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Analyzing sedimentary rocks to determine hydrodynamic conditions of Anambra basin, South-Eastern Nigeria

Christian Agbo[a*], Samuel Okechukwu Onyekuru[a], Diugo Okereke Ikoro[a], Timothy Chibuike Anyanwu[a]

[a] Department of Geology, School of Physical Sciences, Federal University of Technology, Owerri, Imo State, Nigeria

A B S T R A C T

The Anambra Basin in southeastern Nigeria is a notable sedimentary basin with a complex geological history shaped by marine, fluvial, and deltaic processes. This study examines the sedimentary rock formations within the basin, focusing on the Nkporo, Mamu, Ajali, and Nsukka Formations. The main goal is to reconstruct past hydrodynamic conditions and sediment transport mechanisms that influenced sediment deposition. Using a combination of field observations and quantitative methods, we estimated key paleohydrodynamic parameters such as channel depth, bedform height, sediment transport modes, and flow velocities. Analyzing these parameters provides insights into the ancient environmental conditions during deposition. Our findings reveal diverse depositional environments in the Anambra Basin. The Nsukka Formation is linked to transitional flow conditions with moderate sediment suspension, indicating a balance between transport and settling. In contrast, the Ajali Formation reflects a stable environment dominated by bed load transport, suggesting consistent flow. The Mamu Formation indicates dynamic and turbulent flow conditions that facilitated both bed load and suspended sediment transport. Additionally, the Owelli Sandstone Formation shows transitional flow characteristics typical of coastal or shallow marine environments influenced by both marine and continental processes. This study enhances our understanding of sedimentary processes in the Anambra Basin and lays a foundation for future research on its geological history and sedimentary dynamics.

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*Corresponding author
E-mail address:
cc.agbo@mouau.edu.ng
(C. Agbo)

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1. Introduction

The analysis of sedimentary rocks to determine paleohydrodynamic conditions provides invaluable insights into the geological history and sedimentary processes of a given region. Understanding these conditions is critical in regions like the Anambra Basin in southeastern Nigeria, where sedimentary sequences contain clues about the ancient environmental and depositional processes that shaped the basin. This study is essential for multiple reasons, including its potential applications in petroleum geology, where knowledge of ancient depositional environments helps to assess reservoir quality and hydrocarbon potential (Jolayem et al., 2023).

Furthermore, the evaluation of hydrodynamic conditions contributes to the broader field of sedimentology by offering a detailed reconstruction of ancient river systems and the transport mechanisms that influenced sediment deposition. These findings, in turn, can be applied to similar geological settings globally (Nichols, 2018; Erepamo et al., 2024). Sediment transport dynamics are largely governed by the flow characteristics of the transporting medium, such as water or air, and these dynamics are crucial to interpreting past depositional environments. Key hydrodynamic parameters, including flow depth, bedform height, and sediment settling velocity, offer insights into the energy regimes of ancient environments. For instance, higher flow depths typically indicate more energetic conditions, where faster-moving water was capable of transporting larger sediment particles, while lower flow depths reflect quieter depositional settings (Bridge and Demicco, 2008). The sedimentary structures preserved in rock formations, such as cross-bedding, ripple marks, and grain-size distributions, also provide evidence of the flow regime, bedload transport, and suspension processes that occurred during deposition (Miall, 2018; Nichols, 2018). These theoretical foundations underlie the analysis of sedimentary records and help to interpret the paleohydrodynamic conditions that shaped formations like the Nkporo, Mamu, Ajali, and Nsukka within the Anambra Basin.

In the context of the Anambra Basin, this study applies these theoretical concepts to the sedimentary rock formations within the basin to reconstruct ancient flow conditions. Field studies, including measurements of bedform heights, channel depth, and grain-size distributions, were combined with quantitative analyses to estimate flow velocities and sediment transport dynamics (Reijers, 1996). The paleohydrodynamic conditions observed in formations like the Ajali Sandstone and Mamu Formation reflect varying depositional environments, ranging from high-energy fluvial systems to lower-energy coastal or deltaic settings. This variability in depositional environments is key to understanding the basin's geological evolution, as well as its potential as a hydrocarbon reservoir (Adeyemi et al., 2023). By analyzing these formations, this research contributes to a clearer understanding of how sedimentary processes and hydrodynamic conditions evolved over time, helping to piece together the basin's depositional history.

The importance of analyzing hydrodynamic conditions extends beyond academic interest. In regions like the Anambra Basin, sedimentological studies have direct implications for natural resource exploration, particularly in the oil and gas industry (Erepamo et al., 2024). The ability to reconstruct the conditions under which sedimentary layers were deposited provides clues to the location and quality of potential hydrocarbon reservoirs. For instance, the Nkporo Formation, known for its potential as a source rock, and the Ajali Sandstone, recognized for its reservoir potential, are directly influenced by the flow regimes that dominated during their deposition. This study, therefore, not only enhances our understanding of sediment transport and depositional environments but also informs practical applications in resource management and exploration (Jolayem et al., 2023; Erepamo et al., 2024).

This research investigates the sedimentary formations of the Anambra Basin with the goal of reconstructing paleohydrodynamic conditions that influenced sediment transport and deposition. By examining key formations such as the Owelli, Mamu, Ajali, and Nsukka Formations, the study aims to provide a detailed understanding of the depositional environments that shaped the basin's sedimentary architecture. Theoretical foundations, such as flow dynamics, sediment transport, and bedform development, underpin the analysis, while field observations and quantitative methods provide concrete data on past flow conditions. Ultimately, this research not only advances the field of sedimentology but also offers valuable insights into the geological history and hydrocarbon potential of the Anambra Basin (Reijers, 1996; Nichols, 2018; Miall, 2018).

