SiO_2$	$Al_2O_3$	$Fe_2O_3$	$TiO_2$	$K_2O$	$CaO$	$MnO$	$P_2O_5$
A3	60.6	21.9	7.58	3.79	2.51	0.826	0.138	1.56
A5	62.8	22.9	4.77	4.09	2.35	0.666	0.218	1.54
A12	64.2	21.6	4.11	4.49	2.17	0.836	0.0736	1.46
A23	67.6	20.9	3.36	4.33	1.09	0.538	0.0132	1.41
A25	67.2	21.4	3.84	3.82	1.18	0.472	0.0164	1.51
A29	68.1	19.3	3.83	3.78	2.28	0.526	0.0295	1.50
A31	67.1	21.9	3.59	3.93	1.08	0.378	0.0138	1.56

The major oxide data for the Gombe Formation mudstones reveal a lithochemical signature dominated by siliceous and aluminous constituents, typified by high  $SiO_2$  (60.6-68.1 wt%) and  $Al_2O_3$  (19.3-22.9 wt%). These values indicate a mature siliciclastic composition, characteristic of sediments derived from a felsic continental source, likely the granitic and gneissic basement rocks of the northern Benue Trough region.

The elevated  $SiO_2/Al_2O_3$  ratio, averaging around 3.0, points to significant quartz enrichment and sedimentary recycling, while the steady  $TiO_2$  content (3.7-4.5 wt%) implies

a relatively uniform provenance dominated by stable heavy minerals such as rutile and ilmenite. The observed variation between samples suggests subtle fluctuations in detrital influx rather than drastic changes in sediment source.

$Fe_2O_3$  values, ranging from 3.36 to 7.58 wt%, decrease upwards through the section, reflecting a progressive decline in iron-bearing clay minerals and possibly in the content of Fe-oxide cement. This trend, coupled with low and declining  $CaO$  contents (0.83-0.38 wt%), indicates progressive depletion of carbonate phases and enhanced chemical weathering

toward the top of the formation. The consistently low MnO and moderate K<sub>2</sub>O values (1.1-2.5 wt%) suggest dominance of illite and kaolinite clays, with minimal feldspar diagenesis. The geochemical maturity of the mudstones increases upward, demonstrating a transgressive to regressive cycle, where early deposits formed under relatively quiescent marine conditions and the upper beds were deposited under more oxygenated, proximal settings.

The Al<sub>2</sub>O<sub>3</sub>-TiO<sub>2</sub> association provides additional insight into sediment provenance. Their positive correlation implies derivation from weathered continental crust materials rather than mafic volcanic sources. The higher Al<sub>2</sub>O<sub>3</sub> and TiO<sub>2</sub> in the lower units (A3-A5) point to clay-rich intervals, consistent with low energy, distal depositional environments, possibly corresponding to maximum flooding phases when detrital dilution was minimized. The upward trend of increasing SiO<sub>2</sub> with decreasing Fe<sub>2</sub>O<sub>3</sub> and Al<sub>2</sub>O<sub>3</sub> corresponds to a shift from clay rich marine mudstones to more quartzose, nearshore deposits, signaling regression and basin shallowing.

Overall, the major oxide geochemistry of the Gombe Formation supports deposition from weathered felsic source rocks, reworked by longshore or deltaic currents under alternating oxidizing and reducing conditions. The combination of high SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub>, low CaO, and moderate Fe<sub>2</sub>O<sub>3</sub> suggests deposition in a non-calcareous, silicate-dominated setting, with variations tied to paleoredox fluctuations and sedimentation rate. This interpretation is consistent with regional studies on Upper Cretaceous formations in the Gongola Sub-basin, which describe the Gombe mudstones as the uppermost siliciclastic unit of the Campanian-Maastrichtian regression, characterized by quartz dominated detritus sourced from the uplifted basement terranes of northeastern Nigeria.

#### Trace Element Geochemistry

The analyzed mudstones are enriched in several trace elements, particularly those sensitive to redox conditions. Table 3 summarizes the raw concentrations of key trace elements (ppm).

