



Original Research

Reconstructing paleoenvironments of the late Cretaceous sequence in the Anambra Basin, Nigeria: New insights from grain texture and morphology

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ARTICLE INFO

Article history:

Received 7 October 2025

Received in revised form

27 May 2026

Accepted 5 June 2026

Available online 11 June 2026

Keywords:

Particle size analysis

SEM-EDX

Diagenesis

PCA

Depositional environment

Northern Anambra Basin

ABSTRACT

This study investigates Campano-Maastrichtian sediments from the northern Anambra Basin, Nigeria, to refine existing paleoenvironmental models through a multi-proxy integration of particle size analysis, scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX), and principal component analysis (PCA). While previous studies relied on first-order textural data, the current integrated approach provides new insight into the interplay of provenance, episodic energy fluctuations, and diagenetic overprinting. Seventeen samples of sandstone, siltstone, and ironstone were collected from the Ajali and Mamu formations at Odagbo, Egume, and Iyale. Granulometric analysis reveals predominantly fine to medium-grained, unimodal, and poorly to moderately sorted sediments. Linear discriminant functions suggest deposition in a mixed fluvial and shallow marine setting, with potential episodic influence of high-energy density flows or storm-induced turbulence. SEM imaging shows grain morphologies ranging from angular to rounded, with microtextures such as: conchoidal fractures, dissolution pits, and quartz overgrowth, reflecting variable transport distances and diagenetic modifications. EDX spectra confirm quartz-dominated mineralogy with variable aluminosilicate, iron oxide, and traces of heavy mineral contributions, while the PCA identified three compositional groups: (1) quartz-rich, texturally mature assemblages; (2) feldspathic and clay-rich sediments of proximal origin; and (3) organic and iron (Fe)-bearing sediment reflecting redox variations. These results demonstrate that sediment supply was derived from cratonic interior sources, modified by fluvial input and reworked under shallow marine conditions with subsequent diagenetic overprinting. By integrating textural and geochemical data, this study highlights the interplay of provenance, episodic hydrodynamic fluctuations, and diagenesis, providing new insight into the paleoenvironmental evolution of the Anambra Basin.

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1. Introduction

The Anambra Basin in southeastern Nigeria is a significant late Cretaceous depocenter, with its Campano-Maastrichtian stratigraphy shaped by transgressive and regressive cycles (Ekwenye

et al., 2015; Nwajide, 2013). Investigating the textural and morphological characteristics of these sediments is critical for paleoenvironmental reconstruction and assessing reservoir potential. The particle size of sediments provides rich information on the energy of the transport media, the depositional mechanism, and how far the sediment particles have traveled from their source area. Particle size is a critical tool in sedimentology that provides insight into the depositional environment of sediment particles. Sedimentologists use it to infer the physical conditions under which sediment particles were transported, sorted, and deposited. Three aspects of particle size which are of particular interest to sedimentologists are: (i) measurement techniques, (ii)

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Peer review under the responsibility of editorial board of International Journal of Sediment Research

summarizing large amounts of data and presenting the data graphically and statistically, and (iii) the genetic significance of these data (Boggs, 2012; Singh et al., 2015). The process of measuring sediment particle diameters and classifying them into size categories is known as particle size analysis. Techniques such as sieve analysis for coarse sediment and laser diffraction or sedimentation methods for finer particles are commonly utilized. Patterns related to sorting, depositional processes, and energy of the transporting medium are illustrated by using the results to create grain size distribution curves (Arun et al., 2019). For instance, poorly sorted sediment particles signify lower-energy settings like lake beds or floodplains, but well-sorted sands generally indicate high-energy environments like beaches or river channels.

Geologists can determine the depositional environment by analyzing the particle size data. In a sediment sample, for instance, the predominance of tiny particles like silt and clay often indicates a low-energy environment, such as deep lake or lagoon. On the other hand, a high-energy environment, like a delta or alluvial fan, could be indicated by coarse particles that vary widely in size. This analysis helps in reconstructing past environments, understanding sedimentary processes, and making predictions about resource distribution and environmental changes. While several studies have investigated the depositional environment and hydrodynamics of sediment particles (Baiyegunhi et al., 2017, 2020; Folk & Ward, 1957; Friedman, 1961, 1979; Khalil, 2023; Sahu, 1964; Shepard, 1960; Shepard & Moore, 1955; Sly et al., 1983), reliance on this alone can be ambiguous, as there are possibilities that multiple transport histories and post-depositional mechanisms could produce sediment with the same fractions.

Scanning electron microscopy (SEM) combined with energy-dispersive X-ray spectroscopy (SEM–EDX) provides high-resolution identification of mechanical abrasion and chemical diagenetic signatures on grain surfaces. This technique is particularly effective for quartz grains ($> 200 \mu\text{m}$), where surface microtextures serve as diagnostic fingerprints of transport history and paragenetic pathways (Hossain et al., 2024; Kim et al., 2023; Krinsley & Doornkamp, 1973; Mahaney, 2002). Differentiating between mechanical features, which yield angular morphologies, and chemical processes, such as etch pits or authigenic overgrowths, facilitates a robust interpretation of depositional energy and post-depositional modification. Furthermore, SEM–EDX allows for the direct integration of microtextural observations with mineralogical data to refine provenance and fluid–rock interaction models.

Complementing these observations, Principal Component Analysis (PCA) provides a robust method for reducing dimensionality and identifying latent geochemical factors within multi-element datasets (Jolliffe & Cadima, 2016). By simplifying EDX data into defined orthogonal axes, PCA highlights primary compositional controls. This technique has been used in studies such as Reid and Spencer (2009), Garcia et al. (2020), and Srivastava et al. (2024). Furthermore, it effectively discriminates between organic/seawater-influenced geochemical signals and detrital silicate signatures in complex deltaic and marine systems (Su et al., 2023).

Previous studies have demonstrated that granulometric parameters and grain surface microtextures provide valuable information regarding sediment transport history, depositional processes, and paleoenvironmental conditions (Boutiba, 2006; Krinsley & Doornkamp, 1973; Itamiya et al., 2019; Kim et al., 2023; Krinsley & LeRibault, 1975; Mahaney, 2002). SEM has further enhanced these interpretations by revealing microstructural features produced by physical, mechanical, chemical, and biological processes prevalent during sediment transport, deposition, and early diagenesis (Costa et al., 2019; Helland & Diffendal, 1993;

Kermani & Boutiba, 2023; Madhavaraju et al., 2009; Mahaney et al., 2001; Warriar et al., 2016).

In the Anambra Basin, granulometric studies consistently indicate that Campano–Maastrichtian sediments record deposition under mixed fluvial–marine conditions. Textural characteristics ranging from fine to coarse-grained, commonly poorly to moderately sorted, skewed, and leptokurtic sands have been interpreted to reflect tidal, fluvial, coastal, and fluvio-deltaic environments, with variations in hydrodynamic energy and episodic turbulence across the basin (Adeigbe & Salufu, 2009; Ajadi et al., 2022; Ezike, 2023; Lukman et al., 2018; Odumodu & Ugwuona, 2013). Collectively, these studies highlight the effectiveness of granulometry for first-order environmental interpretation, while also underscoring the need for integrated microtextural and geochemical analyses to refine depositional reconstructions. While recent studies such as Ezike (2023) have utilized granulometric and paleocurrent data to provide a fundamental textural framework for the Anambra Basin, identifying the precise interplay between transport energy and post-depositional modification remains less clear.

The current study refines the findings of Ezike (2023) by moving beyond first-order textural descriptions. By integrating high-resolution SEM microtextural analysis with SEM–EDX elemental data and PCA, a more robust differentiation between mechanical transport processes and diagenetic overprinting, specifically within the northern sector of the basin, is provided. The novelty of the current study lies in the integration of the conventional granulometric analysis, SEM microtextural observations, and SEM–EDX elemental data with PCA analyses, for the first time in the northern Anambra Basin. The aim of this study is to provide a high-resolution paleoenvironmental reconstruction of the Campano–Maastrichtian sequence in the northern Anambra Basin by integrating textural, morphological, and geochemical datasets. To achieve this, the following objectives were established: (1) to statistically characterize grain size distributions as proxies for hydrodynamic energy; (2) to evaluate quartz surface microtextures as diagnostic indicators of transport history; and (3) to model elemental distribution patterns to determine sediment provenance. By addressing these objectives, this study seeks to answer the following research questions: (1) How do grain size variations reflect the transition between steady-state deposition and episodic high-energy events in this sequence? (2) To what extent can specific microtextures differentiate between primary transport signatures and early diagenetic overprinting? (3) How do the geochemical clusters identified via PCA discriminate between proximal basement-derived inputs and distal, recycled cratonic sources? (4) Can a multi-proxy approach provide a more refined depositional model than traditional granulometric analysis alone? This integrated study, therefore, presents new data on the textural characteristics of the Campanian–Maastrichtian sediments from the northern Anambra Basin, and a more robust reconstruction of the sedimentary history of the basin, contributing to a broader understanding of the Late Cretaceous depositional systems of West Africa.

2. Geological setting

2.1. Location, basin evolution, and tectonic setting

The Anambra Basin, a Cretaceous sedimentary basin in southeastern Nigeria, extends approximately $54,000 \text{ km}^2$ across Anambra, Enugu, Benue, and Kogi States (Fig. 1(a)). It has a distinctive triangular geometry, bifurcated by the Niger River into western and eastern sections (Fig. 1(b)). With sedimentary fill up to 9 km thick, it is bordered to the north by the Bida Basin and

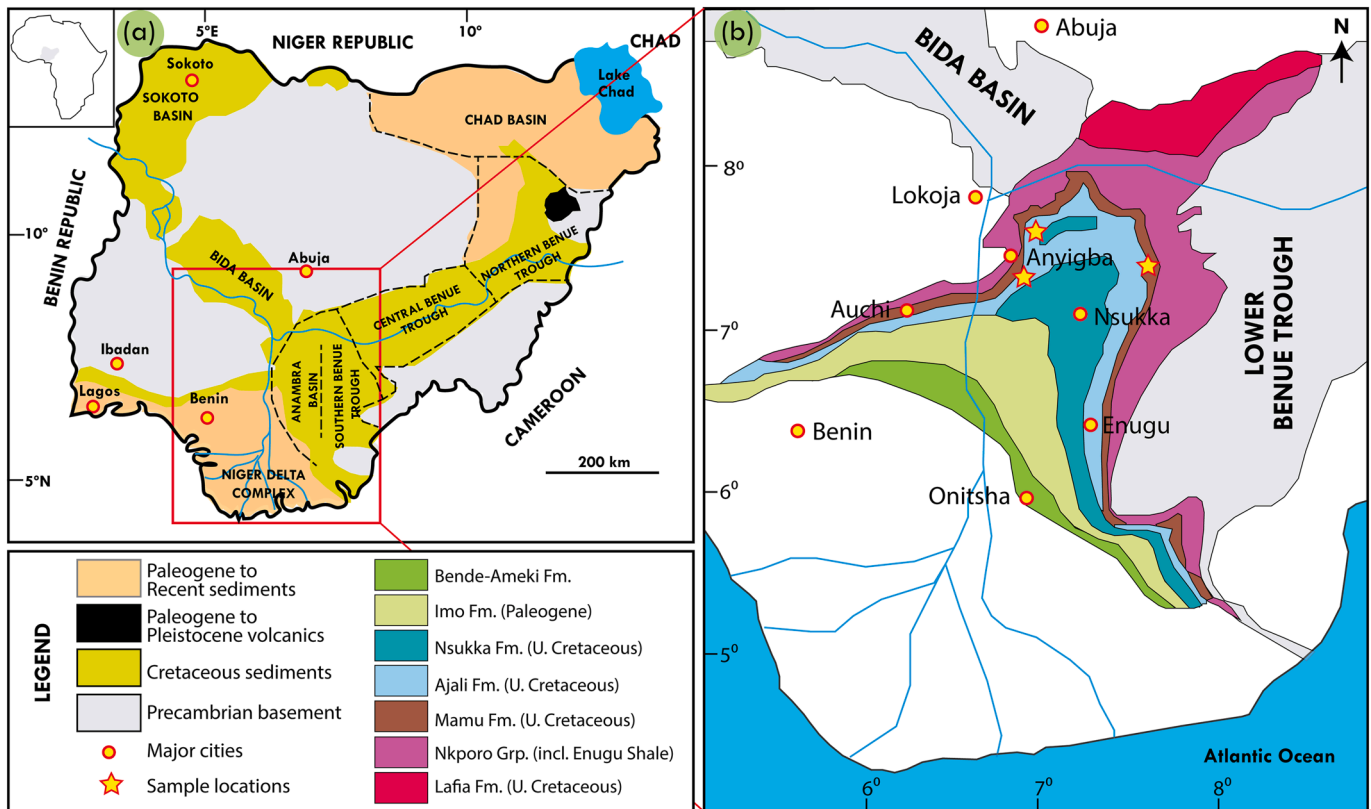


Fig. 1. Geological map of Nigeria showing the (a) location of the Anambra Basin, within the rectangular block; and (b) location of the studied outcrops. (Note: Fm. denotes Formation, Grp. denotes Group, incl. denotes including, and U. denotes Upper.)

Northern Nigerian Massif, to the east by the Lower Benue Trough, to the west by the West African Massif, and to the south by the Niger Delta (Fig. 1).

The basin was formed in a similar circumstance with the Benue Trough as a result of the separation of the African and South American plates in the Mesozoic period (Mode et al., 2018) and was shaped by a series of tectonic and sedimentary events. The pre-Santonian, post-Santonian, and Lower Tertiary were the three evolutionary phases that contributed to the basin's structural evolution. The major events included rifting, sediment deposition, marine transgression and regressions, and coal formation, with a series of subsidence. The Trans-Saharan Seaway was reestablished, connecting the Tethys Ocean to the Atlantic Ocean via the Bida Basin to the north, during the eustatic sea-level changes from the Campanian to the Maastrichtian periods, which resulted in the formation of the post-Santonian basin fills (Ajidahun et al., 2025; Edegbai et al., 2019).

2.2. Stratigraphic framework

The Campanian Nkporo Group is the oldest deposit in the Anambra Basin, which forms the basal unit, resting unconformably on the pre-Santonian units. In addition to local limestone beds created by transient marine incursions, it comprises the Nkporo, Oweli, and Enugu formations (Fig. 2), which are made up of organic-rich shales and sandstones deposited in a brackish to shallow-marine setting (Akande & Mücke, 1993; Chiadikobi et al., 2013; Dim et al., 2017; Nwajide, 2013; Odunze et al., 2013; Omietimi et al., 2024). The Maastrichtian Mamu Formation (Fig. 2), which is deposited in estuary floodplains and marginal to shallow-marine settings, overlies the Nkporo group. Its thickness ranges from 75 m to over 1000 m and comprises a mix of sandstones, silty

shales, siltstones, mudstones, and coal seams (Akande et al., 2011; Chiadikobi et al., 2013; Nwajide & Reijers, 1997; Obi et al., 2013; Reyment, 1964). This is followed by the unconsolidated, poorly sorted, coarse to fine-grained “false-bedded” sandstones of the Ajali Formation (Fig. 2), with thickness varying from less than 300 m to over 1,000 m. It is texturally mature, predominantly quartz arenite, and displays sedimentary structures such as cross bedding, tidal bundles, and channel fills, reflecting high-energy fluvio-deltaic and tidal processes (Chiadikobi et al., 2013; Obi, 2000).

The decline in eustatic sea level from the mid-Maastrichtian to Danian periods prompted the accumulation of regressive units such as the Nsukka Formation (Edegbai et al., 2019; Omietimi et al., 2024). The latter two formations mark the depositional transition from the Anambra Basin succession to those of the overlying Niger Delta Basin (Dim et al., 2017; Ejeh, 2021), constituting a portion of its outcropping units. The Nsukka Formation conformably overlies the Ajali sandstone (Maastrichtian–Early Paleocene). It is composed of carbonaceous shales, thin beds of siltstones, clays, and coarse-to medium-grained sandstones which exhibit progressive fluvio-deltaic sedimentation (Obi et al., 2001; Yahaya et al., 2018). Overlying the Nsukka Formation, the Imo Shale Formation signifies the beginning of Paleocene marine transgression. With a thickness of roughly 500 m, it is composed of blue-grey shales, calcareous sandstones, marl, and limestone that were deposited in a shallow marine environment (Akande et al., 1992; Kogbe, 1989; Ladipo, 1988; Nwajide, 1990; Reyment, 1965; Simpson, 1954; Short & Stäuble, 1967).