2. Material and Methods

2.1. The Study Area

The study area extends between latitudes 6°30' to 7°00' N and longitudes 6°40' to 7°30' E in southeastern Nigeria, covering a significant portion of the Anambra Basin (Fig. 1). The sampling locations are separated by approximately 1 km intervals. The Anambra Basin is bounded by the Abakaliki Fold Belt to the east and the Niger Delta Basin to the south, making it a key feature of Nigeria’s sedimentary basins. The basin is primarily composed of Cretaceous to Tertiary sediments, including formations such as the Nkporo Shale, Mamu Formation, Ajali Sandstone, and Nsukka Formation. These formations reveal a diverse geological history shaped by marine, fluvial, and deltaic depositional environments, with sediment types ranging from sandstones and shales to coal beds and limestone layers.

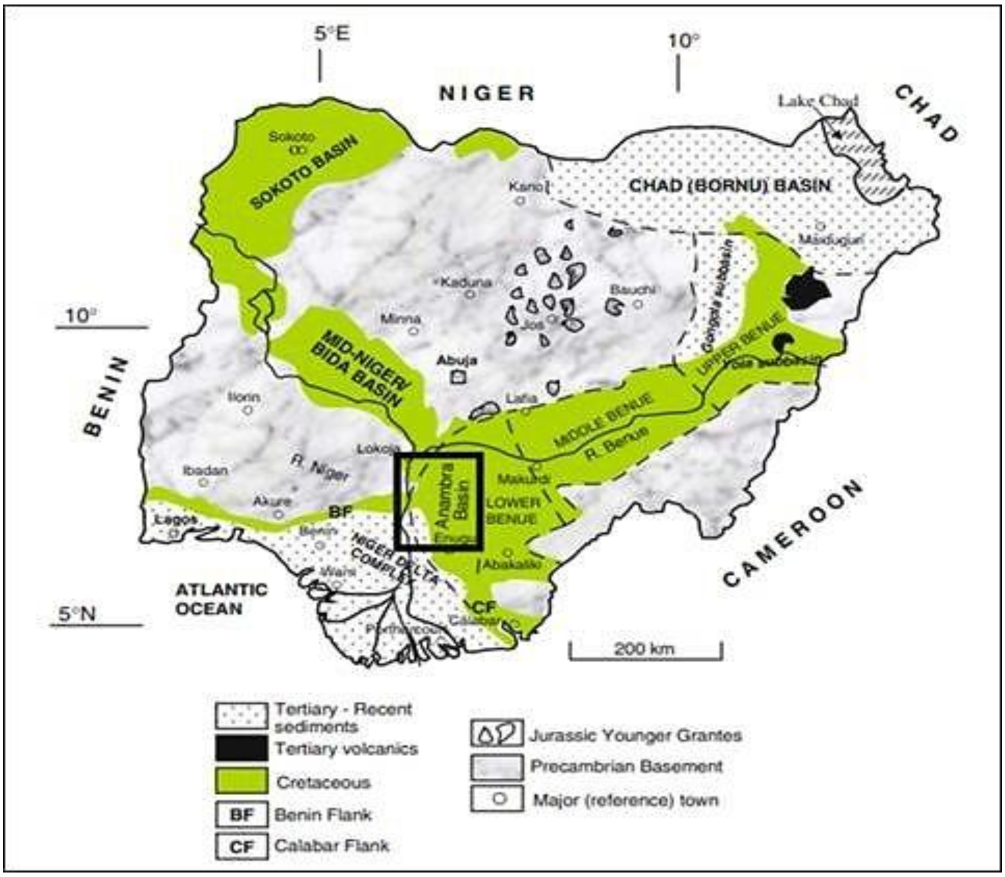

Fig. 1. Geologic map of Nigeria showing the location of Anambra basin (Inset Africa Map, Modified after NGSA, 2001).

2.2. Field Observations and Data Collection

Sedimentological data were collected from eight locations (Table 1), each featuring vertical sections ranging from 5 to 10 meters, primarily observed along road-cut exposures across the eight study areas. Choosing eight strategically distributed locations within the Anambra Basin for study is essential for ensuring a comprehensive representation of its diverse geological formations and sedimentary characteristics. These locations (Umuasua, Akara Junction, ABSU-Uturu Road, Onyekaba Mine, Ohofia, Ihube, Agbaogugu, and Ikpankwu Ihube – table 1) encompass key formations like Nsukka, Ajali, Mamu, and Owelli, allowing for an in-depth analysis of various hydrodynamic conditions and sediment transport dynamics (Didei & Ajaegwu, 2024; Jolayem et al., 2023). This selection facilitates thorough field observations and statistical analyses while also capturing the temporal and spatial variability in sedimentary processes across the basin (Reijers, 1996; Erepamo et al., 2024). Ultimately, the strategic choice of these eight locations not only supports robust research findings but also enhances the potential for collaboration and comparative studies in the region. Fig. 2 shows the accessibility map of the study area.

At each outcrop, multiple measurements were taken, including set thickness, average grain size, and total thickness. Cross-bed set thicknesses (Fig. 3) were specifically measured using a 30 cm scale. The cross-bedding sets in the study area were interpreted predominantly as dunes based on several observations: the cross-bedding sets exhibit truncation, the paleocurrent directions display significantly less variability than typically seen in bar formations, even when bars are present within the data, they generally consist of numerous layers of truncated dunes, all observed ripples on the outcrops flowed in the same direction as the cross-bedding sets, rather than in divergent directions. To ensure thoroughness, each outcrop was meticulously examined, and data were systematically recorded to provide a comprehensive understanding of the sedimentological characteristics and depositional environments of the study area.

