ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

Facies Architecture and Sedimentological Controls as Indicators of Reservoir Potential in The Tidally Influenced Fluvial–Estuarine Deposits Within the Frontier Anambra Basin, Southeastern Nigeria.

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DOI: https://doi.org/10.51583/IJLTEMAS.2025.1410000082

Received: 02 October 2025; Accepted: 10 October 2025; Published: 11 November 2025

Abstract: Comprehensive sedimentological investigations of the Awkuzu outcrops within the frontier part of the Anambra Basin, southeastern Nigeria, reveal two major facies associations: (i) fluvial/tidally influenced fluvial facies and (ii) estuarine facies. These facies correspond to the Eocene Nanka Formation, deposited in a tidally influenced fluvial–estuarine system characterized by alternating high- and low-energy depositional regimes. Integration of field observations, paleocurrent measurements, ichnological evidence, and pebble morphometric analyses provides insights into the facies architecture, depositional processes, and reservoir potential.The fluvial/tidally influenced fluvial facies comprises medium- to coarse-grained, moderately sorted sandstones and conglomeritic beds arranged in multistoried, fining-upward successions. Sedimentary structures such as planar and trough cross-bedding, erosional channel bases, and mud drapes suggest deposition under high-energy fluvial conditions intermittently modified by tidal currents. Trace fossils including *Ophiomorpha*, *Planolites*, and *Arenicolites* indicate episodic marine influence. Pebble morphometry shows Maximum Projection Sphericity (MPS) values of 0.76–0.85, Flatness Index (FI) of 58–67%, and OPI ranging from –0.12 to +0.18, denoting moderately high sphericity and rounding typical of sustained fluvial transport with limited tidal reworking. These features point to excellent reservoir potential, enhanced by high porosity, permeability, and lateral sand continuity.The estuarine facies comprises heterolithic and laminated fine- to medium-grained sandstones, siltstones, and claystones displaying flaser, wavy, and lenticular bedding indicative of tidal cyclicity. *Skolithos* and *Planolites* ichnofabrics reflect deposition in a well-oxygenated, shallow marine to inner estuarine setting. Pebble morphometry results (MPS: 0.68–0.77; FI: 70–80%; OPI: predominantly negative) indicate moderate sphericity and sub-rounded, oblate shapes, characteristic of low-energy, oscillatory tidal currents with limited abrasion. Although reservoir quality is reduced by mudstone intercalations, lateral sand continuity supports potential fluid connectivity.

Overall, the facies architecture demonstrates that sedimentological controls and depositional energy variations fundamentally influence reservoir heterogeneity and quality within the tidally influenced fluvial–estuarine deposits of the Nanka Formation in the Frontier Anambra Basin.

Keywords: Tidally influenced fluvial facies, Estuarine facies, Facies architecture, Pebble morphometric analysis, Paleocurrent analysis.

I. Introduction

In recent years, the resurgence of hydrocarbon exploration within Nigeria's inland basins has intensified, driven by the need to diversify energy resources beyond the mature Niger Delta Province. Among these inland basins, the Anambra–Afikpo Basin complex has gained significant research attention owing to its extensive sedimentary successions and evolving understanding of its petroleum system. Exploration focus in this frontier basin is gradually shifting from well-defined structural traps, traditionally mapped through seismic data, toward the more subtle yet promising stratigraphic and facies-controlled traps within the Paleogene successions. This paradigm shift is necessitated by the increasing recognition that facies architecture and sedimentological heterogeneity exert strong controls on reservoir quality and hydrocarbon distribution.

The Paleogene period (approximately 66–23 million years ago) represents a critical epoch in the geologic evolution of southern Nigeria, marked by extensive sedimentation that has preserved a range of depositional environments and lithofacies associations. These successions are well developed in the Anambra Basin (Fig.1), as well as parts of the Niger Delta and Benin Basins, forming a continuous stratigraphic framework that has been correlated regionally (Short and Stäuble, 1967; Avbovbo, 1978). The Paleogene formations—comprising the Imo, Ameki, and Ogwashi-Asaba Formations—are the temporal equivalents of the Akata, Agbada, and Benin Formations of the Niger Delta, respectively (Fig.2 and 3). This correlation highlights the petroleum potential of the Anambra Basin, suggesting that its depositional systems may share similar stratigraphic and reservoir characteristics with the prolific Niger Delta Province.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

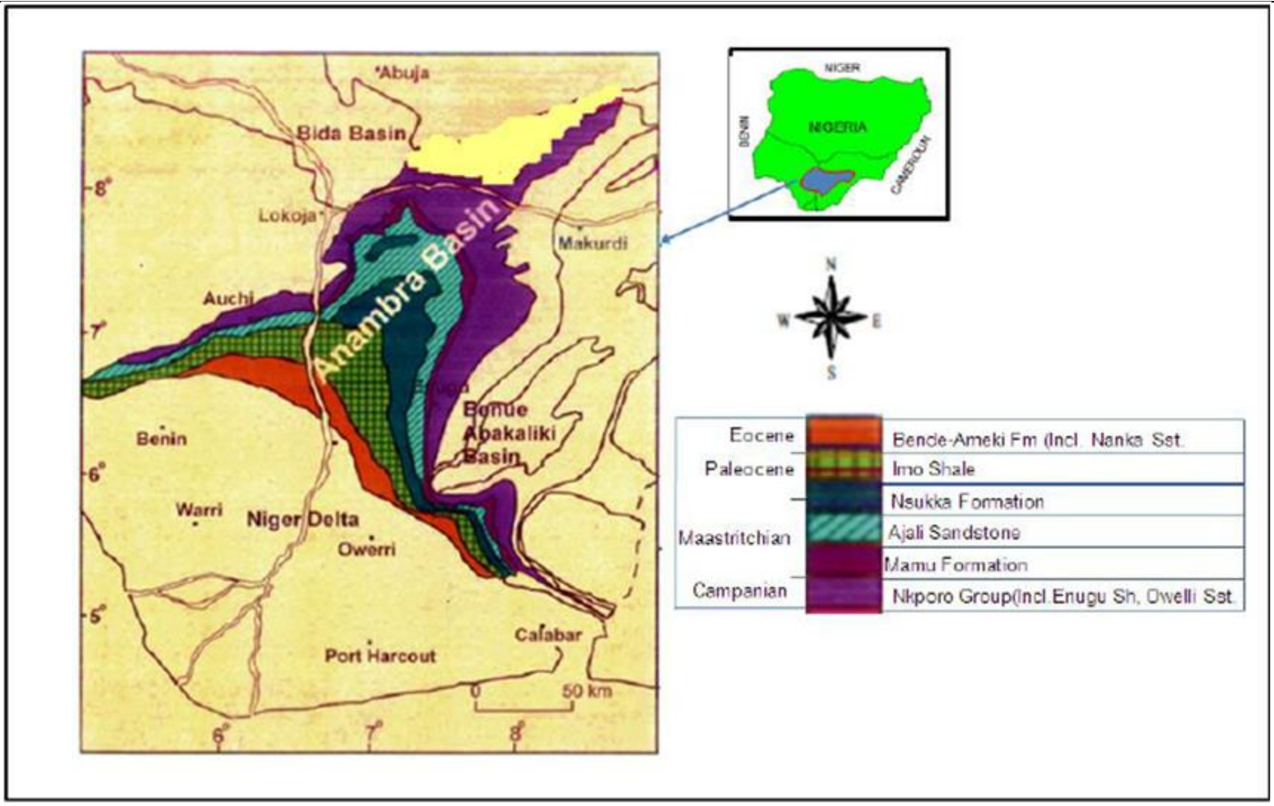

Fig. 1: Geologic Map Setting of Anambra basin (Maju et.al., 2019)