3. Materials and methods

Seventeen (17) fresh, poorly indurated and friable representative sediment samples were obtained from three outcropping

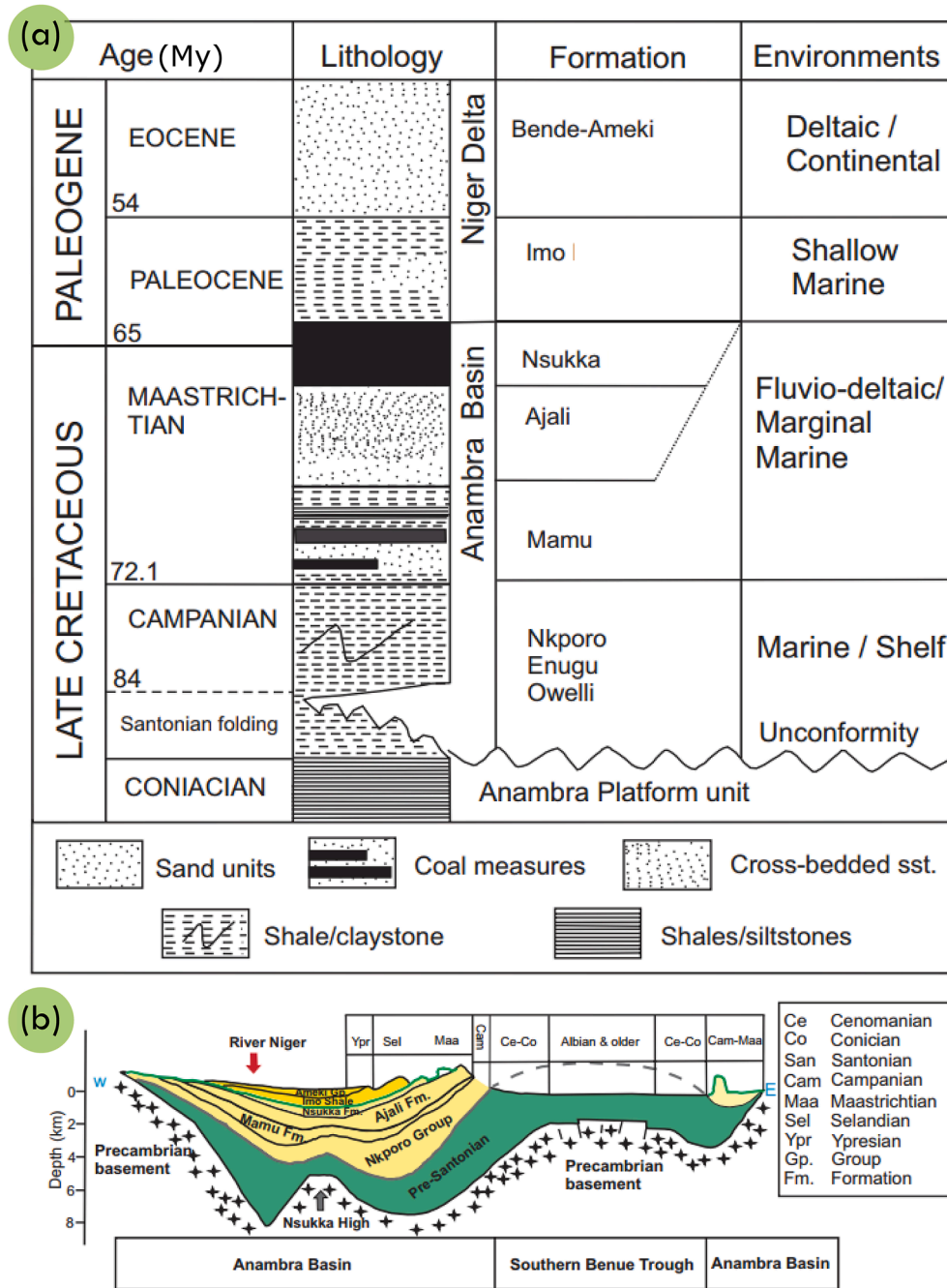


Fig. 2. (a) Stratigraphy and depositional environments of the Anambra Basin (Tijani et al., 2010; Omiotimi et al., 2022; note: sst = sandstone), and (b) a west–east (W–E) cross section of the Anambra Basin showing lithostratigraphic units (modified from Edegbai et al., 2019).

exposures at Odagbo (OGB), Egume (EGM), and Iyale (IYL) (Fig. 3), comprising sandstones ($n = 13$), siltstones ($n = 3$), and ironstone ($n = 1$). The selection of these samples was designed to be representative of the dominant lithofacies observed in the measured sections. Sandstones and siltstones constitute over 90% of the stratigraphic thickness in the studied outcrops of the Mamu and Ajali formations, justifying their higher sampling density. The single ironstone sample (IYL-4G) was obtained from a discrete, ferruginized capping horizon at the Iyale section (Fig. 3(a)). Prior to sample collection, these sections were studied, systematically described and logged. The attitude of the beds and facies information were studied and documented adequately, and the location

and elevation details of each section was captured using a Garmin-72H portable global positioning system (GPS) device.

Samples were oven-dried at 60 °C for 24 h. Disaggregation of the friable sandstones and siltstones was achieved through gentle manual pressure using a porcelain mortar and a rubber-tipped pestle, ensuring the separation of individual grains along cement boundaries without inducing artificial mechanical fracturing. The more indurated ironstone was carefully disaggregated using the same method until the constituent framework grains were liberated. Granulometric analysis was done following the ASTM D422-63 protocol. Approximately 100 g of each disaggregated sample was passed through a nested stack of standard U.S. mesh sieves.

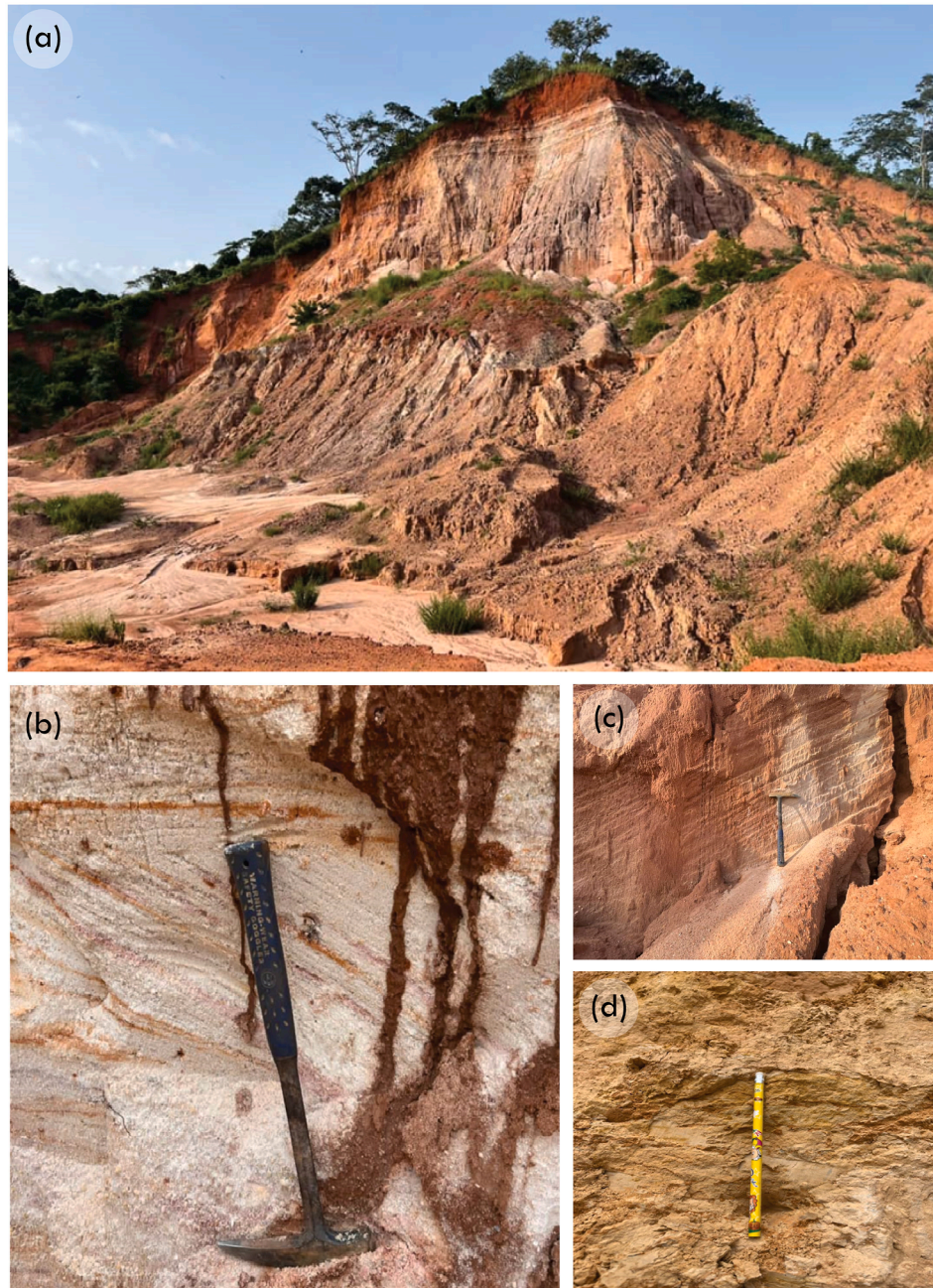


Fig. 3. Field images of the studied sections (a) **EGM**—Panoramic view of a steeply eroded sandstone escarpment (~40 m high) showing reddish brown colouration due to iron staining, capped by ferruginized horizon. The outcrop exhibits stratified sandstone packages with visible cross bedding and horizontal lamination and is dissected by active gully erosion; (b) **IYL**—Cross-bedded sandstone, friable, light to reddish-brown with fine to medium grains. Foresets dip at low to moderate angles, diagnostic of fluvial migration. Iron staining along vertical fractures highlights post-depositional fluid movement; (c) **EGM**—Horizontally laminated fine to medium-grained sandstone with laterally continuous laminae; interpreted as upper plane bed or sheet-like fluvial deposits formed under relatively uniform flow conditions; (d) **OGB**—brownish to yellowish, fine to medium-grained siltstone.

The sieve stack consisted of 11 sieves ranging from -1.0ϕ (2.0 mm) to 4.0ϕ (0.063 mm) at 0.5ϕ intervals. Samples were agitated using a mechanical Ro-Tap shaker for 15 min. The fraction retained on each sieve was weighed to a precision of 0.01 g. The cumulative percentages of particle size were used to compute statistical parameters, including Graphic Mean (M_z), Inclusive Graphic Standard Deviation (IGSD or σ_1), Graphic Skewness (Sk_1), and Graphic Kurtosis (K_G), following the standard graphical methods and formulae defined by Folk and Ward (1957). Conversion of particle size diameter (D) from millimeters (mm) to phi (ϕ) was done as Eq. (1).

$$\phi = -\log_2 D \quad (1)$$

The particle size distribution was visualized using cumulative frequency curves and histograms following the Udden-Wentworth scale for sediment classification. Designated percentiles were identified on the cumulative percentages versus grain size (ϕ) unit plots (Figs. S1–S17 in the supplementary material), and grain statistics such as the M_z , σ_1 , Sk_1 , and K_G were computed using values at the 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles of the cumulative frequency curves. Computations and plots were done using MSExcel 2016 version. The hydrodynamics and

transport mechanisms of the Mamu and Ajali sediments were evaluated by constructing a $C-M$ plot following the [Passeea \(1957, 1964\)](#) method. The bivariate plot correlates the coarsest one-percentile (C) with the median grain size (M) of the sediment population. The C value (calculated as D_1 in μm) represents the “competence” of the transporting medium (the maximum energy available to move particles), while the M value (calculated as the median particle size (D_{50}) in μm) reflects the average energy of the environment.

Samples were plotted against the standard tractive current segments: NO – rolling; OP – rolling with some suspension; PQ – graded suspension with some rolling; QR – graded suspension; RS – uniform suspension; and T – pelagic suspension. To distinguish between depositional settings and processes, different bivariate plots based on the [Sahu \(1964\)](#) linear discriminant function (LDF) and textural parameters were used. Various depositional processes and environments have shown a strong link with the use of LDFs as a tool for determining changes in energy and fluidity factors during sediment deposition ([Sahu, 1964](#)). He distinguished between shallow agitated water and beach, beach and shallow marine, shallow marine and deltaic or lacustrine, and turbidity and deltaic environments, using LDFs of Y_1 , Y_2 , Y_3 , and Y_4 respectively. The mathematical formulae for Y_1 , Y_2 , Y_3 , and Y_4 are given in Eqs. (2)–(5):

$$Y_1 = -3.5688Mz + 3.7016\sigma_1^2 - 2.0766Sk_1 + 3.1135K_G \quad (2)$$

The environment is a beach if Y_1 is more than -2.7411 , and shallow agitated water if Y_1 is less than -2.7411 ,

$$Y_2 = 15.6534Mz + 65.7091\sigma_1^2 + 18.1071Sk_1 + 18.5043K_G \quad (3)$$

In Eq. (3), if Y_2 exceeds -63.3650 , the environment is shallow marine; if Y_2 falls below -63.3650 , the environment is beach.

$$Y_3 = 0.2852Mz - 8.7604\sigma_1^2 - 4.8932Sk_1 + 0.0482 K_G \quad (4)$$

The environment is considered shallow marine if Y_3 is higher than -7.4190 , and lacustrine or deltaic if Y_3 is less than -7.4190 ,

$$Y_4 = 0.7215Mz - 0.4030\sigma_1^2 + 6.7322Sk_1 + 5.2927K_G \quad (5)$$

In Eq. (5), Y_4 indicates turbidity current deposition if it is less than 9.8433 , and deltaic deposition if it is greater than 9.8433 .

Seventeen clastic sediment samples were examined using SEM together with SEM-EDX to determine their surface morphology and elemental composition. Samples were air-dried and gently disaggregated using a porcelain mortar and pestle to release individual grains without inducing artificial mechanical fractures. The resulting material was sieved to isolate the sand-sized fraction ($63-500 \mu\text{m}$) for microtextural analysis. This size range was selected to ensure that original grain surface features were preserved and visible, avoiding the inclusion of fine matrix silt or clay-sized particles that could obscure the quartz surfaces. Grains were mounted on aluminum stubs using conductive carbon tape and sputter-coated with $\sim 20 \text{ nm}$ of iridium to prevent charging. Analysis was done using an FEI Apreo™ C Field Emission Gun (FEG)-SEM (Penn State MCL). Imaging was done at an accelerating voltage of $5-20 \text{ kV}$ using secondary-electron (SE) and backscattered-electron (BSE) detectors to capture surface topography and mineralogical variations. The EDX spectra and elemental maps of individual particles were captured using Oxford Aztec software (as shown in [Fig. 4](#)) for each sample. About, 5 to 10 individual grains per sample were selected for the EDX analysis. The selection criteria followed a dual-purpose strategy: (1) random selection of the primary

framework grains to establish a representative bulk elemental profile, and (2) targeted selection of grain boundaries, coatings, and pore-filling materials to characterize diagenetic phases (e.g., iron oxides and clays). This analysis was done at the Penn State Materials Characterization Lab and the College of Earth and Mineral Sciences, Penn State University, PA, USA.

The statistical summary of numerical data was done using MS Excel while PCA was used to evaluate the relations among elemental compositions obtained from SEM-EDX and to identify the dominant geochemical controls on sediment composition and diagenesis. The analysis was implemented in a cloud-based Python environment using Google Colab, which ensures computational reproducibility and accessibility. The PCA computation was done using the *scikit-learn* library ([Pedregosa et al., 2011](#)). Prior to analysis, the dataset was screened for completeness, and only elements consistently detected across all samples (e.g., Si, aluminium (Al), iron (Fe), potassium (K), calcium (Ca)) were retained. Elements such as titanium (Ti) and zirconium (Zr) were excluded because they were not uniformly reported across the dataset, and their inclusion would introduce bias due to missing values and reduce statistical robustness. The dataset was standardized using z-score normalization to ensure comparability among variables. Only complete cases were analyzed, and no imputation was applied. PCA was done on the standardized data, and the principal components, which explain most of the variance, were retained. Loadings were used to assess variable contributions, while scores were used to evaluate sample relations and compositional trends. Eigenvalues and cumulative variance were used to determine the number of principal components retained, with components explaining $> 95\%$ of the total variance considered significant.

