Depositional Environment of the Maastrichtian Mamu Formation, Anambra Basin; Integrated Sedimentological and Foraminiferal Analysis

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ABSTRACT

This study integrates sedimentological and foraminiferal analyses to investigate the depositional environment of a part of the Maastrichtian Mamu Formation, exposed in the Ibagba quarry (Owukpa) and Onyeama road-cut sections, Anambra Basin, southeastern Nigeria. Detailed field mapping, stratigraphic logging, and representative sample collection facilitated subsequent laboratory investigations. Lithological units are characterized by interbedded fine to medium-grained sandstones, shales, silty shales, and coaly units. Sedimentological analysis of the sandstones reveals moderate to poor sorting, leptokurtic to very platykurtic kurtosis, and strongly coarse to fine-skewed grain size distributions, indicative of a fluvially influenced paralic depositional setting with rapid deposition and varying hydrodynamic conditions, evidenced by grain size parameters and sedimentary structures (massive bedding and diverse laminations). Petrographic studies of the sandstone reveal an assemblage of quartz 92-93% and rock fragments of almost 4-5%, with no occurrence of feldspar, suggesting the grains are mineralogically mature and have been transported over a significant distance from their source. The low-diversity benthic foraminiferal assemblage, recovered from the shale units and dominated by agglutinated species (*Ammobaculites, Ammotium, Haplophragmoides, Reophax globosus, Ammobaculoides,* and *Lituola senoniensis*), suggests a dysoxic to suboxic paleoenvironment within a harsh, shallow, marine paralic setting characterized by fluctuating salinity (brackish to outer-shelf). The juxtaposition of these sedimentological and micropaleontological findings indicates a complex fluvio-marine transitional environment within the Anambra Basin during the Maastrichtian, marked by episodic marine incursions into a predominantly terrestrial, fluvial-dominated system.

Keywords: Mamu Formation, Sedimentology, Foraminifera, Paleoenvironment, Anambra Basin.

INTRODUCTION

The Anambra Basin, located in southeastern Nigeria, is characterized by a significant Cretaceous sedimentary succession, with the Maastrichtian Mamu Formation serving as a pivotal stratigraphic unit. This study examines the sedimentology and depositional environments of the Mamu Formation within the Owukpa Quarry and Onyeama road-cut sections to reconstruct the basin's paleoenvironmental evolution.

To comprehensively interpret the depositional dynamics of the Mamu Formation, a multi-proxy approach integrating sedimentological and foraminiferal analyses is employed. This method leverages the complementary nature of these techniques: sedimentological analysis elucidates sediment transport and depositional processes, while foraminiferal assemblages provide insights into paleoenvironmental conditions and the influence of the marine environment.

The primary objectives of this research are (i) to establish a detailed lithostratigraphic framework of the Mamu Formation at Owukpa and Onyeama through facies analysis and sedimentary structure documentation; and (ii) to quantitatively reconstruct the paleo-depositional environment, including salinity and oxygenation levels, using grain size parameters and foraminiferal assemblages. These objectives are achieved through field investigations focused on the Owukpa Quarry and Onyeama road-cut sections.

Previous studies have established a foundational understanding of the Mamu Formation. Simpson (1954) and Reyment (1965) documented its lithological framework, noting the interbedding of sandstones, shales, mudstones, and sandy shales that conformably overlie the Enugu Shales, as well as coal seams ranging in thickness from centimeters to 3.5 meters. Nwajide and Reijers (1997) linked the Mamu facies' coaling to Early Maastrichtian sea-level and climatic shifts, which promoted the growth of vegetation. Umeji (2000) classified the coal as sub-bituminous, indicative of coastal plain or strand plain deposition, and interpreted the formation as a deltaic complex. Gebhardt (1998), using benthic foraminifera, suggested that marine-to-brackish deltaic environments range from prodelta to lagoon and interdistributary bay settings.

Geological Setting

Regional Geology of the Anambra Basin

The Anambra Basin, a significant sedimentary province in southeastern Nigeria, originated from the extensional tectonics associated with the separation of the African and South American plates during the Mesozoic (Tijani et al., 2010). This basin, covering approximately 40,000 km² (Nwajide & Reijers, 1996), exhibits substantial sediment accumulation, reaching a thickness of up to 5,000 m (Uma & Onuoha, 1997). The basin is characterized by considerable lithological heterogeneity, both laterally and vertically, reflecting diverse paleoenvironmental settings from the Campanian to the Recent (Akaegbobi, 2005). A significant tectonic event during the Santonian, marked by deformation, folding, faulting, and uplift of Albian-Coniacian sediments (Benkhelil, 1989), initiated the primary phase of sediment deposition within the Anambra Basin (Nwajide, 1990; Tijani et al., 2010).

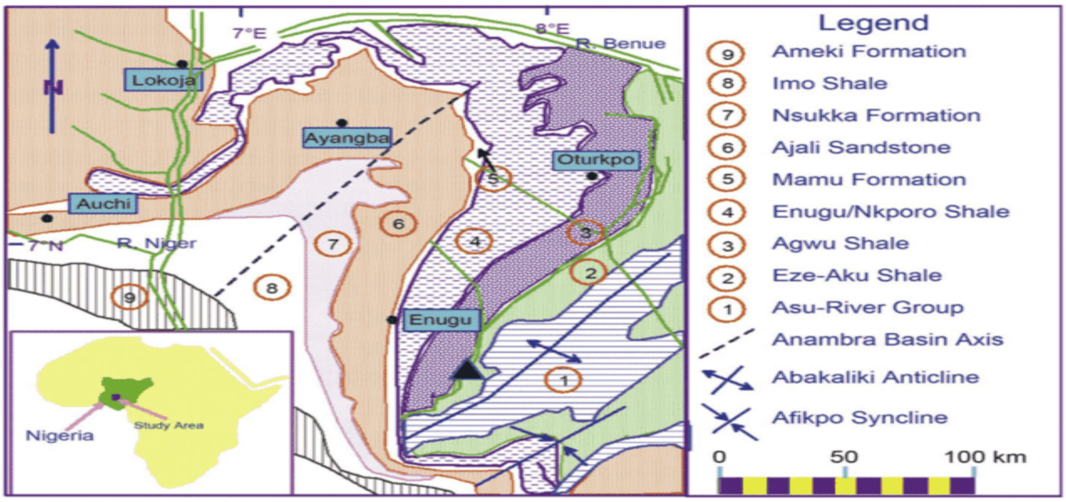

Fig. 1. Geological map of the Anambra Basin, southeastern Nigeria, showing the distribution of Cretaceous formations, including the Mamu Formation (5), and the location of key structural features. (Modified from Nton & Bankole, 2013).

Stratigraphic Framework of the Cretaceous Formations

The stratigraphic succession within the Anambra Basin begins with the Nkporo Group, representing the basal facies of the Mid-to-Late Cretaceous sedimentary cycle. This group, deposited during the Late Campanian, unconformably overlies the Agwu Formation and transitions upward into the Mamu Formation without a discernible break in sedimentation. The Nkporo Group is characterized by a coarsening-upward deltaic sequence of shales, interbedded sands and shales, and occasional thin limestone beds, indicative of a brief marine transgression (Ladipo *et al.,* 1992).

The Nkporo cycle is succeeded by the Lower Maastrichtian Mamu Formation, a deltaic unit consisting of sandstones, shales, siltstones, mudstones, and interbedded coal seams (Akande *et al.,* 2011). Restricted to the Anambra Basin and the Afikpo Syncline (Kogbe, 1989), the Mamu Formation reaches a maximum thickness of approximately 1000 m (Reyment, 1965). Overlying the Mamu Formation is the Ajali Sandstone, a thick, friable, poorly sorted sandstone that is typically white or iron-stained (Reyment, 1965). The Ajali Sandstone is conformably overlain by the Late Maastrichtian Nsukka Formation, which, similar to the Mamu Formation,

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comprises alternating sandstones, dark shales, and sandy shales with thin coal seams (Simpson, 1954; Reyment, 1965).