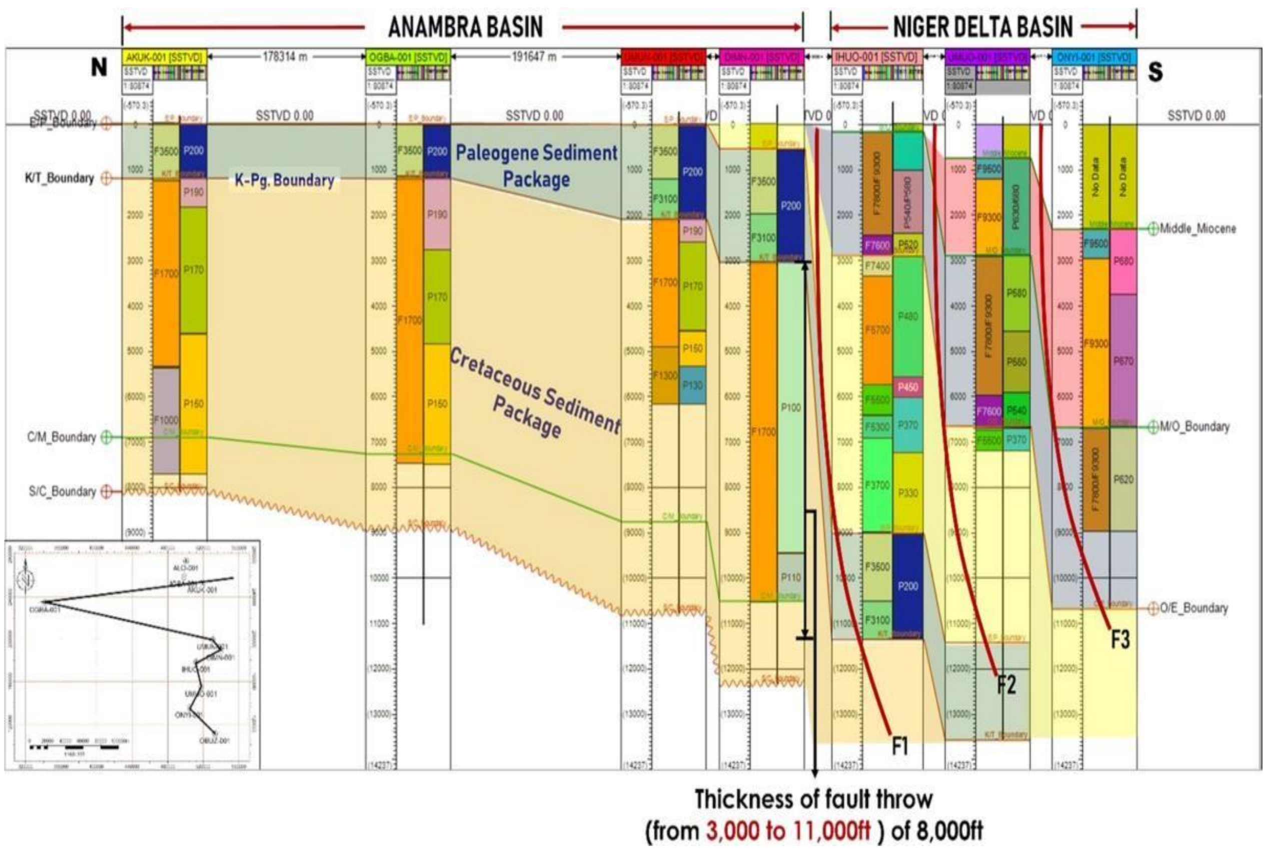

Fig.2: Regional correlation section between the Anambra Basin and Niger Delta Basin illustrating equivalent formations delineated by tectonic events (Dim C.I.P, et. al., 2021)

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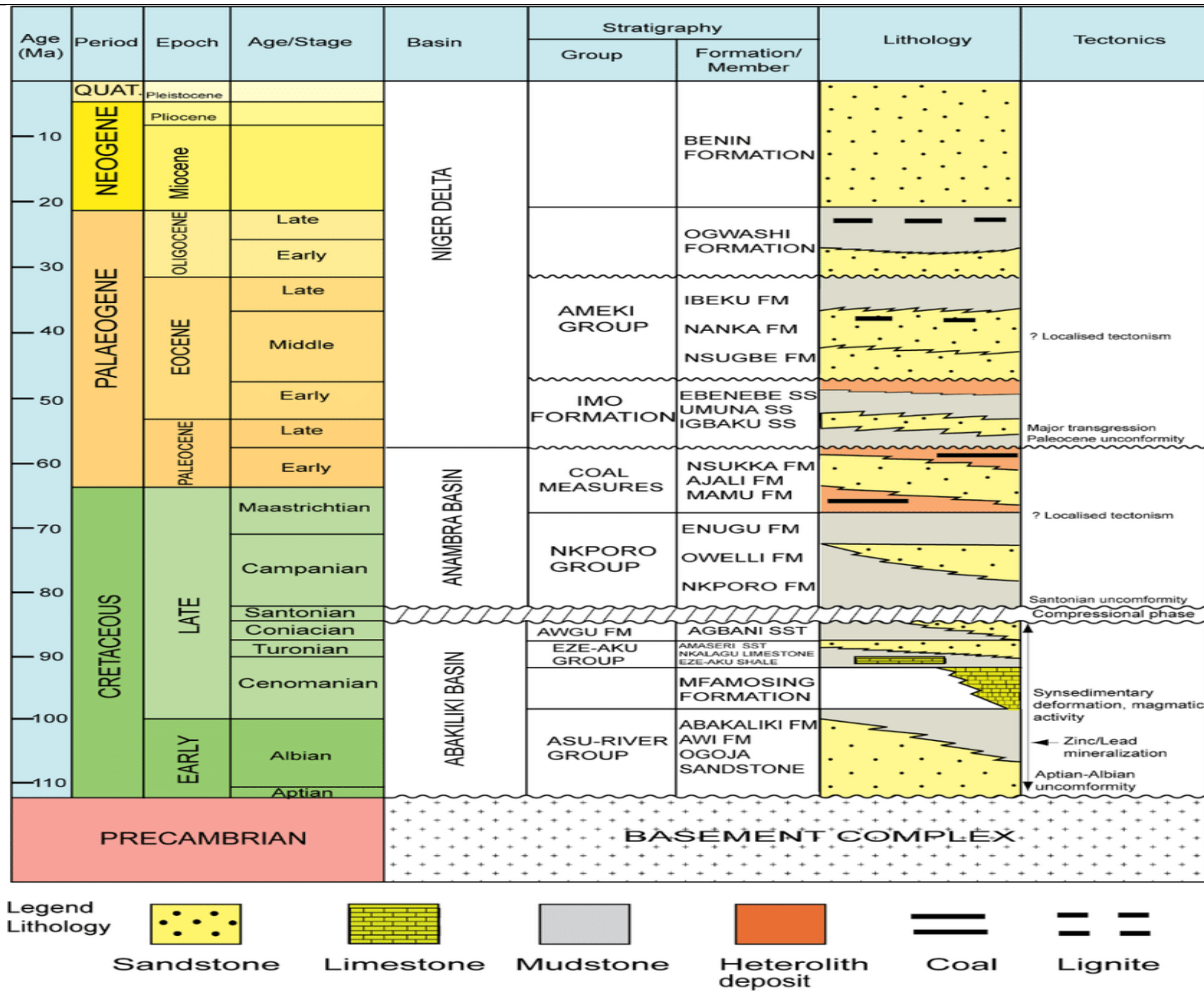

Fig. 3: Stratigraphic Succession in the Anambra Basin and Outcropping Niger Delta (Ekwenye and Nichols, 2016).

The stratigraphic succession of the Paleogene sediments in southeastern Nigeria includes the Maastrichtian–Paleocene Nsukka Formation (~350 m), Paleocene Imo Formation (~1,000 m), Eocene Ameki Group (~1,900 m), and Eocene–Oligocene Ogwashi–Asaba Formation (~250 m). The Ameki Group, comprising the Ameki Formation, Nanka Sands, and Nsugbe Sandstone, represents one of the most important sedimentary packages within this interval. The Nanka Sands, which underlie the study area, have been the focus of several sedimentological and stratigraphic studies (Tattam, 1944; Simpson, 1954; Reyment, 1965; Adegoke, 1969; Nwajide, 1979). These sands are dominantly siliciclastic, medium- to coarse-grained, and exhibit well-developed sedimentary structures such as cross-bedding, planar laminations, ripple marks, and channel scour surfaces. Such features are indicative of deposition in high-energy, tidally influenced fluvial to estuarine environments, where hydrodynamic fluctuations controlled sediment transport, sorting, and facies stacking patterns.