4. Results

4.1. Grain-size characteristics

The sediment samples from the OGB, EGM, and IYL sections display variable grain size characteristics. They show mostly unimodal distribution patterns with peaks at 2.74ϕ and mostly asymmetrical distributions based on the cumulative curve with a standard arithmetic ordinate scale and histograms. The textural parameters were calculated using the [Folk and Ward \(1957\)](#) formulae. Detailed description of the textural terms and their range of values is listed in [Table 1](#) while graphic measurement of grain sizes and their statistical interpretations are as listed in [Tables 2 and 3](#), respectively. The sediments are mostly medium to fine-grained, as shown by the graphic mean (M_z) values for these samples, which vary from 1.894ϕ to 2.377ϕ ([Table 2](#)). Samples with M_z values between 1ϕ and 2ϕ are categorized as medium-grained, while those with values from 2ϕ to 4ϕ are considered fine-grained sands ([Folk & Ward, 1957](#)). The majority of sediments are classified as moderately to poorly sorted based on the sorting values, which are expressed as the IGSD (σ_1), and range from 0.855ϕ to 1.153ϕ ([Table 2](#)). Most samples are fine-skewed ($Sk_1 = 0.10-0.29$) and mesokurtic to leptokurtic ($K_G = 0.92-1.14$) ([Table 2](#)). Sand fractions dominate most samples ($> 95\%$), with minor silt contributions ([Table 2](#)). Cumulative frequency curves and histograms for representative samples are presented in ([Figs. S1–S17](#) in the supplementary material).

4.2. $C-M$ plot characteristics

The results of the $C-M$ analysis ([Fig. 5](#)) show that all studied samples cluster within the tractive currents domain. The median

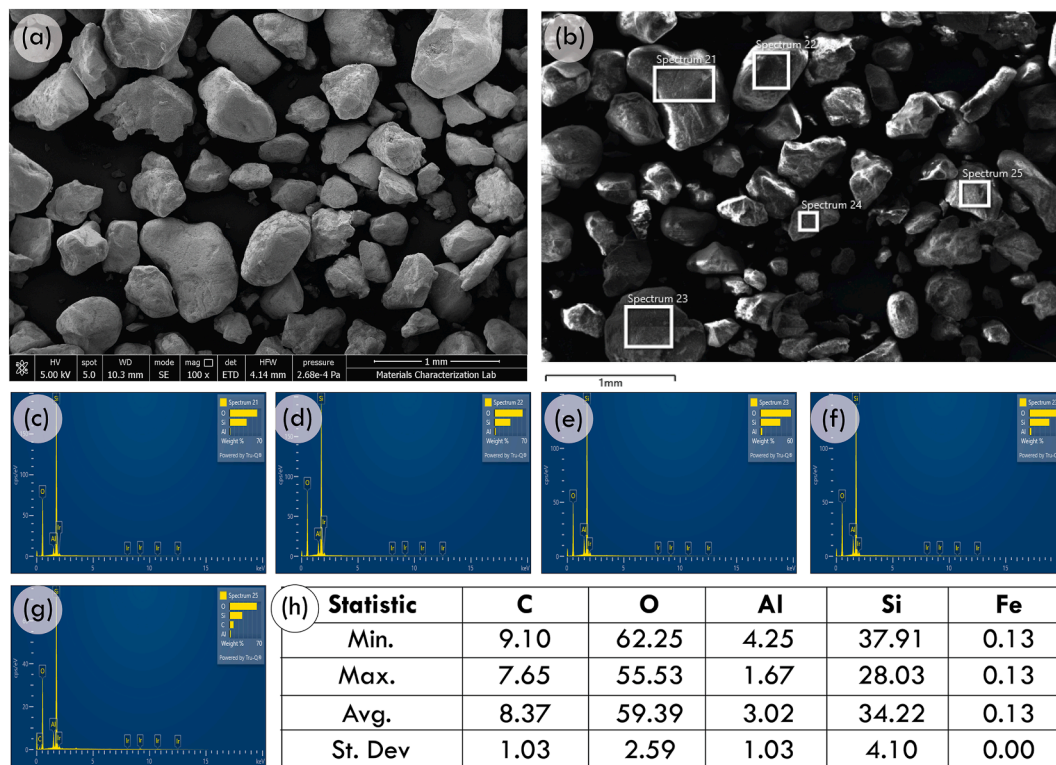


Fig. 4. Scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDS) analysis of sandstone sample (IYL-4F). (a) SEM micrograph showing the general morphology of the sandstone grains—sub-angular to sub-rounded grains, displaying irregular micro-relief with cleavage planes, pits, and minor conchoidal fractures; (b) SEM image highlighting locations for EDS point analyses (spectra 1–5), selected to represent mineralogical diversity across grains; (c)–(g) EDS spectra corresponding to spectra 1 to 5 respectively, showing major elemental peaks; and (h) summary statistics of the spectra showing dominance of silicon (Si) and oxygen (O).

grain size (M) for the ensemble ranges from approximately 214 μm to 301 μm , while the one-percentile (C) values exhibit a broader range, from 659 μm to 1866 μm (Table 2). The data points are predominantly distributed across the PQ and QR segments of the Passega diagram. Specifically, the OGB and EGM samples cluster primarily in the PQ and OP transition zones. This indicates a transport regime dominated by graded suspension with a significant contribution from saltation and rolling of coarser grains. The IYL samples are largely concentrated in the QR segment representing a shift toward a pure graded suspension. All samples plot outside the RS and T fields, indicating no low-energy, quiescent settling during the primary deposition of these sand bodies.

4.3. Bivariate relationships and linear discriminant function (LDF) analysis

Bivariate plots of graphic mean vs. inclusive graphic standard deviation, skewness vs. mean, kurtosis vs. mean, and related combinations are shown in Figs. 6–8. The studied samples are fine to medium-grained and moderately to poorly sorted, according to the bivariate plot of the graphic mean size vs. sorting (IGSD) (Fig. 6(a)). With the predominance of fine sand, the sediments exhibit a unimodal overall impression. These sediments are primarily fine-skewed and fine to medium-grained, according to the bivariate plot of the graphic mean vs. skewness (Fig. 6(b)). The samples plotted in the inland dune environment of the Friedman (1961) scheme, as revealed by the skewness vs. mean cross plot (Fig. 7(a)). According to the graphic mean vs. kurtosis bivariate plot, the clastic sediments under study are fine to medium-grained, with mesokurtic character predominating (Fig. 7(b)). The majority of the grain mixture is composed of fine-grained

sands, with smaller proportions of medium-grained sands. According to the graphic skewness vs. IGSD bivariate plot, the sediments are primarily fine-skewed and moderately sorted (Fig. 8(a)). The kurtosis vs. skewness bivariate plot reveals that the sediment samples are fine-skewed and predominantly mesokurtic (Fig. 8(b)).

In order to categorize the depositional environment of the sediments, the LDF analysis applied to the grain size data revealed that the samples' Y_1 , Y_2 , Y_3 , and Y_4 values ranged from -2.624 to -0.063 , 104.300 to 141.491 , -12.021 to -6.983 , and 7.378 to 8.627 , respectively (Table 4). Bivariate plots (Figs. 6–8) show clustering within fields commonly associated with beach, shallow agitated, fluvial, and turbidity current regimes. LDF analysis (Table 4; Fig. 9) yields Y_1 – Y_4 values that classify the sediments across beach, shallow agitated marine, fluvial, and turbidity current domains.

4.4. SEM microtextural observations

To ensure a robust environmental interpretation, quartz grain surface microtextures were analyzed using a hybrid semi-quantitative approach. The diagnostic nomenclature and frequency classes (Abundant, Common, Present, Rare, Absent) of Mahaney (2002) were integrated with the process-based genetic groupings (Mechanical, Chemical, Mixed) and the "Checklist" quantification method proposed by Vos et al. (2014). For each of the 17 samples, a minimum of 20 grains were randomly selected, and the presence or absence of 18 distinct features was determined. This multifaceted methodology allows for the statistical decoupling of primary transport signatures from post-depositional diagenetic overprinting. The degree of grain roundness was

Table 1

Textural parameters and their corresponding verbal description (Folk, 1974), as modified in the current study.

*Mean (M_z)		Sorting (σ_1)		Skewness (Sk_1)		Kurtosis (K_G)	
phi	Description	phi	Verbal sorting	Calculated	Verbal skewness	Calculated	Verbal kurtosis
(−1.00) – (+0.99)	Coarse-grained	< 0.35	Very well sorted	> 0.30	Strongly fine skewed	< 0.67	Very platykurtic
1.00–1.99	Medium-grained	0.35–0.49	Well sorted	0.30–0.09	Fine skewed	0.67–0.89	Platykurtic
2.00–4.00	Fine-grained	0.50–0.70	Moderately well sorted	0.10–(−0.09)	Near symmetrical	0.90–1.10	Mesokurtic
		0.71–1.00	Moderately sorted	−0.10–(−0.30)	Coarse skewed	1.11–1.49	Leptokurtic
		1.01–2.00	Poorly sorted	< −0.30	Strongly coarse skewed	1.50–3.00	Very leptokurtic
		2.01–4.00	Very poorly sorted			> 3.00	Extremely leptokurtic
		> 4.00	Extremely poorly sorted				

Note: *Folk and Ward (1957). The textural scheme used in this study has been modified since a value of 0.90 of kurtosis previously resides in two categories—platykurtic and mesokurtic. Following the principle of “no duplication”, the ranges have been adjusted, in accordance with standard practice in sedimentology to treat the upper bound as “up to but not including” or to use specific decimal increments.

Table 2

Graphic measurement of grain size parameters for the Campano-Maastrichtian sediments of the northern Anambra Basin.

Sample ID	Lithology	ϕ_5	ϕ_{16}	ϕ_{25}	ϕ_{50}	ϕ_{75}	ϕ_{84}	ϕ_{95}	Sand (%)	Silt (%)	C (μm)	M (μm)
OGB-1D	Siltstone	1.085	1.404	1.568	2.115	2.715	3.259	3.976	95.210	4.790	1000.000	230.850
OGB-1E	Sandstone	0.976	1.368	1.534	2.066	2.655	3.142	3.961	95.390	4.610	1000.000	238.770
OGB-1F	Sandstone	0.520	0.979	1.221	1.777	2.649	3.114	3.757	98.980	1.020	1414.214	291.760
OGB-1G	Sandstone	0.468	0.953	1.182	1.762	2.559	2.967	3.722	98.910	1.090	1741.101	294.778
EGM-3A1	Sandstone	1.170	1.419	1.580	2.145	2.822	3.330	3.952	95.680	4.320	1000.000	226.051
EGM-3A2	Sandstone	1.022	1.397	1.571	2.115	2.690	3.130	3.758	99.070	0.930	1866.066	230.882
EGM-3B	Sandstone	0.503	1.006	1.262	1.792	2.625	3.074	3.736	99.230	0.770	1866.066	288.872
EGM-3C	Sandstone	0.584	1.028	1.271	1.729	2.593	3.039	3.725	99.250	0.750	1515.717	301.734
EGM-3D	Sandstone	0.979	1.340	1.474	1.924	2.582	2.945	3.702	99.190	0.810	933.033	263.439
EGM-3E	Sandstone	0.960	1.371	1.553	2.094	2.656	3.068	3.757	98.730	1.270	1515.717	234.165
IYL-4A	Sandstone	0.509	1.189	1.380	1.874	2.507	2.734	3.645	99.110	0.890	1319.508	272.837
IYL-4B	Sandstone	0.517	1.141	1.363	1.865	2.493	2.718	3.608	99.470	0.530	1866.066	274.505
IYL-4C	Siltstone	1.116	1.436	1.621	2.223	2.982	3.474	4.229	93.450	6.550	1319.508	214.209
IYL-4D	Siltstone	1.044	1.406	1.579	2.153	2.822	3.347	3.989	95.020	4.980	659.754	224.770
IYL-4E	Sandstone	0.557	1.186	1.380	1.880	2.499	2.722	3.624	99.260	0.740	1866.066	271.635
IYL-4F	Sandstone	0.556	1.225	1.398	1.912	2.534	2.795	3.645	99.470	0.530	1866.066	265.759
IYL-4G	Ironstone	0.523	1.035	1.305	1.927	2.808	3.338	3.987	95.050	4.950	1866.066	263.055

Table 3

Statistical description and their interpretations for the studied sediment samples from granulometric analysis.

Sample ID	M_z	σ_1	Sk_1	K_G	Interpretation
OGB-1D	2.259	0.946	0.260	1.034	Fine-grained, moderately sorted, fine skewed, mesokurtic
OGB-1E	2.192	0.941	0.241	1.092	Fine-grained, moderately sorted, fine skewed, mesokurtic
OGB-1F	1.957	1.073	0.238	0.929	Medium-grained, poorly sorted, fine skewed, mesokurtic
OGB-1G	1.894	1.046	0.200	0.968	Medium-grained, poorly sorted, fine skewed, mesokurtic
EGM-3A ₁	2.298	0.942	0.269	0.917	Fine-grained, moderately sorted, fine skewed, mesokurtic
EGM-3A ₂	2.214	0.889	0.186	1.002	Fine-grained, moderately sorted, fine skewed, mesokurtic
EGM-3B	1.957	1.056	0.222	0.972	Medium-grained, poorly sorted, fine skewed, mesokurtic
EGM-3C	1.932	1.026	0.287	0.974	Medium-grained, poorly sorted, fine skewed, mesokurtic
EGM-3D	2.070	0.855	0.289	1.007	Fine-grained, moderately sorted, fine skewed, mesokurtic
EGM-3E	2.178	0.891	0.168	1.039	Fine-grained, moderately sorted, fine skewed, mesokurtic
IYL-4A	1.932	0.909	0.121	1.141	Medium-grained, moderately sorted, fine skewed, leptokurtic
IYL-4B	1.908	0.909	0.105	1.122	Medium-grained, moderately sorted, fine skewed, leptokurtic
IYL-4C	2.377	1.028	0.258	0.937	Fine-grained, poorly sorted, fine skewed, mesokurtic
IYL-4D	2.302	0.976	0.238	0.971	Fine-grained, moderately sorted, fine skewed, mesokurtic
IYL-4E	1.930	0.895	0.117	1.123	Medium-grained, moderately sorted, fine skewed, leptokurtic
IYL-4F	1.978	0.907	0.124	1.115	Medium-grained, moderately sorted, fine skewed, leptokurtic
IYL-4G	2.100	1.153	0.208	0.945	Fine-grained, poorly sorted, fine skewed, mesokurtic

determined through visual comparison with the Powers (1953) roundness scale, classifying grains into six categories ranging from very angular to well-rounded, while grain sphericity was assessed using the Krumbein and Sloss (1963) chart. The integrated semi-quantitative analysis of the quartz grain microtextures (Table 5) reveals the distribution of identified features across the study locations.