The Imo Formation conformably overlies the Maastrichtian Nsukka Formation, the outcrop lithofacies equivalent of the Akata Formation in the subsurface Niger Delta (Short & Stauble, 1967; Avbovbo, 1978). The Imo Formation is succeeded by the regressive Ameki Group, an Eocene sandstone succession (Reyment, 1965), consisting of the Nanka Sand, Nsugbe Formation, and Ameki Formation (Nwajide, 1979). The youngest sedimentary unit within the Anambra and Afikpo Synclines is the Ogwashi-Asaba Formation, an unconformable deposit of alternating coarse-grained sandstones, lignite seams, and continental clays (Kogbe, 1976).

AGE		ABAKALIKI - ANAMBRA BASIN	AFIKPO BASIN
m.y 30	Oligocene	Ogwashi - Asaba Formation	Ogwashi - Asaba Formation
54.9	Eocene	Ameki / Nanka Formation/ Nsugbe Sandstone (Ameki Group)	Ameki Formation
65	Palaeocene	Imo Formation Nsukka Formation	Imo Formation Nsukka Formation
73	Maastrichtian	Ajali Formation Mamu Formation	Ajali Formation Mamu Formation
	Campanian	Nkporo Oweli Formation / Enugu Shale	Nkporo Shale/ Afikpo Sandstone
83 87.5	Santonian		
	Coinacian	Agbani Sandstone / Awgu Shale	Non-deposition / erosion
	Turonian	Eze Aku Group	Eze Aku Group (incl. Amasiri Sandstone)
93 100	Cenomanian-Albian	Asu River Group	Asu River Group
119	Aptian Barremian Hauberivian	Unamed Units	
	Precambrian	Basement Complex	

Fig 2. Stratigraphic sequence in the Anambra Basin (modified after Nwajide, 2005)

Study Area: Owukpa and Onyeama

This study focuses on field investigations conducted at Owukpa, Benue State, and Onyeama, Enugu State, situated within the geographic coordinates of N6°55’ to N6°30’ latitude and E7°25’ to E8°05’ longitude. The accessibility of well-exposed stratigraphic sections at the Ibagba quarry (Owukpa) and road cut sections (Onyeama) facilitated detailed geological mapping and sedimentological analysis. These exposures, resulting from mining and road construction activities, provide optimal conditions for examining the sedimentology and depositional environments of the Mamu Formation.

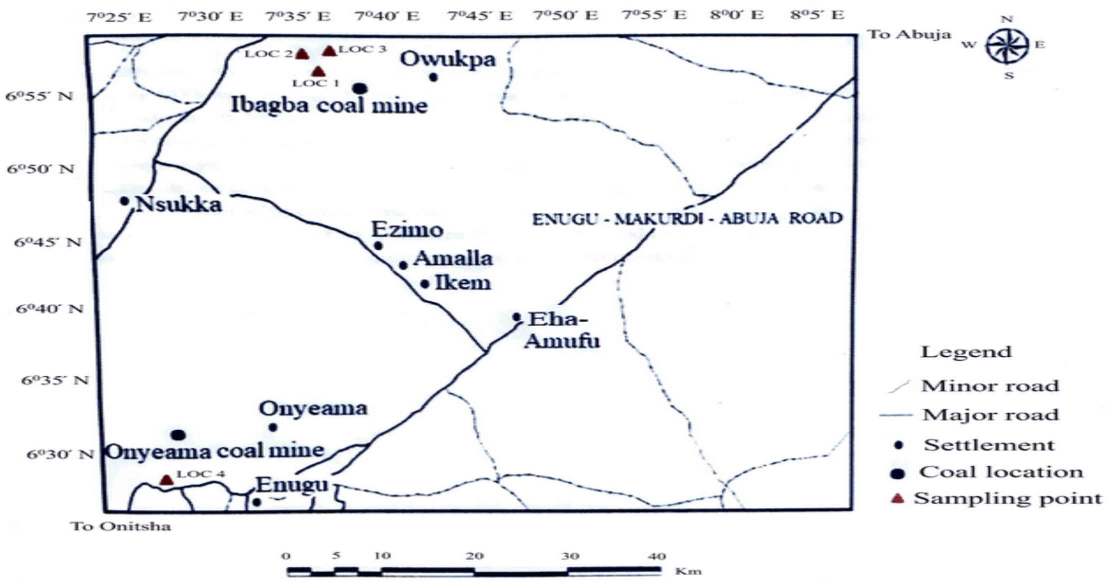

Fig 3. Location and Accessibility map of Owukpa and Onyeama areas

METHODOLOGY

This study employed a multi-faceted approach to investigate the Maastrichtian Mamu Formation at Owukpa and Onyeama. Four stratigraphic sections were meticulously mapped, involving detailed logging, section measurement, and the collection of sixty-four fresh, representative samples. At each location, sedimentary structures, textural characteristics, and lithological properties (color, grain size, and fossil presence) were carefully documented. Photographic records were maintained for comprehensive documentation. Field equipment included GPS, compass, clinometers, hammer, chisel, sample bags, measuring tape, and field notebooks.

Thirty-three samples from Ibagba and Onyeama were subjected to grain size analysis to determine the grain size distribution of the sandstone units. Each sample was air-dried and disaggregated to separate the constituent grains. A 100g subsample was weighed to ensure quality control. The weighed samples were then sieved using a Rotap machine with a stack of sieves at 0.5 phi intervals. Cumulative weight percentages retained were plotted against phi values, and grain size parameters were calculated and interpreted according to Folk's method (1974). This analysis was performed at the Sedimentology Laboratory, University of Ilorin.

Petrographic analysis was conducted on two resin-impregnated thin sections of sandstone samples, prepared using standard techniques at the Department of Geology and Mineral Sciences, University of Ilorin. Point counting of minerals was performed using a petrological microscope at the Petrology Laboratory, University of Ilorin, Nigeria.

Sixteen shale and silty shale samples were processed to extract foraminifera. Each 200g sample was dried to remove moisture. Samples were then digested in a 1:3 solution of concentrated hydrogen peroxide (H_2O_2) and water for 24 hours. The resulting residue was washed through a 0.063 mm sieve under running water, air-dried, and stored in labeled, sealed plastic bottles. Foraminiferal species were subsequently identified, picked, and described using a binocular microscope. This analysis aimed to determine species occurrence and distribution, reconstruct the paleoenvironment, and conduct biostratigraphic evaluation.

Sedimentological Results

Detailed Litho-facies Descriptions and Interpretations:

Four stratigraphic sections within the Maastrichtian Mamu Formation, specifically at Owukpa and Onyeama, were meticulously logged to elucidate the lithological succession. The identified lithofacies include coal, shale, silty shale, and sandstone. Three sections (OWK-1, OWK-2, and OWK-3) were documented within the Owukpa coal mine (Benue State), while the fourth (PRODA-4) was compiled from a road-cut exposure at the PRODA Bridge (Onyeama, Enugu State).

- **Section OWK-1:** Located at the northernmost extent of the Owukpa mine, this section exhibits a total thickness of approximately 10 meters. The basal unit is characterized by a 2.3-meter-thick fractured coal seam, overlain by dark gray shale interbedded with silty shale. The upper portion of this section transitions into sandstone facies, dominated by medium- to fine-grained sands that display evidence of burrows and intense bioturbation, indicating significant biological activity.

- **Section OWK-2:** Situated in the central region of the Owukpa mine, this section measures approximately 13.7 meters. It commences with a 2.4-meter-thick fractured coal seam, followed by a 2.5-meter-thick dark gray shale unit that grades upward into silty shale. The overlying sandstone facies, composed of medium-grained sandstone, are capped by a reddish-brown ironstone layer and subsequently overlain by fine-grained sandstone. This unit reveals sedimentary structures, including lamination, burrows, and significant bioturbation.

- **Section OWK-3:** Logged at the southernmost part of the Owukpa mine, this section attains a total thickness of 13.8 meters. The basal unit, a 4-meter-thick coal seam, represents the thickest coal interval observed within the study area. This seam is overlain by a 3.3-meter-thick dark gray shale unit, which grades upward into silty shale. The overlying sandstone facies, comprising fine-grained sand, medium-grained sand, and reddish-brown ironstone, exhibit lamination, abundant burrows, and intense bioturbation.