Recent sedimentological investigations across the Anambra Basin, particularly in localities such as Awkuzu, Nanka, and Umunya, have revealed compelling evidence of tidally influenced fluvial–estuarine depositional systems. These deposits exhibit a complex interplay of fluvial channel sand bodies, tidal bars, and estuarine mudflats, characterized by cyclic fining-upward successions, mud drapes on foreset planes, and rhythmic alternations of sand and silt layers that reflect tidal modulation. Sedimentary features such as herringbone cross-stratification, flaser and lenticular bedding, reactivation surfaces, and bioturbation structures provide diagnostic evidence for tidal reworking and estuarine circulation (Nwajide, 1990; Obi and Okogbue, 2004; Odoh et al., 2018). These authors documented the widespread development of such tidally influenced facies within the Anambra Basin, noting that the transition from fluvial-dominated channels to tidally modulated estuarine complexes played a major role in shaping reservoir architecture and heterogeneity. The recognition of these tidally influenced facies highlights the dynamic depositional regime of the basin, where sediment supply, relative sea-level fluctuations, and tidal currents interacted to produce laterally and vertically heterogeneous reservoirs

Within this geological framework, the present study focuses on the tidally influenced fluvial–estuarine deposits exposed at Awkuzu, Anambra State, Southeastern Nigeria. The Awkuzu outcrop section represents part of the Eocene Nanka Formation, where alternating sand, silt, and clay beds record multiple episodes of channel migration, tidal reworking, and estuarine sedimentation. The study area offers a natural laboratory for understanding the facies architecture, depositional dynamics, and sedimentological

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controls that define the reservoir potential of such transitional systems. By examining these outcrops, the research provides insight into how tidal modulation and fluvial influx influence sandstone body geometry, connectivity, and petrophysical quality—factors critical for reservoir characterization in inland basins.

Textural and compositional characteristics of the Nanka Sandstones—rich in quartz with subordinate feldspar and lithic fragments—suggest a provenance derived largely from igneous and metamorphic terranes, with significant sediment reworking in transitional depositional settings. These attributes, combined with the presence of tidal rhythmites, mud drapes, and bioturbation features, reveal a complex facies architecture reflecting the interplay of tidal, fluvial, and estuarine processes. Understanding these processes is critical because facies heterogeneity and sedimentological variability govern porosity–permeability relationships, connectivity of reservoir bodies, and ultimately, the hydrocarbon storage and flow capacity of these units.

Globally, many of the world's major hydrocarbon accumulations occur in siliciclastic fluvial–estuarine reservoirs, where facies architecture plays a crucial role in reservoir continuity and performance (Magoon and Dow, 1994). Heterogeneities such as clay and mud drapes on foreset planes, ferruginized horizons, carbonate cementation, and offshore mud intercalations can significantly influence the petrophysical quality of reservoir sands. These factors are equally relevant in the Anambra Basin, where the Nanka and Ameki formations display marked vertical and lateral facies variations indicative of tidally modulated depositional cycles

Previous studies within the Anambra Basin have extensively documented its petroleum system elements, particularly the source rock potential of the Campanian–Maastrichtian shales. Researchers have identified the Nkporo, Mamu, and Imo Formations as the primary source rock units, characterized by organic-rich, fine-grained sediments deposited under marginal marine to paralic conditions. Geochemical analyses from earlier works revealed Type II and mixed Type II–III kerogens with moderate to good total organic carbon (TOC) content, indicating substantial hydrocarbon generation potential, especially for gas and condensate. The maturity profiles and burial histories of these formations suggest that thermal evolution within parts of the basin has reached the oil and gas window.

Reyment (1965) described the Ogwashi–Asaba Formation as containing lignite and shale intervals with variable total organic carbon (TOC) content, signifying potential gas-prone source material. Similarly, Obaje et al. (2000) reported that the Imo Shale exhibits moderate to high TOC values—often exceeding 1%—suggesting adequate organic richness for hydrocarbon generation. More recently, Adeleye et al. (2023) provided molecular geochemical evidence supporting the hydrocarbon potential of these Paleogene units. These findings collectively provide a strong geochemical foundation supporting the reservoir potential established in this study, emphasizing that the Nanka Formation sandstones at Awkuzu likely form part of a petroleum system where the underlying Nkporo and Mamu shales serve as effective source rocks. Together, these studies support the existence of a working petroleum system, wherein the siliciclastic sandstones of the Nanka and Ameki formations could serve as effective reservoir rocks if their facies attributes and sedimentological controls are properly characterized.

Azubuike-Ijomah and Okafor (2017) in their study, provide a useful analogue for understanding the influence of facies architecture and sedimentological controls on reservoir potential in tidally influenced settings, showing how the interplay of medium-to-coarse grained sandstones interbedded with fine lithologies, plus cementation, depth of burial, and the positioning of fluid contacts, can significantly degrade or enhance reservoir performance. Such observations resonate with the Awkuzu section of the Nanka Formation, where high-energy fluvial sand bodies with minimal clay content and good sorting may behave like the Pota reservoir intervals under favorable diagenetic regimes.

The present study seeks to conduct a detailed facies and sedimentological characterization of the tidally influenced fluvial–estuarine deposits within the frontier Anambra Basin, with emphasis on their facies architecture and sedimentological controls as indicators of reservoir potential. By integrating field-based sedimentological analyses with facies modeling and stratigraphic interpretation, the research aims to unravel the depositional dynamics, heterogeneity patterns, and reservoir implications of these Paleogene siliciclastic successions. The outcomes are expected to contribute significantly to the understanding of reservoir analogs in inland basins and to guide future hydrocarbon exploration strategies in southeastern Nigeria.

Significance of The Study

The Anambra Basin represents one of Nigeria's most geologically significant inland basins, endowed with substantial hydrocarbon potential yet remaining relatively underexplored compared to the mature Niger Delta Basin. Despite extensive research on the basin's stratigraphy and sedimentology, key uncertainties persist regarding the distribution, quality, and connectivity of potential reservoir units. These uncertainties stem largely from the basin's complex depositional framework, which is influenced by the interplay of fluvial, tidal, and estuarine processes that govern facies heterogeneity and stratigraphic architecture (Nwajide, 1990; Obi and Okogbue, 2004; Odoh et al., 2018). The resulting heterogeneous lithologies, rapid facies transitions, and variable sedimentary energy regimes have made reservoir prediction, characterization, and correlation within the basin particularly challenging.

Given these complexities, this study holds significant importance for advancing the sedimentological and depositional understanding of the tidally influenced fluvial–estuarine successions of the Anambra Basin, particularly those exposed within the Awkuzu area of the Nanka Formation. Tidally influenced fluvial–estuarine environments are known to produce highly variable sandstone bodies that can serve as excellent hydrocarbon reservoirs where their facies architecture and petrophysical attributes are

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

well understood. However, when poorly constrained, these same systems can result in compartmentalized reservoirs with unpredictable connectivity, leading to suboptimal exploration and production outcomes.

By conducting detailed facies analysis, sedimentological characterization, and depositional interpretation, this research aims to contribute new insights into the spatial and vertical facies distribution, reservoir geometry, and heterogeneity controls within these Paleogene deposits. The outcomes will enhance the ability to predict the spatial continuity and compartmentalization of sandstone bodies, which are critical for improved reservoir modeling and hydrocarbon recovery strategies. Furthermore, the study’s findings will serve as a reference analog for similar tidally modulated fluvial–estuarine systems globally, providing a framework for understanding how tidal and fluvial interactions influence sediment deposition, reservoir architecture, and fluid flow behavior.

From an exploration and development perspective, the significance of this study lies in its potential to bridge the knowledge gap between outcrop-based sedimentological studies and subsurface reservoir characterization. Integrating the results from field observations, facies interpretation, and depositional modeling will aid in the prediction of reservoir quality zones, especially in frontier basins such as the Anambra, where direct subsurface data are limited. The study’s contribution is therefore not only academic but also practical, supporting exploration risk reduction, better reservoir forecasting, and sustainable development planning within Nigeria’s inland hydrocarbon provinces.

