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Original Research Article

Sedimentary Facies Analysis and Depositional Environment Reconstruction of Clastic Successions in Opi and Environs, Anambra Basin (Ajali and Nsukka Formations)

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Abstract

Detailed sedimentary facies and depositional environment studies were carried out on clastic deposits outcropping around Opi and its environswithin the Ajali and Nsukka Formation of the Anambra Basin. This defines the depositional facies, and sandstone hydrodynamics. The results revealed sixlithofacies which are systematically recognized into four genetically connected facies associations based on the textural parameters and diverse sedimentary structures derived from the hydrodynamic controls. The sedimentary facies include Structureless sandstone facies, Heterolith facies, Mudstone facies, Wave ripple facies, Parallel laminated sandstone facies and Planar Cross bedded Sandstone facies with its respective structural elements pivotal in the qualitative and quantification of the lithofacies and facies association description. The facies associations systematic paleo-environment diagnosis reveals depositional in fluvial, upper shoreface to lower shoreface depositional settings. The sandstones are predominantly medium to coarse grained and poorly sorted, indicating high-energy depositional conditions. Furthermore, their symmetrical skewness suggests the depositing medium operated at a steady velocity over a prolonged period, a characteristic feature of fluvial systems.
Keywords: Lithofacies, hydrodynamics, sedimentary structures.

INTRODUCTION

This paper discusses onthe reconstruction of past environmental conditions around Opi and its environs within the Ajaliand Nsukka Formations of the Anambra Basin used to define the depositional facies, and sandstone hydrodynamics of the study area. Paleoenvironmental analysis draws on physical, chemical, and biological indicators preserved within sedimentary records to infer factors such as climate, depositional settings, and hydrodynamic processes. Several lithofacies studies have been done and integrated with biostratigraphy to interpret the depositional environments. Oluwajana, O. A., (2024) discussed the provenance interpretation and depositional environment of sandstone of the ajali formation and Uzoegbu, *et al.,* 2013 discussed the lithostratigraphy of the Maastrichtian sediments in Nsukka Formation. The geological units of the Anambra Basin have been observed to be a depression structure that was formed as a result of the Santonian thermo-tectonic event (Nwajide, C. S. 2013., Obi, G. C., 2000; and Reyment, 1965). Two major marine transgressions were recognized- a more extensive one which is the Nkporo Transgression and the less extensive Nsukka Transgression. The Nkporo Group is made up of the Nkporo Formation and its lateral equivalents such as the Enugu Formation and the Owelli Formation. The Mamu, the Ajali and the Nsukka formations are the major lithostratigraphic units of the Coal Measures. This work demonstrates the integrated interpretation of sedimentary rock paleoenvironment processes inherent in the Ajali and Nsukka Formations to discuss the hydrodynamic and paleoenvironment systems inherent in the lithostratigraphic unit of the Anambra Basin (Nwajide, C. S. 2013).

Statement of the Problem

Despite the extensive geological significance of the Ajali and Nsukka Formations within the Anambra Basin, the clastic outcrops around Opi and its environs have not been sufficiently studied in terms of their detailed sedimentary facies, hydrodynamic controls, and depositional environmental evolution. Existing regional studies provide broad lithostratigraphic descriptions but lack high-resolution facies mapping, textural characterization, and quantitative interpretation of sedimentary structures. This knowledge gap limits understanding of the sediment dispersal pattern, flow regime behaviour, paleo-hydrodynamics, and depositional settings responsible for the observed sandstone variability. Furthermore, the poorly sorted and high-energy sandstones in the area require a more comprehensive petro-sedimentologic evaluation to clarify their reservoir potential, paleo-river dynamics, and shoreline processes. Without such an integrated facies analysis, depositional models remain speculative, and the geologic history of clastic infill in Opi remains incomplete.

Aim of the Study

To conduct some integrated sedimentary facies, textural, and depositional environment evaluation of clastic deposits exposed around Opi and its environs within the Ajali and Nsukka Formations of the Anambra Basin.

Objectives of the Study

1. To identify, describe, and classify the lithofacies present within the clastic outcrops in Opi and its environs.
2. To interpret the sedimentary structures and textural characteristics associated with each facies.
3. To group the lithofacies into genetically related facies associations.
4. To reconstruct the depositional environments based on textural parameters, and hydrodynamic evidence.
5. To evaluate the hydrodynamic processes and flow regimes responsible for sandstone deposition in the study area.
6. To assess the implication of the facies characteristics for sediment transport mechanisms and paleoenvironmental evolution of the Ajali and Nsukka Formations.

