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QUANTITATIVE PALEO-HYDRODYNAMIC MODELLING AND SEQUENCE STRATIGRAPHIC FRAMEWORK FOR THE LATE CRETACEOUS CLASTIC SYSTEMS OF THE ANAMBRA BASIN: A REVIEW

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ABSTRACT

Thick successions of fluvial, deltaic, marginal-marine, and shallow-marine clastic deposits make up the Late Cretaceous Anambra Basin in southeast Nigeria. These deposits contain significant hydrocarbon, coal, and groundwater resources. It takes methods beyond descriptive sedimentology to comprehend the stratigraphic architecture, sediment dispersal, and depositional evolution of these successions. With a focus on their combined use for reconstructing ancient depositional systems, this paper examines the principles, techniques, and applications of quantitative paleo-hydrodynamic modeling and sequence stratigraphy.

By utilizing sedimentary structures, grain-size distributions, hydraulic geometry, and transport equations, paleo-hydrodynamic analysis offers quantitative constraints on paleoflow velocity, discharge, shear stress, sediment transport capacity, and bedform formation. Sequence stratigraphy places hydrodynamic interpretations within a temporal and basin-scale framework that is impacted by tectonics, accommodation, sediment supply, and eustatic sea-level fluctuations. It does this by grouping sediments into genetically related packages that are surrounded by important stratigraphic surfaces.

The combined method enhances the interpretation of facies correlations, stacking patterns, paleogeographic evolution, and reservoir heterogeneity in the Campanian–Maastrichtian successions. A review of previous research shows that there is a lack of quantitative flow reconstruction and uncertainty analysis and a greater reliance on qualitative, facies-based interpretations. The study emphasizes the necessity of probabilistic paleo-hydrodynamic frameworks, forward and inverse modeling, and integrated sediment budget estimation.

Sequence stratigraphy and quantitative paleo-hydrodynamics work together to offer a potent, predictive toolkit for improving reservoir characterization, lowering geological uncertainty, and reconstructing basin evolution. In addition to improving knowledge of the Anambra Basin, these techniques provide generalizable strategies for comparable clastic sedimentary systems across the globe.

Keywords: paleohydrodynamics, sequence stratigraphy, paleoflow, facies architecture, Upper Cretaceous, Anambra Basin, Nigeria

INTRODUCTION

Thick successions of fluvial, deltaic, marginal marine, and shelfal sediments were deposited in the Late Cretaceous Anambra Basin in southeast Nigeria during a time of significant sediment input from uplifted hinterlands, regional tectonic reorganization, and varying eustatic sea levels [1],[2],[3]. For both academic and applied geoscientific research, a thorough examination of these successions is essential because they form significant hydrocarbon reservoirs, coal sequences, and aquifer systems. Sequence stratigraphy, which divides sedimentary strata into genetically related packages based on relative sea-level change, sediment supply, and accommodation dynamics [4],[5], and quantitative paleo-hydrodynamic modeling, which reconstructs ancient flow conditions, transport regimes, sediment budgets, and hydraulic parameters [6],[7]. Integrating these ideas improves the interpretation of facies relationships, depositional trends, architectural patterns, reservoir heterogeneity, and paleogeographic evolution [8]. While previous research has often been descriptive, this integration offers a path to more quantitative and predictive geological models for the Anambra Basin. This review paper summarizes the basic ideas, mechanisms, methods, and applications of paleo-hydrodynamic modeling and sequence stratigraphy in relation to the Late Cretaceous clastic systems of the Anambra Basin. The present study is of great interest for future studies that will evaluate the economic potential of the thick sedimentary deposits (up to 6,000 meters) from Anambra Basin, rich in shales and coal deposits derived from terrestrial organic matter, potentially source for oil and natural gas fields.

Overview of Hydrodynamics and Sequence Stratigraphy

An approach that combines hydrodynamic processes with sequence stratigraphic organization is necessary for the reconstruction of Late Cretaceous clastic depositional systems in the Anambra Basin. While sequence stratigraphy provides a temporal and genetic framework that connects sedimentary packages to changes in accommodation, sediment supply, tectonism, and relative sea-level fluctuations, hydrodynamics offers quantitative insight into sediment transport mechanisms, such as flow velocity, shear stress, discharge, and bedform development [9],[10]. When combined, these resources allow for a reliable reconstruction of basin evolution, sediment dispersal routes, and depositional environments.

By controlling grain size, sorting, sedimentary structures, and depositional energy, hydrodynamic conditions have a major influence on the type and distribution of clastic sediments [11],[12]. Variations in paleoflow depth, velocity, and sediment transport modes are recorded in the Late Cretaceous Anambra Basin by preserved sedimentary features like crossbedding, ripple marks, channel architectures, and grain-size trends. These sedimentary characteristics can be converted into estimates of flow competence and transport capacity through quantitative paleohydrodynamic reconstruction using grain-size statistics, bedform geometry, hydraulic geometry relationships, and Shields entrainment criteria [9],[13]. These parameters offer process-based explanations for the formation of the shallow-marine, deltaic, and fluvial facies that define the clastic succession of the basin.

By classifying clastic deposits into genetically related systems tracts surrounded by regionally significant stratigraphic surfaces like sequence boundaries and maximum flooding surfaces, sequence stratigraphy enhances hydrodynamic analysis [14],[15]. The Nkporo–Mamu–Ajali–Nsukka succession in the Anambra Basin reflects recurrent cycles of relative sea-level change that regulated sediment preservation and accommodation creation [1],[16]. While transgressive phases encouraged energy dissipation, sediment starvation, and extensive shale accumulation,

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lowstand and falling-stage conditions favored high-energy fluvial incision and sand-dominated deposition. Progradational stacking of deltaic and fluvial sand bodies and a renewed supply of sediment were characteristics of highstand conditions [13].

It is possible to interpret depositional processes in their proper stratigraphic context by incorporating hydrodynamics into a sequence stratigraphic framework. According to Catuneanu [4] hydrodynamic parameters differ systematically between systems tracts, with peak flow energy generally linked to lowstand deposits and minimum energy conditions corresponding to maximum flooding intervals. The Anambra Basin clastic succession's sandbody geometry, lateral continuity, and reservoir heterogeneity can all be predicted using this process-response relationship. Figure 1 is a paleohydrodynamic–sequence stratigraphic conceptual model for the Late Cretaceous Anambra Basin showing the relationship between relative sea-level change, systems tract development, hydrodynamic energy variations, and depositional environments in conceptual synthesis.