Ultimately, this research advances the geological understanding of the Anambra Basin by emphasizing the role of tidal influence in shaping fluvial–estuarine depositional systems, thereby strengthening the geological basis for improved reservoir prediction, continuity assessment, and exploration strategy development in frontier basins of southeastern Nigeria.

Location of The Study Area

The study area is located within Awkuzu, a town in Oyi Local Government Area, Anambra State, southeastern Nigeria (Fig. 4). Awkuzu lies within the Anambra Basin, one of Nigeria’s major inland sedimentary basins. The area is geographically situated between latitudes 6°15′N and 6°20′N and longitudes 7°04′E and 7°08′E, approximately 25 km northeast of Onitsha, along the Onitsha–Enugu Expressway. The studied outcrop sections occur along major road cuts and stream exposures around the Awkuzu–Nteje–Ogbunike axis, where the Eocene Nanka Formation is well exposed.

The region exhibits the characteristic cuesta topography of southeastern Nigeria—an asymmetrical ridge extending from the River Niger at Idah through Enugu and Okigwe, curving eastward to the Cross River. The scarp face generally overlooks the Cross River Plain, while the dip slope merges with the Anambra River Plain to the west. Outcrops around Awkuzu, particularly along the expressway and adjoining stream channels, expose the Eocene Nanka Formation, displaying cross-bedded sandstones and associated sedimentary structures typical of tidally influenced fluvial–estuarine environments. These natural exposures provide suitable sections for examining the facies architecture and reservoir characteristics of the formation.

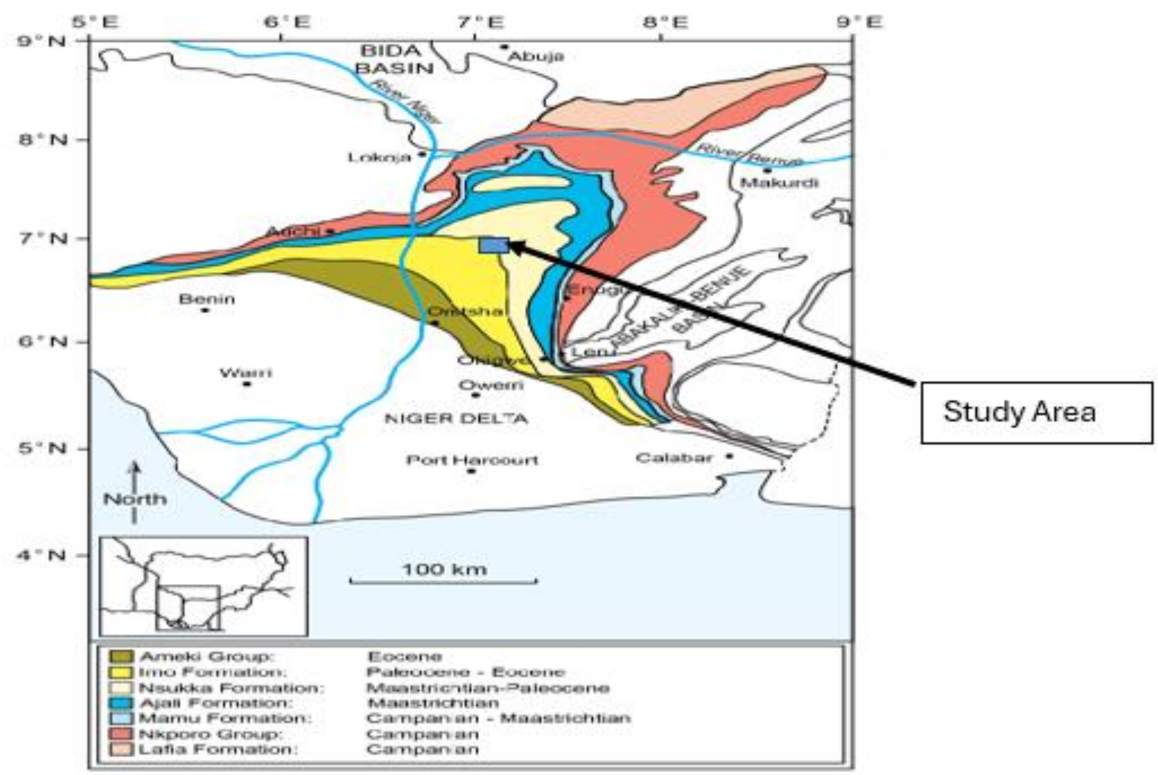

Fig. 4: Geological Map showing location of study Area (modified from Nwajide and Reijers, 1996)

II. Literature Review

The Anambra Basin represents one of the most significant Cretaceous–Tertiary sedimentary depocentres in southern Nigeria, evolving in response to major tectonic reconfigurations during the Santonian orogeny. This tectonic episode profoundly affected the Benue Trough, effectively terminating sedimentation within the Abakaliki Basin and redirecting depositional activities southwestwards into what became the Anambra Basin (Burke et al., 1970; Benkhelil, 1989). Prior to this event, sedimentation across southern Nigeria began in the Early Cretaceous, driven by the progressive rifting associated with the breakup of the African and South American plates, a process that gave rise to the Benue Trough and its associated structural components (Murat, 1972; Oboh-Ikuenobe et al., 2005).

Sedimentation within this region was strongly influenced by three major tectono-sedimentary phases, each producing distinct depocentres and lithostratigraphic successions. The first phase (Albian–Santonian) was marked by the deposition of the Asu River Group, Eze-Aku, and Awgu Formations, which were confined within the Abakaliki–Benue Trough and bounded to the east by the Anambra Platform and to the southwest by the Ikpe Platform (Benkhelil, 1989). The second phase (Campanian–Eocene) was associated with compressive movements along the NE–SW axis, which uplifted and folded the Benue Trough into an anticlinorium, thereby inducing subsidence on the Anambra Platform and establishing the Anambra Basin as a new depocentre (Murat, 1972). The Afikpo Syncline developed contemporaneously to the southeast, forming a complementary structural depression that received similar sedimentary fills (Oboh-Ikuenobe et al., 2005).

The Asu River Group, representing the earliest marine sedimentation in the area, comprises bluish-grey to brown shale, sandy shale, fine-grained micaceous sandstones, and interbedded limestone units (De-Swardt and Casey, 1963; Reyment, 1965). This group was subjected to intense structural deformation during the Santonian tectonic phase, producing complex folding and faulting particularly within Cenomanian-aged strata (Nwachukwu, 1972). Overlying this sequence is the Eze-Aku Formation, which consists predominantly of fossiliferous limestone and shale, attaining thicknesses up to 1200 m (Burke et al., 1970). The formation is occasionally intruded by igneous bodies (Ezepue, 1977) and transitions upward into the Agbani Sandstone, a bluish-grey, bedded shale with fine-grained carbonaceous limestone beds. The Agwu/Ndeaboh Formation, about 400 m thick, comprises bluish-grey, well-bedded shales with subordinate calcareous sandstones and limestones (Kogbe, 1981). These formations are overlain by the Enugu Shale, laterally equivalent to the Nkporo Shale, marking the transition to the younger Maastrichtian–Paleocene deposits. The succession reflects a progressive shift from fluvio-deltaic to marine depositional environments, highlighting the complex interplay of tectonics, subsidence, and sediment supply during the basin's evolution.

Sedimentological processes—including sediment transport, deposition, and post-depositional diagenesis—are critical in controlling the textural, compositional, and structural characteristics of sedimentary rocks (Miall, 1996). These processes directly influence grain size, sorting, sedimentary structures, and porosity–permeability relationships, all of which are essential in determining reservoir quality. Depositional facies, which reflect specific environments of sediment accumulation, provide key insights into spatial variability and heterogeneity within reservoir systems. According to Posamentier and Allen (1999), sequence stratigraphy serves as an invaluable tool for understanding how depositional facies and stratigraphic surfaces interact to control reservoir distribution and quality, especially in fluvio-deltaic settings such as the Anambra Basin.