Jurisdiction of the Work

This research is geographically limited to Opi and its surrounding communities within the Ajali and Nsukka Formations of the Anambra Basin, South-Eastern Nigeria. The scope of the work covers:

- Outcrop mapping and description of clastic sediment exposures.
- Field logging, measurement of stratigraphic sections, and identification of sedimentary structures.
- Textural analysis (grain size, sorting, skewness, kurtosis).
- Lithofacies classification using standard sedimentological schemes.
- Grouping of lithofacies into facies associations.
- Interpretation of paleo-depositional environments (fluvial, upper shoreface, lower shoreface).
- Hydrodynamic characterization of sandstones based on grain size distributions and sedimentary structures.

The study focuses strictly on sedimentological and paleoenvironmental analysis and does not extend into geotechnical modeling, geochemical characterization, or basin-wide sequence stratigraphy beyond the defined area.

Research Questions

1. What lithofacies types occur within the clastic outcrops of Opi and its environs?
2. What sedimentary structures and textural characteristics define each facies?
3. How can the identified lithofacies be grouped into meaningful facies associations?
4. What hydrodynamic conditions controlled the deposition of the sandstones within the Ajali and Nsukka Formations?
5. How do grain size parameters (sorting, skewness, texture) reflect the energy conditions and depositional processes?

MATERIALS AND METHOD

Systematic sedimentary rocks field mapping through sedimentary logging is used to access the dynamic lithology grain sizes, texture, macroscopic biological and other sedimentary rock structural elements along with the bedding characteristics of the Nsukka Formation outcropping sediments (Fig. 1). The study area is part of the outcropping sections of the Anambra Basin, southeastern Nigeria (Fig. 2 and 3). Most of the outcrops were exposed through open burrow pits and quarries while others were exposed through road cuts. Most of the outcrops can be accessed using the Enugu Road from the northern part of the studied area and other minor road within the study area. Detailed sedimentological logging of the outcrops in the vicinity were displayed to define the sedimentary facies types, biological and physical sedimentary structures, sedimentary rock geometries and texture, bedding plane packaging for paleoenvironment reconstruction.