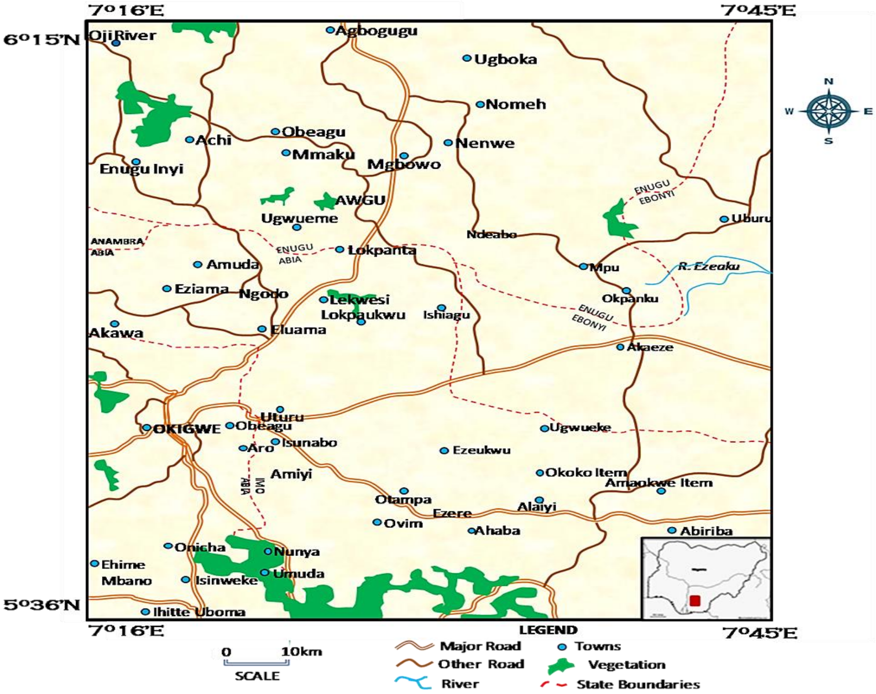

Fig. 2. Accessibility map of the study area (map of Nigeria inset)

Table 1. The Coordinates of Outcrop Locations of the Study Area.

Location Number	Location Name	Longitudes	Latitudes	Probable Formation
1	Umuasua, Isukwato	7.5006	5.7207	Nsukka
2	Akara Junction	7.4590	5.8073	Nsukka
3	ABSU-Uturu Road	7.3938	5.8281	Ajali
4	Onyekaba Mine	7.35817	5.80436	Ajali
5	Ohofia	7.83024	5.64625	Mamu
6	Ihube	7.37264	5.85627	Mamu
7	Agbaogugu	7.47079	6.2558	Owelli
8	Ikpankwu Ihube	7.26632	4.95264	Owelli

Fig. 3. (A) planar crossbeds showing the direction of apparent movement at location. (B) well-spaced planar cross-stratification at location 5 they points towards the southeast, further emphasizing the direction of the dip. (C) indicates the herringbone cross-stratification at location 6, (D) distorted crossbeds at the lower part of location 1.

2.3. Cross-Set Measurements and Grain Size Analysis

Cross-set heights were measured to reconstruct the original bedform heights and formative flow depths. Both trough and planar cross-bedding, indicative of bed load transport, were observed at nearly all field sites. These structures were predominantly found in sand-grade deposits but were also present in the pebble-grade deposits of Owelli Sandstones. To establish mean cross-set heights, the sampling strategy outlined by Harms et al. (1982) was followed.

Grain sizes were measured at each outcrop using a standard 10x hand lens and a grain size card. Grains were classified according to the Udden-Wentworth grain size scale. Grains within each set were generally unimodal or largely represented by a single size, facilitating the determination of the average size within cross-bedding sets. This average size was used as a proxy for D50, representing the median grain size distribution.

The sedimentological data collected from the outcrop exposures included grain size, cross-bedding height, and bar-form height. These data were subsequently used to determine multiple channel geometry, paleohydraulic parameters, and paleo-dynamics, including mean bedform height, channel depth and width, channel belt width, paleoslope, boundary shear stress, Darcy-Weisbach friction factor, paleoflow velocity, paleodrainage, and overall drainage area, following the methodologies outlined by Rubin & McCulloch (1980).

2.4. The Paleo-Channel Depth (Dc) and Bedform Height (Hm)

The paleo-channel depth (Dc) and bedform height (Hm) such as cross set thickness are crucial parameters in understanding the flow dynamics of ancient river systems. The bedform height (Hm) can be estimated from the mean cross-set thickness (Sm) using the empirical relationship given by Leclair AND Bridge (2001) (Equation 1):

$$Hm = 2.90 \times 0.70 \times Sm \qquad (1)$$

Hm is the mean dune height; Sm is the mean cross-set thickness. The mean dune height (Hm) is typically 8 to 10 times the mean cross-set thickness (Sm). The channel depth (Dc) can be estimated from the bedform height (Hm) using the empirical relationship (Equation 2):

$$Dc = 11.6 \times Hm^{0.8} \qquad (2)$$

The paleo-channel flow depth (Dc) can also be estimated from the thickness of lateral macroforms using the Equation 3:

$$Dc = D*/0.9 \qquad (3)$$

Where D∗ is the maximum channel bankfull flow depth, which is represented by the thickness of the sandstone macroform. The empirical equation above is prefereed in this work.

2.5. Paleo-Channel Slope

Paleo-channel slope (Sc) is an important parameter in reconstructing the paleoenvironmental conditions of ancient river systems. Slope affects river plan form and facies boundaries, and paleoslope can be calculated using physics-based methods or empirical equations. One empirical equation used to estimate paleoslope is (Equation 4):

$$Sc = \tau bf50\ RD50 / Dc \qquad (4)$$

Where Sc is the paleoslope, τbf50 is the bankfull Shields number for dimensionless shear stress, Dc is the mean bankfull channel flow depth, R is the submerged dimensionless density of sand-gravel sediment, ρs is the grain density, ρw is the fluid density, and D50 is the median grain size.