The sedimentological framework of the Anambra Basin is dominated by fluvial to shallow marine systems that evolved under the influence of subsidence and marine transgressions. During the early stages of basin development, fluvial processes dominated, depositing channel and floodplain sediments. As subsidence intensified, deltaic processes became prominent, giving rise to a variety of depositional environments, including delta plain, delta front, and prodelta facies. Subsequent transgressions introduced shallow marine and shelfal sedimentation, marking a shift toward more marine-influenced depositional regimes.

Channel deposits are typically composed of well-sorted, coarse-grained sandstones exhibiting cross-bedding and planar stratification indicative of high-energy fluvial systems. Nwajide and Reijers (1996) emphasized the dominance of braided river systems during the Campanian–Maastrichtian periods, which facilitated the deposition of thick sandstone bodies serving as potential hydrocarbon reservoirs. In contrast, floodplain deposits consist primarily of fine-grained siltstones and mudstones formed in low-energy overbank environments. These deposits frequently contain organic-rich layers and coal seams, as documented by Obi and Okogbue (2004) in the Mamu Formation, indicating significant subaerial exposure and vegetation accumulation.

The deltaic facies of the Anambra Basin exhibit evidence of strong fluvial–tidal interactions. Delta plain deposits comprise interbedded coals, carbonaceous shales, and fluvial sandstones, reflecting alternating periods of sediment influx and marine influence (Oboh-Ikuenobe et al., 2005). Delta front deposits, characterized by mouth bar sandstones and distributary channel facies, represent transitional environments between fluvial and marine settings, as earlier described by Murat (1972). Further seaward, prodelta deposits of laminated shales and siltstones record quiet, offshore sedimentation under low-energy conditions (Nwajide and Reijers, 1996).

The marine and shelf facies represent the terminal phase of basin evolution, dominated by shallow marine to deeper offshore sedimentation. Shallow marine deposits typically consist of bioturbated sandstones and shales that record nearshore environments with abundant benthic activity (Petters, 1982; Whiteman, 1982). The shelf deposits, on the other hand, are composed of laminated shales and fine-grained sandstones accumulated in deeper, low-energy marine settings, marking maximum transgressive conditions (Reyment, 1965).

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

Overall, depositional facies within the Anambra Basin are grouped into three major categories—fluvial, deltaic, and marine—each representing a continuum of sedimentary environments linked to the basin's tectono-sedimentary history. The fluvial facies, such as channel sandstones and floodplain mudstones, signify proximal depositional systems characterized by high energy and strong lateral variability (Nwajide, 1990; Obi et al., 2001). The deltaic facies, including distributary channels, mouth bars, and prodelta shales, denote intermediate energy regimes with complex facies associations influenced by sediment supply and relative sea-level fluctuations (Oboh-Ikuenobe et al., 2005). The marine facies, typified by bioturbated and laminated shales as well as occasional limestones, represent distal environments associated with maximum flooding and reduced clastic influx (Petters, 1982; Whiteman, 1982).

Fluvio-deltaic systems such as those in the Anambra Basin are inherently heterogeneous, with variations in grain size, sediment supply, and depositional energy exerting strong control on reservoir architecture. Wright and Marriott (1993) observed that overbank and floodplain deposits often create low-permeability barriers within otherwise high-quality fluvial reservoirs, leading to compartmentalization. Comparatively, studies on the Niger Delta by Doust and Omatsola (1990) demonstrated similar depositional complexities, where alternations between distributary channel sands and floodplain shales strongly influenced hydrocarbon distribution and flow pathways. Understanding the depositional architecture and facies distribution within such systems is therefore critical for accurate prediction of reservoir quality and continuity across the basin.

III. Method of Study

The methodological approach adopted for this study involved several integrated stages—planning and desk study, reconnaissance mapping, detailed field investigation, sample collection, and laboratory analysis—all aimed at characterizing the sedimentological and depositional framework of the Awkuzu section within the Anambra Basin, southeastern Nigeria.

1. Desk Study and Planning Stage

The study commenced with an extensive desk review of existing literature, including geological maps, published articles, dissertations, and regional stratigraphic reports on the Anambra Basin (e.g., Burke et al., 1970; Nwajide, 1990; Obi and Okogbue, 2004; Oboh-Ikuenobe et al., 2005). Relevant geological and topographic maps were consulted to delineate access routes and potential outcrop locations within Awkuzu. A base map of the study area was prepared using topographic sheets (at 1:50,000 scale), which included contour lines, elevation points, drainage patterns, and coordinate grids. The map served as a spatial guide during fieldwork and as a framework for plotting measured sections and structural data.

2. Reconnaissance Survey

Preliminary reconnaissance was conducted to obtain an overview of the terrain, lithologic exposures, and accessibility of the Awkuzu outcrops. This stage facilitated the identification of suitable field sections, particularly along road cuts and erosional gullies where the sedimentary sequences of the Eocene Nanka Formation were well exposed. The reconnaissance exercise also enabled preliminary photographic documentation and the establishment of GPS reference points for subsequent mapping.

3. Field Observation and Data Collection

Detailed fieldwork was carried out along the Enugu–Onitsha expressway at Awkuzu, where the Nanka Formation exhibits extensive exposure of tidally influenced fluvial–estuarine deposits. The outcrop sections were systematically logged, and lithologic variations, sedimentary structures, and stratification patterns were described in detail.

Measurements were made for:

- Lithologic thicknesses using a Jacob's staff and measuring tape,
- Structural orientations (strike, dip direction, and dip amount) using a Brunton compass, and
- Sedimentary structures such as planar and trough cross-bedding, ripple marks, and bioturbation features (notably *Ophiomorpha*, *Planolites*, and *Skolithos*) indicative of tidal and shallow marine influences.

Each logged section was subdivided based on lithologic associations, texture, colour, sedimentary structures, and bounding surfaces to establish parasequence stacking patterns and facies successions.

4. Paleocurrent Measurement

Paleocurrent data were collected from foreset planes of cross-bedded sandstone facies at several representative stations within the Awkuzu outcrops. Measurements of dip amounts and azimuths were taken using a Brunton compass following the procedures of Collinson and Thompson (1989). The mean vector azimuth (MVA), variance (Var), and vector strength (VS) were computed using the Steinmetz (1962) method as follows:

$$MVA = \tan^{-1}\left(\frac{\sum \sin A}{\sum \cos A}\right), Var = \frac{\sum (A_i - \bar{A})^2}{n-1}, VS = \sqrt{\frac{(\sum \sin A)^2 + (\sum \cos A)^2}{n}}$$

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where *n* is the number of readings, and A_I represents individual azimuth readings. These computations aided in determining paleoflow directions and sediment dispersal trends within the fluvial–estuarine depositional system.

5. Pebble Morphometry Analysis

Pebble morphometry analysis was undertaken to infer depositional energy conditions and sediment transport mechanisms associated with conglomeritic and coarse-grained sandstone facies. Pebbles were carefully sampled from representative exposures, and only undeformed, isotropic samples were selected to ensure accuracy. Measurements of the long (L), intermediate (I), and short (S) axes were made using veneer calipers following Dobkins and Folk (1970). The following morphometric indices were calculated:

- Maximum Projection Sphericity (MPS) = $(S^2/LI)^{(1/3)}$ (Sneed and Folk, 1958)
- Oblate–Prolate Index (OPI) = {[L–I]/[L–S] – 0.5}/(S/L) (Dobkins and Folk, 1970)
- Flatness Index (FI) = (S/L) × 100 (Lutting, 1962)

These parameters assisted in distinguishing between fluvial, estuarine, and marine depositional energy regimes.

6. Data Analysis and Interpretation

All collected data—including lithologic logs, sedimentary structure measurements, paleocurrent statistics, and morphometric indices—were analyzed to reconstruct the depositional environments and facies architecture of the Nanka Formation at Awkuzu. Facies analysis was guided by sedimentological models proposed by Miall (1996) and Posamentier and Allen (1999) to interpret the tidally influenced fluvial–estuarine system. Emphasis was placed on recognizing vertical facies successions, parasequence stacking, and biogenic activity to infer paleoenvironmental conditions and reservoir implications.