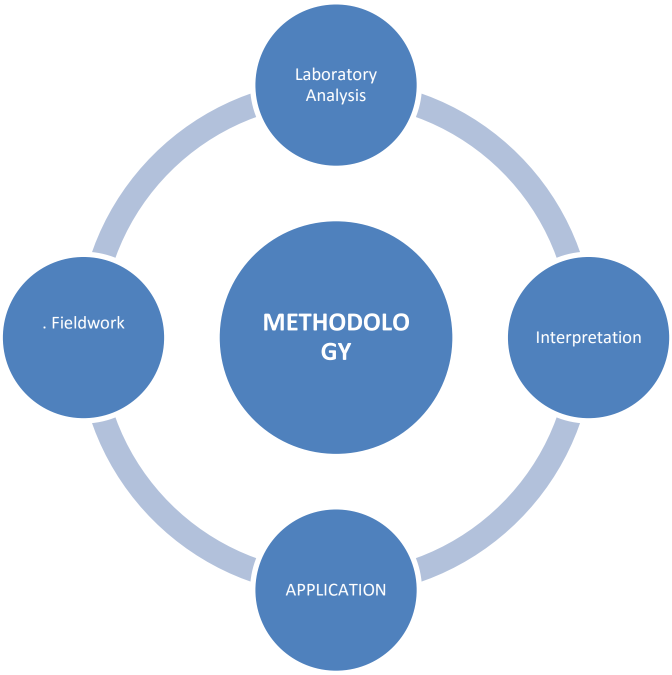

Fig. 1: The Methodology

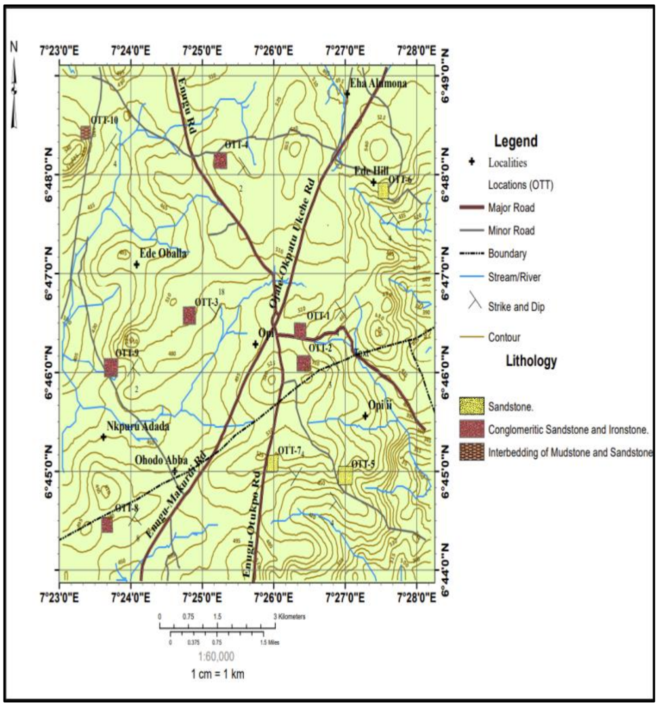

Fig. 2: A map showing outcropping units

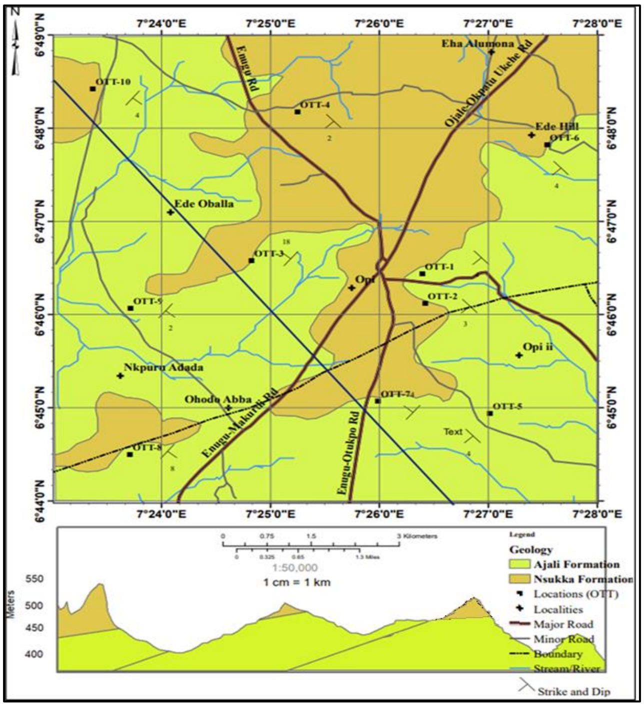

Fig 3: Geologic map and cross-section of the study area

Facies analysis

Facies analysis of six lithofacies were recorded from the study area. Sedimentological logging of the outcrop sections was done and facies were identified based on the differences in internal sedimentary structure, textures, geometry and the contact made with the underlying and overlying bed units. The scheme used here is modified from Miall (2000). The dominant grain sizes arerepresented by the letters; S, M, and H for sandstone, mudstone and Heterolith respectively. The lower-case letters in the code are used to characterize the structural or textural feature present in particular facies

Structureless Sandstone Facies (Ss)

Description

The structureless sandstone facies (Ss)was encountered at Iheanumona (OTT-6), Enugu – Otupo (OTT-7), Ozala (OTT-8), NpuruAdada (OTT-9) and

Enugu – EdeOballa (OTT-4) (Fig. 4a & b). The sandstones at these locations are fine to very coarse grained and appears reddish-brown probably as a result of oxidation of iron. These outcrops thickness ranges from 3m to 4m. The sandstone units atNpuruAdada are large, angular ironstone concretions are embedded in the matrix. Otupo and Iheanumona sandstone units are made up of reddish friable poorly sorted coarse-grained sandstone. At Ozalla the first beds are fine-grained reddish-brown sandstone and are overlain by reddish brown sandstone embedded with angular ironstone.

Interpretation:

Structureless sandstone is suggested to originate from gradual aggradation of sediments beneath steady or near-steady flows. They are attributed to rapid deposition from suspension during floods. They also occur as a result of rapid deposition, through rapid deceleration of sediment-laden current. Massive sandstone can also occur as a result of intense bioturbation or rapid deposition, through deceleration of a heavily sediment-laden current (Collinson et al., 2006). High density turbidity currents are dominated by grain-to-grain interactions and hindered settling, which favours deposition of structureless and well sorted sandstone due to more rapid deposition and damping of turbulence. Massive sandstones, characterized by an absence of internal stratification, are indicative of rapid deceleration and abrupt arrest of high-density turbidity currents (Talling *et al.,* 2012).