2.6 Boundary Shear Stress and Critical Shear Stress in Open Channels

The boundary shear stress (τb) is a critical parameter in understanding the dynamics of sediment transport and the movement of bed materials in open channels. The boundary shear stress can be calculated using the following equation (Equation 5):

$$\tau b = \rho g Dc Sc \qquad (5)$$

Where τb is the boundary shear stress, ρ is the fluid density, g is the gravitational acceleration, Dc is the averaged channel flow depth, and Sc is the averaged water-surface paleoslope. Both field and laboratory experiments have shown that the initial motion of bed materials in coarse-medium grained rivers typically occurs at a transport stage that is moderate (Smith et al., 2021). This relationship between the flow and its container can be applied to all-natural channels with some error and has been recently applied in ancient fluvial deposit (Ninke, 2002)

2.7. Critical Shear Stress

The critical shear stress (τcr) represents the necessary boundary shear to move the bed-load materials, based upon their grain size, grain shape, effective density, and roughness. For non-cohesive sand, the critical shear stress can be calculated using the equation provided by Shield (1939) as follows (Equation 6):

$$tcr = \tau*(\rho s - \rho w) \qquad (6)$$

Where τcr is the critical shear stress, τ∗ is the Shield number for the given particle, ρs is the grain density (assumed to be quartz with a density of 2650 kg/cm^3), ρw is the fluid density (1000 kg/m^3), g is the acceleration due to gravity in m/sec^2, and D50 is the median particle size in meters. Sediment mobility for a given particle size occurs when the boundary shear stress exceeds the critical shear stress, i.e. τb>τcr. This relationship has been observed in the Ajali sandstones of the present study.

2.8. Paleoflow Velocity in Open Channels

Paleoflow velocity is the velocity of the ancient sediment flows that occurred in a specific region or basin. Paleoflow velocity (Vc) is a critical parameter in understanding the dynamics of sediment transport and the movement of bed materials in open channels. Two methods are commonly used to compute the threshold mean velocity (Vc): The Manning roughness coefficient (n) and the Darcy-Weisbach friction factor (f).

Manning Roughness Coefficient:

The Manning roughness coefficient (n) is used to compute the threshold mean velocity (Vc) as follows:

$$Vc = R^{0.67}\ Sc^{\ 0.50}\ n \qquad (7)$$

Where Vc is the paleoflow velocity, R is the hydraulic radius, Sc is the channel slope, and n is the Manning roughness coefficient.

2.9. Darcy-Weisbach Friction Factor

The Darcy-Weisbach friction factor (f) is used to compute the threshold mean velocity (Vt) as follows (Equation 8):

$$Vc = (8gR(Sc/f)\ )^{\ 0.50} \qquad (8)$$

Where Vc is the paleo-flow velocity, g is the gravitational acceleration, R is the hydraulic radius, Sc is the channel slope, and f is the Darcy-Weisbach friction factor. Unlike the Manning empirical equation, the Darcy-Weisbach equation uses a dimensionless friction factor, has a sound theoretical basis, and exact accounts for the acceleration from gravity; moreover, the relative bed roughness does not influence the exponents of hydraulic radius and channel slope. For these reasons, the DarcyWeisbach equation is preferred over the Manning approach as discussed by Kleinhans (2005).

2.10. Rouse Number (Z) for Sediment Transport

The Rouse number (Z) is a non-dimensional scale parameter used to determine the dominant mode of sediment transport. It is calculated as (Equation 9):

$$Z = Ws\ /\ \beta\kappa U* \qquad (9)$$

where β is a constant (taken as 1), κ is the von Karman constant (taken as 0.40), U∗ is the boundary shear velocity, and Ws is the sediment settling velocity. Rouse Number and Sediment Transport. The Rouse number (Z) is used to determine the dominant mode of sediment transport. For Z > 2.5, the dominant mode is typically bed load, while for 1.2 < Z < 2.5, it is 50% suspended load (mixed load).

2.11. Sediment Settling Velocity

The sediment settling velocity (Ws) is calculated as a function of grain size according to Ferguson (2004) as (Equation 10):

$$Ws = Rg(D50)^2\ /\ C1v + (0.75C2Rg(D50)^3)^2 \qquad (10)$$

where g is the Earth's gravitational acceleration, D50 is the median diameter of a particle, v is the kinematic viscosity of water, v is the kinematic viscosity of water (110^{-6} for water at 20^o C and C1 = 18 and C2 = 1 are constants associated with grain sphericity and roundness.

2.12. Boundary Shear Velocity

The boundary shear velocity (U) is determined as (Equation 11):

$$U* = \sqrt{\tau b}\ /\rho w \qquad (11)$$

Where τb is the boundary shear of the fluid and ρw is the mass density of the fluid.

2.13. Reynolds Particle Number (Rep)

The Reynolds particle number (Rep) is a dimensionless number used to collaborate inferred sediment transport modes. It is calculated as (Equation 12):

$$Rep = \sqrt{RgD50}D50/v \qquad (12)$$

Where R is the hydraulic radius, g is the gravitational acceleration, D50 is the median diameter of a particle, and v is the kinematic viscosity of water.

The Reynolds Particle Number (Rep) can take on a wide range of values depending on the specific conditions of the fluid flow and the particle being studied. Here are some general ranges of values for Rep as given by Schlichting & Gersten (2000). Low Reynolds Numbers: Typically, below 10, indicating laminar flow. This range is often associated with smooth, predictable flow patterns. Transition Region: Between 10 and 2000, indicating the onset of turbulence. This range is characterized by a transition from laminar to turbulent flow. High Reynolds Numbers: Typically, above 2000, indicating fully turbulent flow. This range is often associated with chaotic and unpredictable flow patterns

2.14. Froude Number (Fr)

The Froude number (Fr) is a dimensionless parameter that describes different flow regimes in open channel flows. It is a ratio of inertial and gravitational forces. The Froude number (Fr) is a ratio of the inertial force (proportional to the square of the velocity) to the gravitational force (proportional to the depth). When the Froude number is greater than unity, the flow is supercritical, and when it is less than unity, the flow is subcritical (Chow, 2015). The Froude number (Fr) is calculated as (Equation 13):

$$Fr = gDcVc \qquad (13)$$

Where: Vc is the water flow velocity, Dc is the bank-full channel depth, g is the acceleration due to gravity (approximately half of the present during Permian times, i.e., 4.9 m/sec^2).