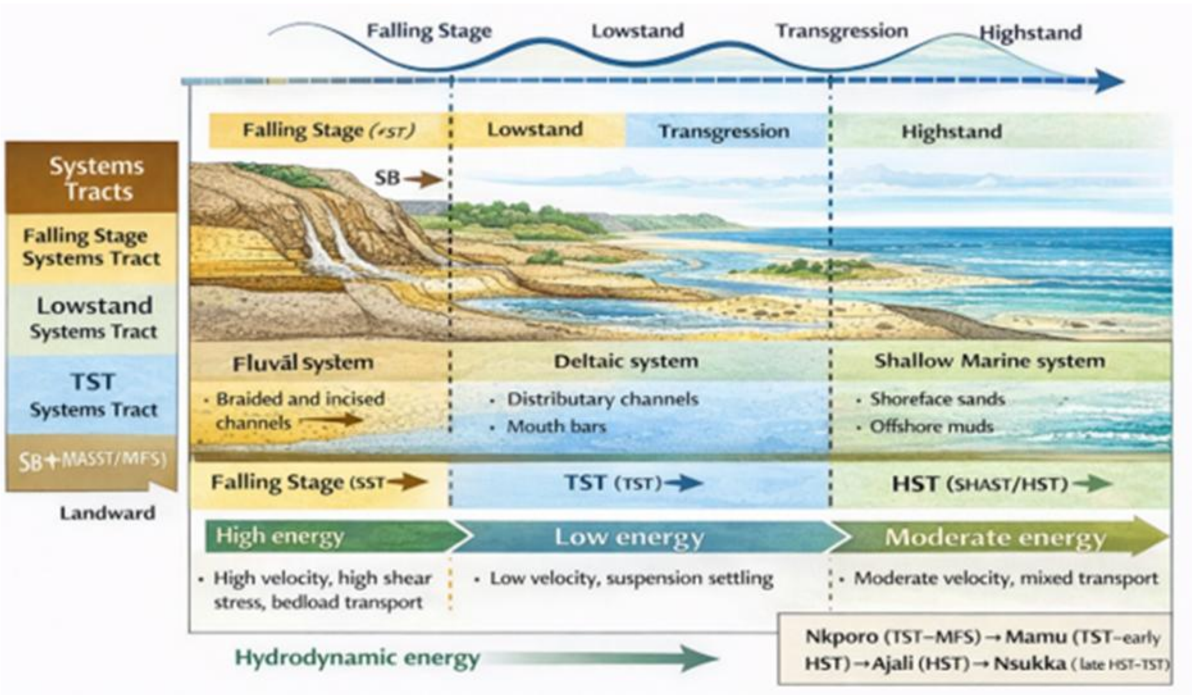

Figure 1. *An integrated paleohydrodynamic–sequence stratigraphic conceptual model for the Late Cretaceous Anambra Basin showing the relationship between relative sea-level change, systems tract development, hydrodynamic energy variations, and depositional environments in conceptual synthesis based on* [4],[13].

HYDRODYNAMIC AND SEQUENCE STRATIGRAPHIC MECHANISMS

The best way to understand depositional systems, according to recent sedimentological research, is to combine quantitative reconstructions of flow processes with stratigraphic organization driven by accommodation change [12],[14],[17]. Through estimates of flow velocity, flow depth, boundary shear stress, sediment transport mode, and transport capacity derived from grain-size statistics, sedimentary structures, and hydraulic scaling relationships, paleohydrodynamic analysis offers quantitative constraints on the movement and deposition of sediment [18],[19],[20]. These parameters enable process-based reconstruction of sediment mobility and depositional energy conditions in shallow-marine, deltaic, and fluvial

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environments. In turn, sequence stratigraphy explains when and why sediment is preserved in the stratigraphic record by providing the temporal and genetic context within which these processes function. In contrast to sea level alone, modern sequence stratigraphic models show that accommodation, sediment supply, tectonic subsidence, and relative sea-level change interact to form stratigraphic surfaces and systems tracts [16],[21],[22]. Using this concept, depositional successions can be separated into genetically related packages that document systematic changes in sediment distribution, facies architecture, and stacking patterns throughout time. Hydrodynamic regime changes predictably throughout systems tracts, according to recent research, underscoring the significance of combining stratigraphic interpretation with flow-process analysis. While transgressive systems tracts show decreasing hydrodynamic energy, increased accommodation, and dominance of suspension settling, culminating at the maximum flooding surface, which represents the lowest-energy phase of the depositional cycle, falling-stage and lowstand systems tracts are typically linked to elevated flow energy, increased shear stress, sediment bypass, and sand-dominated deposition [14],[17],[21]. Under continuous but moderate flow conditions, highstand systems tract renewed sediment delivery, resulting in laterally wide sand bodies and progradational stacking patterns [20],[19]. This enables the simultaneous reconstruction of depositional processes and stratigraphic architecture in the Late Cretaceous Anambra Basin by interpreting fluctuations in flow energy and sediment flux within systems tracts and across important stratigraphic surfaces. Recent basin-scale syntheses of sedimentary basins in West Africa show that the coupling of hydrodynamic processes with accommodation-driven stratigraphic cycles strongly controls paleogeographic evolution, reservoir heterogeneity, and sand body distribution [23]. This integrated approach improves paleoenvironmental reconstruction, increases the prediction of sand-prone intervals, and offers a solid foundation for stratigraphic correlation and reservoir-scale interpretation by integrating quantitative paleohydrodynamic parameters within a contemporary sequence stratigraphic framework [21],[13],[19]. Schematics in Figure 2 shows Hydrodynamic and Sequence Stratigraphic Mechanisms Controlling Depositional Architecture.

Methods of Hydrodynamic and Sequence Stratigraphic Evaluation

To reconstruct depositional processes and stratigraphic architecture of the Late Cretaceous clastic succession of the Anambra Basin, hydrodynamic and sequence stratigraphic evaluation uses an integrated, multi-scale methodology that combines sedimentological observations, quantitative analysis, and stratigraphic framework construction. Within a single process-response framework, the method is intended to connect stratigraphic preservation (when and why sediment accumulated) with flow mechanisms (how sediment flowed) [14],[21].

- ✓ **Development of Stratigraphic Frameworks:** Outcrop descriptions, well logs, core data (if available), and regional stratigraphic correlations are used to create the sequence stratigraphic framework. Facies shift, stacking patterns, erosional contacts, and alterations in depositional trends are used to identify key stratigraphic surfaces, such as sequence boundaries (SBs), transgressive surfaces (TSs), and maximum flooding surfaces (MFSs). Using vertical facies successions and shoreline trajectory analysis, systems tracts (falling-stage, lowstand, transgressive, and highstand) are identified using contemporary sequence stratigraphic approaches that place more emphasis on the relationship between accommodation and sediment supply than on eustasy alone [16],[21],[14].

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✓ **Architectural Analysis and Facies:** By methodically describing the lithology, sedimentary structures, grain size, bed geometry, and fossil content, a thorough facies analysis will be completed. Genetically related depositional elements, including river channels, point bars, mouth bars, delta-front sheets, shoreface successions, and offshore mudstones, can be categorized into facies associations. To determine depositional style, sediment dispersal routes, and spatial heterogeneity within systems tracts, architectural features and stacking patterns are analyzed [20],[17]. The physical connection between stratigraphic and hydrodynamic conditions is provided in this stage.