Fig. 4: (a) Reddish brown structureless sandstone at Iheanuomona (b) Reddish structureless sandstone at NpuruAdada

Heterolith Facies (H)

Description:

This lithofacies was encountered (Fig 5a, b & c) at locations Amangwu (OTT-1 and OTT-2) and Ede Oballa (OTT-3). The heteroliths of the locations are characterized by a conglomeratic texture. At Amangwu is a reddish-brown structure with medium to coarse grained sandstone conglomerates along with the presence of concretionary ironstone nodules. Amangwu and Ede Oballa show similar textures of medium to coarse grained sandstone and horizontal planer laminar of ironstone.

Interpretation

The heterolytic character of this facies suggests variations in physical energy, fluctuating high and low energy setting, lying between the offshore and lower shoreface. The muddy and silty nature of the facies suggests calm and quiet depositional condition, (Boggs, 2001).

Fig. 5: (a& b) Heterolytic sandstone at Amangwu(c) Heterolytic sandstone at Ede Oballa

Mudstone Facies (M)

Description:

This lithofacies was seen at Lejja (OTT-10) (Fig 6a &b). The entire outcrop exhibits a lateral extent of about 20m, and thickness of approximately 6.5m. The first bed is made up of reddish medium to coarse grained massive sandstone about 2 m thick. The second bed consists of dark brown to reddish-brown mudstone unit and the third bed consisting of reddish conglomeritic sandstone.

Interpretation

The mudstone facies suggest the dominance of low energy conditions where the muds are deposited by suspension settling, episodic sedimentation and /or fallout during one or several slack-water periods. Interbedding of sandstones and mudstones denote a cyclic accumulation of sediments referred to as tidal rhythmites (Kvale, 2006).

Fig. 6: (a & b) Planar cross-bedded sandstone at Lejja

Wave Ripple Facies

Description:

This lithofacies is characterized by wave ripples of medium to coarse grained sandstone. This lithofacies was observed (Fig. 7) at Enugu Otupo (OTT-7a) which is a quarry section. This outcrop consists of sandstone with wave ripples.

Interpretation

The wave ripples are asymmetrical produced as a combination of oscillatory waves and unidirectional currents. The ripples become asymmetrical when there is an asymmetry in the orbital current due to the combination with unidirectional current as proved by (Collinson *et al.,* 2006). Wave ripples may also form in conjunction with high rates of deposition. Such conditions result in the formation of aggradational oscillation ripples

Fig. 7: Wave ripple sandstone Enugu - Otupo

Parallel Laminated Sandstone Facies

Description:

This lithofacies was observed at Opi II (OTT-5). The thin laminated parallel sandstone facies in the two locations (Fig. 8a &b) are characterized by a medium grained, friable sandstone bed. The bed thickness is about ranges from 1 to 3m of parallel laminated sandstone and a 3 to 6m thick bed of medium cross bedded sandstone.

Interpretation

The parallel laminated sandstone represents offshore transport of sand during storms on the shoreface. The laminae show parting lineation structures. This suggests deposition in a subaqueous environment at high flow velocities in the upper flow regime (Collinson *et al.,* 2006). The lineations which form parallel to the trend of the current, are produced by turbulent cork screw eddies that are close to the sediment surface (Tucker, 2003). Thin bedded nature of sandstones indicates tidally influenced environment.

Fig. 8: (a & b) Parallel laminated sandstone Oppi 11

Planar Cross Bedded Sandstone Facies

Description:

This particular lithofacies was seen at Opi II (OTT-5) (Fig. 9a & b). This facies is characterized by fine to medium - grained fryable sandstone. The cross bed of this particular sandstone facies is aligned in North direction.

Interpretation:

The cross-bedded sandstone facies, represents deposition in a high-energy environment and is characterized by the dominance of planar cross-stratification, produced by migration of two-dimensional dunes. Planar cross bedding indicates deposition of bedload sediment in the upper flow regime of Upper Shoreface environment (Tucker, 2003).

Fig. 9: (a& b) Planar cross-bedded sandstone at Opi II.

Lithofacies Association

The lithofacies described in the previous section were further grouped into four facies associations based on sedimentary structures, grain textures, bedding contacts, vertical and lateral facies succession and overall geometry of the facies. This aids the interpretation of depositional environment. The facies show a coarsening upward succession and reflect deposition in a marginal marine setting, possibly a tide dominated estuary. The facies associations are discussed in their order of occurrence and are summarized in Table 1.