The SEM micrographs (Figs. 4 and 10) show quartz grains that range from angular to rounded across the different facies. The SEM

micrographs reveal significant aspects of grain morphology, which provide crucial insight into sediment transport, depositional processes, and provenance (Fig. 4(a)). OGB facies display angular to sub-rounded grains with impact pits, dissolution pits, micro-grooves, conchoidal fractures, and step-like fracture planes. EGM facies show angular to sub-angular grains with pitting, grooves, abrasion marks, scratches, and mechanical breakage scars. IYL facies are characterized by sub-angular to rounded grains with smoother surfaces, solution pits, chemical etching, quartz

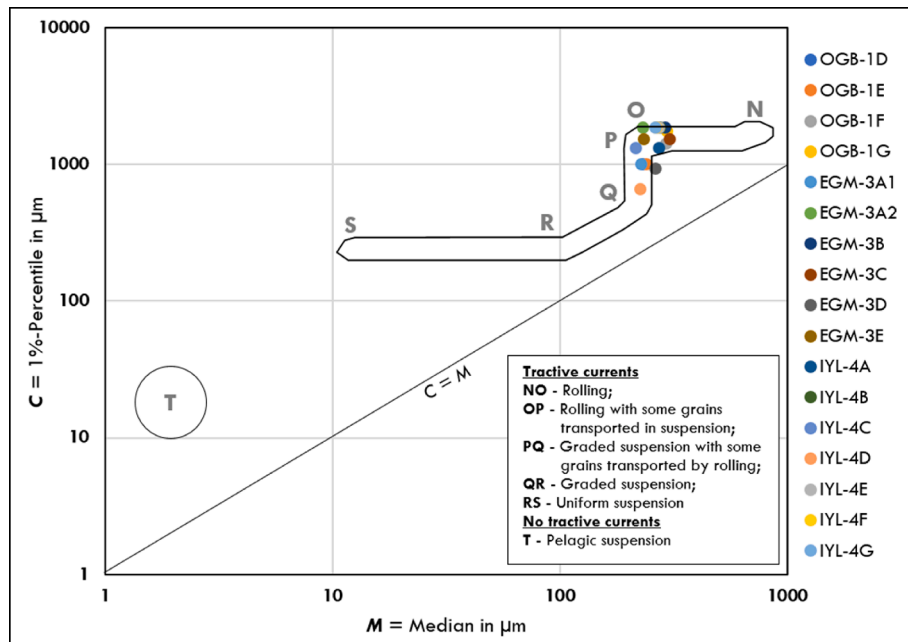


Fig. 5. C–M plot showing the transport mechanism for the Mamu and Ajali sediments (after Passega, 1964).

overgrowths, and diagenetic polishing. A summary of the observed microtextures and associated features was used to infer depositional conditions as listed in Table 6. SEM analysis of the samples reveal a transition from mechanically dominated microtextures in the Mamu Formation to chemically overprinted textures in the Ajali Formation. Conchoidal fractures are abundant in proximal sandstone samples (e.g., OGB-1F), while diagenetic features like quartz overgrowths and solution pits reach abundant levels in distal ironstone and siltstone facies (e.g., IYL-4G, IYL-4C). Authigenic quartz overgrowths (often referred to more broadly as silica overgrowths in the context of silicon dioxide (SiO_2) precipitation) were observed as incipient facets on several grain surfaces (Fig. 10). In these samples, the term “quartz overgrowth” specifically denotes syntaxial overgrowths where authigenic silica has precipitated in crystalline continuity with the host detrital quartz grains during early diagenesis.

4.5. SEM-EDX and principal component analysis (PCA)

The EDX spectra (Fig. 11) indicates dominance of Si and O, with variable contributions from Al and Fe across samples. Silica, O, Al, Fe, and carbon (C) are common in all the samples irrespective of their lithofacies (Fig. 11). Si and O are predominant in all sandstone samples, ranging from 22.57% to 32.36% and 57.22%–59.99% respectively, on average, with low to moderate Al and Fe. The OGB sandstones have generally high Si (mean = 27.92%), while Al ranges from 2.63% to 12.11%, with a highly variable proportion of Fe in the range of 0.59%–2.49%. K, indium (In), tin (Sn), and Ti are present in trace amounts. The IYL sandstones are generally quartz-rich with a clean matrix. They have the highest proportion of Si (mean = 32.36%). Al ranges from 3.02% to 3.94% while Fe is about 1.03% on average, with moderate C (7.66%–8.37%) and trace amounts of Ti (0.13%–0.25%). EGM sandstones contain low to moderate Si (Av. 17.14–30.03%). Al is up to 10.36% in EGM-3D, with high variability and moderate to high Fe (0.60%–2.81%). This sample contains high C and heavy minerals such as zirconium (Zr), Ti, and vanadium (V) in trace amounts.

In this study, PCA analysis was done on raw EDX data for the samples and captured C, O, Al, Si, and Fe. Since Ti, V, Zr, In, K, Sn, and magnesium (Mg) were found in some of the samples and not reported across board, they were excluded from the analysis. In EDX analysis, these elements often fall near or below the instrument's detection limit (~0.1 wt%). Including variables with inconsistent reporting or a high frequency of non-detected values can introduce “noise” and artificial skewness into the principal components, potentially leading to the over interpretation of statistical outliers rather than meaningful geological trends. By focusing on the five most consistently detected elements (Si, Al, Fe, C, and O), the PCA provides a robust representation of the primary mineralogical framework (quartz vs. clay/oxides) and redox-sensitive components. The PCA results (Figs. 12(a)–12(d); Tables 7 and 8) show that the first three principal components explain the majority of the variance, with loadings reflecting quartz enrichment, aluminosilicate-associated elements, and Fe-related signatures.

5. Discussion

5.1. Grain shape and roundness

In general, the sediment grains exhibit low to high sphericity and range from angular to rounded across the different formations, as detailed in the integrated semi-quantitative morphological data in Table 5 and interpreted in Table 6. Grain shapes in the OGB samples range from angular (Fig. 10(a)), to sub-angular to sub-rounded. Sub-rounded grains suggest some mechanical abrasion during fluvial or shallow marine sedimentation processes, whereas angular and sub-angular grains show proximity to the sediment source with relatively little transport. This suggests a mixed provenance with both first-cycle detritus and reworked sediments.

EGM grains show a wider variability; some of the grains are very angular, retaining sharp edges and corners, while others are sub-rounded (Figs. 10(b) and 10(c)), indicating transport abrasion.

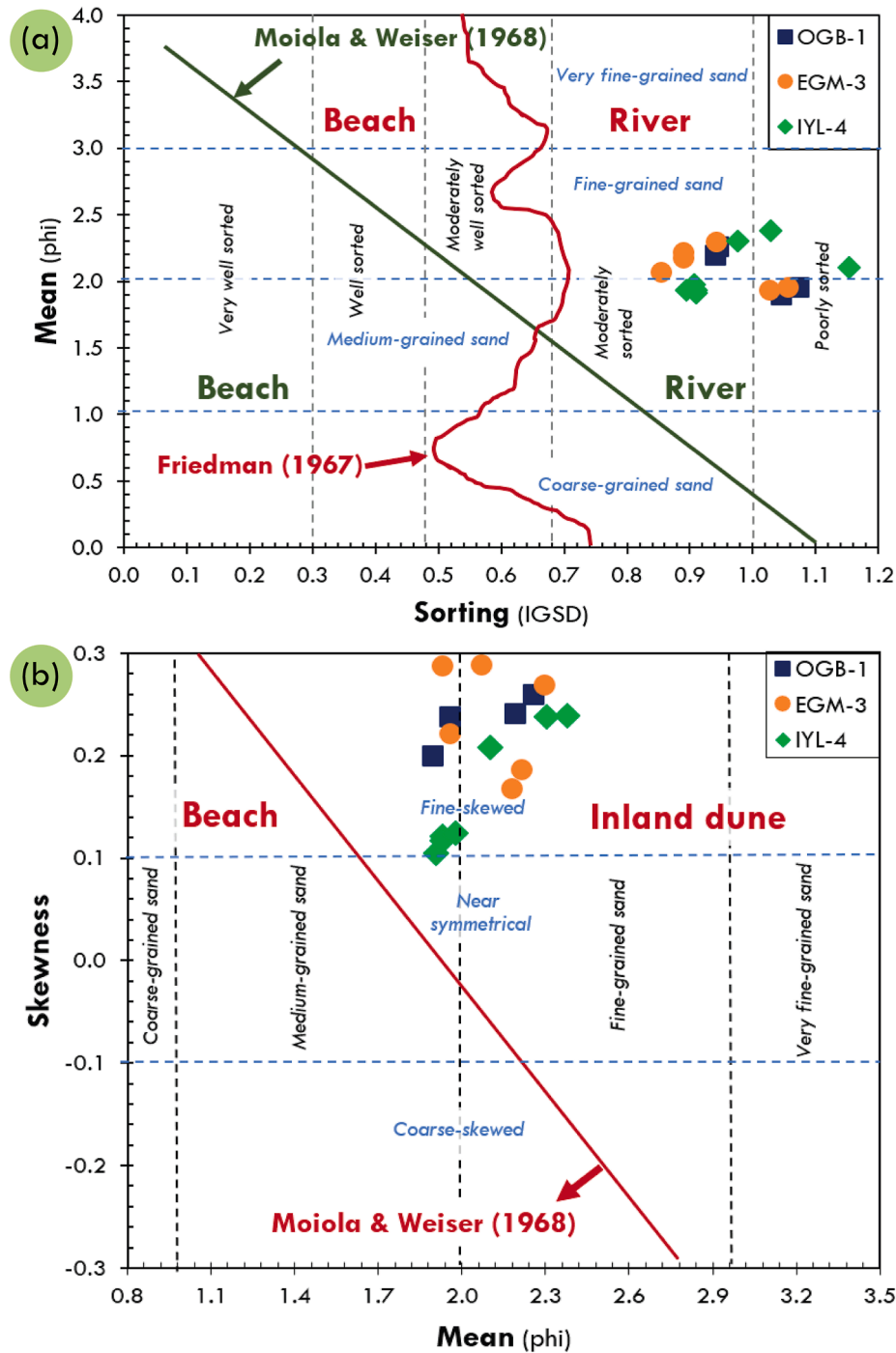


Fig. 6. Bivariate plot of (a) graphic mean vs. IGSD showing the depositional environments (background patterns after Friedman (1967) and Moiola and Weiser (1968)); and (b) skewness vs. graphic mean for the studied sediments showing the grain sizes, skewness, and depositional environments (background patterns after Moiola and Weiser (1968)).

The coexistence of angular and rounded grains indicates multi-source contributions.

IYL sediments are sub-rounded to rounded (Figs. 10(d)–10(j)), with several grains showing relatively smoother surfaces compared to OGB and EGM samples. The higher degree of roundness is suggestive of longer transport or reworking, which is consistent with sediments deposited farther from their source or reworked due to wave action. The rounded morphologies seen are the consequence of mechanical abrasion

caused by repeated hits and collisions when grains are suspended or rolled around the seafloor, which tends to smooth grain edges and corners (Boggs, 2012). According to Ekwenye et al. (2015), stable and mature depositional settings dominated by wave and current actions are generally correlated with this maturity in grain morphology. Furthermore, the occurrence of angular grains could indicate inputs from river discharge that have undergone minimal reworking or contributions from neighboring source areas.

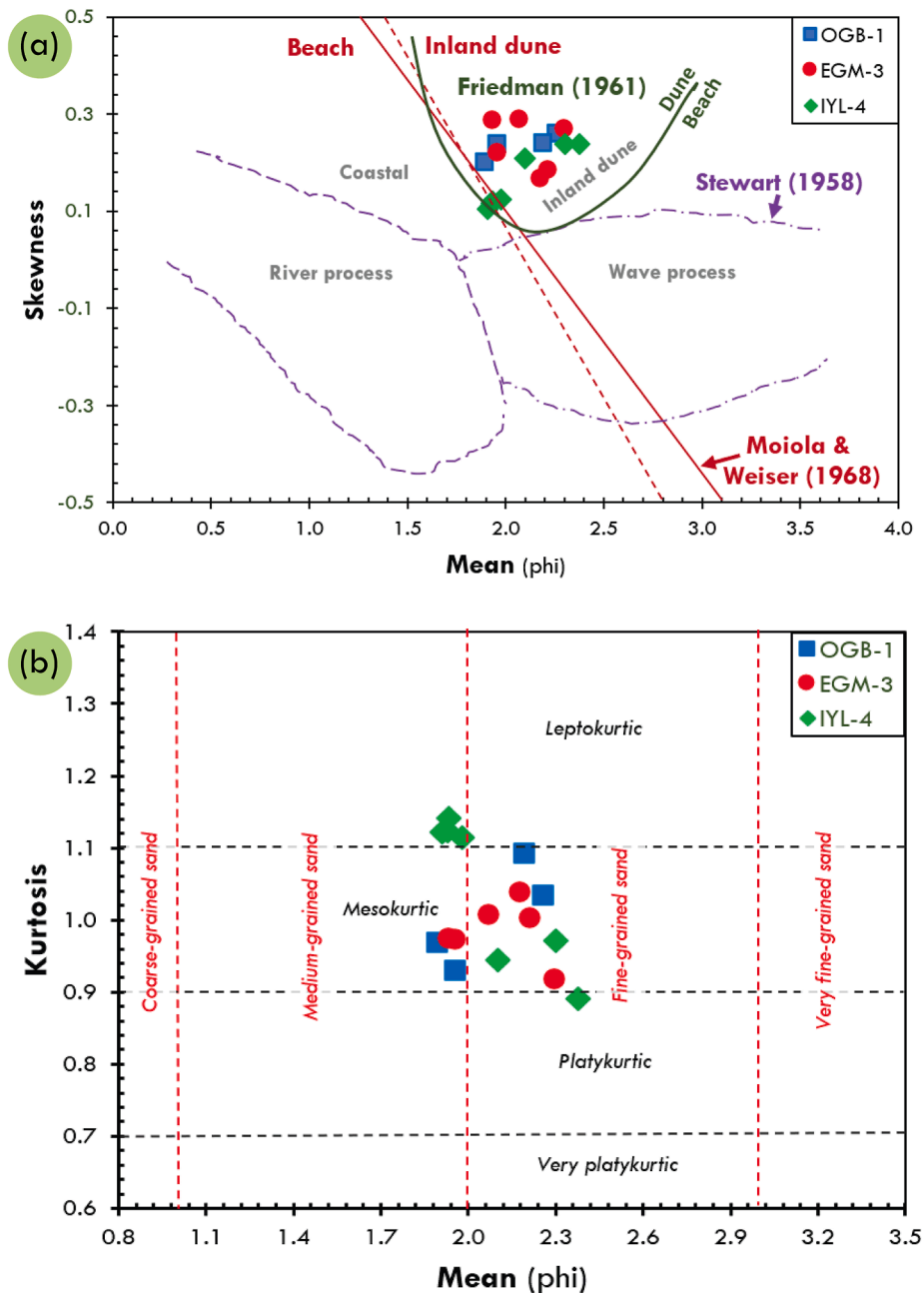


Fig. 7. Bivariate plot of (a) skewness vs. graphic mean for the studied sediments showing the coastal, dune, wave, and river processes (background patterns after Stewart (1958); Friedman (1961) and Moiola and Weiser (1968)); and (b) kurtosis vs. graphic mean for the studied sediments showing the grain size, and kurtosis categories.

5.2. Surface textures and grain size variability

The SEM images show grains with rough to relatively smooth surfaces that occasionally have pitting and irregularities which are indications of chemical weathering and minor mechanical breakdown during sediment transport. Observed microtextures include the following (Table 5): rugged and fractured surfaces with conchoidal breakage and step-like fracture planes, grooves, scratches, and irregular etching; rough with impact pits and micro-grooves (OGB-IF; Fig. 10(a)), and dissolution pits with evidence of incipient silica (quartz) overgrowth, suggestive of early

diagenetic modification. These features suggest rapid sedimentation with minimal transport abrasion in the OGB sediments. The presence of quartz overgrowths shows early diagenetic modification in pore waters.