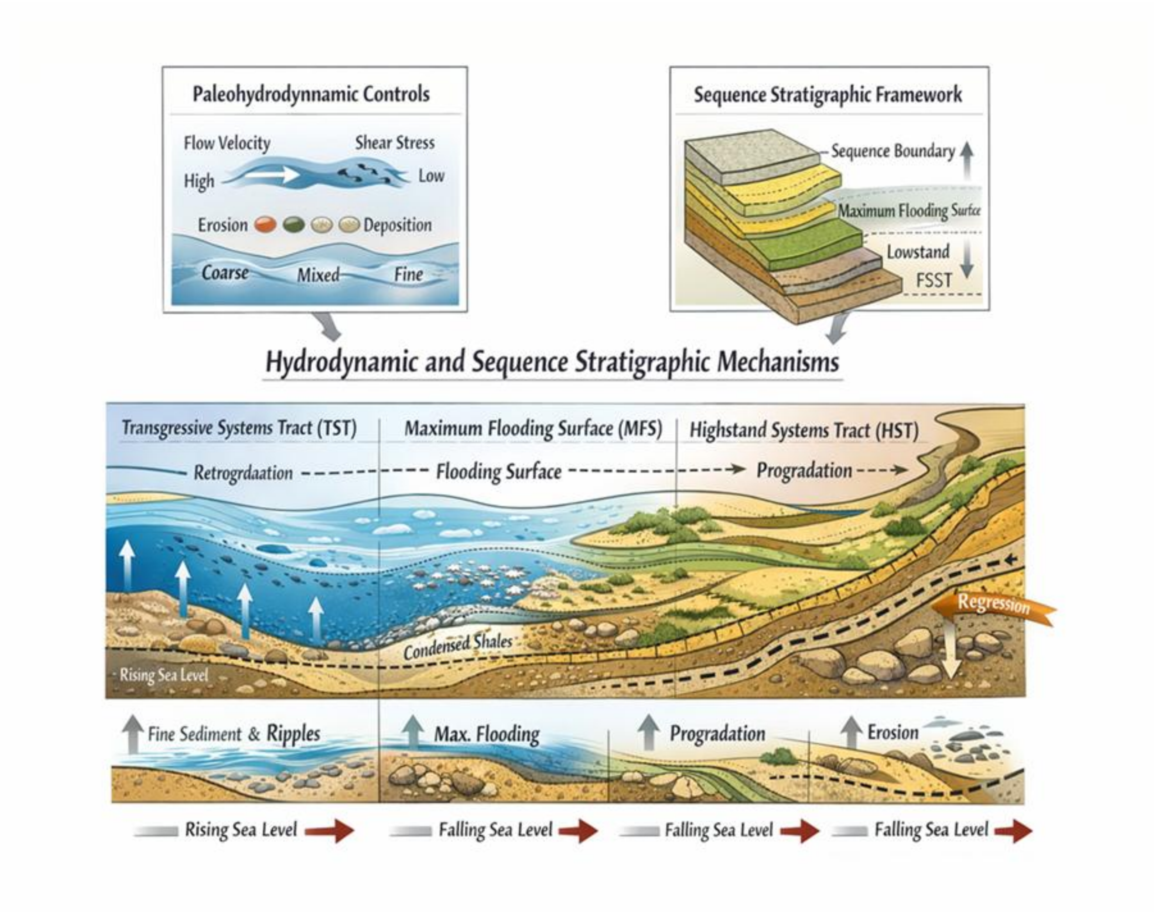

Figure 2. *Integrated hydrodynamic and sequence stratigraphic mechanisms controlling depositional architecture modified after* [16],[14],[19].

✓ **Quantitative Reconstruction of Paleohydrodynamics:** Grain-size statistics, sedimentary structures, and bedform geometry are used to recreate quantitative paleohydrodynamic parameters. Empirical and semi-empirical hydraulic relationships from contemporary experimental and field-based research are used to estimate flow velocity, flow depth, and boundary shear stress. Sediment entrainment and transport capacity are assessed using Shields-type criteria, while flow regime and sediment transport mode were inferred using bedform parameters (e.g., ripple and dune height and wavelength) [12],[18],[19]. Quantitative limitations on depositional energy conditions within specific facies and across depositional settings are provided by these reconstructions.

- ✓ **Integration of Process-Response Across Systems Tracts:** To evaluate how flow regimes reacted to variations in accommodation and sediment supply across time, hydrodynamic results are interpreted within the established sequence stratigraphic framework. To find consistent tendencies related to relative sea-level decline, transgression, and highstand conditions, variations in reconstructed flow energy and sediment transport capacity are assessed across systems tracts and stratigraphic surfaces. In line with contemporary theories of stratigraphic organization as an emergent result of interacting autogenic and allogenic influences, this integration enables the simultaneous assessment of depositional processes, sediment bypass, and preservation potential [20],[21].
- ✓ **Predictive Depositional and Stratigraphic Results:** Finally, the Anambra Basin's paleogeographic development, reservoir heterogeneity, and sandbody distribution are predicted using the combined hydrodynamic–sequence stratigraphic approach. Mud-dominated successions are associated with times of decreased flow energy and increased accommodation, whereas sand-prone intervals are associated with systems tracts with favorable hydrodynamic conditions and limited accommodation. This prediction element offers a process-based framework for comprehending stratigraphic variability in Late Cretaceous clastic systems and improves basin-scale correlation [14],[19].

Parameters used in Paleohydrodynamic Reconstruction

The parameters for paleohydrodynamic reconstruction are depicted in Table 1.

Table 1. *Parameters for paleohydrodynamic reconstruction* [24]

Symbol	***Definition***	***units***
Cv	Volume concentration of solid sediment flow	-
D	Transport distance of clastic material	m
dav	Mean diameter of rudaceous material	m
D50, d84, dn	Grain size percentiles	mm
f	Darcy Weisbach friction factor	-
g	Gravitational acceleration	$m\ s^{-2}$
H	Flow depth	m
S	Energy slope/paleoflow gradient	-
kz	Vertical sediment inhomogeneity coefficient	-
n	Manning roughness coefficient	-
q	Unit sediment discharge	$m^2\ s^{-1}$
V	Depth averaged flow velocity	$m\ s^{-1}$
ρs	Density of solid phase	$kg\ m^{-3}$
ρf	Density of fluid or mixture	$kg\ m^{-3}$
γs	Specific weight of solid phase	$N\ m^{-3}$
γf	Specific weight of fluid	$N\ m^{-3}$
μ	Dynamic viscosity of clear fluid	Pa·s
μf	Dynamic viscosity of sediment laden fluid	Pa·s
x, y, z	Spatial coordinates	-

SHEAR STRESS AND RHEOLOGICAL FLOW TYPES

Non-Newtonian Flow (Bingham Rheology)

Non-Newtonian behavior characteristic of hyper concentrated or debris-flow regimes may be seen in sediment-laden flows with high clay content. The Bingham-Shvedov rheological model provides a sufficient description of these flows [10],[24],[25].

$$\tau = \tau_0 + \mu_m (dV_x / dz) \quad (1)$$

Where:τ is shear stress (Pa), $\tau_0$is yield stress (Pa), μ_m is plastic (dynamic) viscosity (Pa·s), while dV_x/dz is velocity gradient in the vertical direction

Yield stress for clay-rich suspensions (20–30% clay fraction) is given by:

$$\tau_0 = 0.1 \times e^{\wedge}(23(C_v - 0.05)) \quad (2)$$

Where: τ_0 is yield stress (Pa), C_v is volume concentration of solids

Dynamic viscosity of the sediment-fluid mixture is expressed as:

$$\mu f = \mu (1 + 2.5C_v + e^{\wedge}(23(C_v - 0.05))) \quad (3)$$

The Shields Criterion for Turbulent Flow

The Shields criterion Shields, [26] and Parker, [27] is used to assess the start of sediment motion under turbulent Newtonian flow conditions:

$$\tau c = \tau * (\gamma s - \gamma f)\, d\_max \quad (4)$$

Where: τc is critical shear stress (Pa), τ^* is dimensionless Shields parameter, γs is specific weight of sediment (N/m³), γf is specific weight of fluid (N/m³), while dmax is maximum grain diameter (m)

Hydrodynamic Controls in Systems Tracts

- ✓ **Lowstand and Falling Stage Systems Tracts (FSST–LST):** Sand-dominated depositional systems resulted from relative sea-level fall, which decreased accommodation and encouraged fluvial incision, basinward sediment transfer, and sediment bypass [21],[14]. High flow velocities, increased boundary shear stress, and primarily bedload transport are indicated by quantitative paleohydrodynamic indicators such as coarse grain sizes, large dune-scale cross-sets, high critical Shields values, and elevated hydraulic geometry estimates [18],[19]. These circumstances account for the formation of basinward-shifted depocenters, channelized sand bodies, and incised valleys in the Anambra Basin that create laterally limited but vertically sProcess–stratigraphic linkage: Reconstructed paleohydrodynamic parameters limit channel shape, sediment quality, and reservoir quality within the LST, while sequence limits and basal surfaces of forced regression indicate times of peak hydrodynamic energy [21],[14].
- ✓ **Tract for Transgressive Systems (TST):** Energy dissipation, sediment hunger, and extensive fine-grained deposition were the outcomes of rapid accommodation creation during transgression [16]. In marginal-marine environments, paleohydrodynamic reconstruction shows lower flow velocities, low shear stress, and the predominance of suspension settling, with wave and tidal reworking [12],[17]. This tract is characterized by compact sections and fine-grained deposits. Process–stratigraphic linkage: The maximum flooding surface (MFS), which blends flow attenuation with maximum

accommodation, is a regionally correlable surface that corresponds to the smallest hydrodynamic energy state within the stratigraphic cycle [21],[14].