The range of values for the Froude number indicates the type of flow: Subcritical Flow: <1Fr<1 Gravitational forces dominate, flow is slow and tranquil. Both upstream and downstream disturbances propagate. Examples include rivers, lakes, and slow-moving streams. Critical Flow: Fr=1, Inertial and gravitational forces are balanced. Flow is unstable and often sets up standing waves. Examples include hydraulic jumps, where the flow transitions from subcritical to supercritical. Supercritical Flow: Fr>1, Inertial forces dominate. Flow is fast and rapid. Disturbances are transmitted downstream. Examples include rapids, waterfalls, and fast-moving streams.

3. Results and discussion

3.1 Quantitative Results of Paleohydrodynamic Conditions

Tables 2 and 3 present the empirical results and interpretations of paleohydrodynamic conditions derived from the sedimentary formations within the Anambra Basin. Table 2 summarizes key hydrodynamic parameters such as mean crossbed thickness, mean particle size, bedform height, flow depth, channel slope, average velocity, Manning constant, sediment settling velocity, boundary shear stress, Rouse number, Reynolds particle number, and Froude number for the Nsukka, Ajali, Mamu, and Owelli Sandstone formations. These parameters provide critical insights into the sediment transport mechanisms and flow dynamics associated with each formation. Table 3 further interprets these hydrodynamic results, detailing the flow depth, channel slope, average velocity, Rouse number, Reynolds particle number, Froude number, and the inferred transport type, flow regime, and likely environment of deposition. Together, these tables enhance our understanding of the ancient hydrodynamic conditions that shaped the sedimentary characteristics of the Anambra Basin, facilitating a more comprehensive reconstruction of its geological history. The Nsukka Formation, with a flow depth of 15.05 meters and a channel slope of 0.15, reflects depositional settings characteristic of transitional fluvial to deltaic environments. These environments typically exhibit flow depths ranging from 10 to 20 meters, and slopes between 0.1 and 0.2, conditions that promote both bedload and suspended sediment transport (Ehinola et al., 2014; Dim et al., 2016; Mode et al., 2018). The average flow velocity of 0.55 meters per second suggests a transitional flow regime, where sediment transport is influenced by both bed load and suspended sediment. According to the Rouse number of 3.85, sediment transport involves some degree of suspension, though bed load transport remains predominant (Rouse, 1937). The Reynolds particle number of 953.71 and a Froude number of 18.09 further indicate that the flow conditions are consistent with a fluvial or deltaic environment, where varying energy levels support both bed load and suspended sediment transport (Einstein, 1950; Leopold and Maddock, 1953).

Table 2. Results of paleohydrodynamic conditions based on empirical formulae.

	Mean crossbed thickness (m)	Mean particle size (D50)	Bedform height (Hm)	Flow depth (Hm)	Channel slope	Average Velocity	Manning Constant	Sediment Settling Velocity	Boundary shear stress	Rouse number	Reynolds Particle Number (Rep)	Froude Number (Fr)
Nsukka Fm.	0.47	0.75	1.36	15.05	0.15	0.55	0.04	17.37	11.28	3.85	953.71	18.22
Ajali Fm.	0.62	0.68	1.80	18.99	0.11	0.46	0.04	25.69	10.23	6.28	864.70	19.49
Mamu Fm.	0.41	0.83	1.19	13.42	0.19	0.61	0.04	11.58	12.48	2.32	1055.44	18.10
Owelli SSt	0.52	0.69	1.51	16.38	0.13	0.50	0.04	24.24	10.38	5.84	877.41	18.23

Table 3. Interpretation of hydrodynamic results based on empirical formulae

Formation	Flow depth (m)	Channel slope	Average velocity (m/s)	Rouse number (Z)	Reynolds particle number (Rep)	Froude number (Fr)	Transport type	Flow regime	Likely environment of deposition
Nsukka	15.05	0.15	0.55	3.85	953.71	18.09	Bed load transport with some suspension	Transitional	Fluvial or deltaic
Ajali	18.99	0.11	0.46	6.28	864.69	18.97	Predominantly bed load transport	Transitional	Fluvial or shallow marine
Mamu	13.42	0.19	0.61	2.33	1055.44	19.49	Bed load transport with some/incipient suspension	More turbulent	Fluvial or fluvio-deltaic
Owelli Sandstone	16.38	0.13	0.50	5.84	877.41	18.89	Predominantly bed load transport	Transitional	Coastal or shallow marine

The Ajali Formation is characterized by a greater flow depth of 18.99 meters and a channel slope of 0.11, combined with a lower average velocity of 0.46 meters per second. This suggests a transitional flow regime with predominantly bed load transport and minimal suspension (Graf, 1971). The Rouse number of 6.28 supports this observation, indicating that sediment suspension is limited (Rouse, 1937). With a Reynolds particle number of 864.69 and a Froude number of 18.97, the conditions are indicative of a fluvial or shallow marine environment where bed load transport is dominant (Chien & Wan, 1999; Knighton, 1998).

The Mamu Formation exhibits a flow depth of 13.42 meters and a channel slope of 0.19, which suggests a more turbulent environment. The higher average velocity of 0.61 meters per second, along with a Rouse number of 2.33, indicates that sediment transport includes both bed load and incipient suspension (Ackers and White, 1973). The Reynolds particle number of 1055.44 and a Froude number of 19.49 suggest dynamic flow conditions that enhance sediment suspension (Simons & Richardson, 1966; Lane, 1955). This turbulent flow regime is typical of a fluvial or fluvio-deltaic environment where increased velocity and slope contribute to higher sediment suspension potential.

The Owelli Sandstone Formation features a flow depth of 16.38 meters and a channel slope of 0.13, with an average velocity of 0.50 meters per second. This transitional flow regime suggests that sediment transport is predominantly along the bed with some potential for suspension (Williams, 1980). The Rouse number of 5.84 indicates that while bed load transport is predominant, there is some level of sediment suspension (Rouse, 1937). The Reynolds particle number of 877.41 and a Froude number of 18.89 are consistent with a coastal or shallow marine environment where bed load transport is the primary mechanism, but varying flow conditions can influence sediment suspension (McLean, 1981; Allen, 1984).