Table 3: Selected Trace Element Concentrations (ppm)

Trace Elements	V	Cr	Ni	Cu	Zn	Zr	Rb	Sr
A3	471	243	124	116	143	1980	163	766
A5	490	374	91.9	95.4	245	1270	141	248
A12	831	193	61.1	81.7	110	1640	127	260
A23	493	253	44	82	73.9	2050	78.4	123
A25	405	127	62.3	89.6	85.7	1670	63.5	120
A29	406	183	69.2	89.3	84.7	1320	137	168
A31	259	208	63	110	90.6	2020	61.6	114

The trace element concentrations of the Gombe Formation mudstones exhibit systematic vertical variations that provide critical insights into paleo environmental, provenance, and redox dynamics during deposition. Redox-sensitive elements such as V (259-831 ppm), Cr (127-374 ppm), Ni (44-124 ppm), and Cu (82-116 ppm) show pronounced enrichment in the lower and middle samples (A3-A12), indicating deposition under reducing to suboxic conditions. The marked increase in vanadium and nickel in A12 reflects a phase of maximum anoxia, likely corresponding to a maximum flooding surface, when bottom waters were stagnant, organic matter preservation was high, and trace metals were effectively sequestered into the sediments.

In contrast, the upper intervals (A23-A31) show lower concentrations of these redox-sensitive metals, consistent with better-oxygenated depositional environments. The decrease in V and Ni upward signifies a paleo environmental shift from a dysoxic to oxic regime, reflecting basin shallowing or improved water circulation during regression. The presence of moderately high Cu and Zn in some midsection samples may also reflect increased organic productivity, as these elements often associate with planktonic activity and organic matter binding in reducing settings. Their decrease upward implies reduced organic matter input or more oxidizing diagenetic conditions that remobilized these elements out of the sediments.

Detrital proxies such as Zr, Rb, and Sr offer further clues. Zr values ranging from 1270 to 2050 ppm suggest significant contribution of heavy mineral fractions, particularly zircon,

indicating a recycled sedimentary provenance. The moderately high Rb (61-163 ppm) points to a clay-rich mineralogy dominated by illite and mica, reflecting strong chemical weathering of source rocks. Sr values (114-766 ppm) decline upward, supporting a transition from carbonate or shell bearing facies to purely siliciclastic ones, consistent with a regressive phase in which terrestrial sediment input diluted marine components.

Overall, the trace element data reflect deposition in a marine-dominated but variable redox environment, transitioning from anoxic to oxic upward through the stratigraphy. This pattern aligns well with regional studies in the Upper Benue Trough (e.g., Abdullahi et al., 2019; Oha et al., 2021), which report similar trends in redox-sensitive element behavior during late Cretaceous sea-level fluctuations. The enrichment of V and Ni in the lower units underscores their potential as hydrocarbon source intervals, while the upper sandy mudstones (with lower metal enrichment) may act as seal or reservoir transition facies in petroleum systems.

### **Chemostratigraphy of Gombe Formation**

The lithosection of the Gombe Formation has been sub-divided into three chemozones based on the geochemical compositions of the representative samples of mudstones which display the chemostratigraphic signatures of the data which enhance the visibility of the features of the geochemical intervals. This indicates the elemental enrichment, depletion, and continued trends as related to geochemical profiles. The studied intervals have been divided into three distinct chemozones to reflect subtle variations