- ✓ **Tract for Highstand Systems (HST):** Progradational stacking of depositional units resulted from sediment supply exceeding accommodation production during highstand circumstances [14],[21]. Quantitative indications include enhanced sediment flux, channelized delta-front, and distributary processes that have been restored, as well as modest but persistent flow velocities [19],[20]. This regime, which is exemplified by the Ajali Sandstone counterparts, explains laterally widespread sand bodies, mouth-bar complexes, and distributary-channel structures in the Anambra Basin. Process–stratigraphic linkage: Sequence stratigraphy regulates stacking patterns and the spatial predictability of sand bodies within the HST, whereas hydrodynamics affects particle size and depositional energy [16],[14].

Grain Size, Hydraulic Parameters, and Bedforms as Stratigraphic Proxies

Grain-size distributions, hydraulic parameters, and bedform geometries constitute fundamental quantitative proxies for reconstructing paleohydrodynamic conditions and interpreting stratigraphic architecture. In response to variations in flow depth, velocity, shear stress, sediment supply, and accommodation, preserved sedimentary structures and textural characteristics systematically differ across sequence stratigraphic surfaces and systems tracts [18],[17]. As a result, these characteristics offer a clear physical connection between stratigraphic patterns and depositional processes. Transgressive systems tracts (TST) and maximum flooding surface (MFS) intervals are frequently linked to fine-grained sediments, low-angle stratification, and small-scale bedforms like ripples and climbing ripples. These characteristics reflect low-energy flow regimes, reduced sediment transport capacity, and increased accommodation, frequently accompanied by sediment starvation and condensed deposition under rising base level.

Paleohydrodynamic reconstructions from these intervals usually show low shear stress, diminished flow competence, and suspension-dominated transport [18],[28]. On the other hand, coarser grain-size fractions, erosional basal contacts, and bigger bedforms like dunes, antidunes, and gravel bars are characteristics of falling-stage systems tracts (FSST) and lowstand systems tracts (LST). These deposits document high-energy conditions linked to increased sediment bypass, less accommodation, and relative sea-level decline. These stratigraphic locations are characterized by elevated flow velocities, increased bed shear stress, and higher sediment transport rates deduced from bedform dimensions and grain-size parameters [17],[29]. Highstand systems tracts (HST) frequently exhibit increasing bedform scale and upward coarsening, which represent basinward progradation and gradual replenishment of the sediment supply under rather stable accommodation circumstances.

According to paleohydrodynamic indications from HST deposits, laterally continuous facies and well-developed clinoforms are supported by balanced sediment transport regimes, consistent flow depths, and sustained discharge [19],[20]. Reconstructed hydraulic parameters, including paleoflow velocity, flow depth, shear stress, and sediment transport capacity, can be explicitly linked to sequence boundaries, flooding surfaces, and systems tracts thanks to the systematic distribution of grain size and bedform dimensions across stratigraphic surfaces. By rooting stratigraphic design in physically measurable flow dynamics, this integration improves predictive stratigraphic models and lessens interpretive ambiguity, strengthening the process–response underpinning of sequence stratigraphy [21].

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Figure 3 depicts an integrated modelling workflow for quantitative paleohydrodynamic modelling and sequence stratigraphic framework.

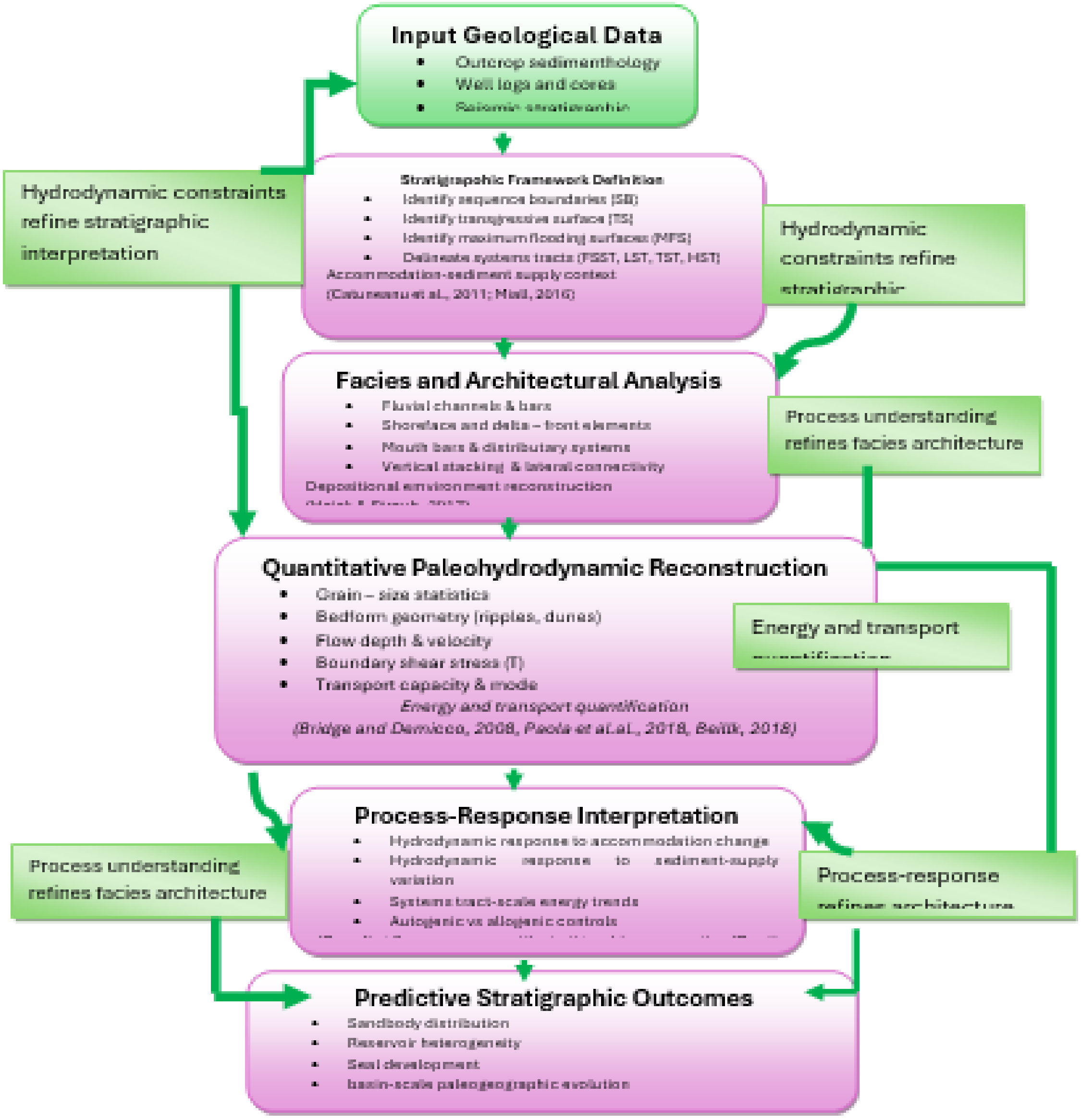

Figure 3. Integrated modelling workflow for quantitative paleohydrodynamic modelling and sequence stratigraphic framework after [18] *and* [19].

PRINCIPLES OF SEQUENCE STRATIGRAPHY AND PALEOHYDRODYNAMICS

Sedimentary successions are arranged into genetically related strata packages using sequence stratigraphy (SS), a stratigraphic methodology that is bounded by regionally significant stratigraphic surfaces like flooding surfaces, maximum flooding surfaces, and sequence boundaries [30],[16]. These surfaces provide a basin-wide historical framework for evaluating depositional systems by documenting changes in accommodation, sediment supply, tectonics, and relative sea-level oscillations.