The EGM sediments are characterized by the following surface textural features: irregular and fractured surfaces, conchoidal fractures and scratches, abrasion smoothing (Fig. 10(b)), grooves, breakage scars and micro-pits (Fig. 10(c)); smooth surface with etch pits and minor quartz overgrowths collision marks and irregular etching; and surfaces with pitting (Fig. 10(c)). Mixed angularity and roundness in EGM sediments suggest a multi-

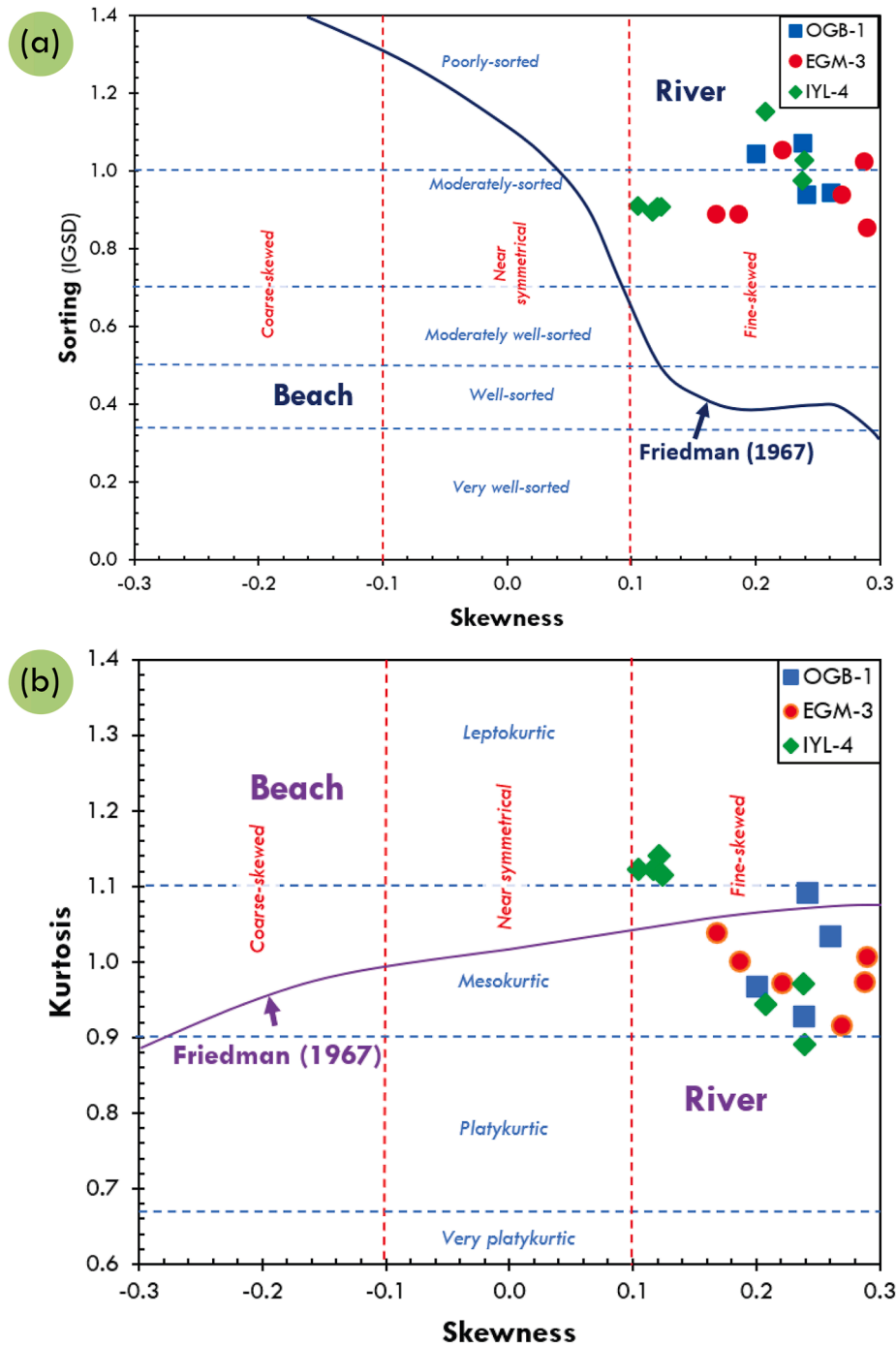


Fig. 8. Bivariate plot of (a) IGSD vs. graphic skewness for the studied sediments showing the grain sorting, skewness categories, and depositional environment (background patterns after Friedman (1967)); and (b) graphic kurtosis vs. graphic skewness for the studied sediments showing the grain kurtosis, skewness categories, and depositional environment (background patterns after Friedman (1967)).

source input with variable transport distances. Poor to moderate sorting indicates rapid deposition under fluvial conditions while the rounded, etched grains indicate secondary reworking in a shallow marine setting. The EGM sediments reflect a fluvio-marine depositional system.

IYL sediments show: quartz overgrowths and minor dissolution features (Figs. 10(g), 10(h), 10(k), and 10(l)); chemical etching and dissolution pits, with smoothened ridges, abrasion marks, dissolution pits (Figs. 10(h) and 10(l)), smooth surfaces with diagenetic polishing (Fig. 10(e)); and irregular micro-relief with cleavage

planes, pits, and minor conchoidal fractures (Fig. 4(a)). These sediments show the highest degree of roundness and sorting, along with chemical overprinting. This indicates long transport and/or wave reworking in a distal, shallow marine depositional setting or beach environment, in contrast to the proximal character of the OGB and EGM sediments.

A depositional environment where sediment grains were carried by a combination of processes such as wave action, currents, and turbulent flows, all of which contributed unique textural signatures, is supported by the existence of both polished and

Table 4
Depositional environment inferred from linear discriminant functions (LDFs) calculated from granulometric analysis of the Campano-Maastrichtian sediments of the northern Anambra Basin.

Sample ID	Discriminant function				Inferred process influence			
	Y ₁	Y ₂	Y ₃	Y ₄	Y ₁	Y ₂	Y ₃	*Y ₄
OGB-1D	−2.074	117.971	−8.414	8.494	Beach	Shallow agitated	Fluvial	Turbidity currents
OGB-1E	−1.650	117.035	−8.256	8.627	Beach	Shallow agitated	Fluvial	Turbidity currents
OGB-1F	−0.322	127.808	−10.651	7.466	Beach	Shallow agitated	Fluvial	Turbidity currents
OGB-1G	−0.112	123.071	−9.976	7.400	Beach	Shallow agitated	Fluvial	Turbidity currents
EGM-3A ₁	−2.624	116.073	−8.384	7.970	Beach	Shallow agitated	Fluvial	Turbidity currents
EGM-3A ₂	−2.242	108.534	−7.160	7.836	Beach	Shallow agitated	Shallow marine	Turbidity currents
EGM-3B	−0.294	125.852	−10.241	7.598	Beach	Shallow agitated	Fluvial	Turbidity currents
EGM-3C	−0.562	122.665	−10.034	8.057	Beach	Shallow agitated	Fluvial	Turbidity currents
EGM-3D	−2.145	104.300	−7.178	8.472	Beach	Shallow agitated	Shallow marine	Turbidity currents
EGM-3E	−1.949	108.475	−7.098	7.884	Beach	Shallow agitated	Shallow marine	Turbidity currents
IYL-4A	−0.537	107.867	−7.229	7.917	Beach	Shallow agitated	Shallow marine	Turbidity currents
IYL-4B	−0.474	106.870	−7.160	7.686	Beach	Shallow agitated	Shallow marine	Turbidity currents
IYL-4C	−2.189	128.708	−9.803	7.989	Beach	Shallow agitated	Fluvial	Turbidity currents
IYL-4D	−2.163	120.909	−8.808	8.019	Beach	Shallow agitated	Fluvial	Turbidity currents
IYL-4E	−0.666	105.735	−6.983	7.800	Beach	Shallow agitated	Shallow marine	Turbidity currents
IYL-4F	−0.797	107.916	−7.200	7.829	Beach	Shallow agitated	Shallow marine	Turbidity currents
IYL-4G	−0.063	141.491	−12.021	7.378	Beach	Shallow agitated	Fluvial	Turbidity currents

Note: *Statistical inference based on [Sahu \(1964\)](#), likely represents episodic high-energy density flows in this setting.

irregular surface textures ([Boggs, 2012](#)). The particle size variation observed in the SEM micrographs, which ranges from medium sand grains to fine silt, highlights the heterogeneity of sediment supply and depositional energy regimes. In beach and shallow marine environments, where sorting by wave and current action is intense, well-sorted fractions with uniform grain sizes are common ([Folk & Ward, 1957](#)). However, the presence of poorly sorted grains with size mixing indicates either high-energy, episodic depositional processes like turbidity currents or fluvial floods, or rapid sedimentation ([Mulder & Alexander, 2001](#)). The combination of all these observations suggests short to medium transport in a moderate energy fluvial or shallow marine setting, with limited reworking.

5.3. Depositional hydrodynamics and transport mechanisms

The interpretation of depositional processes in the northern Anambra Basin requires a multi-faceted approach that reconciles statistical grain size distributions with physical transport models. The Campano-Maastrichtian succession, comprising the Mamu and Ajali formations, records a pivotal period of basin infilling where terrestrial sediment supply intersected with fluctuating marine energy. By integrating granulometric statistics, bivariate relations, multivariate discriminant functions, and C-M patterns, the hydrodynamic energy and fluidity factors prevalent during sediment deposition can be reconstructed with high resolution.

The moderately to poorly sorted values observed suggest fluctuating energy conditions or episodic sediment supply, consistent with mixed coastal and fluvial deposition influenced by varying river discharge, storm waves, and tidal currents. Lower sorting values (e.g. EGM-3D and IYL-4E) might represent rapid sedimentation events caused by turbidity currents, floods, or riverine input, resulting in a mixture of various sediment sizes and contributing to less uniform grain size distributions ([Mulder & Alexander, 2001](#)). The samples exhibit positive skewness values ranging from about 0.105 to 0.289 ϕ (fine skewed), showing an asymmetry in grain size distribution that favors finer particles. Fine skewness is usually a result of sediment deposition from suspension or the distant fallout of finer grains, consistent with shallow marine environments or low-gradient fluvial settings with diminished current strength. Conversely, a few samples demonstrate slightly coarser skewness or nearly symmetrical distributions, suggesting

balanced transport conditions involving both suspended and bedload sedimentation ([Friedman, 1967](#); [Stewart, 1958](#)). Mostly falling between 0.917 ϕ and 1.141 ϕ , kurtosis data show mesokurtic to leptokurtic ranges. A comparatively regular distribution of grain sizes, characteristic of steady sedimentation processes, is shown by mesokurtic distributions, while leptokurtic values (indicating sharper peaks) suggest intermittent or episodic sediment influx or improved sorting of specific grain sizes ([Folk, 1974](#)). These kurtosis measurements reaffirm the dynamic nature of the depositional environment, characterized by consistent background sedimentation interrupted by occasional high-energy events such as storms or turbidity flows.

The depositional environments and conditions of sedimentary rocks are mostly indicated by the grain size, grain packing, sorting, and texture of the sediments. Meanwhile, the evidence from the bivariate plots ([Figs. 6–8](#)) that were applied to these sediments and their statistical values as computed from granulometric analysis ([Table 2](#)) show that the samples are typically fine to medium-grained, moderately sorted to poorly sorted, with mean grain sizes ranging from coarse sand to fine silt. They are mostly mesokurtic and fine-skewed ([Table 3](#)). Specifically, 35% of the sediments are poorly sorted, and 65% of the samples are moderately sorted. In addition, roughly 23% of the sediments are leptokurtic while 77% are mesokurtic.

The cumulative curves for OGB samples are relatively steep, indicating a narrower range of grain sizes, with histograms indicating unimodal distribution with peaks around the medium sand range at 2.74 ϕ . EGM samples on the other hand, are predominantly sandstones, with broader cumulative curves and flatter histogram peaks ([Figs. S5–S10](#) in the supplementary materials), which implies poor to moderate sorting. Some samples show slight bimodality, suggestive of episodic variations in energy or sediment sources. Slow settling in calm waters may be responsible for the silt composition and sorting pattern, which are more widely observed in IYL samples with poor to moderate sorting and, in some cases, higher kurtosis values.

The dominance of fine to medium-grained sediments (1.89 ϕ – 2.37 ϕ) across the OGB, EGM, and IYL sections suggests a relatively consistent energy regime capable of transporting medium-sized clastics. However, the prevalence of moderate to poor sorting (0.85 ϕ – 1.15 ϕ) indicates that the sorting efficiency was hindered by rapid sedimentation rates or the proximity of the

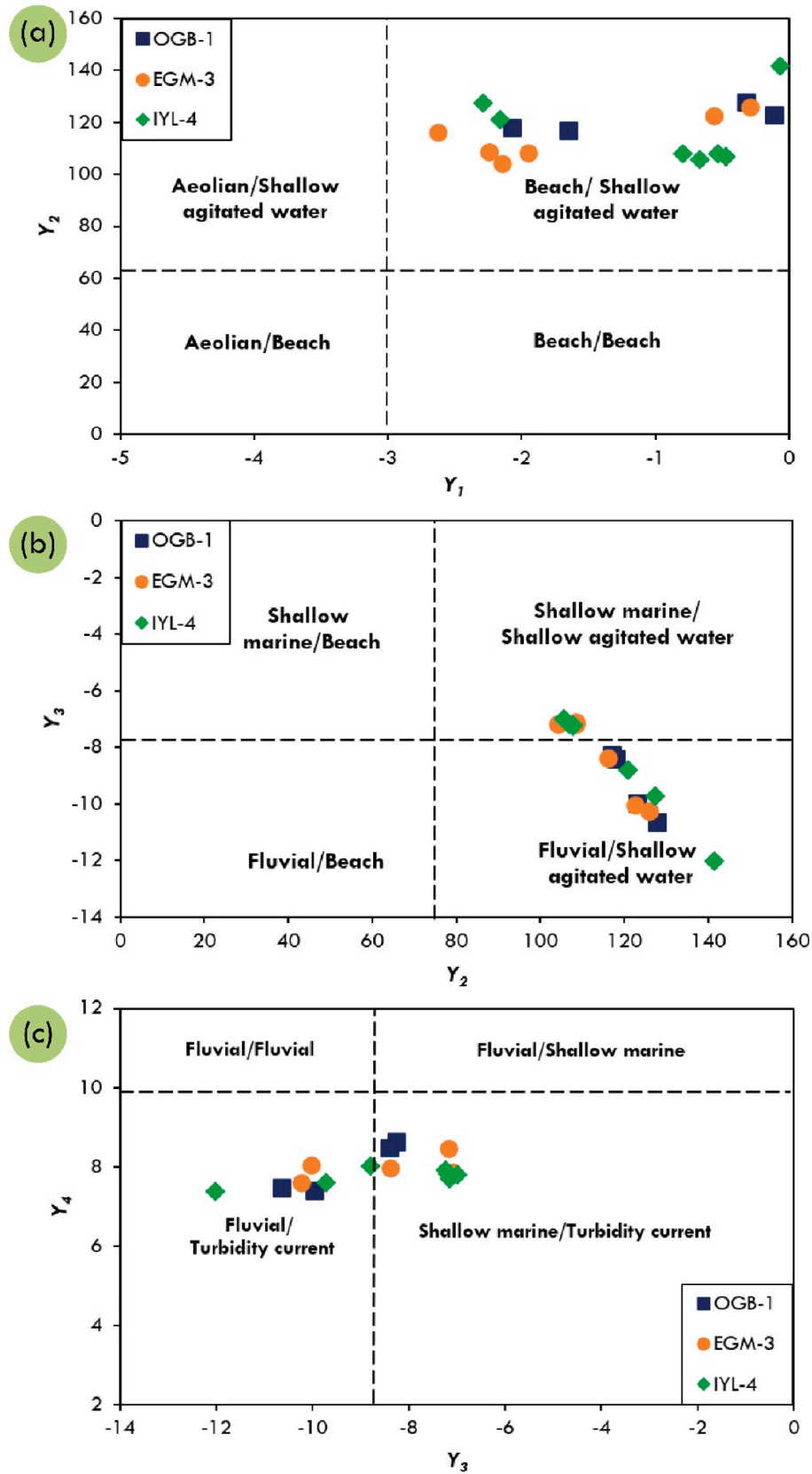


Fig. 9. Depositional environments and processes for the sediments inferred from linear discriminant function (LDF) binary plot (a) Y_1 vs. Y_2 ; (b) Y_2 vs. Y_3 ; and (c) Y_3 vs. Y_4 .

Table 5
Integrated semi-quantitative frequency (Avg.%) of quartz grain microtextures and features.

Genetic group (Vos et al., 2014)	Microtexture features (Mahaney, 2002)	OGB	EGM	IYL
		(Avg. %)		
Mechanical/physical	Conchoidal fractures	A (88)	C (42)	R (4)
	Step-like fractures	C (35)	P (12)	– (0)
	V-shaped aqueous pits	R (3)	C (58)	C (45)
	Mechanical grooves/scratches	P (18)	P (22)	P (10)
Chemical/diagenetic	Solution pits/etching	P (12)	C (55)	A (82)
	Syntaxial quartz overgrowth	R (2)	P (18)	C (68)
	Diagenetic polishing	– (0)	R (4)	C (42)
	Adhering particles	C (65)	C (48)	P (24)

Frequency classes based on Mahaney (2002): A = Abundant (75%); C = Common (25%–75%); P = Present (5%–25%); R = Rare (<5%); and – = Absent (0%). Percentages follow the grain-count checklist method of Vos et al. (2014) ($n = 20$ grains per sample).

sediment source. According to Folk and Ward (1957), such sorting values are characteristic of environments where various sediment sizes are mixed during high energy discharge events, such as fluvial floods or storm-driven surges. The consistently positive skewness (0.10–0.28) observed in the majority of samples reflects an asymmetrical distribution with a tail of fine particles. In the northern Anambra Basin, this “fine-skewness” is interpreted as the result of sediment deposition from suspension or the infiltration of fines into the pore spaces of a pre-existing sand framework during the waning stages of a current (Friedman, 1961). This aligns with the “unimodal” distribution identified in the histograms, suggesting a primary sediment population periodically influenced by lower energy deposits.