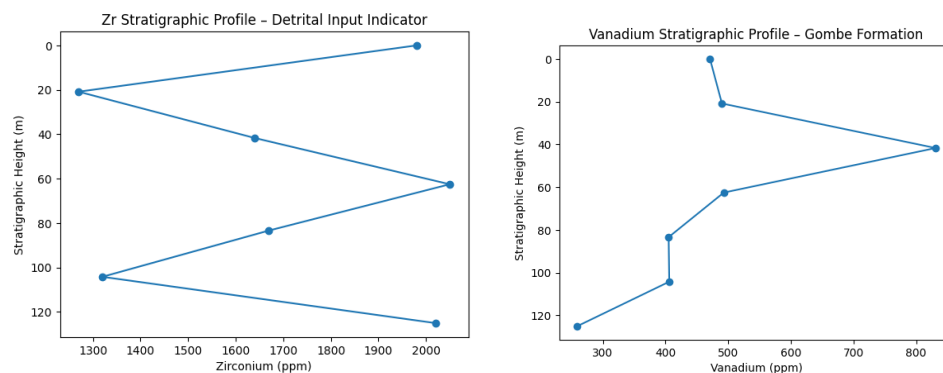


Figure 3: Chemostratigraphic profile of Zr and V

### Chemozone 1 (CZ-1)

Chemozone 1 is characterized by relatively high  $\text{SiO}_2$  (~67 wt%) and moderate  $\text{Al}_2\text{O}_3$  (~3.8-4.1 wt%) and  $\text{Fe}_2\text{O}_3$  (~3.7-4.8 wt%), with trace-element concentrations of  $\text{V} \approx 350$  ppm,  $\text{Cr} \approx 170$  ppm and  $\text{Ni} \approx 65$  ppm. Enrichment factors (EFs) for redox-sensitive elements cluster near unity ( $\text{EF} \approx 0.7-1.2$ ), indicating predominantly detrital control rather than authigenic enrichment. Redox ratios ( $\text{V}/\text{Cr} \approx 2$ ;  $\text{Ni}/\text{Co} < 5$ ) are consistent with oxic to dysoxic bottom-water conditions. The elevated  $\text{Si}/\text{Al}$  ratio indicates a higher quartz (siliclastic) to clay fraction, consistent with deposition from fine siliclastic suspension under well-oxygenated conditions. Thus CZ 1 is interpreted as a relatively oxygenated shelf/marginal marine mudstone deposited under moderate-energy conditions with predominant detrital (siliclastic) supply.

### Chemozone 2 (CZ 2)

Chemozone 2 stands out as a short but pronounced geochemical interval with a near-twofold increase in V ( $\approx 831$  ppm) and a modest increase in  $\text{Fe}_2\text{O}_3$  ( $\approx 4.5$  wt%).  $\text{V}/\text{Cr} > 4$  and  $\text{V}/(\text{V}+\text{Ni}) > 0.6$  place CZ 2 firmly in the anoxic category using conventional geochemical criteria, while V-EF values above 1.3 indicate enrichment beyond detrital background. These signatures are best explained by a transient

episode of reduced bottom water conditions or strong redox stratification leading to enhanced fixation of redox-sensitive metals in sediments (possibly aided by organic matter preservation). The lack of major changes in  $\text{SiO}_2/\text{Al}_2\text{O}_3$  suggests the lithology remained mudstone (detrital input unchanged), so the geochemical anomaly likely reflects water column redox dynamics rather than provenance. CZ 2 is therefore interpreted as a short lived dysoxic to anoxic event (a reducing pulse) within the Gombe Formation, potentially recording a local transgression, stratified basin, or increased organic flux.

### Chemozone 3 (CZ 3)

Chemozone 3 records a return to intermediate trace element concentrations ( $\text{V} \approx 400$  ppm,  $\text{Cr} \approx 185$  ppm,  $\text{Ni} \approx 64$  ppm) and EFs close to unity for most elements, combined with  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$  similar to CZ 1. The  $\text{V}/\text{Cr}$  and  $\text{Ni}/\text{Co}$  ratios indicate dysoxic to oxic conditions, i.e., a transition back from the anoxic pulse of CZ 2 towards more oxygenated bottom waters. Variability in Zr and  $\text{TiO}_2/\text{Al}_2\text{O}_3$  in CZ 3 suggests fluctuations in heavy-mineral content or sediment sorting/supply, indicating episodic shifts in sediment provenance or transport energy. Taken together, CZ 3 represents a stabilization of depositional conditions with dominant detrital input and intermittent minor

redox fluctuations consistent with a prograding shelf environment or re-establishment of normal circulation after a short anoxic event.

### Enrichment Factor (EF)

Formation-Mean Normalized EF

Chemozones were delineated using enrichment factors relative to the formation mean. Samples were normalized using the immobile element Zr. Redox-sensitive elements (V, Ni, Zn, Cr) showed distinct vertical enrichment patterns that permitted subdivision into CZ-1 (base), CZ-2 (middle), and CZ-3 (top).

Table 4: Trace Elements Enrichment Factors (relative to formation mean)

Samples	Elements							
	V	Cr	Ni	Cu	Zn	Zr	Rb	Sr
A3	0.961	0.959	1.134	0.745	1.660	1.157	1.084	0.926
A5	0.884	1.307	0.870	0.642	1.559	1.195	1.106	1.025
A12	1.335	0.662	0.537	0.491	0.700	0.994	0.839	0.962
A23	0.825	0.911	0.387	0.494	0.470	0.711	0.880	1.179
A25	0.678	0.498	0.408	0.540	0.544	0.942	0.917	1.147
A29	0.742	0.719	0.646	0.559	0.537	1.000	1.031	0.961
A31	0.504	1.136	0.650	0.745	0.574	0.379	1.142	0.800

The enrichment factor (EF) analysis relative to the formation mean provides a powerful means of identifying intraformational chemical zonation and isolating redox and provenance variations within the Gombe Formation.