Presentation of Results and Interpretation

Detailed sedimentological investigations carried out in the Awkuzu area, located within the frontier part of the Anambra Basin, reveal two major facies associations:

1. Fluvial/Tidally Influenced Fluvial Facies
2. Estuarine Facies.

These associations correspond closely with Nwajide's (1979) sedimentary model, which describes the Eocene Nanka Formation as deposits laid down within a tidally influenced marine shoreline system, characterized by interbedded fluvial and estuarine sediments. Each facies reflects a specific depositional process and energy regime that controlled grain size distribution, sedimentary structures, and reservoir quality. The analysis integrates field observations, paleocurrent measurements, and pebble morphometric data to interpret reservoir potential in the study area.

Facies Association 1 – Fluvial/Tidally Influenced Fluvial Facies

Lithologic and Sedimentary Characteristics

This facies consists predominantly of medium- to coarse-grained sandstones, locally granular to pebbly, exhibiting poor to moderate sorting. The sediments occur as multi-storey, fining-upward successions with distinct erosional bases. Sedimentary structures include planar and trough cross-bedding, scoured channel bases, mud drapes, and reactivation surfaces, all indicative of high-energy fluvial channels influenced intermittently by tidal currents (Fig. 5).

The lower part of the outcrop shows massive, coarse-grained, quartzose sandstone units, interpreted as braided channel deposits, which are locally conglomeratic and exhibit normal grading (Nilsen, 1982; Miall, 1992). The channel-fill sandstones are overlain by fine-grained, ripple-laminated sandstones and silty clay layers, representing overbank and waning flow conditions(Fig.5).

Tidal indicators such as mud drapes on foresets, bimodal paleocurrent patterns, and occasional bladed or elongate pebbles suggest deposition in a tidally influenced fluvial system (Archer and Kvale, 1989; Leckie and Singh, 1991). The presence of Ophiomorpha, Planolites, and Arenicolites trace fossils (Fig.6) further indicates periodic marine incursions in a high-energy sandy environment (Pemberton et al., 1992).

Paleocurrent and Pebble Morphometry

Paleocurrent data were measured from planar and trough cross-bedded foresets using a Brunton compass. Results from 60 readings show a dominant paleoflow direction towards the northeast (NE), with subordinate southeast (SE) trends (Fig. 7a).This unidirectional flow pattern supports deposition under a fluvial regime, later reworked by tidal currents, confirming the fluvial-dominated tidal channel model for this facies.

Vector analysis yielded a mean vector azimuth (MVA) of 48° NE, and a vector strength (R) of 0.84, indicating a strong directional current typical of confined fluvial channels.Variance values were low (0.12–0.18), suggesting consistent paleoflow orientation within the channel belt.

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Pebble morphometry analysis conducted on conglomeritic beds revealed subrounded to rounded quartz pebbles. Measured parameters include:

1. Maximum Projection Sphericity (MPS): 0.76–0.85
2. Oblate–Prolate Index (OPI): -0.12 to +0.18
3. Flatness Index (FI): 58–67%

These values indicate moderate sphericity and rounding, characteristic of high-energy transport and short reworking distances (Dobkins and Folk, 1970). The dominance of subrounded pebbles suggests a fluvial origin, while slight elongation in shape reflects tidal modification during deposition. The results imply an environment where channelized flow and reworking by tidal pulses coexist (Fig. 7b).

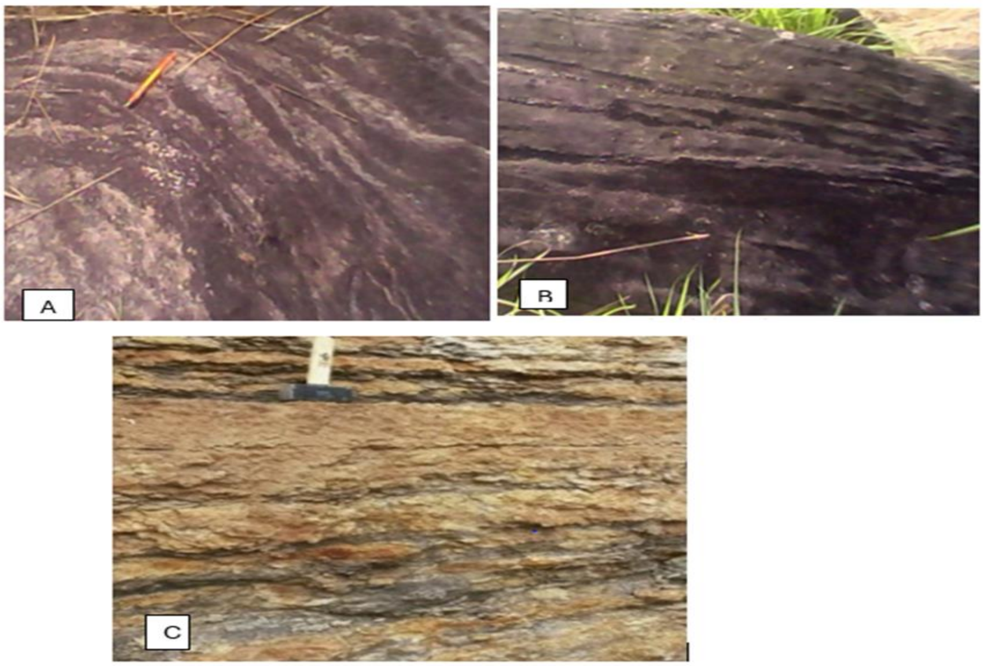

Fig. 5: A-Trough Cross bedded sandstone with Mud drapes B-Planar Cross bedded sandstone C-Ripple laminated section showing sandstone, siltstone and dark-gray shale units

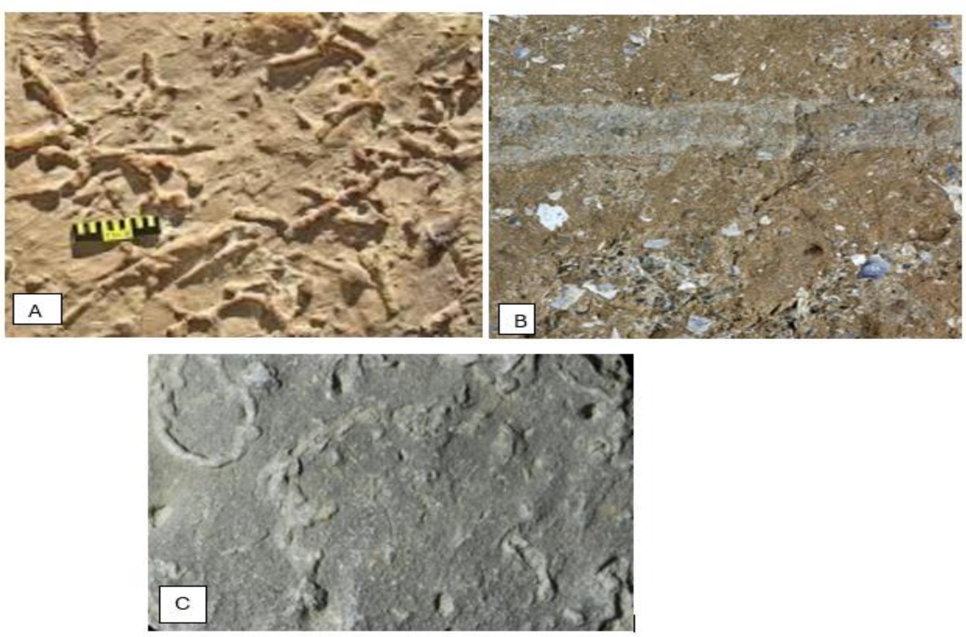

Fig. 6: Rock sections showing trace fossils of: A-Ophiomorpha, B-Planolites, and C-Arenicolites