- **Section PRODA-4:** Logged at the Onyeama road-cut exposure, this section reveals a distinct lithological succession. The basal unit consists of a 4-meter-thick, fine-grained sandstone, overlain by a 2-meter-thick, medium-grained sandstone. A 1-meter thick interval of interbedded coal and silty shale succeeds this. The overlying sandstone facies, composed of medium-grained sandstones, are capped by fine-grained sandstone and a 4-meter-thick medium-grained sandstone unit, which is in turn overlain by a very fine-grained sandstone unit.

Coal

The coal units in the mine at Owukpa form the basal bed and are overlain by the dark gray shale facies. They are generally massive, heavily fractured, black, and have a high luster. The coal beds have thicknesses ranging from 2m to 4m, with the thickest at the southernmost part of the mine and thinning towards the northern section. The coal seam at Onyeama is only about a meter thick, fractured, black with high luster, interbedded with the sandstone facie and the silty-shale facie.

Shale Facies

The shales occurred as carbonaceous and laminated in the mine. In the northern section, they overlie the coals and are interbedded with the silty shale. They vary in thickness from 0.6m to 3.8m and are essentially dark grey in colour.

Silty – Shale Facies

In Owukpa, they occur as sandy silty shales, laminated to poorly laminated in all the sections. In the northernmost part of the mine, they are interbedded between the shale facies, while in the middle and southern part of the mine, they overlie the shales. In Onyeama, they overlie the coal. The silty-shale beds have a thickness ranging from 1m to 1.6m

Sandstone Facies

This facies comprises very fine-grained, fine-grained, and medium-grained sandstones, whose thickness ranges from 1.5m to 8m. In most sections, they are massive, stratified, and occur as coarsening upward sequences. In Owukpa, the sandstone is interbedded with thin beds of reddish brown ironstone in the middle part of the section. In Onyeama, the sandstones are interbedded with siltstone in the middle part of the section.

Fig. 4. Photo–documentation of the Mamu Formation exposed at Ibagba quarry. Notice the basal coal unit overlain by the dark grey shale and capped by the silty-shale facies.

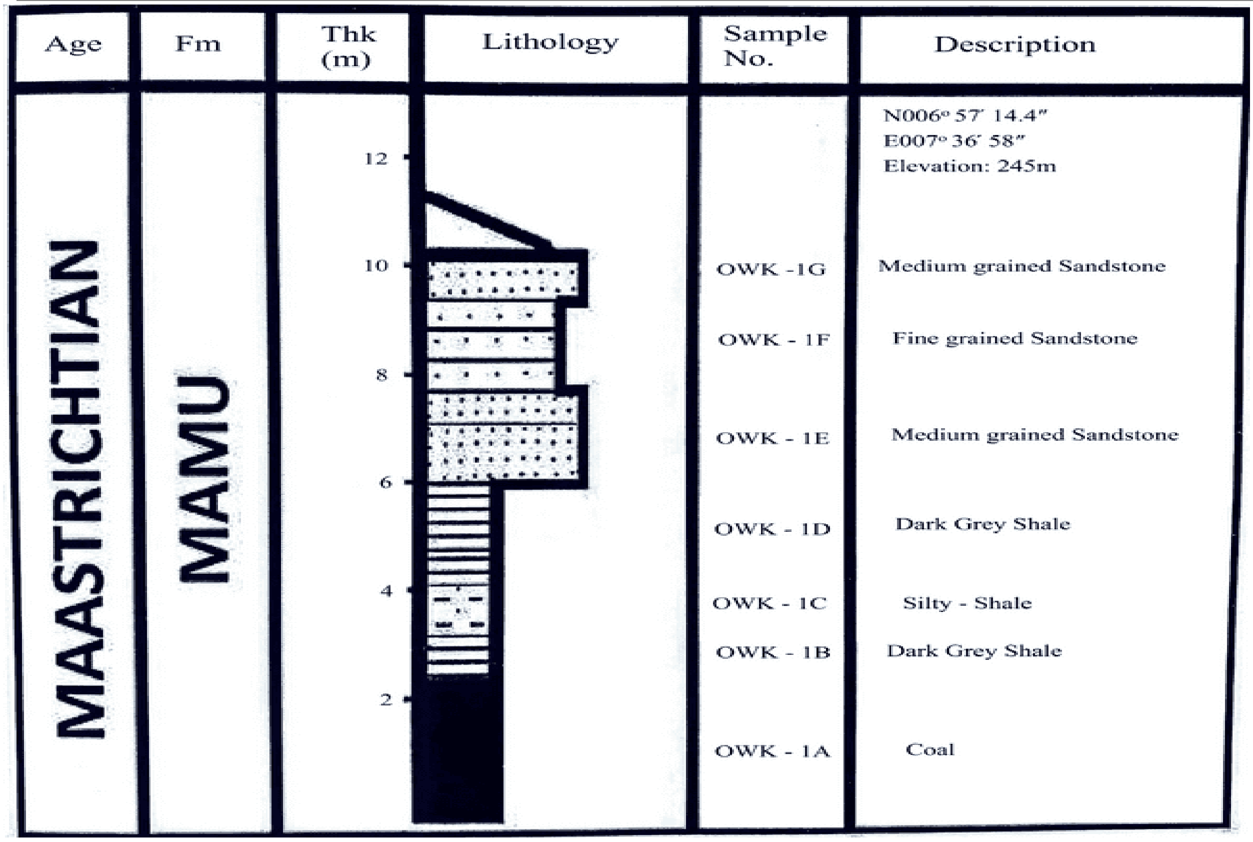

Fig 5. Section 1 (OWK-1) Lithologic section of the Mamu Formation exposed at the north side of the Ibagba coal mine.