The application of bivariate plots (Figs. 6–8) following the schemes of Friedman (1961, 1967) and Moiola and Weiser (1968) provides a graphical discrimination of the depositional settings. The clustering of OGB and EGM samples within the river and beach overlapping fields on the M_z vs. σ_1 plot (Fig. 6(a)) suggests a transitional environment. While the coarse to medium size reflects fluvial competence, the moderate sorting values distinguish these from mature aeolian or beach sands, which typically exhibit superior sorting ($\sigma_1 < 0.5 \phi$). Furthermore, the kurtosis vs. skewness relations (Fig. 8(b)) indicate that 77% of the samples are mesokurtic. This “normal” peakness suggest steady-state sedimentation, while 23% leptokurtic samples indicate episodic “shocks” to the system, likely intermittent high energy influxes that introduced a highly sorted specific grain fraction to the basin floor (Folk, 1974).

The statistical distribution of grain sizes provides a direct proxy for the hydraulic energy and selective efficiency of the transporting medium. The M_z reflects the average hydraulic competence (fluid shear stress) of the paleocurrents. The dominance of medium-grained sands (1.00 ϕ –1.99 ϕ) in the OGB and EGM sections indicates a high-energy regime capable of transporting a robust bedload while bypassing finer fractions. The transition toward fine-grained sediments (2.00 ϕ –4.00 ϕ) in the distal IYL facies signifies a decrease in carrying capacity, consistent with a reduction in flow velocity as the system moved from confined fluvial channels toward lower-energy shoreface environments. Sorting (σ_1) serves as a mechanical indicator of the energy stability and selection efficiency of the depositional system. The observed moderate to poor sorting (0.855 ϕ to 1.153 ϕ) reflects a fluctuating energy regime where rapid variations in flow competence prevented the hydraulic system from reaching equilibrium. This indicates high rates of sediment supply that exceeded the system's winnowing capacity, leading to rapid accumulation, which is supported by the angular grain morphologies observed in the SEM.

The predominantly fine-skewed (Sk_1) nature of the sediments (+0.10 to +0.30) reflects the mechanical entrapment of suspension

loads during waning energy stages. This indicates an environment where primary sand transport was periodically interrupted by lower-velocity conditions, allowing finer particles to settle within the grain framework. Finally, the mesokurtic to leptokurtic (K_G) distributions (0.90–1.50) suggest hydrodynamic pulsing or the mixing of multiple sediment populations. The “peaked” leptokurtic distributions in the Ajali Formation reflect episodic high-energy events (such as storm surges or river floods) that introduced specific grain-size fractions into a previously sorted background population, creating a mixed-energy textural signature.

The LDF analysis provides a robust mathematical framework for distinguishing between environments that share overlapping textural signatures. The Y_1 values from OGB, EGM, and IYL indicate a very minor beach influence, as the samples are not from a beach environment.

Y_2 values (Table 4) on the other hand indicate shallow agitated water conditions for the sediments. These sediments were deposited in a shallow, agitated water environment that was influenced by beaches, as demonstrated by the Y_2 vs. Y_1 cross plot. This is dominant in the entire dataset, with high values typical of a nearshore zone above the wave base where the energy keeps the sediment agitated. The Y_3 values discriminate between fluvial and shallow marine environments, indicating the predominance of beds deposited in fluvial environments (59%) over those deposited in shallow marine environments (41%). The stronger fluvial signal suggests a proximal source of terrestrial sediment from a river delta, confirming that the sediments were ultimately sourced from a fluvial system, which is then reworked. The Y_2 and Y_3 cross plot (Fig. 9(b)) confirmed the dominance of fluvial depositional environment, influenced by agitated water conditions over the shallow marine. Although the sediments were ultimately deposited in a shallow marine environment, Y_4 had the second-highest score, ranging from 7.4 to 8.6, indicating that they had been reworked or influenced by some small-scale turbidity flows or river flood events that carried the sediments from the slope into the basin. The vital role played by turbidity currents in the sedimentation process is confirmed by the Y_3 vs. Y_4 cross plot (Fig. 9(c)), which revealed that these sediments were deposited under small-scale turbidity flows in both fluvial and shallow marine environments. While the Y_4 LDF and leptokurtic grain distributions (Table 4) statistically align with signatures defined as “turbidity” by Sahu (1964), these signals are interpreted as indicative of episodic high-energy density flows or storm-induced turbulence rather than classic deep-marine turbidites. This distinction is necessitated by the absence of preserved graded bedding in the studied outcrops. In this shallow-marine to deltaic context, these statistical signals likely represent rapid, hyperpycnal river-fed pulses during flood events, which delivered immature sediment directly onto the shelf, as evidenced by the

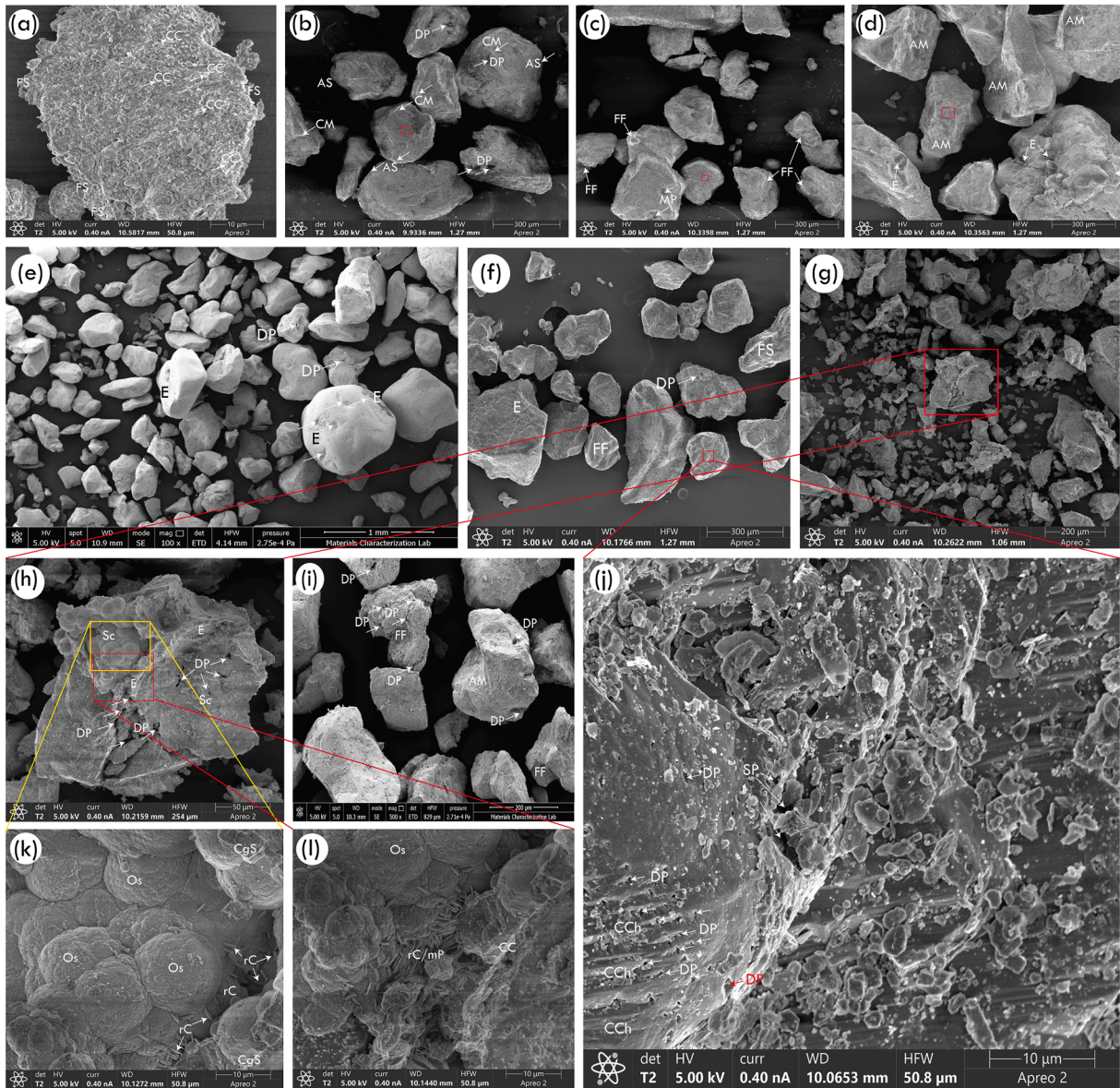


Fig. 10. Scanning electron microscopy (SEM) micrographs showing representative morphology of sediment grains. (a) OGB-1F – Sandstone, very angular aggregate grain, irregular aggregate grain with jagged edges and non-equant geometry. Prominent rough fracture surfaces (FS) and possible clay coatings (CC), indicating minimal transport and dominant mechanical weathering. (b) EGM-3B – Sandstone, sub-angular to sub-rounded grains showing abrasion smoothing (AS), grain collision marks (CM), and incipient dissolution pits (DP). (c) EGM-3C – Sandstone, angular to sub-angular grains with fresh fracture faces (FF) and minor pitting (MP), reflecting limited transport. (d) IYL-4A – Sandstone, sub-angular to sub-rounded grains exhibiting abrasion (AM) and early-stage etching (E). Displays transitional morphology with improved edge smoothing. (e) IYL-4C: Siltstone, mixed sub-rounded to rounded grains with improved sorting and smooth surfaces indicative of prolonged transport. Surface display chemical etching (E) and dissolution pits (DP), with smoothened ridges. (f) IYL-4C – Siltstone, sub-angular to sub-rounded. Enlarged view showing dissolution pits (DP) and etching (E) superimposed on mechanically modified grains. Chemically modified but still retaining some angularity. (g) IYL-4G – Ironstone, angular to sub-angular grains. Poorly sorted assemblage with angular fragments and minor dissolution features. Fragmented grains mixed with fines; poor shape maturity. (h) IYL-4G – Ironstone, sub-angular grain with moderate relief. High-magnification image highlighting intense chemical alteration, including etch features (E), dissolution pits (DP), and surface coatings (Sc) which could be overgrowth or encrustation. Diagenetic overprint masks original edges. (i) IYL-4D: Siltstone, angular grains, surfaces exhibit abrasion marks, dissolution pits (DP), and silica precipitation features. Angular grains with fresh fracture surfaces (FF), indicating dominant mechanical processes. (j) IYL-4C – Siltstone, intensely corroded grain surfaces showing high-density dissolution pits (DP), corrosion channels (CCh), and secondary porosity (SP). (k) IYL-4G – Ironstone, botryoidal (globular) quartz overgrowths (Os), rod-like (needle-like) crystals (rC), and cementation features (CgS), indicative of advanced diagenetic rounding (not transport-driven). (l) IYL-4G – Ironstone, fibrous and flaky authigenic clay coatings (CC), rod-like crystals (rC)/platy minerals (mP), and pore-filling material associated with late-stage diagenetic alteration, occludes pore space.

angular grains and fresh fracture faces observed in the SEM images (Fig. 10). This supports the idea that the basin was a highly dynamic system where fluvial discharge was occasionally intercepted by slope-instability events or storm-wave reworking (Mulder & Alexander, 2001).

The LDF analysis (Table 4) confirms that while fluvial processes dominated the OGB facies (Mamu Formation), the EGM and IYL

facies (Ajali Formation) record increasing wave agitation (Y_2 values) and shallow marine influences (Y_3 values). This shift from unidirectional fluvial flow to oscillatory wave reworking is a critical factor in the textural maturity observed in the IYL sediments (Fig. 10). The basin was energetic, as evidenced by the shallow agitation, with sediment-laden flows periodically moving into the area (Table 4; Fig. 9).

Table 6

Depositional history inferred from observed microtextures in the Campano-Maastrichtian sediments of the northern Anambra Basin.

Formation	Sample location	Observed microtexture	Shape of quartz grains	Transport dynamics	Diagenetic features	Refinement of previous models	Depositional environment
Mamu	OGB (Sandstone)	Aggregate grains, jagged edges, rough fracture surface	Very angular	Minimal transport, dominantly mechanical weathering.	Early clay coatings	Identifies proximal stagnation not captured by grain size alone.	Proximal fluvial
	OGB (Siltstone)	Impact and dissolution pits, microgrooves, conchoidal breakage, step-like fracture planes, grooves/micro-grooves, scratches	Angular to sub-rounded	High energy, short distance saltation.	Minor dissolution pits	Links high energy fractures to silt-sized fractions.	Fluvial/distal deltaic, with episodic high-energy reworking.
Ajali	EGM (Sandstone I)	Abrasion smoothing, grain collision marks	Sub-angular to sub-rounded	Moderate transport, fluctuating energy.	Incipient dissolution pits	Confirms fluctuating energy via physical collision marks.	Fluvial (Mixed load)
	EGM (Sandstone II)	Minor pitting (small – medium, etch and micro pits), fresh fractures faces (irregular with sharp ridges, conchoidal)	Angular to sub-angular	Limited reworking, rapid deposition.	Minor silica coatings	Distinguishes rapid burial from long distance transport.	Fluvial/shallow marine
	IYL (Sandstone)	Edge smoothing, abrasion marks, etching	Sub-angular to sub-rounded	Transitional, improved edge rounding.	Early-stage etching	Visualizes the transitional boundary of the Ajali Formation.	Distal fluvial/shoreface
	IYL (Siltstone)	Dissolution pits, smooth surfaces, corrosion channels, secondary porosity	Sub-rounded to rounded	Prolonged transport and wave reworking.	High density dissolution, intense corrosion	Refines distal character by linking rounding to wave action.	Shallow marine (distal)
	IYL (Ironstone)	Etch feature, botryoidal quartz overgrowths, rod-like crystals	Sub-rounded (diagenetic)	Low energy, high chemical reactivity.	Intense chemical alteration, authigenic clay	Reveals advanced diagenesis masking original grain size signals.	Shallow marine (shelf/ironstone)

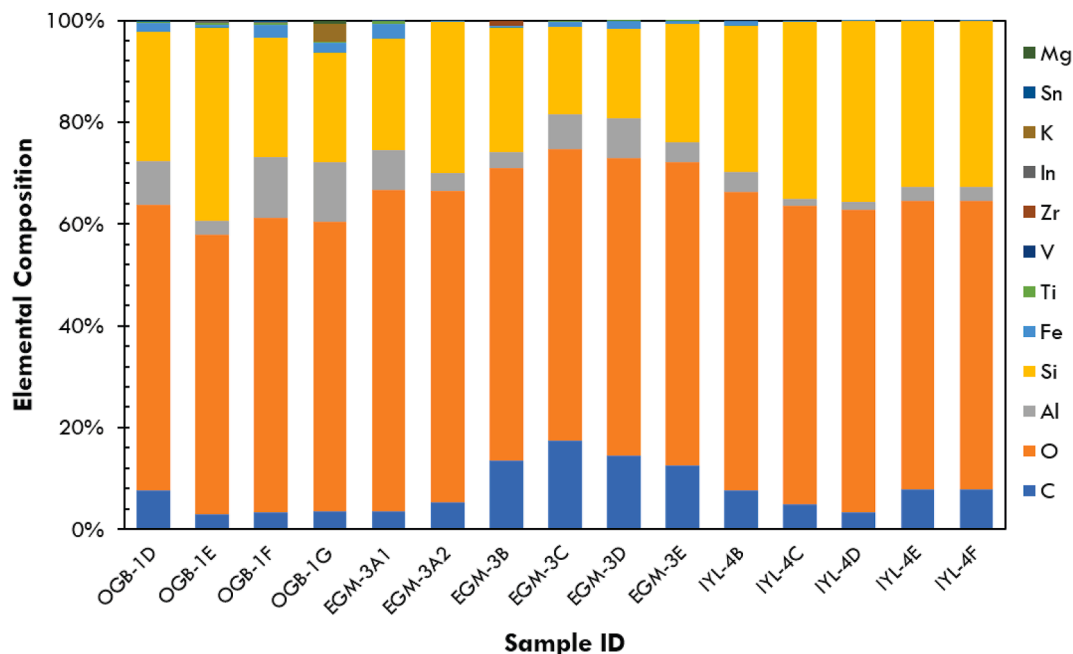


Fig. 11. Elemental composition across samples based on the EDX spectra.