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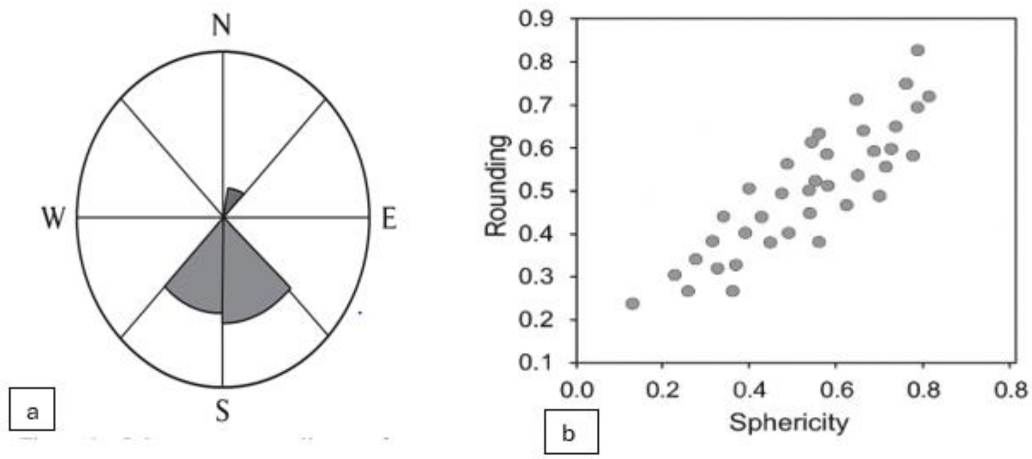

Fig 7: a. Paleocurrent Rose for Facie Association 1 showing dominant NE-directed unidirectional fluvial flow.

b. Pebble Morphometric plot for Facie Association 1 showing moderately high spericity and rounding, typical of Fluvial environment.

Reservoir Implications

The fluvial/tidally influenced facies exhibits excellent reservoir potential, primarily due to its coarse grain size, high primary porosity, and well-developed cross-bedding which enhances permeability anisotropy. The unidirectional paleoflow suggests predictable reservoir connectivity along the channel axis, while the minor tidal reworking may introduce local heterogeneities that act as baffles or barriers to vertical flow.

The matrix-supported conglomerates and braided channel sandstones form high-quality reservoir units, potentially serving as hydrocarbon-bearing intervals. However, mud drapes and thin clay intercalations between fining-upward successions could compartmentalize the reservoir, influencing fluid migration and production dynamics. Overall, this facies represents the most promising reservoir unit within the studied section of the Anambra Basin.

Facies Association 2 – Estuarine Facies

Lithologic and Sedimentary Characteristics

This facies comprises heterolithic and laminated units, typically 15–20 m thick, consisting of fine- to medium-grained sandstones, siltstones, and claystones (Fig.8a). The lithology displays alternating beds of sandstone and mudstone, often with wavy and lenticular laminations indicative of tidal influence(Fig.8b). Mud-draped cross-laminations, flaser bedding, and rhythmic alternations between sand and mud layers are common.

The facies is also characterized by bioturbated intervals containing Skolithos and Planolites ichnofacies (Fig.8c), reflecting a well-oxygenated shallow marine environment. The vertical facies succession—from muddy heteroliths to coarsening-upward sandstone bodies—suggests tidal channel and proximal estuarine deposition, likely during periodic marine transgressions (Walker and Plint, 1992; Nwajide and Reijers, 1996).

Paleocurrent and Pebble Morphometry

Paleocurrent analysis of cross-laminated beds within the estuarine facies revealed a bimodal pattern, with flow directions trending NE–SW and NW–SE (Fig. 9a). This pattern reflects reversing tidal currents, confirming a tidal channel or inner estuarine depositional environment. The vector strength (R = 0.65) indicates moderate orientation strength, consistent with bidirectional flow oscillations.

Pebble morphometry was conducted on granule- to fine-pebble-sized fragments found in coarser sand layers. The data indicate subangular to subrounded, flattened pebbles, with the following computed parameters:

1. MPS: 0.68–0.77
2. FI: 70–80%
3. OPI: Predominantly negative, indicating oblate pebble shapes

These values suggest low-energy reworking and deposition from oscillatory tidal currents, where bidirectional flow led to limited abrasion and flattening of grains (Sneed and Folk, 1958; Dobkins and Folk, 1970).

The results confirm cyclic energy fluctuations, typical of tidal flat or marginal estuarine systems (Fig. 9b).

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Reservoir Implications

Reservoir potential within this facies is moderate to low, controlled by its heterolithic nature and mudstone intercalations. The alternation of sand and clay layers creates a baffled reservoir architecture, where vertical permeability is reduced but lateral sand continuity remains effective.

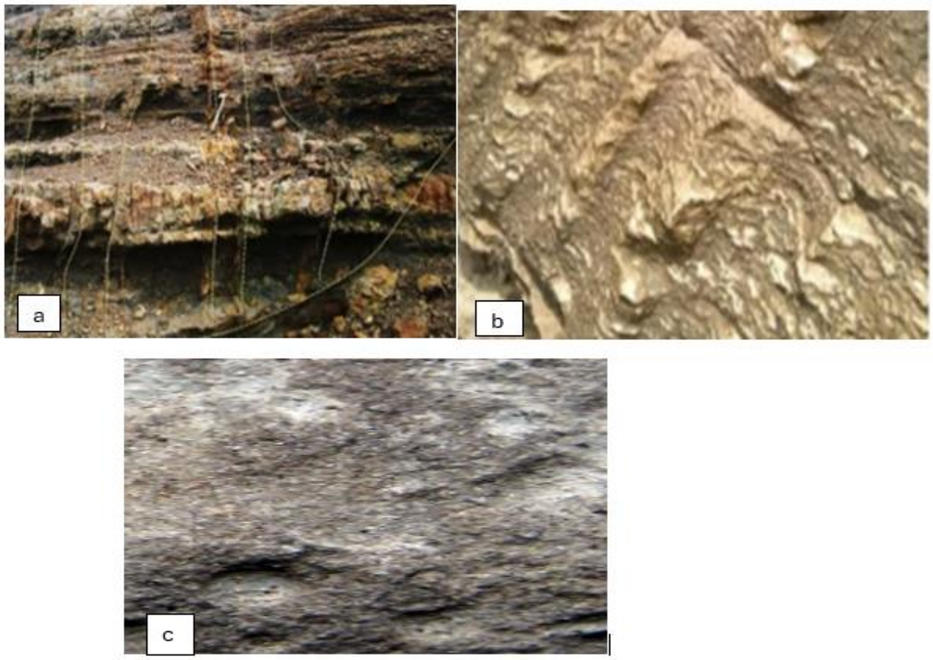

Fig.8: a- Heterolithic sandstone, siltstone and shale unit, b- Wave rippled laminated sandstone unit, c-Rock section showing Skolithos trace fossil

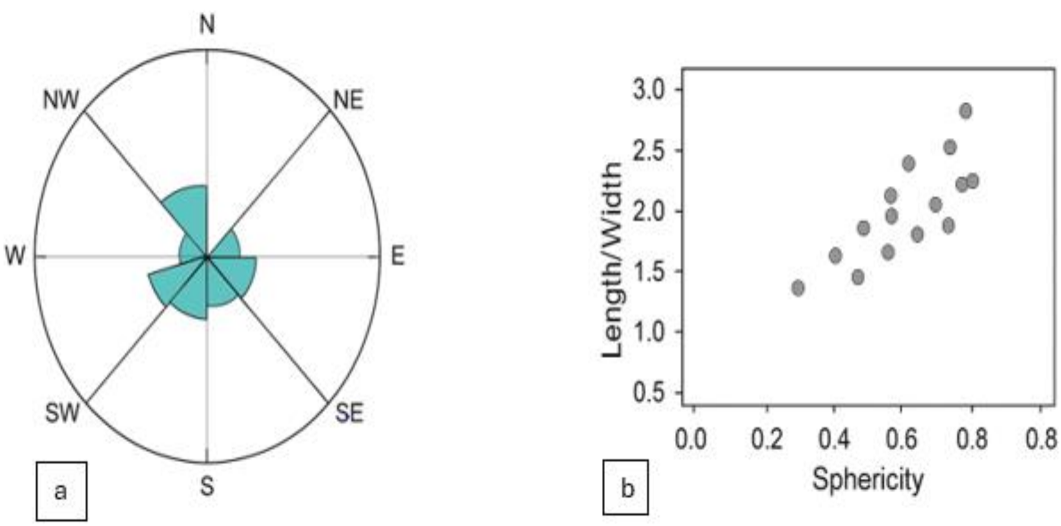

Fig. 9: a- Paleocurrent Rose for Facie Association 2 showing bimodal tidal flow orientations (NE-SW and SW- NE).

b- Pebble Morphometric plot for Facie Association 1 showing moderately spherical and sub-rounded typical of tidal flat or marginal estuarine systems environment.