Facies Association

Offshore Transition Deposit (FA1)

It comprises of the heterolith facies, and mudstone facies. It also retains the general coarsening upward nature of the rocks and is marked by a basal grey mudstone unit which averages about 1m thickness. Sand input was probably initiated during periodic storm events, which generated shallow water turbidity currents on the shelf (Pattison et al., 2007).

Lower Shoreface Deposits (FA2)

This facies association is characterized by, fine to medium-grained parallel laminated sandstone like in location Opi II. It involves deposition in a subaqueous environment at high flow velocities in the upper flow regime of Lower Shoreface environment of deposition. The thin laminae of sandstone beds indicate tidally influenced coastal environment (Ekwenye *et al.,*2014).

Upper Shoreface Deposits (FA3)

This facies association is dominated by amalgamated, coarsening and thickening-upward, medium grained planar cross-bedded sandstone lithofacies and wave ripple sandstone facies, The occurrence of symmetrical wave, wave-ripple laminated sandstone suggests deposition/reworking by oscillatory wave processes or wave reworking of tractional current ripples that dominate in the upper shoreface environment, above fair-weather wave base, while observed coarsening and thickening upward trend suggest increasing energy level during progradation/shoaling (Ekwenye *et al.,*2014).

Fluvial Channel Deposits (FA4)

It comprises of fine to medium grained, reddish brown structureless sandstone facies. This facies association also has the reddish-brown muddy conglomeritic sandstones in locations Amangwu and Ede Oballa. However, overall, this facies association is stacked to form coarsening/thickening-upward successions that indicate waxing fluvial currents, typical of fluvial channels settings (Howard and Reineck 1979, 1981).

Table 1: Lithofacies Occurrence, Facies Association and Depositional Process Interpretation

Lithofacies	Facies Association	Locations	Depositional Process and Interpretation
Structureless sandstone facies.	FA4	OTT-6,9,8,7,4	This represents deposition in a fluvial channel bar system.
Heterolith facies.	FA1	OTT-1, 2, 3	Suspension settles-out in a dysoxic, distal offshore transition environment, with frequent terrigenous sediment influx from storm-induced currents.
Mudstone facies.	FA1	OTT-10	Suspension settles-out in a dysoxic, distal offshore transition environment, with frequent terrigenous sediment influx from storm-induced currents.
Wave ripple facies	FA3	OTT-7a	Lower flow regime (Miall, 1978). Oscillatory wave processes that dominate in the upper shoreface environment,

Lithofacies	Facies Association	Locations	Depositional Process and Interpretation
			above fair-weather wave base (Gowland, 1996)
Parallel laminated sandstone facies	FA2	OTT-5	It involves deposition in a subaqueous environment at high flow velocities in the upper flow regime of Lower Shoreface EOD. The thin laminae of sandstone beds indicate tidally influenced Coastal Environment.
Planar Cross bedded Sandstone facies	FA3	OTT-5	Dunes (lower flow regime), (Miall 1978, 1996). Bars deposits within tidal inlets.

Granulometric (Grain Size) Analysis

Six (6) sandstone samples were collected fromOpi II (OTT-005), Iheanumona (OTT-006), and Enugu –Otupo(OTT-007), and were used to carry out sieve analysis. The raw data for the different sandstone samples are presented alongside the plots of the data for each sample. Sample statistics and plots from Univariate, Bivariate and Multivariate parameters are shown in Table 2.

Table 2: Univariate Parameters of Sandstones in the Study Area

Location	Mean size (Mz)	Sorting	Skewness (Ski)	Kurtosis (KG)	Description
OTT-005a	0.792	1.211	-0.218	1.111	Coarse sand, poorly sorted, coarse skewed, leptokurtic
OTT-005b	1.725	0.980	-0.311	1.778	Medium sand, moderately sorted, very coarse skewed, very leptokurtic
OTT-006	0.733	1.385	-0.129	0.883	Coarse sand, poorly sorted, coarse skewed, platykurtic
OTT-007a	0.180	1.409	-0.086	0.520	Coarse sand, poorly sorted, symmetrical, very platykurtic
OTT-007b	1.119	1.238	-0.078	0.904	Medium sand, poorly sorted, symmetrical, mesokurtic
OTT-007c	2.125	0.944	-0.453	1.387	Fine sand, moderately sorted, very coarse skewed, leptokurtic