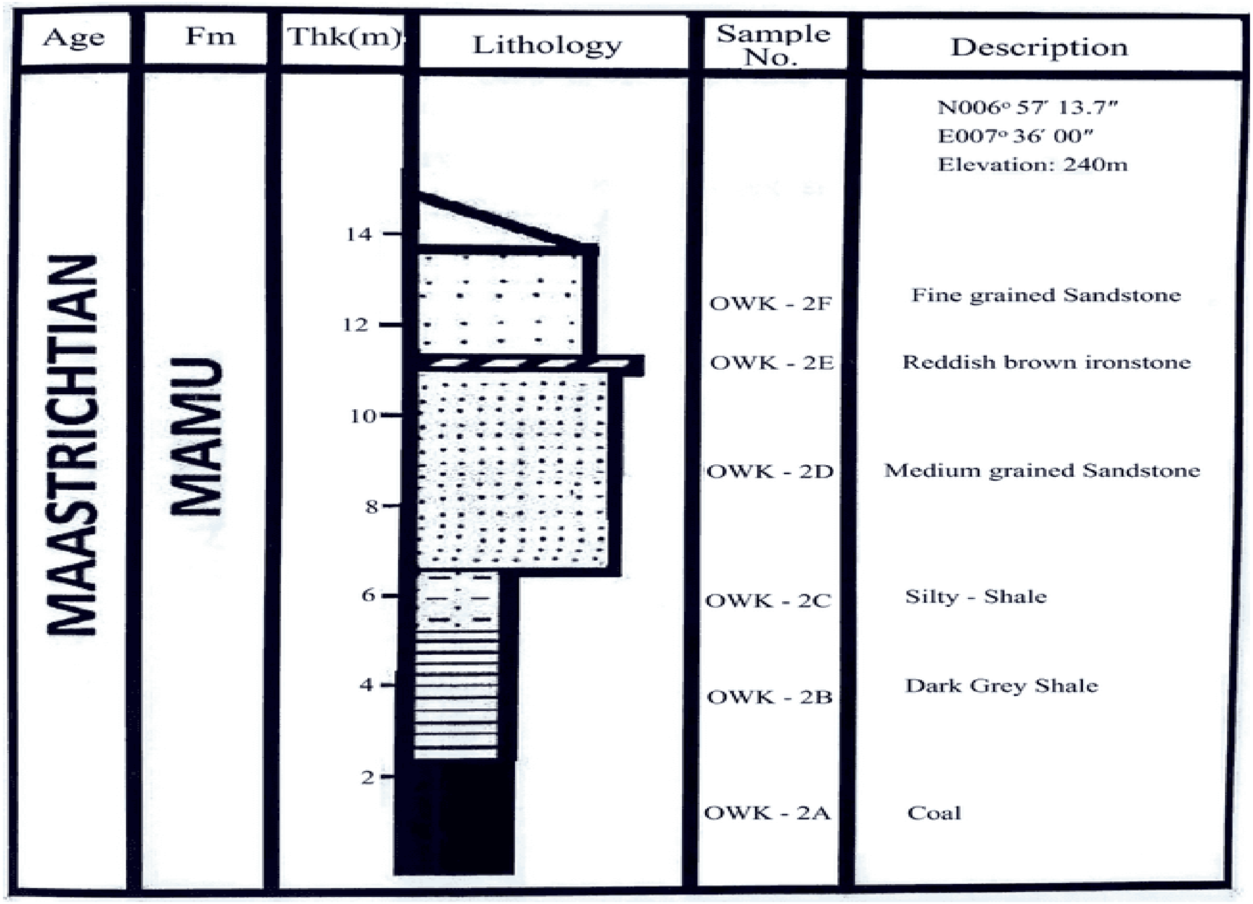

Fig 6. Section 2 (OWK-2) Lithologic section of the Mamu Formation exposed at the central part of the Ibagba coal mine.

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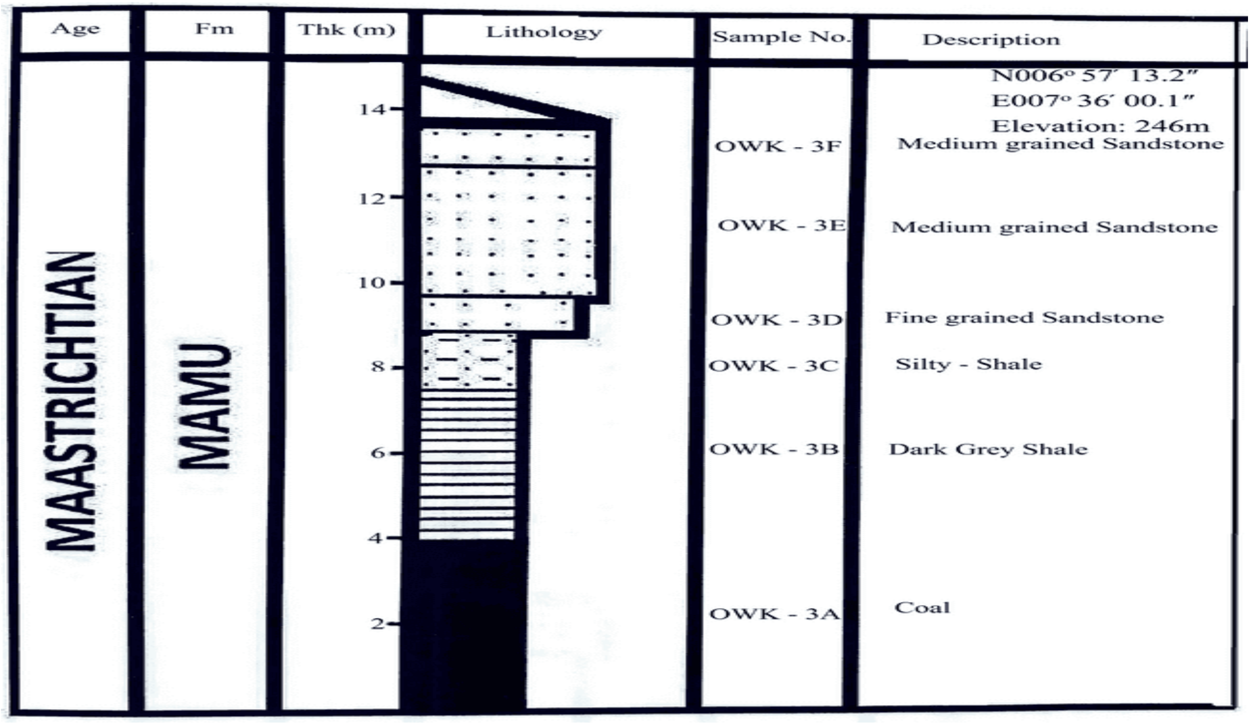


Fig 7. Section 3 (OWK-3) Lithologic section of the Mamu Formation exposed at the south side of the Ibagba coal mine.

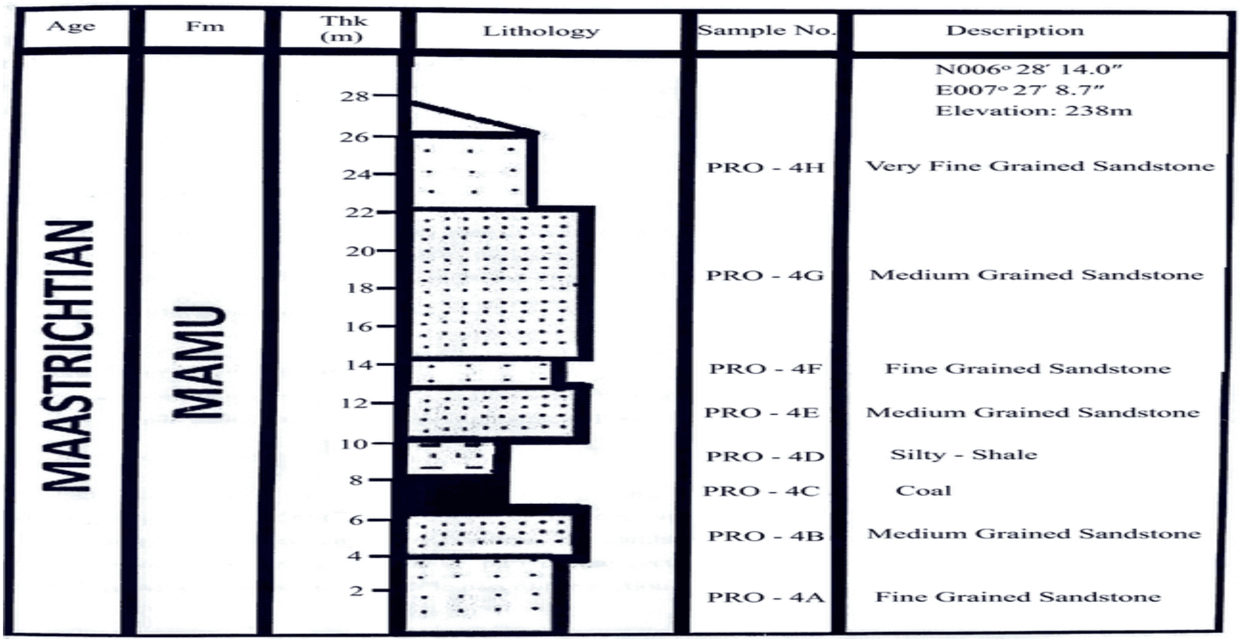


Fig 8. Section 4 (PRODA – 4) Lithologic section of the Mamu Formation exposed by the road cut at Proda Bridge, Onyeama

Sedimentary Structure Descriptions and Implications:

Sedimentary structures, formed by primary depositional processes, provide critical insights into the paleoenvironmental conditions prevailing during sediment accumulation.

- **Massive Bedding:** Massive bedding, characterized by thick, homogeneous beds exceeding 1 cm in thickness and lacking discernible internal stratification, indicates rapid sediment deposition. This structure was observed within the sandstone units of sections OWK-1, OWK-2, OWK-3, and PRODA-4, suggesting episodic high sediment influx events.

- **Laminations:** Laminations, defined as thin, distinct layers within sedimentary rocks, indicate deposition under relatively quiescent hydrodynamic conditions. The observed laminations within all studied sections (OWK-1, OWK-2, OWK-3, and PRODA-4) include parallel, wavy, ripple, and planar types. These diverse lamination types reflect varying degrees of flow energy and depositional processes across the stratigraphic intervals. The presence of ripple laminations, in particular, suggests the influence of current or wave action, reflecting dynamic water conditions.