The bimodal paleocurrent trends promote lateral facies connectivity, enhancing fluid migration pathways across tidal channels. However, mud drapes and tidal rhythmites act as local sealing layers, resulting in anisotropic flow patterns and potential reservoir compartmentalization.

In the context of reservoir characterization, this facies represents a secondary reservoir target, capable of serving as fluid migration conduits or secondary traps adjacent to high-quality fluvial sands. Its stratigraphic position and lateral connectivity with the fluvial

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facies highlight the complementary nature of both facies in controlling reservoir heterogeneity and production behavior within the Nanka Formation of the Anambra Basin.

IV. Conclusion

The detailed facies analysis, paleocurrent measurements, and pebble morphometric studies carried out on the Awkuzu exposures of the Nanka Formation within the Frontier Anambra Basin have provided valuable insights into the facies architecture, sedimentological processes, and their implications for reservoir potential. The integration of lithologic descriptions, sedimentary structures, and textural analyses reveals that deposition within the study area occurred under a tidally influenced fluvial–estuarine system, characterized by alternating high-energy and low-energy depositional regimes.

Two principal facies associations were recognized — the Facies Association 1 (Fluvial/Tidally Influenced Fluvial Facies) and the Facies Association 2 (Estuarine Facies). The fluvial/tidally influenced facies are typified by medium to coarse-grained, moderately sorted sandstones and conglomeritic beds with well-developed planar and trough cross-bedding, fining-upward successions, and erosional channel bases. Paleocurrent data show a dominant unidirectional flow towards the northeast, suggesting fluvial channel migration under strong hydrodynamic conditions. Pebble morphometry analysis indicates moderately high sphericity and rounding, reflecting sustained fluvial transport with minor tidal reworking. These characteristics, combined with their good textural maturity and lateral continuity, suggest that these channel sandstones form excellent reservoir intervals. Their high porosity and permeability, inferred from coarse grain sizes and minimal clay content, are enhanced by the lateral sheet geometry and cross-bedding, which provide effective pathways for fluid flow.

The Estuarine Facies Association is defined by heterolithic and laminated successions of fine-grained sandstones, siltstones, and claystones, showing evidence of tidal cyclicity, mud drapes, and intense bioturbation belonging to the *Skolithos ichnofacies*. Paleocurrent analysis reveals a bimodal pattern (NE–SW and NW–SE), consistent with tidal reversals, while pebble morphometry reflects moderate sphericity and dominance of oblate shapes, suggesting tidal reworking and low transport energy. These features indicate deposition in a transitional estuarine environment where tidal currents periodically alternated with riverine flow. Although these deposits exhibit reduced reservoir quality due to finer grain sizes, pervasive bioturbation, and mud draping, localized sandy units within the heteroliths may serve as secondary reservoir compartments, particularly where burrows such as *Ophiomorpha* enhance vertical permeability.

Overall, the facies architecture demonstrates a clear sedimentological control on reservoir heterogeneity. The fluvial channel sandstones with their multistoried geometry and high-energy depositional characteristics possess superior reservoir potential compared to the estuarine heteroliths. The cyclic alternation of fluvial and tidal processes produced vertically stacked yet laterally variable sandstone bodies, resulting in compartmentalized but interconnected reservoirs. This hierarchical organization reflects the dynamic interplay between fluvial discharge, tidal influence, and relative sea-level changes that governed sediment dispersal and reservoir quality in the Awkuzu section of the Frontier Anambra Basin.

The reservoir potential established in this study is further supported by previous investigations that have confirmed the presence of mature and prolific source rocks within the Anambra Basin. Earlier geochemical and stratigraphic studies have shown that the Nkporo, Mamu, and Imo Formations contain organic-rich shales deposited under marginal marine to paralic settings, serving as effective hydrocarbon source intervals. These formations are characterized by Type II and mixed Type II–III kerogens with moderate to high total organic carbon (TOC) values, indicating significant potential for both oil and gas generation. The thermal maturity levels recorded in these units suggest that large portions of the basin have attained the oil and gas window, thereby providing the necessary charge to the overlying Nanka Formation sand bodies. Consequently, the well-developed, tidally influenced fluvial–estuarine sandstones recognized in the present study not only possess excellent reservoir qualities but are also favorably positioned within a petroleum system framework supported by proven source rocks. This integrated evidence reinforces the basin's overall prospectivity and underscores the Frontier Anambra Basin as an emerging hydrocarbon province with promising reservoir–source rock relationships comparable to those of the Niger Delta.

Conclusively, the study establishes that facies architecture and sedimentological controls are key determinants of reservoir potential in tidally influenced fluvial–estuarine systems. The Awkuzu deposits, particularly the tidally influenced fluvial sand bodies, constitute promising hydrocarbon reservoir analogues within the Anambra Basin. The findings from this study also reveal that the Awkuzu section of the Nanka Formation, within the Frontier Anambra Basin, possesses significant potential for hydrocarbon accumulation and storage due to its well-developed fluvial and tidally influenced depositional systems. The recognition of multistoried, laterally continuous, moderately sorted fluvial channel sand bodies with good textural maturity, stratigraphic stacking, coupled with their high porosity and inferred permeability, points to promising reservoir-quality intervals comparable to those found in the Niger Delta Basin.

V. Recommendations

Given the findings from this research study of the promising reservoir characteristics of the tidally influenced fluvial–estuarine deposits within the frontier Anambra Basin, the following recommendations are proposed:

Enhanced Geological and Geophysical Exploration:

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Future petroleum exploration efforts in the Awkuzu area should be prioritized and intensified. High-resolution seismic surveys, integrated with well log calibration and sequence stratigraphic interpretation, should be conducted to delineate the lateral and vertical continuity of the identified fluvial channel sandstones and to map the heterolithic tidal and estuarine successions that may act as seals or baffles. Such studies will improve the understanding of reservoir compartmentalization and aid in identifying prospective hydrocarbon traps.

Exploratory Drilling and Reservoir Evaluation:

Exploratory wells should be drilled to validate the sedimentological predictions and confirm the presence and quality of the reservoir units inferred from surface studies. Core analysis, porosity-permeability tests, and petrophysical characterization should be employed to quantitatively assess the reservoir quality of the fluvial channel sands and to determine the sealing efficiency of interbedded claystone and mudstone units.

Integration with Basin Modeling and Sequence Stratigraphy:

It is recommended that future research integrates basin modeling and sequence stratigraphic frameworks to better understand the temporal evolution of depositional environments and their control on sediment dispersal and reservoir connectivity. This integration will help identify regional stratigraphic pinch-outs, erosional surfaces, and potential stratigraphic traps, improving exploration success rates.

Use of Advanced Sedimentological and Petrophysical Techniques:

To refine the interpretation of facies architecture and reservoir distribution, modern analytical tools such as digital outcrop modeling, ground-penetrating radar (GPR), and high-resolution drone-based photogrammetry should be employed. These techniques will provide 3D visualization of outcrop geometries and improve prediction of subsurface reservoir analogs.

Consideration for CO_2 Sequestration:

Given the favorable porosity and permeability attributes of the fluvial sandstone bodies in Awkuzu, future studies should also explore their potential as CO_2 storage reservoirs. This would enhance the environmental and economic utilization of the basin beyond hydrocarbon exploration.

Collaborative Research and Data Integration:

A collaborative approach involving academia, research institutions, and the petroleum industry is recommended to integrate sedimentological, petrophysical, and geophysical datasets for comprehensive reservoir modeling. Such synergy would also facilitate the development of predictive models applicable to other frontier basins in Nigeria.

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