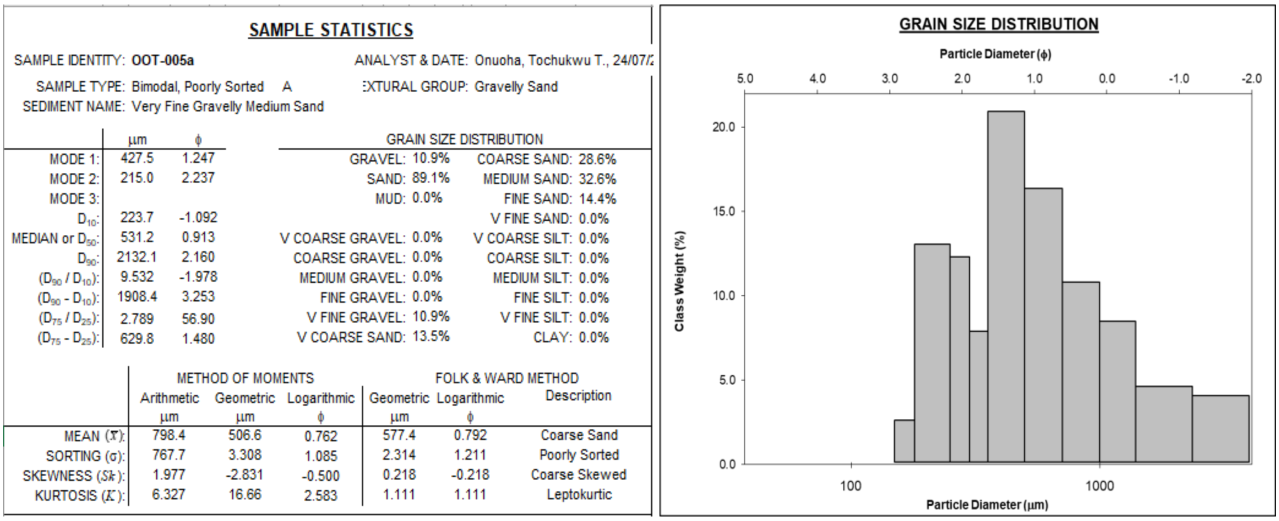

Fig. 10: Plots for sandstone OOT-005a (a) Sample statistics (b) Frequency distribution plot

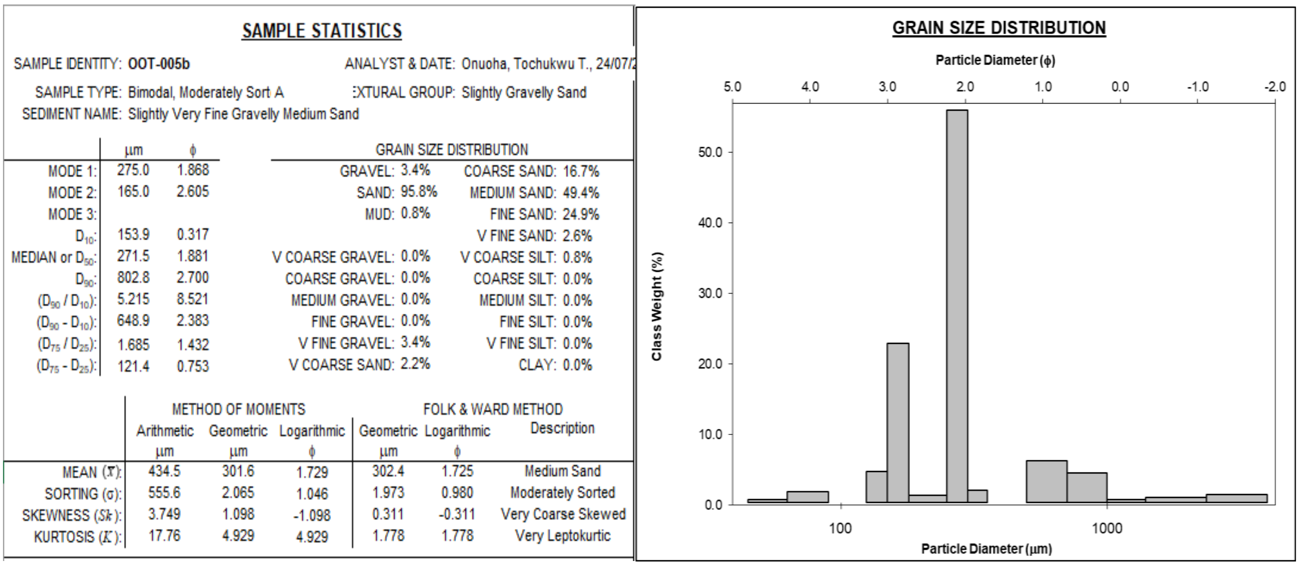

Fig. 11: Plots for sandstone OOT-006 (a) Sample statistics (b) Frequency distribution plot