The fundamental idea of sequence stratigraphy is the methodical evaluation of genetically linked facies in the context of such chronostratigraphically significant surfaces [31]. A sedimentary facies is a body of rock that reflects depositional processes and environments and is distinguished by a unique combination of lithology, sedimentary structures, geometry, fossil content, and paleocurrent characteristics [32].

Sequence stratigraphy and paleohydrodynamic reconstruction both rely on facies analysis as their primary observational foundation. To reconstruct depositional gradients and system evolution, vertical facies successions inside conformable stratigraphic packages are employed to infer coeval lateral facies relationships across depositional surfaces [14]. Vertical stacking patterns show systematic changes in hydrodynamic conditions, sediment supply, and accommodation when facies transitions occur gradually.

The quantitative reconstruction of historical flow conditions and sediment transport mechanisms that cause sediment deposition is the main goal of paleohydrodynamics. To estimate parameters like paleoflow velocity, discharge, shear stress, flow depth, and sediment transport capacity, it uses sedimentary structures, grain-size distributions, bedform geometry, paleocurrent data, hydraulic geometry relationships, and sediment transport equations [33],[28],[14]. These quantitative limitations offer process-based confirmation for reconstructions of the depositional environment and facies interpretations.

Paleohydrodynamic analysis is assessed within a strong temporal and stratigraphic context when combined with sequence stratigraphy. While paleohydrodynamics measures the flow regimes and transport mechanisms functioning inside certain system tracts, sequence stratigraphy limits the chronology, spatial extent, and stacking patterns of depositional systems. Depositional sequence interpretation, system tract architecture, sediment dispersal paths, and reservoir heterogeneity are all improved by this combination. Additionally, it reduces interpretive ambiguity by enabling the testing of sequence stratigraphic models against physically feasible flow circumstances.

In general, a complementary and predictive framework for reconstructing depositional processes, basin evolution, and stratigraphic architecture in clastic sedimentary systems is provided by the combined concepts of sequence stratigraphy and paleohydrodynamics. For complicated basins like the Anambra Basin, where fluvial–deltaic–shallow marine interactions are heavily influenced by shifting hydrodynamics and accommodation throughout time, this integrated approach is especially beneficial. Table 2 shows the principles of sequence stratigraphy and paleohydrodynamics, while Figure 4 is a Predictive tool for linking flow processes, stratigraphic position and reservoir–seal relationships in the Anambra Basin.

Table 2. *Principles of sequence stratigraphy and paleohydrodynamics*

Section	***Concept/Element***	***Description / Key Characteristics***	***Key references***
1	Accommodation Space (AS)	The space available for sediment accumulation at a given time, controlled by relative sea level, subsidence, and sediment supply. Water depth represents the vertical distance between the sediment surface and the base level. From a paleohydrodynamic perspective, AS directly controls flow depth, flow velocity, shear stress distribution, and sediment transport capacity, thereby governing vertical stacking patterns, bedform development, and facies architecture	[16],[34],[21],[33],[28]

2	Geometric analysis of depositional sequences	Framework for evaluating depositional architecture using unconformities, sequence boundaries, systems tracts, parasequences, and sequence models. Paleohydrodynamic conditions (energy regime, discharge variability, flow confinement) influence stratal geometries, clinoform development, and facies observed within these geometric elements.	[16],[35],[21],[14]
2(a)	Unconformities	Surfaces representing non-deposition or erosion separating older from younger strata. Paleohydrodynamically, unconformities often reflect high-energy flow conditions, increased shear stress, sediment bypass, or subaerial exposure leading to erosion. They are fundamental to basin analysis using seismic, well, and outcrop data.	[16],[14],[36],[28]
2(b)	Relationship of sequence boundaries to strata	Seismic sequences are relatively conformable packages of genetically related reflections bounded by discontinuities identified by onlap, downlap, toplap, and truncation. These reflection terminations correspond to changes in sediment flux, flow regime, and depositional energy linked to base-level fluctuations.	[16],[34],[33]
2(c)	Sequences	Depositional sequences are relatively conformable successions bounded by subaerial unconformities and their correlative conformities. Paleohydrodynamic processes control internal facies distribution by regulating flow strength, sediment calibre, and transport mechanisms through time.	[16],[14],[28]
2d	Parasequences (PS)	Relatively conformable, genetically related bed sets bounded by marine flooding surfaces. Typically display upward-shallowing cycles. Paleohydrodynamic indicators include systematic grain-size trends, bedform transitions, and vertical changes in flow regime reflecting gradual shifts in accommodation and energy conditions.	[16],[36],[32],[33]
2e	Lowstand systems tract (LST)	Deposits formed after relative sea-level fall and during early rise, including valley fills, basin-floor fans, and lowstand wedges. Characterized by increased sediment bypass, higher flow velocities, and enhanced sediment transport efficiency due to reduced accommodation.	[16],[14],[37],[38]
2f	Transgressive systems tract (TST)	Sediments deposited during shoreline landward migration from transgression onset to maximum flooding. Paleohydrodynamics reflects decreasing flow energy, sediment starvation, reduced transport capacity, and dominance of finer-grained deposition under rising accommodation.	[16],[34],[28]
2g	Highstand Systems Tract (HST)	Progradational to aggradational deposits formed when sediment supply exceeds accommodation creation. Hydrodynamic conditions are relatively stable, with sustained discharge, predictable sediment transport pathways, and well-developed clinoforms.	[16],[14],[37],[39]
2h	Falling stage systems tract (FSST)	Deposits formed during relative sea-level fall following regression onset. Paleohydrodynamics is dominated by forced regression, flow acceleration, erosion, and	[16],[33],[28]

		sediment bypasses, commonly producing sharp-based shoreface and shelf-edge deposits.	
3	Sequence Boundary (SB)	A composite surface consisting of a subaerial unconformity updip and correlative conformity downdip. Represents basinward facies shift driven by forced regression and hydrodynamic reorganization beyond Walther's Law.	[39],[4],[14]
3a	Basal Surface of forced regression BSFR	Surface marking the onset of forced regression and formation of marine sediment wedges. Paleohydrodynamically associated with increasing flow competence and sediment export basinward.	[16],[14]
3b	Regressive Surface of Marine Erosion	Diachronous erosional surface formed on the inner shelf during base-level fall. Typically reflects short-lived high-energy marine reworking rather than prolonged subaerial exposure.	[16],[34],[33]
3c	Maximum Regressive surface (MRS)	Diastemic surface marking the transition from regression to transgression. Paleohydrodynamic indicators include a shift from high-energy, coarse-grained transport to lower-energy, finer-grained sedimentation.	[16],[36],[32]
3d	Maximum Flooding Surface (MFS)	Surface separating TST from HST and marking deepest water conditions. Represents minimum sediment flux and lowest energy depositional conditions, often associated with condensed sections.	[16],[14],[34],[28]
3e	Transgressive Surface (TS)	Major flooding surface capping the LST. Represents rapid base-level rise, reduced flow competence, and landward shift of depositional systems.	[16],[34],[33]