Fig 9. Photo-documentation of the Mamu Formation exposed at Owukpa showing massive beddings in the sandstone facies

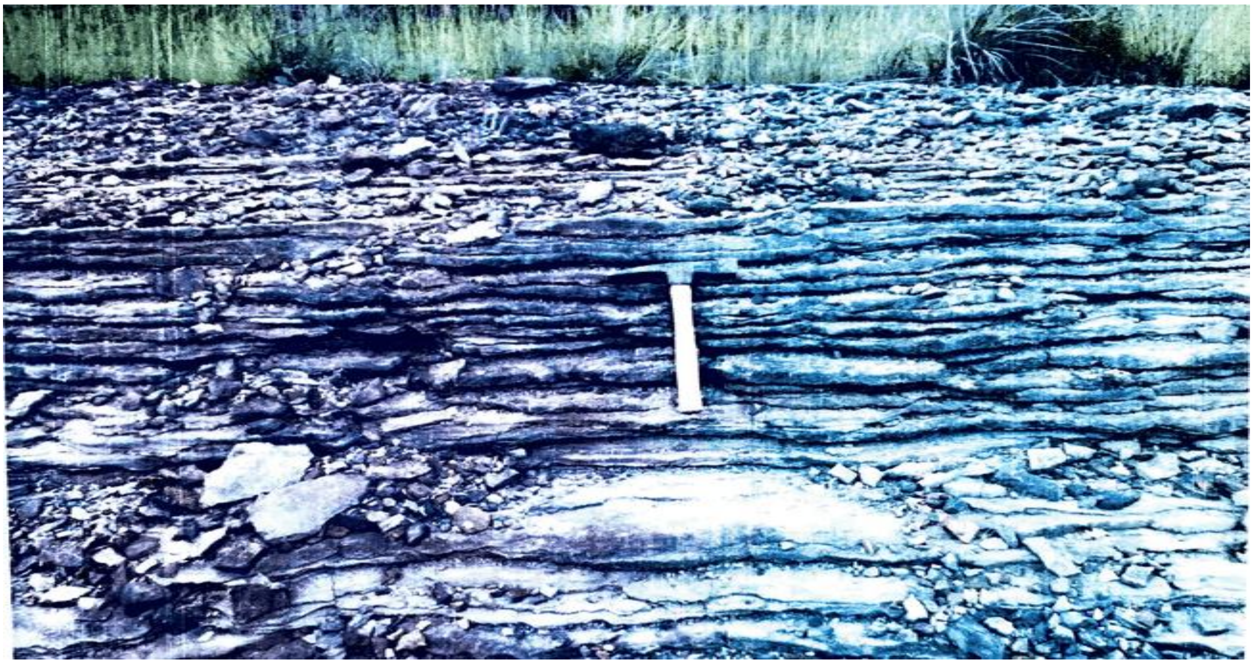


Fig 10. Photo documentation of the Mamu Formation exposed at Onyeama shows planar lamination in the top section and ripple lamination in the bottom section of the sandstone.

Depositional Environment

Grain size analysis provides important clues to sediment depositional conditions and transportational history (Folk & Ward, 1957; Friedman, 1967; Bui *et al.*, 1990). The primary objective of the analysis is to determine the depositional environment, mode of transportation, and particle size distribution in the sandstone facies of the study area. Thirty-three sandstone samples were selected from the four Lithologic sections for grain size analysis. Results from this analysis indicate that they are essentially fine-grained sandstones that are poorly sorted, leptokurtic, and essentially strongly negatively skewed.

Based on the Y3 vs. Y2 discriminant plot, the analyzed sediment samples appear to have originated from a range of depositional environments. Some samples indicate deposition in a shallow marine environment, with one sample suggesting lower energy conditions and others indicating more agitated shallow marine conditions. The majority of the samples point toward a fluvial environment with significant energy or agitation. The trend observed suggests a possible transition or mixing of influences between shallow marine and fluvial environments for some samples.

Based on the scatter plot of Skewness against Sorting, the majority of the analyzed sediment samples appear to have characteristics consistent with a fluvial depositional environment. They generally exhibit moderate to poor sorting and a wider range of skewness values, including positive, near-zero, and negative. This variability likely reflects the dynamic nature of river systems with varying flow regimes and sediment sources.

Based on the C-M pattern plot, the majority of the analyzed sediment samples were deposited under moderate energy conditions, where traction and saltation were significant modes of transport. The cluster in Zone IV and extending towards V suggests a relatively consistent depositional environment with some variations likely represented by the labeled sub-areas. Some samples indicate deposition from the suspension of finer sediments, with occasional coarser input, suggesting quieter water environments further away from the main sediment source or influenced by different processes. A few samples suggest a very low-energy environment dominated by the settling of fine particles with occasional larger grains.

The data suggest a complex depositional environment where a dynamic, moderate to high-energy fluvial system interacted with a shallow marine environment. A combination of traction, saltation, and suspension transported sediments. The overall setting might be best described as a fluvio-marine transitional environment, such as a delta or estuary, where riverine processes are dominant, but marine influences are significant.

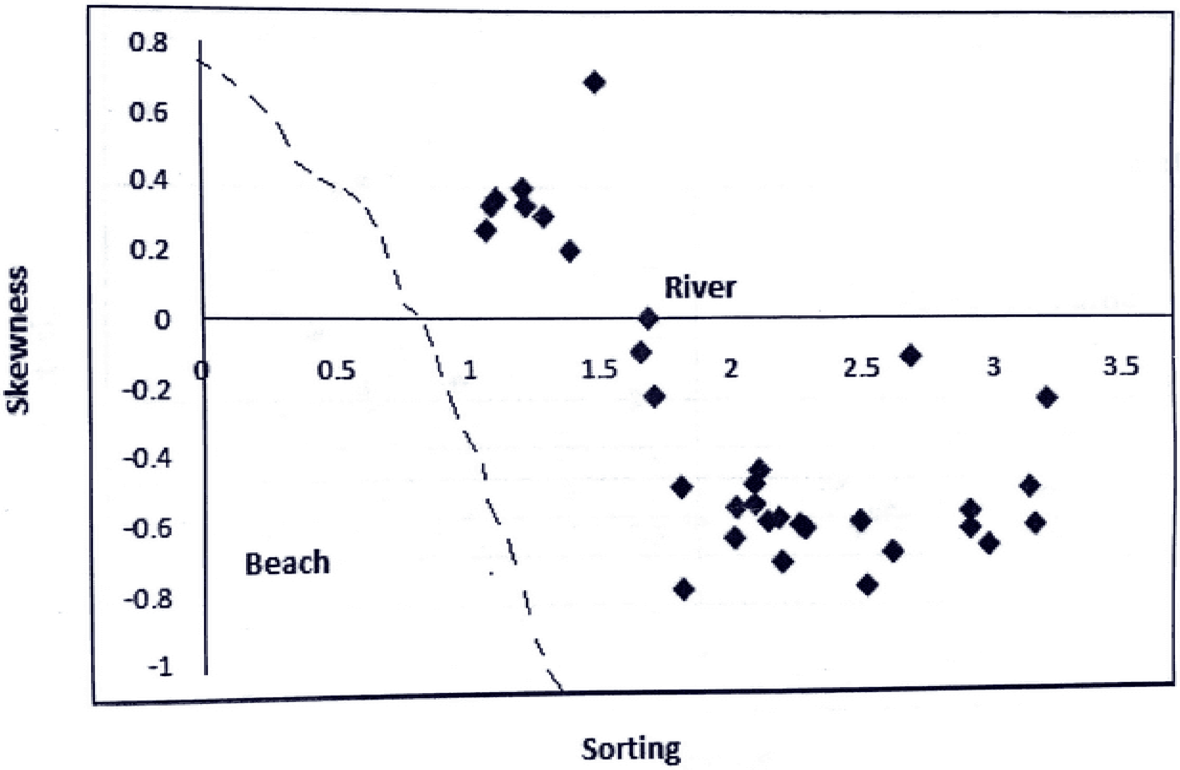


Fig 11. Scatter plot of skewness against sorting (modified after Friedman 1962), showing the distribution of samples and illustrating the moderate to poor sorting and variable skewness characteristic of fluvial depositional environments.