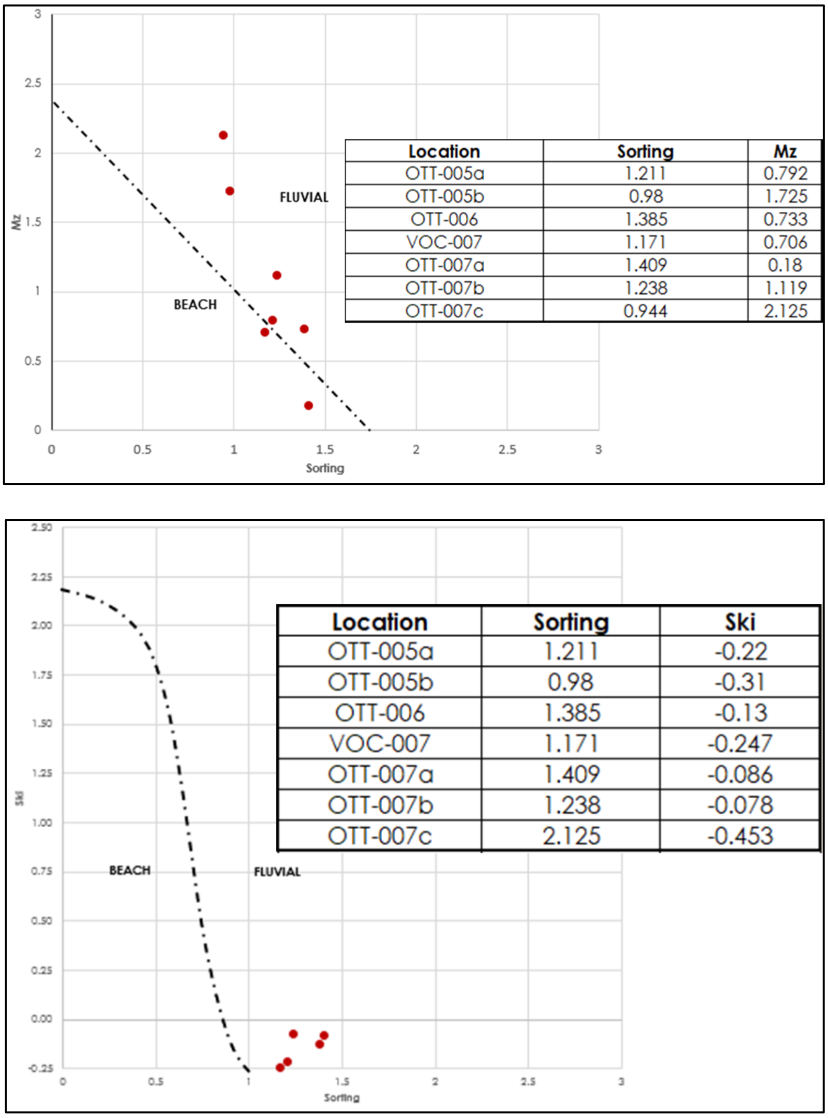

Fig. 12: Bivariate plots for sieve samples (a) Mean Size vs. Sorting (Moiola and Weiser, 1968) (b) Skewness vs. Sorting (Friedman, 1961)

Multivariate Parameters

Table 3: Multivariate Parameters of Sandstones in the Study Area (YShallow marine: Fluvial)

ENVIRONMENT OF DEPOSITION						
Location	Mz	Sorting	Ski	Ku	Yu	Environment
OTT-005a	0.792	1.211	-0.218	1.111	-9.263	FLUVIAL
OTT-005b	1.725	0.98	-0.311	1.778	-6.486	SHALLOW MARINE
OTT-006	0.733	1.385	-0.129	0.883	-11.25	FLUVIAL
VOC-007	0.706	1.171	-0.247	1.049	-8.798	FLUVIAL
OTT-007a	0.18	1.409	-0.086	0.52	-11.85	FLUVIAL
OTT-007b	1.119	1.238	-0.078	0.904	-10.1	FLUVIAL
OTT-007c	2.125	0.944	-0.453	1.387	-5.38	SHALLOW MARINE

Table 4: Multivariate Parameters of Sandstones in the Study Area (YBeach: Shallow marine)