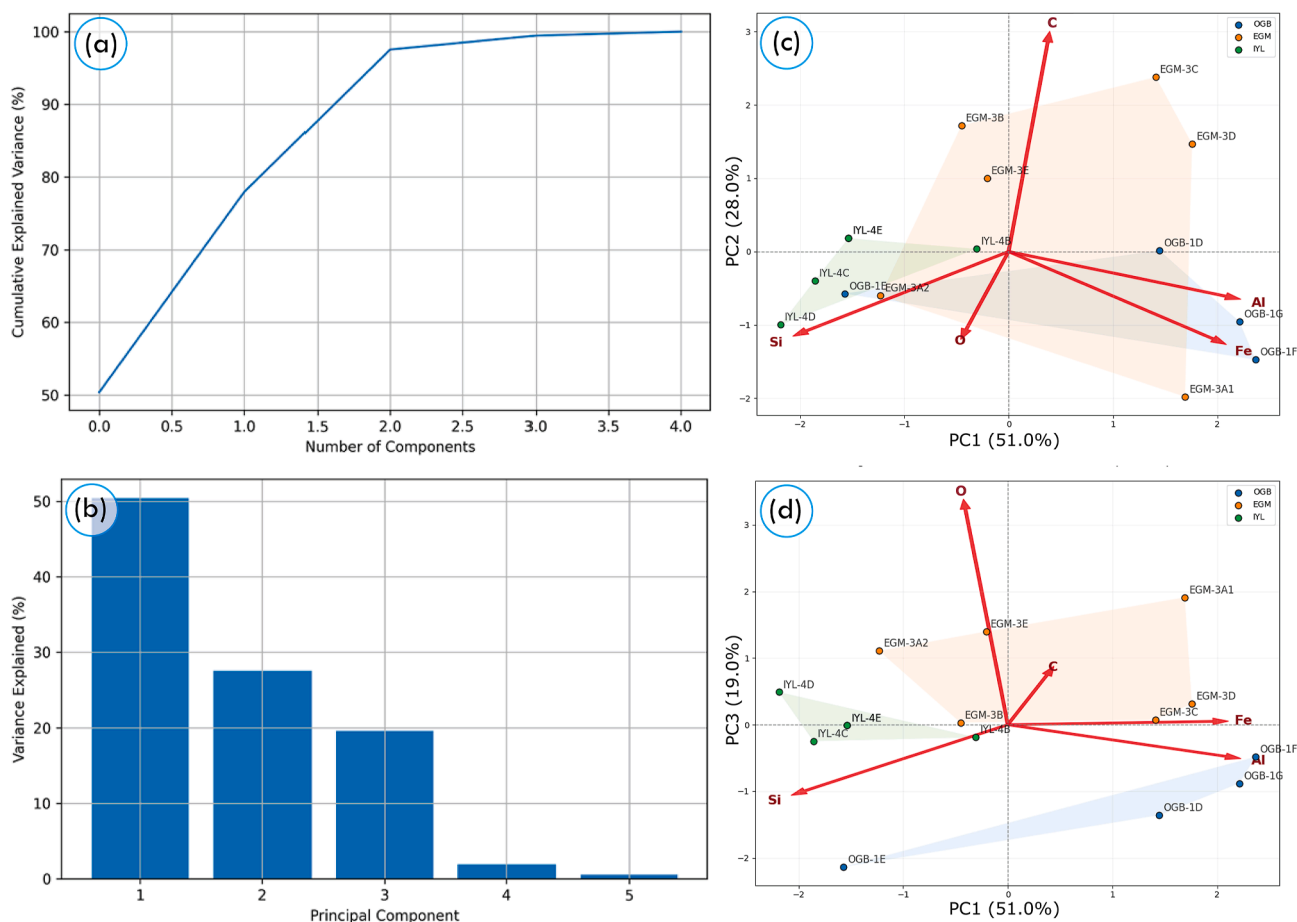


Fig. 12. Results of the Principal Components Analysis performed on the EDX data: (a) explained variance vs. principal components; (b) explained variance contributed by each principal component; (c) PCA biplot (PC1 vs. PC2). This plot illustrates the geochemical separation between the quartz-dominated IYL group (associated with Si) and the clay/iron-rich OGB group (associated with Al and Fe). The EGM group shows high variance, particularly influenced by C; and (d) PCA biplot of PC1 vs. PC3. This plot highlights the role of oxidation, with the O vector separating the samples based on their degree of oxidative weathering or mineralogical composition.

Table 7
PCA Scores for the sediment samples.

Sample	PC1	PC2	PC3	PC4	PC5
OGB–1D	1.447	0.015	–1.359	0.156	0.086
OGB–1E	–1.572	–0.572	–2.136	0.386	–0.065
OGB–1F	2.367	–1.475	–0.485	–0.211	0.220
OGB–1G	2.212	–0.955	–0.881	–0.585	–0.229
EGM–3A ₁	1.690	–1.979	1.910	0.608	–0.015
EGM–3A ₂	–1.228	–0.600	1.107	–0.518	–0.198
EGM–3B	–0.452	1.718	0.031	0.070	–0.192
EGM–3C	1.410	2.378	0.076	0.008	–0.030
EGM–3D	1.758	1.466	0.312	0.060	0.032
EGM–3E	–0.208	0.998	1.398	–0.013	0.072
IYL–4B	–0.307	0.036	–0.190	0.360	–0.102
IYL–4C	–1.858	–0.394	–0.248	0.157	–0.145
IYL–4D	–2.187	–0.996	0.489	–0.140	–0.039
IYL–4E	–1.536	0.181	–0.012	–0.170	0.302
IYL–4F	–1.536	0.181	–0.012	–0.170	0.302

The granulometric signature of the Mamu and Ajali sediments reflects a transition from high-energy tractive currents to wave-influenced marine conditions. The C–M (Passega) plot (Fig. 5) indicates that the primary transport mechanism was graded suspension (PQ and QR segments). This suggests a high energy environment where turbulence was sufficient to maintain medium-grained sand in suspension. The clustering of OGB and EGM samples near the OP segment, where rolling becomes prominent, supports the interpretation of a proximal fluvial/distributary channel setting with high sediment supply from the crystalline hinterland (Lukman et al., 2018; Passega, 1964).

The results of the C–M plot are consistent with recent sedimentological studies of the Anambra Basin. The “rolling” component, characterized by C values exceeding 1000 μm (1 mm), suggests the presence of very coarse sand or granules that were likely moved during peak discharge events in a fluvial or river dominated deltaic setting (Omietimi et al., 2022). Lukman et al. (2018) utilized similar Passega plots for the Ajali sandstone in southeastern Nigeria and reported a dominance of graded suspension, which they attributed to high energy tidal-fluvial currents. Furthermore, the total absence of samples in the RS (uniform suspension) and T (pelagic suspension) fields confirms that these sediments were not deposited in stagnant, deep-water conditions but were instead governed by tractive, near-bed turbulence. This hydrodynamic fingerprint is consistent with a prograding deltaic-shoreface complex where high energy fluvial pulses were the primary engine of sediment delivery to the marine shelf (Edegbai et al., 2019). Consequently, while the LDF results statistically identify a “turbidity” influence, these signals in the Mamu and Ajali formations are better interpreted as episodic high-energy density flows or hyperpycnal pulses resulting from storm-induced turbulence in a shallow-marine setting. While these granulometric parameters establish the primary hydrodynamic framework, the physical energy of the environment only tells half the story. The true history of these sediments, including their provenance and the subsequent chemical stability of the reservoir, is hidden in their surface microtextures and elemental associations. The following sections utilize SEM-EDX and PCA to decouple these primary transport signatures from the chemical diagenesis that followed burial.

5.4. Geochemical fingerprinting and multivariate characterization of lithofacies

The elemental architecture of the Mamu and Ajali sediments, as revealed by SEM-EDX and multivariate statistical analysis,

provides critical insight into the interplay between provenance, weathering intensity, and depositional redox conditions. By reducing the dimensionality of the multi-element dataset through PCA, primary detrital signals and secondary diagenetic overprints can be effectively distinguished (Weltje & von Eynatten, 2004).

5.4.1. Elemental composition and mineralogical implications

The overwhelming dominance of Si and O confirms a mineralogically mature, quartz-rich framework and a limited clay matrix and accessory minerals. However, the varying concentrations of Al and Fe act as sensitive indicators of lithofacies heterogeneity. The geochemical signatures of the siltstone facies reflect significant spatial heterogeneity in sediment partitioning and depositional redox conditions. IYL siltstones are characterized by high silica enrichment (Si: 35.0%–36.5%; O: ~59%–61%) and significant depletion in Al (1.48%–1.64%) and Fe (0.12%–0.26%) relative to their sandstone counterparts. In contrast, the OGB siltstone exhibits a more aluminous (Al = 8.76%) and ferruginous (Fe = 1.79%) character, with lower Si (25.21%), high C (7.61%), and trace Sn and Ti. This relative enrichment in aluminosilicates and detrital heavy minerals in the OGB suite suggests a more distal, clay-rich, and potentially more oxidized depositional environment than the IYL siltstones.

Collectively, EDX spectra across all fine-grained samples are dominated by Si and O peaks, providing robust evidence for high compositional maturity within the grain population. Such mineralogical stability is characteristic of well-developed coastal and shallow marine systems, where prolonged transport and intense chemical weathering facilitate the dissolution of unstable framework grains like feldspar (Ekwenye et al., 2015). Furthermore, the presence of iron-bearing minerals in these facies aligns with regional occurrence of ironstone layers, signaling a transition toward localized chemical sedimentation or pervasive diagenetic modification.

The classification of the Ajali Formation (IYL) as a quartz arenite is attributed to polycyclic recycling and high-energy hydrodynamic sorting rather than *in-situ* “arenitisation” (chemical leaching) post-deposition. The high textural and mineralogical maturity of the IYL samples (negative PC1 scores) suggests a distal or recycled source where unstable grains were removed during previous sedimentary cycles. In contrast, the Mamu Formation (OGB and EGM) exhibits a more immature, feldspathic character. The presence of illite, indicated by the potassium (K) levels in the EDX, is interpreted as a primary weathering product of muscovite and biotite from the proximal northern Nigerian Massif. While kaolinite is the expected product of intense tropical leaching in this region, the presence of illite suggests a direct contribution from the crystalline basement where chemical weathering was incomplete or where mica-rich schists were the primary source. This “mixed clay” assemblage (kaolinite and illite) confirms the first possibility that these sediments were deposited relatively close to their crystalline source, before significant polycyclic maturation could occur.

5.4.2. PCA analysis

The PCA results (Fig. 12) effectively partition the geochemical variance into three dominant components, explaining a cumulative 98% of the total variance (51%, 28%, and 19%, respectively), indicating that the dataset is effectively described by a small number of geochemical controls. This exceptionally high capture of variance is attributed to the inherent chemical simplicity and high inter-element correlation within the five-element dataset (Si, O, Al, Fe, and C). Specifically, Si and O are strongly coupled within the quartz framework (SiO_2), while Al, Fe, and O are geochemically linked within clay minerals and iron oxides. Because these five

Table 8
PCA Loadings of major elements.

Elements	PC1	PC2	PC3	PC4	PC5
C	0.107	0.816	0.213	0.141	0.507
O	−0.116	−0.303	0.925	−0.120	0.158
Al	0.595	−0.174	−0.136	−0.663	0.396
Si	−0.554	−0.309	−0.284	0.069	0.715
Fe	0.560	−0.340	0.014	0.722	0.223

variables represent only three primary mineralogical phases: detrital quartz, secondary aluminosilicates (clays), and iron oxides/hydroxides. This limited mineralogical diversity allows the first three principal components to represent nearly the entire geochemical signal of the basin fill.

The eigenvalues for PC1, PC2, and PC3 were 2.55, 1.40, and 0.95, respectively, confirming that the first two components satisfy the Kaiser criterion (eigenvalue > 1) for significant data representation. The measure of variance explained by the principal components is shown by the PCA proportion and the scree plots (Figs. 12(a) and 12(b)), while the scores and loadings are listed in Tables 7 and 8, respectively. The first three principal components are represented on the biplots (Figs. 12(c) and 12(d)). The loadings reveal that the first principal component (PC1) distinguishes between aluminosilicate and Fe-bearing minerals (positive loadings of Al and Fe) versus quartz-rich components (negative loadings of Si). Samples with high positive PC1 scores (such as OGB-1F and OGB-1G) are enriched in Al and Fe, suggesting that they were derived from felspathic and clay-rich sources, which indicate immature sediments with probable limited transport, and deposited close to their provenance. The negative PC1 scores observed in the IYL samples indicate quartz enrichment, which is consistent with prolonged sediment recycling and transport typical of shallow marine sediments. Similar interpretations have been made in PCA-based sedimentary studies (Armstrong-Altrin & Natalhy-Pineda, 2014; Armstrong-Altrin et al., 2005; Hossain et al., 2024; Itamiya et al., 2019; Weltje & von Eynatten, 2004), where quartz-rich assemblages were linked to sediment maturity and longer transport distances.

PC2 is strongly influenced by carbon (C) with positive loadings, and negatively by Fe and Si. Samples with high positive PC2 scores (such as EGM-3C, EGM-3D) suggest significant organic or carbonate contributions, possibly reflecting deposition in low-energy environments. Conversely, the negative PC2 scores of some OGB and EGM samples suggest a more silicate-dominated composition with limited organic input.

PC3 is dominated by oxygen (O) with a high positive loading, reflecting the role of oxides and hydroxides. Samples with strong positive PC3 scores (such as EGM-3A₁ and EGM-3E) likely represent sediments that have undergone significant oxidative weathering, indicating subaerial exposure or deposition under oxic conditions. In contrast, low or negative PC3 scores suggest reduced weathering or more stable detrital input. Similar oxygen-linked PCA signatures have been reported in fluvial-lacustrine settings, where Fe-oxide formation and clay alteration marked oxic depositional conditions (Weltje & von Eynatten, 2004).

The positive loading of Al on PC1 (Table 8) does not necessarily imply high absolute concentrations of aluminum within the bulk sediment, but rather indicates its residual enrichment relative to more mobile cations. In the humid, tropical conditions of the Late Cretaceous Anambra Basin, intense chemical weathering of felsic basement precursors led to the leaching of soluble elements such as K, sodium (Na), and Ca. As these elements were removed, Al concentrated *in-situ* through the formation of stable secondary aluminosilicates, primarily kaolinite and illite. Consequently,

samples with higher relative Al/Si ratios (e.g., the OGB series) represent sediments subject to more prolonged or intense chemical weathering of their parent materials, whereas the Si-dominated IYL samples reflect either high-energy winnowing of these clay fractions or a polycyclic origin where such weathered products were previously removed.

Generally, the PCA highlights three dominant geochemical signatures which are (1) quartz-rich mature sediments (IYL samples) derived from prolonged transport and recycling; (2) clay-Fe-rich feldspathic sediments (OGB samples) indicative of proximal sources; and (3) organic and oxygen influenced sediments (EGM samples) reflecting variable redox conditions. These groups identified via PCA (Fig. 12) reflect distinct provenance and weathering pathways. The IYL sediments, defined by high Si and low Al/Fe, represents a mineralogically mature end-member. This signature is indicative of sediments that have undergone either prolonged distal transport from the stable cratonic interior or represent the recycling of older sedimentary sequences within the basin.

The OGB samples on the other hand, show high positive loadings for Al and Fe, which serves as a chemical proxy for the weathering products of the northern Nigerian Massif (crystalline basement). The Al-loading reflects the kaolinitization of K-feldspars and plagioclase from proximal granitoid and gneissic source rocks. The high Fe-loadings suggest the presence of iron-bearing accessory minerals (e.g., biotite or ilmenite) or the early formation of ferruginous matrices in proximal, terrestrial settings. However, the EGM samples, which are characterized by high C and O, reflect the unique redox-sensitive and paludal conditions of the Mamu Formation. The high C-loading is directly linked to the coal-bearing nature of these estuary-floodplain deposits, while the O-loading highlights intense oxidative weathering and the development of oxides in fluctuating marginal-marine settings. This interpretation is consistent with previous regional studies (e.g., Ekwenye et al., 2015; Tijani et al., 2010) which identified a mixed crystalline-basement and recycled-sedimentary provenance for the Campano-Maastrichtian fill of the Anambra Basin.