These formations reveal distinct characteristics that highlight the variability in sediment transport and depositional environments. The Nsukka and Owelli Sandstone formations both exhibit transitional flow regimes with significant bed load transport, but the Nsukka Formation shows a greater potential for sediment suspension. The Ajali Formation, with its lower velocity and higher Rouse number, shows predominantly bed load transport and a more stable flow regime. The Mamu Formation, with its higher velocity and more turbulent conditions, suggests a dynamic environment where both bed load and suspended sediment transport are important.

3.2. The Scatter Plots Comparison

The scatter plots with trends on Fig. 4 shows sedimentary parameters across the Nsukka, Ajali, Mamu, and Owelli Sandstone Formations, providing insights into the hydrodynamic conditions of the Anambra Basin. For flow depth, the Ajali Formation shows the highest depth (around 19 m), while the Mamu Formation has the lowest. Channel slope exhibits a slight upward trend, indicating that steeper slopes may exist in formations like Mamu, which correlates with faster flow conditions. Average velocity is relatively constant across the formations, though Mamu shows slightly higher velocities. The Rouse number (Z), representing sediment suspension, increases from Ajali to Owelli Sandstone, indicating varied sediment transport mechanisms (Rouse, 1937). Reynolds particle number (Rep) shows a declining trend, suggesting a decrease in flow turbulence across formations (Schlichting & Gersten, 2000), while the Froude number (Fr) highlights an increase in flow regime energy, especially in the Nsukka and Owelli Sandstone formations, pointing to higher flow velocities and bedform formation (Chow, 1959). These trends collectively reveal the diverse hydrodynamic environments across the formations, from high-energy conditions in Ajali to lower-energy environments in Mamu (Smith et al., 2016; Bridge, 2012; Nichols, 2018).

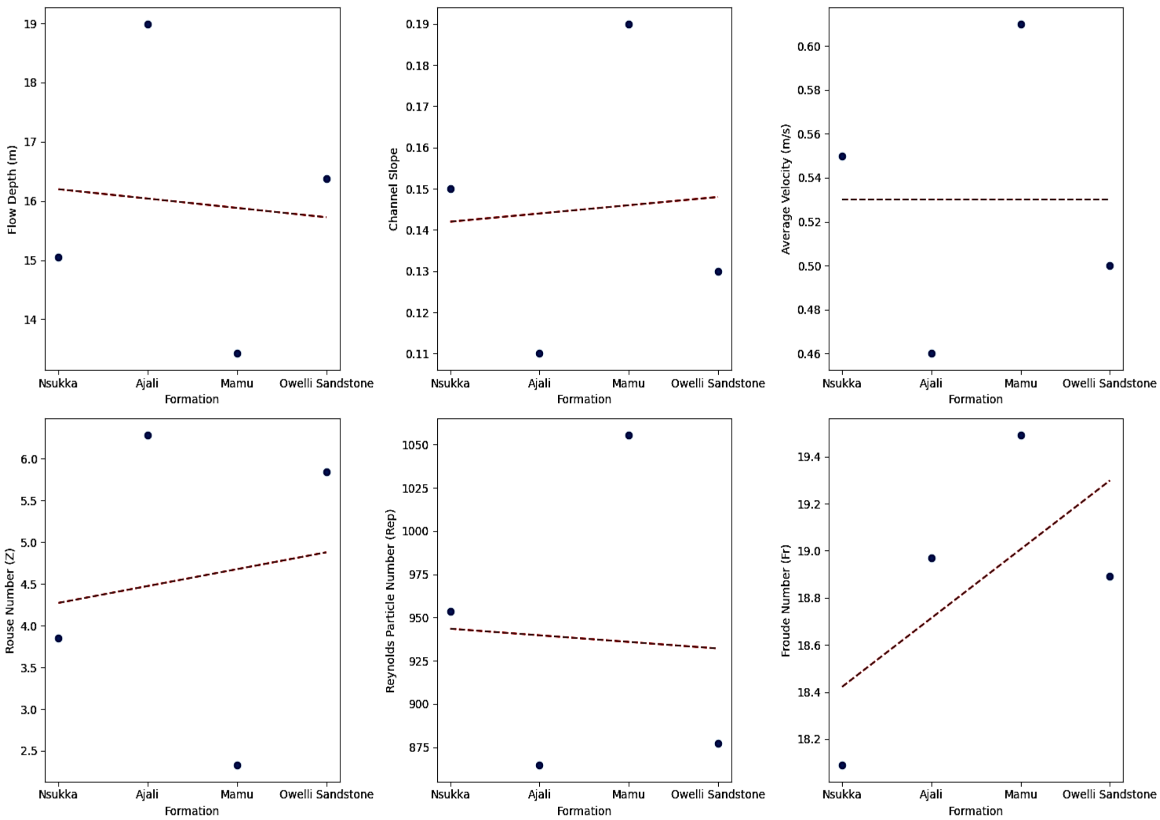

Fig. 4. Comparative analysis using scatter plot of hydrodynamic parameters across Nsukka, Ajali, Mamu, and Owelli sandstone formations in the Anambra basin.

3.3. Multiple Bar Charts Comparison

Mamu Formation has the steepest slope (0.19), indicating faster flow and coarser sediment transport potential (Leeder, 2011). The steeper slope suggests a more energetic environment in Mamu Formation compared to slower flow in Ajali Formation (Nichols, 2018). Mamu Formation shows the highest average velocity (0.61 m/s), indicating higher energy conditions for sediment transport, while Ajali Formation has a lower velocity (0.46 m/s) suggesting calmer conditions (Coleman et al., 2015). Higher velocities in Mamu Formation indicate deposition in high-energy environments; lower velocities in Ajali Formation reflect floodplain-like conditions (Allen, 2012). Manning constant all formations have the same Manning constant (0.04), indicating similar channel roughness and suggesting that sediment differences arise from factors like slope and energy rather than roughness (Chow, 2015). Variations in sedimentary parameters are influenced by flow rate and slope rather than channel roughness.