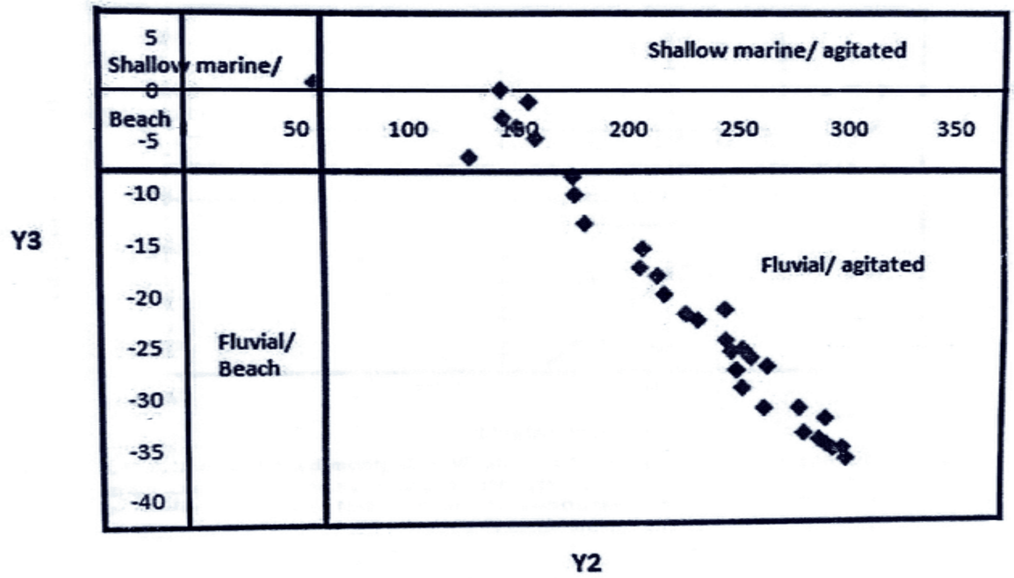
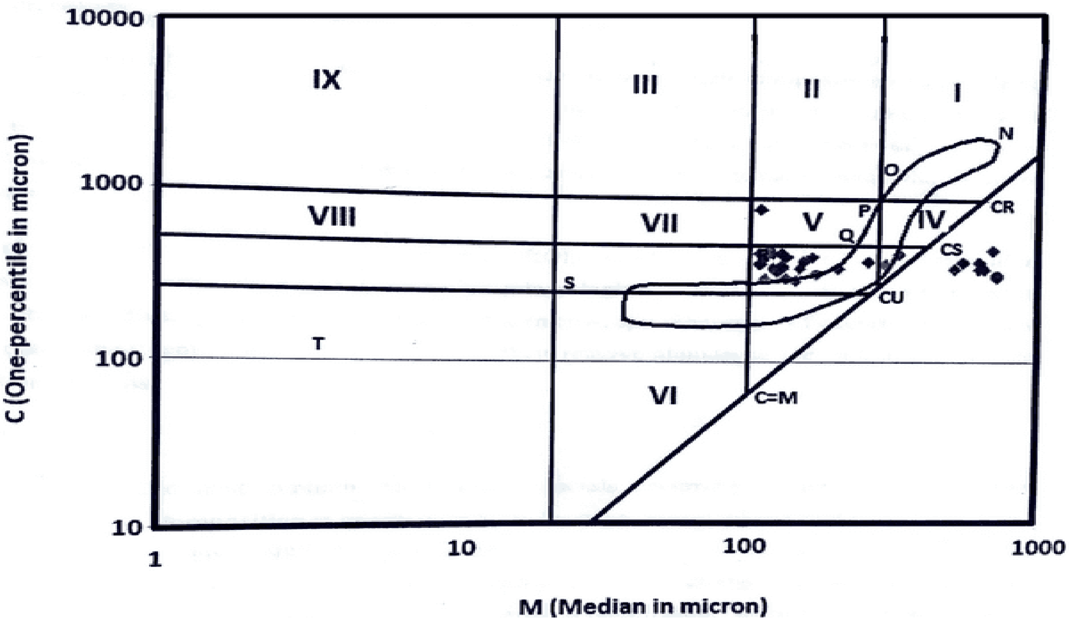


Fig 12. Discriminant function plot (Y3 vs. Y2) showing estimated depositional environments (modified after Alsharhan & El-Sammak, 2004).



I, II, III, IX = Rolled sediment; IV, V, VI, VII, VIII = Suspension sediments; CU = Maximum grain size transported as uniform suspension; CS= Maximum grain size transported as graded suspension; N O = Rolling; O P= Bottom suspension and rolling; P Q = Suspension and rolling; Q R = Graded suspension, no rolling; R S = Uniform suspension; T = Pelagic suspension

Fig 13. C-M Pattern Plot (modified after Passega, 1964) highlighting the clustering of samples in Zone IV, indicative of moderate energy conditions.

Mineralogy

The composition of source rocks greatly influences the ultimate composition of sandstones; as a result, provenance studies are mainly based on modal analysis of detrital framework grains (Dickinson & Suczek, 1979; Dickinson *et al.*, 1983). The main constituents of sandstones include quartz, feldspar, mica, rock fragments, and amorphous iron oxide minerals that act as cementing material.

Two representative sandstone samples, OWK-1GM and PRODA-4AT, were examined for compositional analysis. The detailed qualitative and quantitative mineralogical composition of these sandstones was determined

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using conventional petrographic microscopy. The mode of occurrence of every individual constituent, cementing material, and their relative abundance were carefully examined from thin sections.

Quartz: This is the most common rock-forming mineral, occurring as the main constituent of sandstones, and its composition is nearly pure SiO2. Because of its hardness and lack of cleavage, it is highly resistant (Folk, 1980). It is recognized in thin sections by the clear and unaltered habit of lack of cleavage, and cross-polarized light shows grey or white interference colours with undulose extinction, which is usually a result of stress after crystallization. In both sandstone samples, quartz is the dominant constituent mineral of the framework component, with relative abundance ranging from 92-93% and an average of 92.5%. Polycrystalline quartz was observed in sample OWK-1GM, while sample PRODA-4AT is dominated by monocrystalline quartz. The quartz grains are sub-rounded to rounded, showing that the grains have travelled a considerable distance from their source.

Feldspar: It is the most abundant group of minerals in the earth crust. It is a group of aluminosilicate minerals that contain calcium, sodium, and potassium. They normally provide evidence for paleoclimate. Feldspar shows relatively low relief and low birefringence and good cleavages with slight relief and diagnostic twinning multiples, lamellar or polysynthetic. No feldspar was observed in slides, which confirms that the grains have travelled a very long distance which led to the removal of the feldspars through weathering, leaving behind only the stable minerals.

Rock Fragments: They are fragments of older sedimentary rocks, and are as common in sandstones as reworked fragments of shale. In samples OWK-1GM and PRODA-4AT, they constitute about 4%

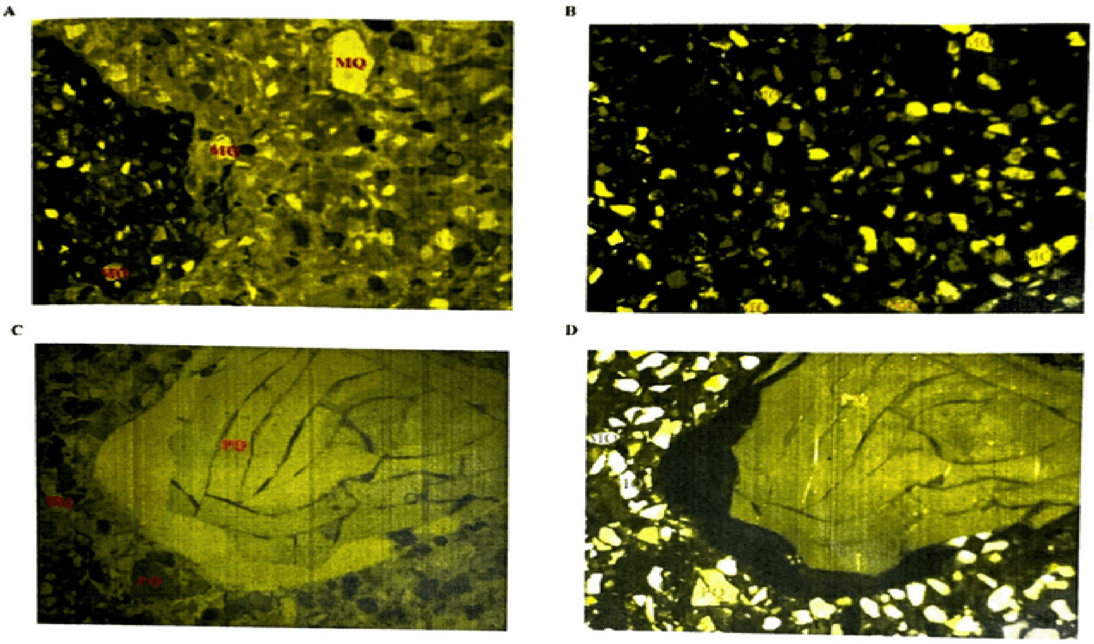

Fig 14a. Photomicrograph showing the mineralogical composition and texture of sample OWK-1GM under plane light.