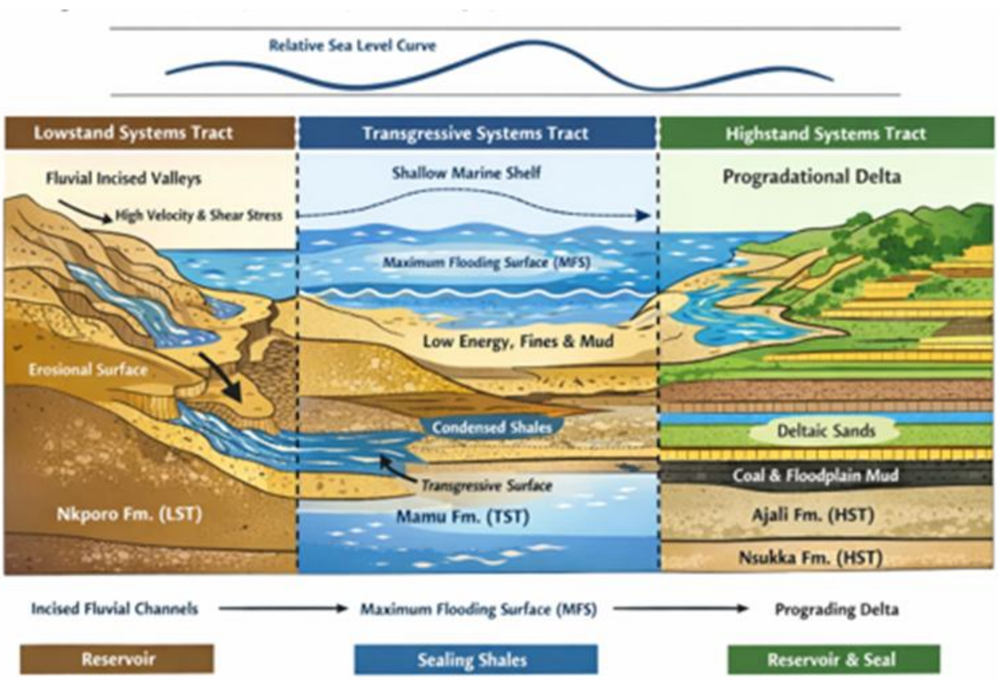

Figure 4. *Predictive tool for linking flow processes, stratigraphic position and reservoir–seal relationships in the Anambra Basin modified after Miall* [13].

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Overview of the Niger Delta and Anambra Basin

The Anambra Basin (Figure 5) is a syn-sedimentary basin that trends to NE-SW and was created during the Late Cretaceous because of the tectonic evolution of the Benue Trough [1]. Later, it functioned as the growing Niger Delta depocenter's northern staging area. It later served as the northern staging area for the expanding Niger Delta depocentre.

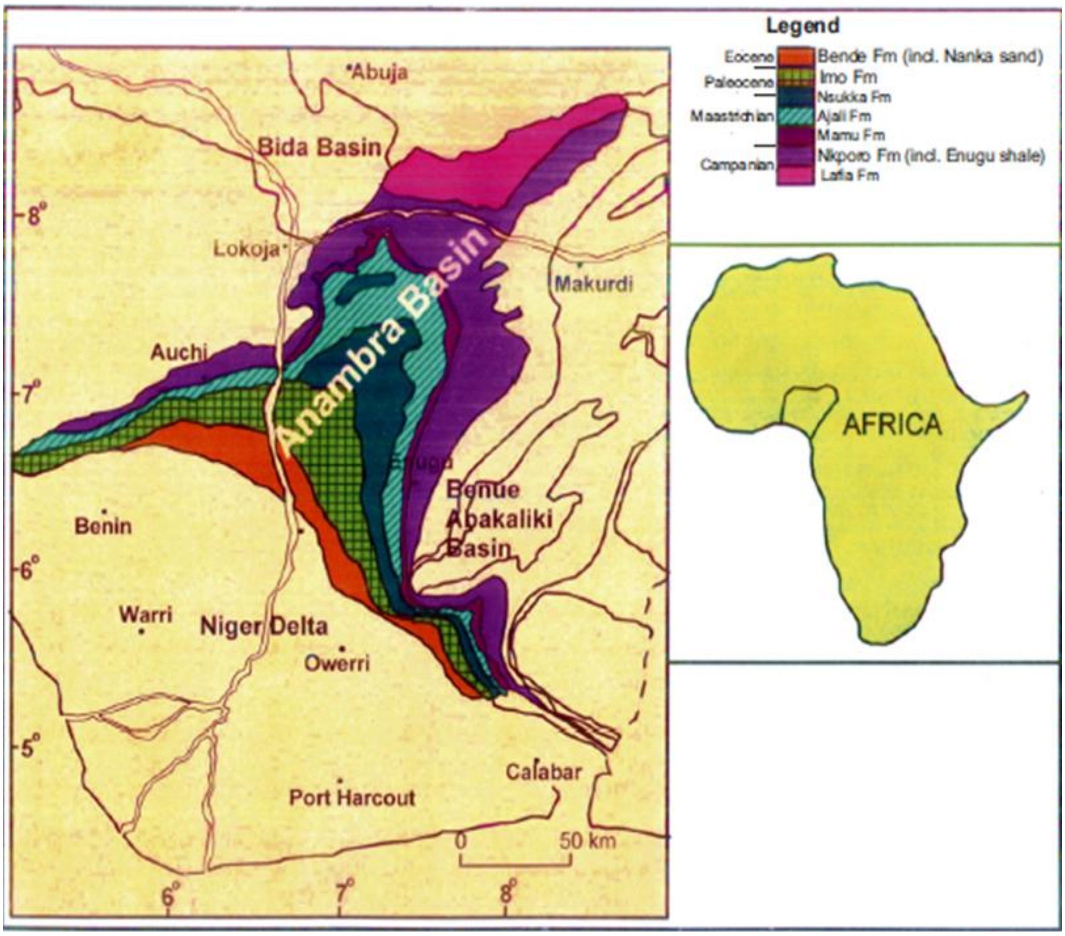

Figure 5. *Geologic map of Anambra Basin showing the various lithostratigraphic units* [52].

Regional Stratigraphic Setting

Though the stratigraphic succession of the Anambra Basin has been described by several authors [40],[41],[42], the first detailed study of the stratigraphy of Southern Nigerian Sedimentary Basin was carried out by Reyment [43] and he proposed many of the lithstratigraphic units in the region. According to Onyekuru and Iwuagu [44], sediment deposition in the Anambra Basin started in the Campanian with a short marine transgression followed by a regression. Basically, the Anambra is a Cretaceous depocentre that received Campanian to Tertiary sediments [1],[45]. The Anambra Basin contains about 6km thick Cretaceous/Tertiary sediments and is the structural link between the Cretaceous Benue Trough and the Tertiary Niger Delta [46]. The sedimentological and stratigraphic settings (Figure 6) of the sediments within the Anambra Basin are defined by three main evolutionary stages [47],[48],[49],[50]. The first two cycles belong to the Pre-Santonian sediments while the third cycle belongs to Post Santonian sediments [1].