Lower samples (A3-A5) exhibit EF values  $>1$  for V, Ni, and Zn, signifying enrichment relative to the overall formation average. This enrichment points to deposition under reducing conditions, possibly within stagnant sub-basins where trace metals accumulated in association with organic matter. The relatively high Cr and Zr in these intervals support detrital influx concurrent with metal enrichment, implying mixed detrital and authigenic controls.

Midsection samples, notably A12, show strong depletion in most elements ( $EF < 1$ ), except for moderate enrichment in V (1.335). This pattern reflects deposition during a maximum flooding event, where dilution by fine-grained detritus and uniform marine geochemistry produced

more homogenized trace element concentrations. The decrease in detrital proxies such as Zr and Rb during this interval suggests reduced sediment input, consistent with a deep-water, low-energy setting.

Upward through the sequence (A23-A31), redox-sensitive elements show pronounced depletion ( $EF < 1$ ), while Rb and Sr exhibit slight enrichment. This pattern suggests a shift to more oxygenated, shallow-marine environments with increased detrital and carbonate input. The enrichment of Sr, in particular, implies enhanced biogenic or carbonate contributions during late-stage regression, while Rb enrichment reflects increasing clay and feldspar input from proximal sources.

These trends delineate a vertical evolution from anoxic, metal-rich bottom waters to well-oxygenated nearshore conditions,

representing a typical transgressive-regressive cycle. Thus, the formation mean normalized enrichment patterns serve as chemostratigraphic markers, defining Chemozone 1 (A3-A5) as metal-enriched and reducing, Chemozone 2 (A12) as transitional and stratified, and Chemozone 3 (A23-A31) as oxidizing and proximal. The vertical alternation of enrichment and depletion zones closely mirrors sequence stratigraphic frameworks

observed in analogous Upper Cretaceous formations of the Benue Trough (e.g., Gongila and Pindiga formations), reinforcing the value of intraformational chemostratigraphy as a quantitative correlation tool.

**Upper Continental Crust-Normalized EF**

Using Upper Continental Crust (UCC) values (Rudnick & Gao, 2003), (Table 1) enrichment factors were recalculated

Table 5: Trace Elements Enrichment Factors (relative to UCC)

Samples	Elements							
	V	Cr	Ni	Cu	Zn	Zr	Rb	Sr
A3	3.312	1.857	2.565	1.128	2.454	1.512	1.209	0.934
A5	3.295	2.734	1.818	0.972	2.289	1.563	1.234	1.034
A12	5.925	1.496	1.281	0.843	1.027	1.301	0.936	0.971
A23	3.633	2.026	0.954	0.849	0.690	0.930	0.982	1.189
A25	2.914	0.993	1.319	0.929	0.798	1.232	1.024	1.157
A29	3.240	1.587	1.624	0.962	0.787	1.308	1.152	0.970
A31	1.821	1.590	1.303	1.128	0.840	0.497	1.276	0.808

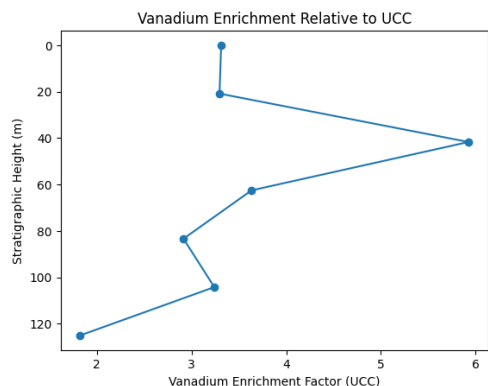


Figure 4: Vanadium enrichment relative to UCC

Normalization of trace elements to the Upper Continental Crust (UCC) provides an absolute basis for assessing enrichment or depletion relative to average crustal composition, highlighting both provenance and environmental controls. The lower and middle samples (A3-A12) exhibit strong V (3.3-5.9× UCC), Cr (1.5-2.7×), and Ni (1.2-2.6×)

enrichment, revealing deposition under suboxic to anoxic marine conditions conducive to trace metal fixation. These enrichments suggest effective scavenging of metals from seawater by organic matter and sulfides in a dysoxic water column. Cu and Zn, moderately enriched (0.8-2.4× UCC), further corroborate this interpretation, reflecting bioproductivity and

organic association within the lower succession.