The Ajali Formation exhibits the thickest crossbeds (0.62 m), indicating higher-energy conditions likely related to river channels or strong currents (Smith et al., 2016). In comparison, the Owelli Sandstone (0.52 m), Nsukka Formation (0.47 m), and Mamu Formation (0.41 m) display progressively thinner crossbeds, suggesting less energetic depositional environments (Gibling, 2011). The largest particle size (0.83 m) is found in Mamu Formation, reflecting higher energy flows capable of transporting coarser sediments, while Ajali Formation has smaller particle sizes (0.68 m), indicative of lower energy flows (Miall, 2018; Schieber et al., 2021). This indicates that Mamu Formation represents higher energy conditions, such as those in braided river systems, while Ajali Formation suggests deposition in low-energy environments like floodplains.

Ajali Formation shows the highest bedform height (Fig. 5), indicating strong flow conditions, whereas Mamu Formation has the smallest (1.19 m), suggesting gentler flow (Bridge, 2012; Boggs, 2014). Larger bedforms are typically associated with high-energy environments, whereas smaller ones suggest calmer conditions. Mamu Formation has the steepest slope (0.19), implying faster flow capable of transporting coarser sediments (Leeder, 2011). Conversely, the lower slope in Ajali Formation (0.11) suggests slower flow conditions that favor deposition over erosion (Nichols, 2018). Mamu Formation exhibits the highest average flow velocity (0.61 m/s), indicating high-energy conditions for sediment transport, while Ajali Formation has the lowest (0.46 m/s), suggesting calmer flow conditions (Coleman et al., 2015; Allen, 2012). All formations share a uniform Manning constant of 0.04, indicating similar channel roughness (Chow, 2015). This consistency implies that variations in sediment characteristics are likely due to factors such as slope and energy rather than channel roughness.

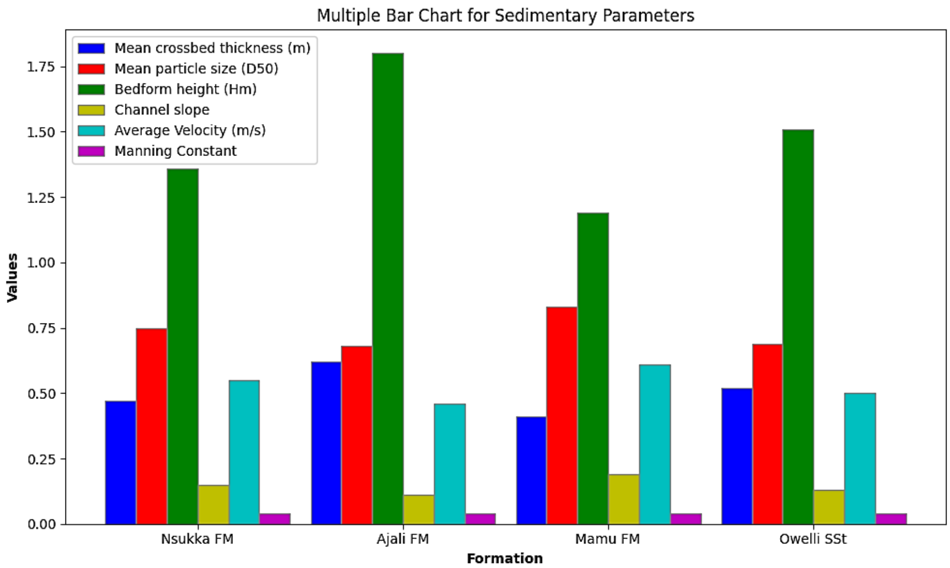

Fig. 5. Comparison of mean Crossbed thickness, mean particle size, Bedform height, Channels Slope, Average velocity and Manning Constant for different formations in the Anambra Basin.

Variations in flow depth (Fig. 6) suggest changes in water depth or channel geometry, with deeper flows often indicating higher energy regimes and greater sediment-carrying capacities (Leeder, 2011). Sediment settling velocity reflects the rate at which particles settle out of the water column, with higher velocities implying coarser or denser particles, possibly indicating shifts in sediment supply or flow energy (Miall, 2018). Boundary shear stress, the force exerted by water on the sediment bed, plays a critical role in initiating sediment movement and influencing bedform development, with variations reflecting changes in flow velocity or bed roughness (Knighton, 1998). The Rouse number relates sediment settling velocity to the velocity of turbulent eddies, determining the mode of sediment transport such as suspension or bedload (Rouse, 1937). The Froude number characterizes the flow regime, indicating subcritical or supercritical flow conditions and is influenced by channel slope or discharge variations (Chow, 1959).