Fig 14b. Photomicrograph showing the mineralogical composition and texture of sample OWK-1GM under cross-polarized light (same view as Fig. 14a).

Fig 14c. Photomicrograph showing the mineralogical composition and texture of sample OWK-1GM under plane light.

Fig 14d. Photomicrograph showing the mineralogical composition and texture of sample OWK-1GM under plane light (same view as Fig. 14c).

MQ = Monocrystalline Quartz, PQ = Polycrystalline Quartz

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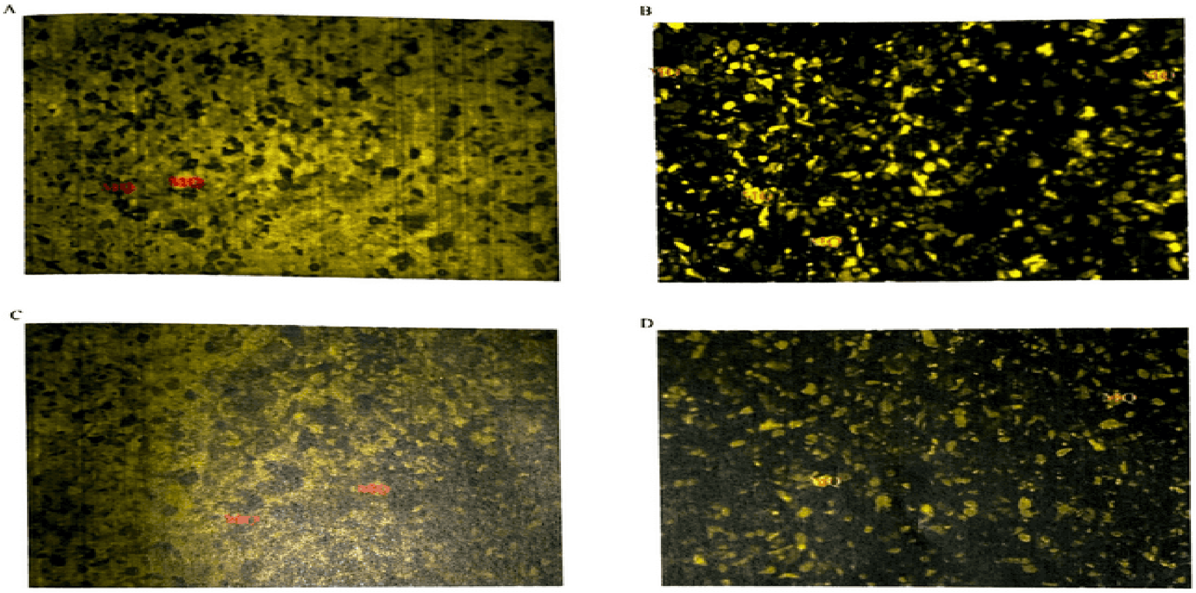

Fig 15a. Photomicrograph showing the mineralogical composition and texture of sample PRODA-4AT under plane light.

Fig 15b. Photomicrograph showing the mineralogical composition and texture of sample PRODA-4AT under cross-polarized light (same view as Fig. 15a).

Fig 15c. Photomicrograph showing the mineralogical composition and texture of sample PRODA-4AT under plane light.

Fig 15d. Photomicrograph showing the mineralogical composition and texture of sample PRODA-4AT under plane light (same view as Fig. 15c).

MQ = Monocrystalline Quartz, PQ = Polycrystalline Quartz

Foraminiferal Results:

Foraminiferal Distribution Charts and Illustrations:

Sixteen samples of shale and silty shale from Owukpa and Onyeama were analyzed for foraminiferal content. The yield of foraminifera from these samples was low, with only four samples containing identifiable specimens. This limited recovery is primarily attributed to the challenging paleoenvironmental conditions that prevailed during the deposition of the Mamu Formation. Specifically, the dominance of siliciclastic input, as evidenced by the sandy nature of the shales, likely created a substrate unfavorable for foraminiferal preservation. Additionally, the abundance of coaly units within the Mamu Formation suggests the potential for acidic conditions, which would have further hindered the preservation of calcareous foraminiferal tests through dissolution. The taxonomic identification of foraminifera in this study was limited to the genus level. The recovered assemblage is dominated by benthic species, including *Ammobaculites* spp., *Ammotium* spp., *Haplophragmoides* spp., *Litnola senonensis*, *Ammobaculoides* spp., and *Reophax globosus*, which are known to tolerate stressed environments. The presence of this tolerant assemblage provides valuable paleoenvironmental information, supporting interpretations of a marginal marine setting with fluctuating salinity and periods of reduced oxygenation. Future research should explore the potential of complementary proxies, such as palynological analysis, to further refine the paleoenvironmental reconstruction and address the limitations imposed by the foraminiferal data.

Detailed Foraminiferal Analysis and Paleoecological Interpretation:

Foraminifera, ubiquitous in aquatic environments, serve as valuable tools in biostratigraphy and paleoenvironmental reconstructions due to their diverse ecological tolerances and well-preserved tests. In this study, the limited abundance and preservation of foraminifera, particularly the prevalence of agglutinated tests, suggest a depositional environment characterized by significant siliciclastic input. This influx likely created unfavorable conditions for foraminiferal survival, reflected in the sandy nature of the shales.

- **Environmental Factors:** The distribution of foraminiferal species is influenced by a combination of factors, including substrate type, light intensity, water temperature, food availability, oxygen levels, salinity, and current energy (Murray, 1991). The recovered assemblage, primarily composed of benthic foraminifera, provides insights into the paleoenvironmental conditions of the studied successions.

- **Species-Specific Paleoecology:**

  - *Ammobaculites spp*. and *Ammobaculoides spp*. These genera, infaunal deposit feeders, inhabit muddy sediments with brackish to normal marine salinities, tolerating a wide range of environments from marsh to bathyal, including low-oxygen conditions (Culver & Buzas, 1981; Koutsoukos *et al*., 1990; Murray, 1991). Their presence suggests variable salinity conditions, potentially including brackish influence (Bandy, 1956; Ellison & Murray, 1987).

  - *Ammotium* spp.This infaunal deposit feeder is indicative of shallow, brackish water environments, including tidal marshes, lagoons, and estuaries, with a broad salinity tolerance (4-41%) but a preference for brackish conditions (Murray, 1968, 1991; Bronnimann, 1992).

  - *Haplophragmoides* spp.This probable detritivore, infaunal genus is commonly found in muddy to sandy substrates across a wide range of marsh to bathyal environments, primarily of marine origin.

  - *Reophax globosus*: This infaunal deposit feeder inhabits muddy and sandy substrates in lagoons, shelves, and bathyal regions, predominantly in marine environments but also reported from brackish lagoon and estuary sand (Culver & Buzas, 1981; Murray, 1991; Brazier, 1980).

- **Salinity Interpretation:** The benthic foraminiferal assemblage suggests a mixed salinity environment. *Ammotium* spp. indicates brackish conditions, while *Ammobaculites spp.* and *Reophax globosus* suggest a wider salinity range, including slightly reduced salinity levels.