In contrast, the upper samples (A23-A31) show progressive depletion of these redox-sensitive elements ( $EF < 1$ ), coupled with increased Zr enrichment (up to  $1.56 \times UCC$ ). This pattern marks a provenance shift toward detrital heavy mineral input and more oxygenated conditions that suppressed trace metal accumulation. The positive correlation between Zr and  $SiO_2$  suggests sediment derivation from a quartz-zircon-rich felsic source, consistent with mature sediment recycling and shoreline reworking during regression.

The Rb and Sr enrichment patterns provide additional constraints. Rb values near or slightly above UCC ( $0.9-1.3 \times$ ) imply an illitic clay component derived from weathered feldspathic source rocks, while Sr ratios near unity indicate minimal carbonate contribution and overall non-calcareous character. The vertical pattern of decreasing V-Ni-Cr coupled with stable Rb and increasing Zr suggests a transition from deep-water, reducing to shallow-water, oxidizing depositional conditions.

Overall, the UCC-normalized enrichment factors delineate three geochemically distinct zones consistent with the previously defined chemozones. Chemozone 1 (A3-A5) records the highest enrichment in redox-sensitive elements, representing a dysoxic-anoxic transgressive phase; Chemozone 2 (A12) captures maximum flooding with sustained metal accumulation; and Chemozone 3 (A23-A31) depicts the onset of regression and oxygenation. The magnitude of enrichment is comparable to values reported for Late

Cretaceous black shales in the Pindiga Formation and the Nigerian Anambra Basin, affirming the regional paleoceanographic controls on trace metal distribution during the Maastrichtian.

### **Interpretation of the chemozones using Upper Continental Crust Enrichment values**

The interpretation was made based on Rudnick & Gao (revised) UCC values for the elements relevant to the dataset (Table 3 and 4).

#### **Chemozone 1**

$EF(V) UCC \approx 3.3$  (moderate-to-strong enrichment vs UCC),  $EF(Cr) UCC \approx 2.3$ ,  $EF(Ni) UCC \approx 2.2$ . Vanadium is enriched relative to global crust ( $EF > 1.5$ ), but Cr and Ni show only moderate enrichment. In combination with major-oxide indicators ( $SiO_2$  high, Si/Al elevated), the package suggests predominantly detrital mudstone that nevertheless carries moderate vanadium enrichment. That pattern commonly indicates (a) enhanced supply or concentration of V-bearing detrital phases OR (b) some authigenic V fixation during early diagenesis in mildly reducing pore waters especially if TOC is low/moderate. Because V is strongly enriched but Ni only moderately, the setting is best described as mostly oxic-dysoxic with persistent moderate V enrichment, perhaps due to intermittently reducing microenvironments or background basin chemical conditions that favor some V accumulation but not sustained water-column anoxia.

#### **Chemozone 2**

$EF(V) UCC \approx 5.9$  (strong enrichment),  $EF(Cr) UCC \approx 1.50$ ,  $EF(Ni) UCC \approx 1.28$ . V/Cr and V/(V+Ni) ratios are also consistent with a reducing (anoxic) classification. There is an authigenic enrichment of Vanadium  $EF(V) > 3$

which is typically taken as strong enrichment relative to crustal background and commonly records redox-driven fixation of V under anoxic conditions (often coupled to organic matter preservation). The co-occurrence of elevated  $\text{Fe}_2\text{O}_3$  and strong V enrichment but only modest Cr/Ni enrichment implies a short-lived but clearly anoxic episode (water-column or pore water), during which redox-sensitive V was preferentially removed to the sediment. This is the clearest redox event in the section.

### Chemozone 3

EF(V) UCC  $\approx$  2.66 (moderate enrichment), EF(Cr) UCC  $\approx$  1.39, EF(Ni) UCC  $\approx$  1.42. Zr EF (high in some samples) indicates episodic heavy-mineral/zircon concentration. After the strong anoxic pulse at A12, conditions returned to more oxygenated/dysoxic conditions (V and Ni EF lower than A12), but moderate V enrichment persists relative to UCC. Combined with variable Zr and Ti signals this suggests a return to dominantly detrital mud deposition with episodic changes in sediment supply/sorting, and occasional local diagenetic V fixation but not sustained anoxia. It shows a recovery to more oxidic/dysoxic conditions with sedimentary provenance variability.