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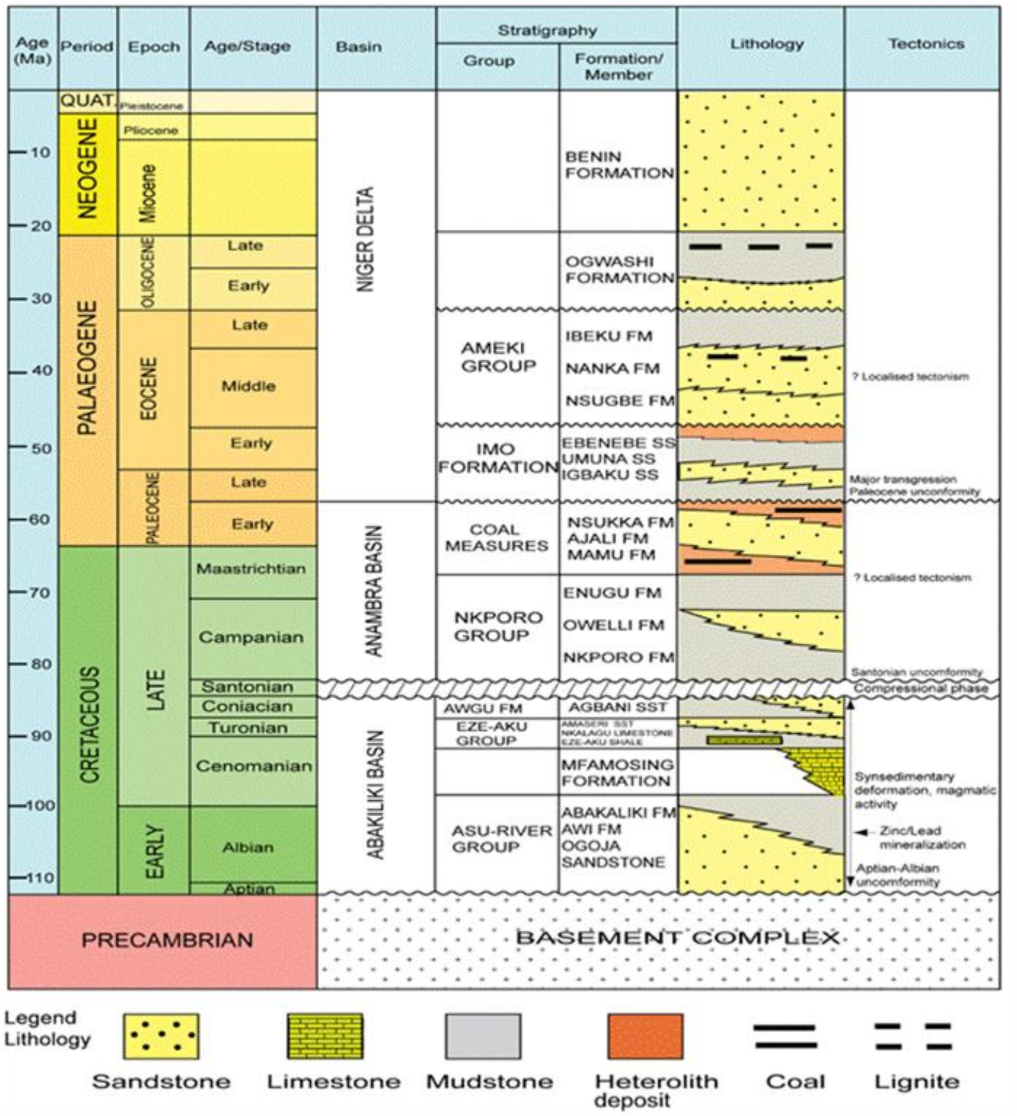

***Figure 6.** Stratigraphic succession in the Anambra Basin and outcropping Niger Delta after* [30].

- ✓ First Phase: The first phase which has also been called the Abakaliki-Benue phase by Olubayo [47], defines Pre-Santonian history (Aptian-Santonian), characterized by a strong subsidence in the Abakaliki domain of the Benue Trough, while the Anambra domain remained a platform where mud was deposited in a restricted marine environment [49]. The more than 3000m of rocks comprising the Asu River Group and the Eze-Aku and Awgu formations, were deposited during this first phase in the Abakaliki-Benue Basin, the Benue Valley and the Calabar Flank [49]. It has also been reported by Ehinola [48], that the Asu River Group is a lateral equivalent of the Bima Sandstones in the Upper Benue Trough, and Awe/Arufu/Uomba Formations in the Middle Benue Trough.
- ✓ Second Phase: The second phase, which is also referred to as the Anambra- Benin Phase (Campanian-Mid Eocene), was characterized by compressive movements along the NW-SW axis, which resulted in the folding and uplift of the Trough into an

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Anticlinorium. This forced the Anambra Platform to subside and the depocentre to shift south-westwards to the newly formed Anambra Basin and the Afikpo Syncline in the southeast [50], characterized by a shallow marine system. The resulting succession comprises the Nkporo Group, Mamu Formation (Lower Coal Measures). The Mamu formation is overlain by the continental beds of the Ajali Sandstone (False bedded sandstone), followed by a return to partially paralic conditions and the deposition of the Nsukka Formation (Upper Coal Measures) [44], The Imo Shale (Paleocene) overlies the Nsukka Formation, while the Eocene stage was characterized by regressive phase that led to the deposition of Ameki Group [51].

- ✓ Last Phase: The third phase (also called the Niger Delta phase) credited for the Formation of the Petroliferous Niger Delta commenced in the Late Eocene because of a major earth movement that structurally inverted the Abakaliki region [47]. This structural inversion further shifted the depocenter downdip (southwards) to form the Niger Delta Basin [51].

APPLICATION TO THE LATE CRETACEOUS ANAMBRA BASIN

The Nkporo–Mamu–Ajali–Nsukka succession records cyclic connection between hydrodynamic energy and accommodation change. Sand-rich channel fills were produced by lowstand incision and high-energy fluvial systems; regionally widespread shale markers linked to hydrodynamic minima were produced by transgression phases; and laterally continuous but stratigraphically ordered sand bodies were formed by highstand progradation. Therefore, incorporating quantitative paleohydrodynamic parameters into the sequence stratigraphic framework offers a predictive reconstruction of basin history, reservoir quality, and depositional architecture that outperforms qualitative facies-based models.

Systems-Tract–Scale Integration for the Anambra Basin Formations

This section links stratigraphic position with quantitative paleohydrodynamic characteristics by explicitly mapping the Nkporo–Mamu–Ajali–Nsukka formations onto systems tracts.

- ✓ Nkporo Formation (Late Campanian)

Transgressive Systems Tract (TST), which ends at the Maximum Flooding Surface (MFS), is the dominant systems tract.

Hydrodynamic regime: decreased shear stress, low to extremely low flow velocities Minimal bedload transit, fine-grained sediment flux, and the predominance of suspension settling with episodic storm reworking

Stratigraphic expression: Condensed portions indicate maximal accommodation; regionally widespread shales with fine sands beneath them.

Integrated interpretation: A basin-wide hydrodynamic minimum coincidence with maximum accommodation is recorded in the Nkporo Formation. Their proximity to the MFS is consistent with quantitative paleohydrodynamic indicators (fine particle size, lack of massive bedforms), making it an important regional correlation marker and useful seal unit.

- ✓ Mamu Formation (Early Mid Maastrichtian)

Dominant systems tract: Late TST transitioning into early Highstand Systems Tract (HST)

Hydrodynamic regime: Low to moderate flow velocities with high spatial variability, Alternation between suspension settling and low-energy bedload transport, Periodic tidal and fluvial influence causing varying shear stress.

Stratigraphic expression: Retrogradational to weakly aggradational stacking of interbedded sandstones, shales, siltstones, and coal seams.

Integrated interpretation: Increasing sediment supply under growing accommodation is shown in the Mamu Formation. Sequence stratigraphy limits their temporal organization within the transgressive, early highstand era, but quantitative hydrodynamic fluctuations explain rhythmic sand–mud alternations and coal formation.

- ✓ Ajali Sandstone (Mid–Late Maastrichtian)

Dominant systems tract: Highstand Systems Tract (HST), locally extending into Falling Stage Systems Tract (FSST)

Hydrodynamic regime: mostly bedload transport with huge dune and cross-bedded designs; moderate to high flow velocities; elevated shear stress surpassing critical Shields values for sand transport.

Stratigraphic expression: high net-to-gross ratios, progradational stacking patterns, and thick, laterally widespread cross-bedded sandstones.

Integrated interpretation: Under persistent hydrodynamic energy, the Ajali Sandstone represents the maximal sediment supply. Grain size, bedform scale, and reservoir quality are explained by paleohydrodynamic estimates, while lateral continuity and predictable stacking are explained by its HST position.

- ✓ Nsukka Formation (Latest Maastrichtian–Paleocene)

Dominant systems tract: Late HST to renewed Transgressive Systems Tract (TST)

Hydrodynamic regime: Transport competency was lower than that of Ajali Sandstone due to decreasing flow velocities, decreased shear stress, higher suspension fallout, and sporadic low-energy fluvial intrusions.