The PCA results demonstrate its usefulness in differentiating sediment sources and depositional pathways. The results suggest that the basin experienced inputs from both proximal basement-derived feldspathic material and more mature, quartz-rich sediment sources, with organic matter and weathering processes, which further modifies the depositional signatures. This geochemical partitioning reinforces the interpretation of a heterogeneous depositional system. The move from Al-rich proximal facies to Fe–C-rich distal facies confirms that the basin's chemistry was shaped as much by the progradational architecture of the delta as by the late-stage diagenetic fluids that utilized these primary pathways (Omietimi et al., 2024). While the exclusion of trace elements like Zr and Ti (proxies for heavy minerals), and K and Mg (proxies for specific clay types or feldspars) limits the ability to distinguish between specific accessory mineral suites, the high cumulative variance (98%) captured by the first three components suggests that the major elements are the "master variables" of the system. The strong loading of Al and Fe already serves as a reliable proxy for the aluminosilicate and iron-oxide fraction, which are the primary carriers of provenance and diagenetic information in these Campano-Maastrichtian sediments. Thus, the refined PCA model remains a reliable tool for discriminating between the quartz-mature and clay-rich/iron-rich depositional domains.

5.5. Diagenetic evolution and implications for reservoir quality

The angularity observed in the EGM sediments (Fig. 10(c)) is a primary textural feature reflecting short-distance fluvial transport.

However, this angularity was secondarily enhanced by diagenetic processes such as pressure solution and grain-contact microfracturing. At points of high stress during burial, chemical dissolution and mechanical splintering created new, sharp-edged facets on otherwise sub-angular grains, maintaining a 'high-relief' angular appearance despite transport. In contrast, the rounded morphologies in the IYL sediments (Fig. 10(e)) are interpreted as a combination of prolonged transport maturation and diagenetic smoothing. Syntaxial quartz overgrowths filled primary pore spaces and "healed" mechanical impact pits, effectively rounding out grain corners and creating a secondary, smooth surface. This "diagenetic rounding" masks the original mechanical history of the grains, resulting in the high-sphericity, low-relief surfaces observed in the Ajali Formation.

The SEM and EDX data (Figs. 10 and 11) reveal a protracted diagenetic history, transitioning from mechanical to intensive chemical stages. A three stage paragenetic sequence is proposed as follows:

Stage 1: Eodiagenesis (Early Burial)—Initial burial is marked by mechanical compaction and the development of early clay coatings (CC in Fig. 10(l)). The presence of grain collision marks (CM) and fresh fracture faces/conchoidal fractured surfaces (FF/FS) in the Mamu (OGB) and Ajali (EGM) samples suggests that the grains entered the depositional basin with high mechanical energy. However, the early precipitation of authigenic clay minerals (kaolinite platelets/illite laths) likely began shortly after deposition, driven by the breakdown of unstable feldspars in a humid tropical climate, a characteristic feature of the Campano-Maastrichtian of West Africa (Omietimi et al., 2022).

Stage 2: Mesodiagenesis (Deep Burial and Chemical Alteration)—This stage is characterized by intense silica cycling. High magnification SEM (Fig. 10(k)) shows botryoidal (globular) quartz overgrowths (Os). These globules represent the precipitation of amorphous silica from pore fluids saturated during the pressure solution of quartz grains. The transition from smooth mechanical surfaces to "corrosion channels" (CCh) and "dissolution pits" (DP) indicates a shift in pore water pH, likely becoming more alkaline, facilitating quartz dissolution, followed by a subsequent drop in temperature or concentration leading to the globular overgrowth (Os). This diagenetic rounding noted in Fig. 10 masks the original mechanical angularity.

Stage 3: Telodiagenesis and Ferruginization—This most striking feature of the IYL ironstone is the late-stage ferruginization. The high Fe and Al concentrations in the PCA biplot (Fig. 12) and the presence of cementation features (CgS) indicate the infiltration of iron-rich fluids. This occurred during late-stage uplift or exposure to oxygenated groundwater (marine condensation). The delicate "rod-like" crystals (rC in Fig. 10(k)), likely hairy illite or halloysite, grew within the remaining pore spaces and "flaky authigenic clay" (CC in Fig. 10(l)) likely represent goethite or hematite needles and kaolinite, which occlude the secondary porosity created during stage 2. This suggests that while diagenesis initially created porosity through dissolution, late-stage chemical precipitation has significantly reduced reservoir quality. The most significant late-stage event was the infiltration of iron-rich fluids, especially in the IYL facies. This resulted in the formation of ironstone cement (CgS), which is confirmed by the high Fe peaks in the EDS spectra (Fig. 11). This late cementation and the accumulation of platy minerals (mP) acted to "occlude" or block the remaining porosity, significantly affecting the hydraulic conductivity of the formation. Although represented by a single sample, the ironstone (IYL-4G) serves as a critical reference point for the most advanced stage of diagenesis in the basin. Its inclusion allows for a distinct geochemical and microtextural contrast (Table 5; Figs. 10(g), 10(h), 10(k), and 10(l)) against the more pervasive sandstone and siltstone facies, confirming the role of late-stage ferruginization in occluding primary porosity.

Porosity enhancement occurred primarily through chemical dissolution (DP, SP) during early to mid-mesodiagenesis, while porosity reduction was observed dominantly through late-stage chemical processes, specifically globular quartz overgrowths (Os), authigenic clay precipitation (rC, CC), and massive cement growth structures (CgS).

When compared to Tijani et al. (2010), the current results show a higher degree of chemical overprinting in the Ajali Formation. While they emphasize the textural maturity of these sands, the current SEM analysis (Fig. 10) argues that much of the apparent rounding in the distal IYL facies is actually diagenetic smoothing rather than transport-induced abrasion. The PCA (Fig. 12) statistically validates the lithological transition. PC1, which explains 50% of the variance, effectively separates the siliciclastic facies (dominated by Si and O, representing the quartz backbone) from

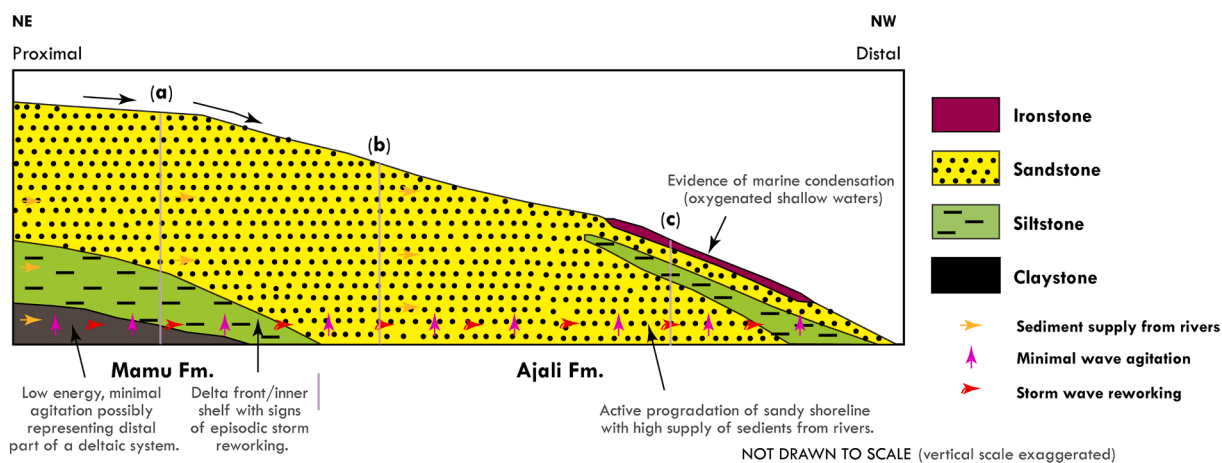


Fig. 13. Conceptual depositional model for the Campano-Maastrichtian sediments of the northern Anambra Basin. The succession indicates a deltaic-shoreface complex prograding north-westward into a shallow marine shelf during the Late Cretaceous. (a) OGB facies—fluvial, with angular feldspathic and clay-rich grains; (b) EGM facies—shallow marine, moderately sorted, with wave/current reworking; and (c) IYL facies are distal, with mixed input, Fe and organic-rich sediments.

the Fe-diagenetic facies (dominated by Fe, Al, and trace Ti). The separation of EGM-3 and IYL-4 samples along the PC2 and PC-3 axes (Figs. 12(c) and 12(d)) reflects the varying degrees of clay infiltration and organic carbon (C) content, likely related to the "marine condensation" event depicted in the conceptual model (Fig. 13). This model aligns with the source-to-sink dynamics described by Lukman et al. (2018), where the Anambra Basin acted as a major depocenter for weathered crystalline products from the Oban Massif, later modified by the Maastrichtian sea-level fluctuations.

5.6. Multi-proxy synthesis and environmental model for the northern Anambra Basin

The integration of granulometric and microtextural data provides a higher degree of environmental resolution than single-proxy analysis. For example, while the LDF statistical model (Y_2 and Y_3) for the IYL samples suggests a shallow-marine influence, it is the SEM microtextural evidence, specifically the coexistence of well-rounded morphologies with intense chemical etching and diagenetic polishing (Table 6), that confirms a distal, low-energy setting with high residence time. Conversely, in the OGB facies, the poor sorting identified through granulometry could be interpreted as either a fluvial or a gravity-flow deposit. However, the SEM observation of "very angular" aggregate grains with fresh, unweathered fracture faces (Fig. 10(a)) indicates these are proximal, first-cycle sediments derived directly from the nearby crystalline basement with minimal transport reworking. This multifaceted approach resolves the "textural mimicry" where different environments produce similar grain-size distributions, allowing for a more accurate reconstruction of the depositional environments in the northern Anambra Basin.

The textural results of this study align with the fine to medium-grained, moderately sorted characterization reported by Ezike (2023). However, the current integrated approach allows for a deeper refinement; where previous research inferred environment primarily through size distribution, the current SEM observations of conchoidal fractures and dissolution pits (Table 5; Fig. 10) allow the primary high-energy transport events to be distinguished from the subsequent chemical weathering. Furthermore, the application of PCA to geochemical data (Fig. 12) adds a provenance dimension not present in purely textural studies, identifying the specific transition from proximal basement-derived inputs to recycled quartz-rich assemblages. The integration of textural, microtextural, and geochemical data allows for a refined reconstruction of the Campano-Maastrichtian depositional architecture, as synthesized in the conceptual model (Fig. 13). This model illustrates a prograding deltaic-shoreface complex where sediment distribution is controlled by the competing influences of fluvial discharge and marine reworking.

5.6.1. Proximal fluvial dominance (OGB facies)

The OGB facies represent the landward-most segment of the model, the proximal delta plain and distributary channels. The sedimentological evidence for this placement is robust: the angular quartz morphologies (SEM), poor sorting (granulometry), and high aluminosilicate content (PCA/EDX) all point to rapid deposition with minimal transit time. As depicted in the model (Zone A), these sediments were delivered by high-energy tractive currents, where the "rolling" component identified in the C-M plot reflects the primary mode of bedload transport in a confined fluvial setting.

5.6.2. Transitional shoreface dynamics (EGM facies)

Moving basinward, the EGM facies occupy the transitional shoreface and delta front (Zone B). Here, the model illustrates the interplay between fluvial input and the onset of wave-current reworking. This is supported by the "mixed" microtextural signature (Fig. 10), where fresh mechanical fractures coexist with incipient quartz overgrowths. The moderate Y_2 scores from the LDF analysis statistically validate this zone as a "shallow agitated" environment where high-energy wave action began to overprint the primary fluvial signal, leading to the "diagenetic rounding" observed in the SEM micrographs.

5.6.3. Distal shelf and marine condensation (IYL facies)

The IYL facies represent the most distal, shelfal environment in the proposed model (Zone C). The model highlights this as a zone of "marine condensation", characterized by low siliciclastic sedimentation rates. Geochemically, this is confirmed by the PCA-defined Fe–C-rich signature, suggesting a redox-sensitive environment where ironstones could precipitate. Texturally, the high degree of quartz maturity and quartz overgrowths in these samples (Fig. 10) reflect prolonged residence time on the seafloor and extensive fluid-rock interaction with silica-saturated marine pore waters.

The proposed model (Fig. 13) extends the earlier reconstructions of Tijani et al. (2010) and Edegbai et al. (2019) by explicitly linking microtextural diagenesis to depositional energy zones. While the Mamu and Ajali formations have traditionally been viewed as simple regressive sands, the proposed integrated model demonstrates a more complex heterogeneous system. The spatial evolution from mechanical compaction in the proximal OGB facies to chemical-dominated diagenesis in the distal IYL facies provides a new predictive framework for understanding reservoir heterogeneity across the northern Anambra Basin.

6. Conclusions

The current study demonstrates that depositional heterogeneity within the northern Anambra Basin cannot be adequately resolved using granulometric data alone. Instead, it provides an integrated framework combining grain-size statistics, quartz grain microtextural analysis, SEM–EDX elemental characterization, and multivariate statistical techniques, which provides a more robust basis for reconstructing sedimentary processes and paleoenvironmental evolution of the basin. The results indicate that the studied Campano–Maastrichtian sediments record variable hydrodynamic regimes influenced by fluctuating fluvial and marginal-marine conditions, with textural maturity reflecting changes in transport distance and energy rather than a single depositional process. Quartz grain microtextures and elemental associations further reveal the role of mechanical abrasion, chemical modification, and early diagenetic overprinting in modifying primary depositional signatures. The application of PCA highlights compositional groupings that refine provenance interpretations and distinguish between quartz-rich mature sediments, feldspathic–clay-influenced inputs, and iron-rich facies deposited under variable redox conditions.

These findings extend previous granulometric-based interpretations of the Anambra Basin by demonstrating the value of integrating sediment surface textures and geochemical data in complex depositional settings. The sediments of the Mamu and Ajali formations record a transition from a proximal fluvial/deltaic system (Mamu) to a wave-influenced shoreface and distal shelf (Ajali). Granulometry reveals a tractive transport regime

dominated by graded suspension. However, the true history of these sediments is hidden in their microtextures: a journey from high-energy mechanical fracturing to a complex diagenetic regime of silica dissolution, globular overgrowth, and late-stage ferruginization. These findings suggest that reservoir potential in the northern Anambra Basin is controlled as much by post-depositional chemical fluid flow as by initial depositional energy.

The current study provides a methodological framework that is transferable to other intracratonic basins where sedimentary processes are controlled by the interplay of multiple depositional and post-depositional factors. Ultimately, it demonstrates that grain size statistics provide the hydrodynamic framework, while quartz microtextures provide the transport history, and PCA provides the geochemical source. Only through this integrated, multifaceted analysis can the complex interplay between provenance, episodic energy fluctuations, and diagenetic overprinting be fully decoupled. A targeted follow-up study on the geochemical and mineralogical characteristics of these sediments is recommended to gain further insight into the provenance, paleoredox, and depositional settings of these sediments.

CRedit authorship contribution statement

Taiwo A. Bolaji: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gbemisola E. Abiola:** Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis. **Olumide S. Ogunmodimu:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Formal analysis. **Olushola S. Ayanda:** Writing – review & editing, Visualization, Validation, Project administration. **Ayuk C. Ayuk:** Writing – review & editing, Software, Methodology, Formal analysis.

Data availability

All data used in this article (raw granulometric data, SEM micrographs, and PCA code) are archived and publicly available via Zenodo at <https://doi.org/10.5281/zenodo.19140611> to ensure reproducibility.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors gratefully acknowledge the use of facilities and instrumentation at the Penn State Materials Characterization Laboratory (MCL), which is part of the Materials Research Institute. Also, the support and encouragement received from Dr M. S. Kolawole and Mr Baba Yahaya in the course of the field studies are gratefully acknowledged. We also appreciate valuable discussions with Prof. Oladotun A. Oluwajana in the course of writing this article. We would like to express our gratitude to the anonymous reviewers and editorial team for their insightful remarks that helped make this article better.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijsrc.2026.06.001>.

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