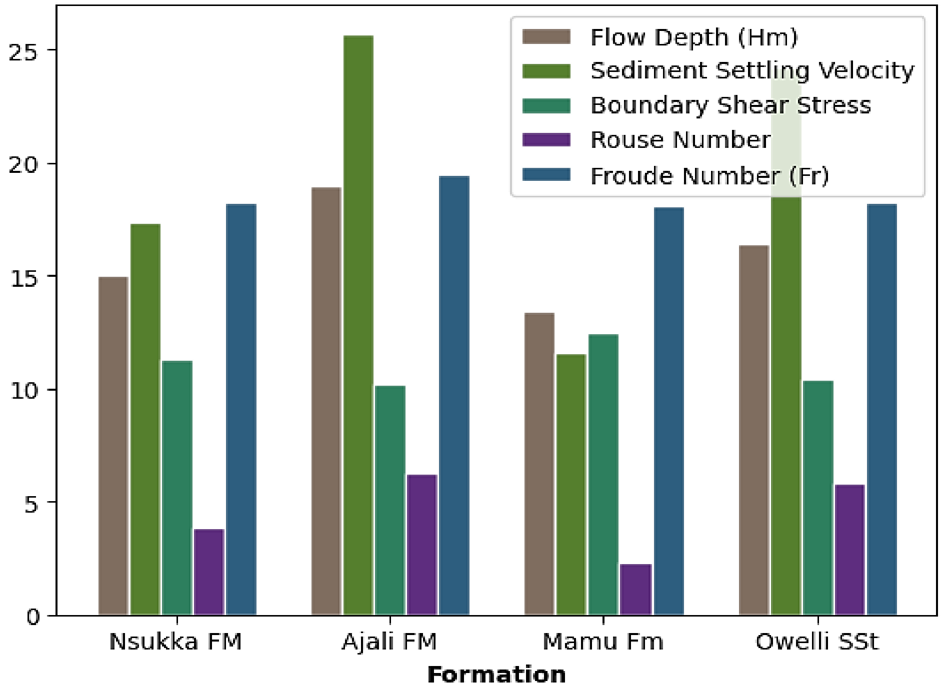

Fig. 6. Comparison of flow depth, sediment settling velocity, boundary shear stress, Rouse number, and Froude number for different formations in the Anambra Basin.

3.4. Box Plots

The box plots provide a visual representation of the distribution of different sedimentary parameters across the formations. The box plots (Fig. 7) provide a comprehensive analysis of hydrodynamic parameters—flow depth, channel slope, average velocity, Rouse number, Reynolds particle number, and Froude number—within different sedimentary formations of the Anambra Basin. The median flow depth (around 15.5 m) suggests moderately deep channel systems, while the slopes and velocities indicate relatively moderate energy environments capable of transporting substantial sediment loads. Rouse and Reynolds numbers suggest a mix of suspended and bedload transport, highlighting dynamic flow conditions (Allen, 2012; Miall, 2018). Meanwhile, Froude numbers remain below 1, pointing to subcritical, stable flows typical of alluvial and fluvial environments. The lack of extreme outliers indicates consistent depositional environments across the basin, with variations reflecting local geomorphic influences, as seen in other studies of sedimentary dynamics (Bridge, 2012; Boggs, 2014).

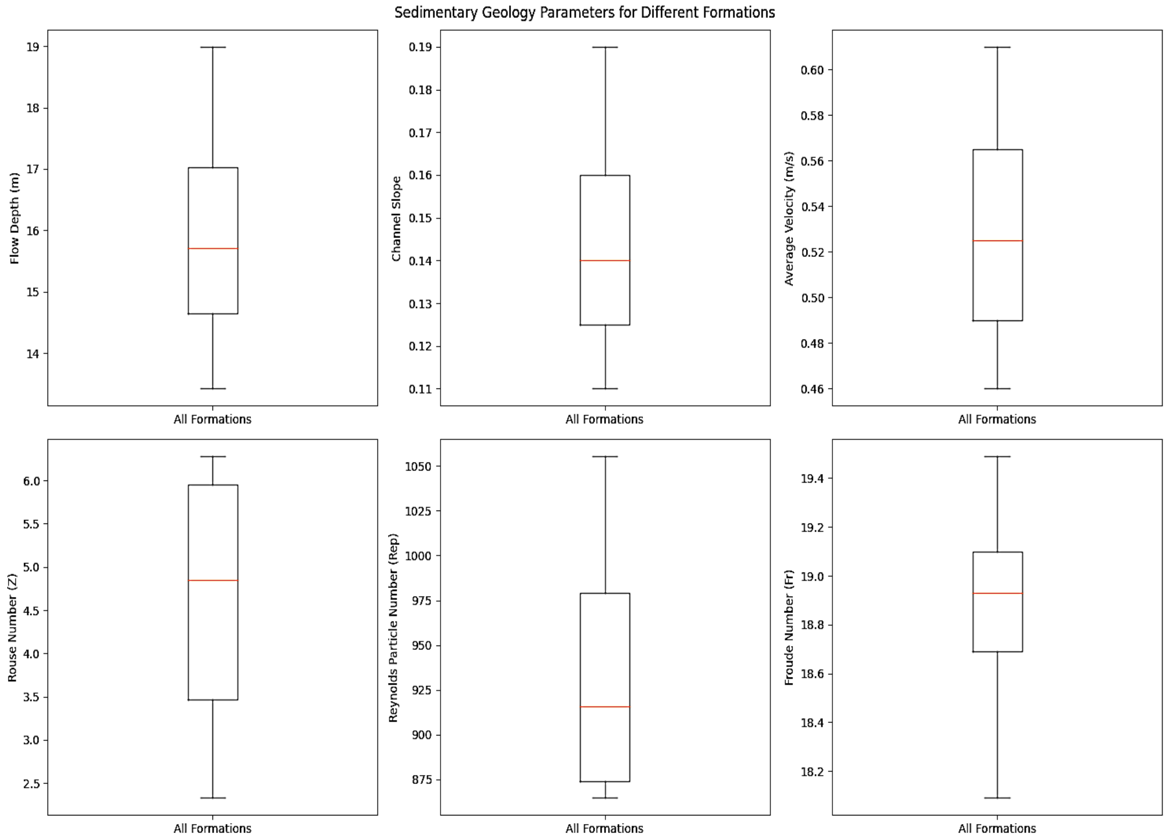

Fig. 7. Box Plot comparison of all Formations within Anambra Basin

4. Conclusion

The examination of hydrodynamics and sedimentary rocks within the Anambra Basin offers a comprehensive understanding of the region's ancient environmental conditions and geological evolution. By meticulously analyzing paleohydraulic parameters, researchers can reconstruct past flow dynamics and sediment transport processes that played a crucial role in shaping the basin's sedimentary framework. This detailed insight into the historical water flow and sediment deposition patterns enhances our grasp of how the geological features of the Anambra Basin were formed. Additionally, this research has broader implications for predicting future sedimentary processes and resource distribution in the region. Understanding the interplay between hydrodynamic forces and sedimentary deposition can inform models that forecast how similar environments might evolve under different conditions. Such knowledge is invaluable for geological surveys, resource exploration, and environmental management strategies. Overall, this study not only enriches our geological knowledge of the Anambra Basin but also provides a foundation for future research and practical applications in sedimentology and basin analysis.

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