Sandstones, shales, and coal seams alternate in stratigraphic expression; aggradational to retrogradational stacking

Integrated interpretation: Waning hydrodynamic energy associated with fresh accommodation creation is recorded in the Nsukka Formation. Sequence stratigraphy situates these deposits in a late highstand–transgressive setting, while quantitative flow decrease explains coal development and finer grain sizes.

- ✓ Basin-Scale Synthesis

Systematic variation in paleohydrodynamic energy is highly correlated with systems-tract evolution throughout the Anambra Basin. Low-energy, mud-dominated successions are typical of transgression phases, while high-energy, sand-dominated deposits are more common in lowstand and highstand environments. The distribution of reservoirs, seal development, and basin dynamics can all be predicted using this integrated approach. Table 2 shows the review of previous work.

Table 2. *Review of previous work*

S/N	*Study Focus*	*Key Contributions*	*Relevance to Current Study*	*Authors/year*
1	Sedimentology and facies analysis	Detailed descriptions of sedimentary facies, coal cycles, estuarine and deltaic deposits within the Anambra Basin	Provides foundational understanding of depositional environments and lithofacies architecture	[1]

2	Paleogeography and tectonic evolution	Recontruction of basin evolution, tectonic setting, and regional paleogeography of southeastern Nigeria	Establishes tectonic controls influencing sediment supply, accommodation, and basin development	[2],[53],[54]
3	Sequence stratigraphy frameworks	Development of qualitative sequence stratigratigraphic interpretations across Nigerian Sedimentary basins	Offers stratigraphic context but lacks quantitative flow and sediment transport contraints	[55],[56],[57]
4	Hydraulic and fluvial system analysis	Estimation of hydraulic parameters and sediment dispersal patterns in west African fluvial systems	Provides regional hydrodynamic analogs interpretations	[58]
5	Forward stratigraphic modelling	Use of numerical and forward models to simulate clastic shelf evolution and stratigraphic architecture	Supplies modeling approaches applicable to reconstructing sedimentary basin fill	[59]
6	Paleoenvironmental and provenance study of Ajali Sandstone in Igbere area, Afikpo Basin	Integrated sedimentological and Provenance analysis (framework Composition, texture, depositional processes) of Ajali Sandstone in Igbere Area	Provides lateral equivalent and provenance analogs to Anambra Basin Ajali Sandstone	[3]
7	Sedimentologic and petrographic analysis (Ajali Sands)	Petrographic and sedimentological characterization of Ajali Sandstone Outcrops, including grain composition, texture, maturity, and diagenetic features	Establishes sandstone provenance, reservoir quality, and depositional texture controls	[60]
8	Paleoenvironmental and paleohydrodynamic reconstruction of Maastrichtian Ajali Sanstone sediments	Reconstruction of depositional environments of the Maastrichtian Ajali Sandstone using sedimentary structures, grain size trends, and facies associations and the estimation of Discharge capacity, paleoflow directions, and relative energy conditions controlling sediment dispersal in the Ajali Sandstone	Establishes environmental setting (fluvial-deltaic to shallow marine) for paleo-flow analysis and Provides foundation for basin-specific paleo-hydrodynamic reconstruction	[7]

GAPS FOR FURTHER RESEARCH

To comprehend depositional processes, reservoir architecture, and basin evolution, there is still a significant gap in the integration of quantitative paleohydrodynamic reconstruction techniques with sequence stratigraphic frameworks, despite the Anambra Basin's extensive sedimentological and stratigraphic studies.

- ✓ Limited Quantitative Paleohydrodynamic Research: In the Anambra Basin, most of the current research concentrates on qualitative interpretations of depositional settings using textural descriptions and sedimentary facies (e.g., sandstone geometry, facies relationships). Nevertheless, there are still few quantitative reconstructions of palaeoflow characteristics as flow velocity, water depth, shear stress, and transport competence. Although it has not been fully incorporated into basin scale models, quantitative paleohydrodynamic analysis (using techniques like grain-size based estimates, hydraulic equations, and paleocurrent data) offers vital constraints on energy conditions that control sediment distribution and reservoir quality.

- ✓ Under-utilization of Integrated Sequence Stratigraphy: The Anambra Basin has mainly used sequence stratigraphy for correlation and interpretation of important surfaces, such as maximum flooding surfaces and sequence boundaries. Sequence stratigraphic frameworks define stacking patterns and systems tracts, but they are not well integrated with hydrodynamic indicators to quantitatively understand lateral and vertical facies alterations. This hinders a thorough comprehension of how reservoir heterogeneity and sediment transport processes were impacted by basin dynamics and relative sea-level fluctuations.
- ✓ Disconnect Between Depositional Dynamics and Reservoir Prediction: When predicting the distribution, continuity, and quality of reservoirs, the stratigraphic models of the basin frequently neglect to include quantitative flow and energy characteristics. The distribution, connectedness, and heterogeneity of reservoir sandbodies cannot be predicted without connecting paleoflow reconstructions to sequence stratigraphic architecture. Accurate depositional models are crucial for petroleum exploration, groundwater investigations, and CO2 storage potential evaluation.
- ✓ Lack of Integrated Predictive Models: For basin-scale interpretation, integrated predictive models that integrate sequence stratigraphic surfaces with paleo-hydrodynamic constraints are lacking. Predictions of facies distribution, reservoir fairway identification, and stratigraphic trap evaluation can all be enhanced by such integrated models. These models are yet unexplored in the context of the Anambra Basin, while being essential for defining the timing and controls of sedimentation during basin evolution.
- ✓ Regional Applicability and Comparison: In other basins (such as the Niger Delta and offshore basins), comparative studies combining quantitative paleo-hydrodynamics and sequence stratigraphy have shown enhanced reservoir characterization and depositional knowledge. There is a gap in methodology transfer and regional stratigraphic synthesis, nevertheless, because comparable integrated methodologies have not been methodically applied to the Anambra Basin.

To improve depositional models, improve reservoir prediction, and improve interpretations of basin evolution, this project aims to close these gaps by creating an integrated quantitative paleo-hydrodynamic and sequence stratigraphic framework for the Anambra Basin.

CONCLUSIONS

From the review study titled “Quantitative paleohydrodynamic modelling and sequence stratigraphic framework for the Late Cretaceous clastic systems of the Anambra Basin”, the following conclusions can be drawn:

(1) The Late Cretaceous Anambra Basin's depositional evolution can be fully understood by combining quantitative paleo-hydrodynamic reconstruction with sequence stratigraphy. Paleohydrodynamic analysis constrains important flow parameters like water depth, flow velocity, shear stress, and sediment transport mechanisms, enabling detailed reconstruction of ancient fluvial, deltaic, and shallow marine systems.

(2) Sequence stratigraphy complements this by organizing sediments into a temporal and genetic framework, identifying sequence boundaries, systems tracts, and important flooding surfaces that contextualize depositional processes within sea-level and tectonic cycles.
(3) By connecting hydrodynamic energy conditions with stratigraphic architecture, the integration of both methods lowers interpretational uncertainty and allows for more precise prediction of reservoir heterogeneity and facies distribution.
(4) The method offers improved basin evolution models, providing insights into sediment routing, basin-fill history, and the interaction of tectonics, climate, and relative sea-level changes in controlling depositional systems.
(5) This combined framework is critical for reservoir characterization, improving predictions of sandbody distribution, seal continuity, and stratigraphic trap locations, which are essential for hydrocarbon exploration, groundwater management, and CO_2 storage planning.
(6) The approach provides enhanced basin evolution models, offering insights into sediment routing, basin-fill history, and the interplay of tectonics, climate, and relative sea-level change in controlling depositional systems.

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