### CONCLUSION

#### Provenance, diagenesis, and tectono-sedimentary control:

Provenance:

The combination of high  $\text{SiO}_2/\text{Al}_2\text{O}_3$  ratios and significant but consistent  $\text{TiO}_2$  and Zr levels reflects derivation from a felsic continental basement source, most likely the granitic and gneissic terrains of the Nigerian Basement Complex bordering the Benue Trough.

Tectono-sedimentary control:

The observed vertical facies and chemozonal shifts reflect basin subsidence and sediment supply variations during the Late Maastrichtian regression of the Gongola Sub-basin. The interplay of tectonic uplift of the source terrain and gradual marine withdrawal controlled the progression from offshore muds to fluvial sands.

#### Global and regional correlations

Regionally, the integrated geochemical characteristics of the Gombe Formation align with those of the Pindiga and Gongola formations in the upper Benue Trough and with equivalent Campanian-Maastrichtian deltaic-marine successions in the Niger Delta and Chad Basin. These successions similarly show lower anoxic shales overlain by progressively coarser, oxygenated sandstones; interpreted as transgressive-regressive cycles.

Globally, comparable chemostratigraphic and textural evolution is observed in Cretaceous foreland basins (e.g., Western Interior Seaway, USA) and African intracratonic basins (e.g., Karoo, Tanzania), where trace-metal enrichment corresponds to maximum flooding intervals and quartz enrichment tracks regression and delta progradation. The high V and Ni enrichment factors (up to  $6\times$  UCC) are comparable to those in the Aptian-Albian oceanic anoxic shales of the Atlantic margins, though the Gombe values are less extreme, suggesting localized anoxia rather than global OAE conditions.

These correlations confirm that the Gombe Formation captures the regional paleoenvironmental transition from marine to continental systems during the terminal Cretaceous, a trend consistent across West Africa.

## Petroleum and paleoenvironmental implications

Chemozone 1 and 2 (fine-grained, matrix-rich, anoxic) represent potential hydrocarbon source rocks and top-seal intervals, due to high metal enrichment, high matrix content, and compacted texture.

Chemozone 3, dominated by quartzose sandstones with ferruginous cement, forms potential reservoir intervals, although diagenetic compaction and hematitic cement may locally reduce quality.

The observed vertical facies transition from anoxic mudstones to oxic sandstones suggests a self-sourcing, self-sealing system, a favorable configuration for small-scale petroleum entrapment within the Gombe Formation Gongola sub-basin system.

Paleoenvironmentally, the data record a shift from quiet, stratified, dysoxic marine shelf conditions to well-oxygenated, fluvio-deltaic systems, consistent with progressive regression and deltaic progradation during the Late Maastrichtian

This analysis portrays the Gombe Formation as a tectonically stable but climatically and eustatically dynamic depositional system, responding to sea-level and sediment supply changes that shaped its chemostratigraphic architecture and petroleum potential

Comparisons with analogous Cretaceous formations (e.g., the Campanian-Maastrichtian regressive successions of the Western Interior Seaway, USA, and the Karoo Basin, South Africa) demonstrate that the Gombe Formation represents a regional manifestation

of widespread Late Cretaceous regression across tropical Gondwanan basins.

Basically, the Gombe Formation is subdivided into three chemozones based on major and trace element variations, reflecting progressive environmental and provenance shifts. The Gombe Formation evolved from a low-energy, anoxic marine environment (CZ-1) through a maximum flooding interval (CZ-2) to a high-energy, oxic fluvial-deltaic system (CZ-3).

Comparison with Upper Cretaceous marine-deltaic successions globally show that Gombe Formation geochemistry is consistent with a regressive phase following localized anoxia, typical of Late Cretaceous foreland basins.

From a petroleum standpoint, the lower and middle fine-grained, metal-enriched mudstones constitute potential hydrocarbon source and seal intervals, whereas the upper quartzose sandstones represent possible reservoir facies, though secondary porosity may be reduced by ferruginous cementation.

Therefore, this dataset provides a high-resolution chemostratigraphic model applicable for correlation across the Gongola Sub-basin and for guiding future exploration efforts in the Benue Trough.

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