- **Oxygenation Interpretation:** The dominance of agglutinated foraminifera and the abundance of infaunal forms suggest oxygen-depleted conditions. Applying Bernhard's (1986) oxygen level categorization, the environment is interpreted as dysoxic to oxic. The prevalence of infaunal mud dwellers, adapted to low-oxygen interstitial waters, supports this interpretation.

- **Depositional Environment:** The low foraminiferal abundance, poor preservation, and dominance of agglutinated tests indicate a depositional environment characterized by a significant influx of clastic sediments and potentially fluctuating salinity conditions. The prevalence of infaunal foraminifera indicates a depositional environment with low oxygen levels.

Table 1. Distribution of benthic foraminifera in the shales.

Sample ID	*Ammobaculities sp*	*Haplophragmoides sp.*	*Ammotium sp.*	*Ammobaculoides sp.*	*Reophax globosus sp.*	*Litnola-Senoniensis sp.*	Total
OWK - 1 AB	N/A	1	1	1	N/A	N/A	3
OWK - 1 AT	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 1B	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 1C	4	N/A	N/A	N/A	N/A	N/A	4
OWK - 1D	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 2AB	N/A	N/A	1	N/A	1	N/A	2

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OWK - 2AT	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 2BB	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 2BT	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 2C	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 3AB	2	N/A	N/A	N/A	1	N/A	3
OWK - 3AT	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 3BB	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 3BT	N/A	N/A	N/A	N/A	N/A	N/A	N/A
OWK - 3C	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PRO - 4B	N/A	N/A	N/A	N/A	N/A	N/A	N/A
PRO - 4C	N/A	N/A	N/A	N/A	N/A	N/A	N/A

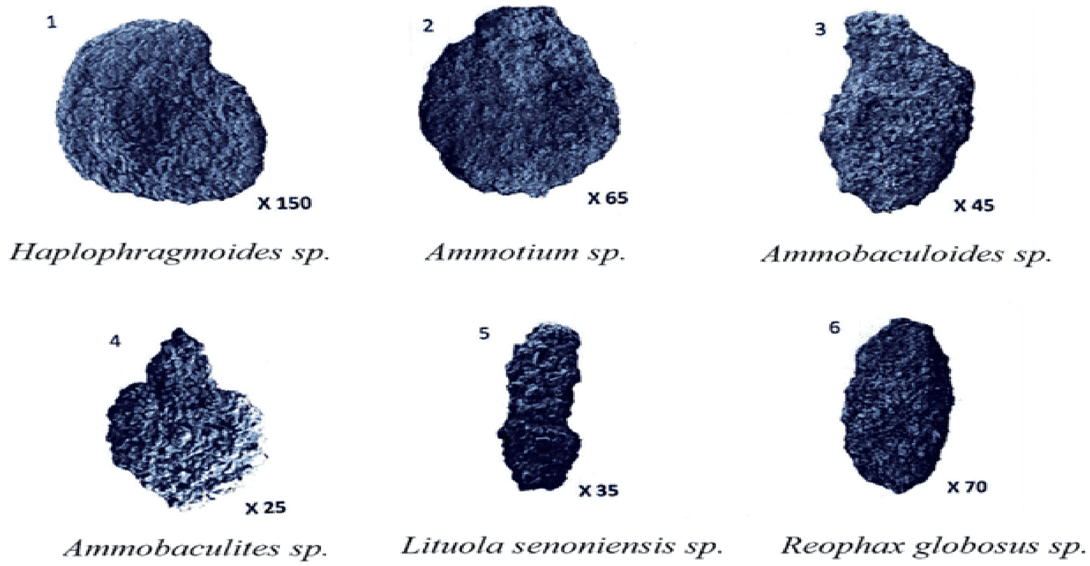

Fig. 16. Benthic foraminifera identified in the Owukpa Shales.

DISCUSSION

The Maastrichtian Mamu Formation at Owukpa reveals a complex paleoenvironment characterized by alternating terrestrial and marginal marine depositional settings, as revealed through integrated sedimentological and foraminifera analyses. The lithostratigraphic succession, transitioning from coal measures to shale and sandstone facies, signifies a shift from a continental to a marine environment of deposition. The poorly sorted, fine-grained sandstones, displaying massive bedding and diverse laminations, are interpreted as having a fluvial origin, deposited via graded suspension under variable hydrodynamic regimes. Their mineralogical maturity, evidenced by a dominance of monocrystalline quartz and absence of feldspar, indicates a significant transport from the source.

The sparse and poorly preserved foraminiferal assemblages provide critical insights into the marine phases. The dominance of agglutinated benthic foraminifera, including *Ammotium* spp., *Ammobaculites* spp., *Haplophragmoides* spp., and *Reophax globosus*, suggests a stressed paleoenvironment marked by high siliciclastic influx and fluctuating salinity regimes, ranging from brackish to normal marine, potentially with dysoxic to anoxic bottom waters. The occurrence of foraminifera within the shale and silty shale facies establishes a Late Cretaceous marine influence. Specifically, the abundance of *Ammotium* spp. in samples OWK-1A and OWK-2AB strongly implies an estuarine influence, punctuated by episodic marine incursions indicated

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by the co-occurrence of euryhaline *Ammobaculites* spp. However, the limited micropaleontological data and lack of species-level identification preclude a high-resolution reconstruction of paleoenvironmental gradients.

The coal seams, indicative of terrestrial swamp environments, with marine-influenced shales, provide further evidence of episodic marine transgressions, suggesting repeated eustatic or relative sea-level fluctuations or changes in coastal proximity during the Maastrichtian. These transgressive events observed in the Mamu Formation at Owukpa and Onyeama may correlate with documented Late Cretaceous transgressive phases along the West African margin, potentially linked to global sea-level rise or regional tectonic subsidence.

The paleoenvironmental evolution at the Owukpa Quarry commenced with terrestrial swamp conditions, characterized by coal accumulation. Subsequent deposition of shales and silty shale sediments, containing the sparse foraminiferal assemblage, indicates a transition to aquatic conditions driven by episodic marine incursions. The overlying fluvial sandstones suggest a return to predominantly continental deposition, albeit still influenced by proximity to brackish or marine water bodies, as inferred from the fluctuating salinity indicated by the foraminifera. The prevalence of infaunal agglutinated foraminifera suggests potentially dysoxic to oxic bottom conditions, influenced by organic matter and fine-grained sediment input from both fluvial and marine sources.

In essence, the Owukpa section reflects a dynamic paleoenvironment characterized by repeated oscillations between continental and marginal marine depositional settings, driven by eustatic or relative sea-level changes, resulting in the observed lithological and paleontological heterogeneity within the Maastrichtian Mamu Formation.

CONCLUSION

This study, through the integrated sedimentological and foraminiferal analyses of the Maastrichtian Mamu Formation in the Owukpa and Onyeama areas of the Anambra Basin, provides a comprehensive understanding of its dynamic paleoenvironmental evolution. Sedimentological investigations of the interbedded lithological units (fine- to medium-grained sandstones, shales, silty shales, and coaly units) reveal a predominantly fluvially influenced paralic depositional setting. Grain size analysis of the sandstones indicates poorly sorted, fine-grained sediments likely transported via graded suspension. This interpretation is further supported by sedimentary structures such as massive bedding and diverse laminations, which suggest rapid sediment influx and varying hydrodynamic conditions within a dynamic fluvial system. Conversely, foraminiferal analysis of the shale units points to a significant marginal marine influence. The low-diversity assemblage, dominated by benthic agglutinated species and the absence of planktonic and calcareous forms, indicates a harsh, shallow paralic environment characterized by dysoxic to suboxic conditions and fluctuating salinity ranging from brackish to outer-shelf. This micropaleontological evidence suggests episodic marine incursions into what was primarily a fluvial-dominated system. The observed juxtaposition of fluvial sandstones and marine-influenced shales clearly highlights the complex interplay between terrestrial and marine processes during the deposition of the Maastrichtian Mamu Formation in the Anambra Basin. This study elucidates a dynamic paleoenvironment shaped by the interaction of fluvial and marginal marine forces, contributing to a more nuanced understanding of the basin's Cretaceous sedimentary history.

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