ENVIRONMENT OF DEPOSITION						
Location	Mz	Sorting	Ski	Ku	Yu	Environment
OTT-005a	0.792	1.211	-0.218	1.111	115	SHALLOW MARINE
OTT-005b	1.725	0.98	-0.311	1.778	247.7	SHALLOW MARINE
OTT-006	0.733	1.385	-0.129	0.883	121.5	SHALLOW MARINE
VOC-007	0.706	1.171	-0.247	1.049	109.5	SHALLOW MARINE
OTT-007a	0.18	1.409	-0.086	0.52	107.8	SHALLOW MARINE
OTT-007b	1.119	1.238	-0.078	0.904	118	SHALLOW MARINE
OTT-007c	2.125	0.944	-0.453	1.387	124.2	SHALLOW MARINE

Interpretation

Analysis from sieve gave univariate parameters of mean size, sorting, skewness and kurtosis for all the three (3) samples locations; OTT-005, OTT-006, and OTT-007. From the results as shown in Table 2, the samples are medium to coarse sands, poorly to moderately sorted, symmetrical to coarse skewed, and range from platykurtic to mesokurtic to leptokurtic. These univariate parameters were further employed in bivariate plots of skewness vs. sorting (Friedman, 1961) and plots of mean size vs. sorting (Moila and Weiser, 1968) to distinguish between beach and fluvial sands. Almost all of the samples, plot in the fluvial section both in the sorting vs. mean size graph (Fig. 12a) and in the sorting vs. skewness graph (Fig. 12b). This implies that the grain size distribution characteristics are consistent with what is typically observed in river deposits, and suggests the sand likely originated from a fluvial environment or has undergone similar sorting processes.

DISCUSSION

The integration of lithofacies, and grain size of the studied sediments of the Formations, provided insight for the reconstruction of the paleo-depositional and geologic history of the study area.

Depositional Environment from Facies Analysis

Lithofacies analysis reveals that the distribution of the six (6) lithofacies delineated in this study are; Structureless sandstone facies, Heterolith facies, Mudstone facies, Wave ripple facies, Parallel laminated sandstone facies, and Planar Cross bedded Sandstone facies. The distribution of lithofacies successions across the study area shows a predominance of the following: fining upwards/thinning-upwards succession in the South western part, an indication of a transgressive environment (shoreline advancing landward with time), and Coarsening-upwards/thickening-upwards succession towards the Eastern and central part, an indication of regressive shelf environment (shoreline advancing seaward with time).

In addition, the grouping of these lithofacies into four (4) facies association gave more insight to the understanding of the environments of deposition. The heterolith lithofacies and Mudstone facies, are storm wave-dominated shelf deposits (FA1). The parallel laminated sandstone facies, is characterized by planer bed flow, deposition under upper flow regime, plane-bed conditions in marine setting (FA2). The planar cross-bedded and wave ripple sandstones comprise of shorefaces deposits (FA3) above fair- weather wave base. The structureless sandstone and conglomeritic sandstone lithofacies indicates fluvial channel deposits (FA4).

Depositional Environment from Granulometric Analysis

From the granulometric analysis, all of the data gotten from the Skewness vs. Sorting (Friedman, 1961), Mean Size vs. Sorting (Moiola and Weiser, 1968) plots suggest fluvial environment which may invariably be related to deposition in shallow marine setting. Modality of grain size ranges from bimodal to polymodal reflecting a depositional environment where differentiation in sorting is produced by highly variable transport processes or multiple sources. The sandstones are poorly to moderately sorted and may indicate a change in environment, from deeper to shallow water. The symmetrically skewed sands suggest that the depositing medium operated at a steady velocity for a long period of time while positive skewness may indicate that the velocity of the depositing agent operated at a level lower than normal for a long period of time, and are typical of sheltered quiet water areas, rivers and deep environments.

Results from the univariate, bivariate and multivariate parameters show that the sand samples are mainly fluvial sediments. The beach interpretation obtained from the Y Beach: shallow marine analysis implies that the sediments were deposited in shallow agitated waters, while interpretation from YShallow marine: fluvial analysis implies sediment deposition in a fluvial setting with interplay of shallow environment setting.

Conclusion

Economic Geology

The economic geology of the Opi area is defined by its geologic formations which help to offers insight on the potential resources available for exploitation. The Formation of the study area contain valuable resources for the construction industry. Ajali and Nsukka formations are good for obtaining high quality sandstone material which essential for both local and regional construction activities, including roads, buildings and dams. The Formation of the study area contain valuable resources for the construction industry.

CONCLUSION

The outcropping strata within the Opi axis were delineated through integrated lithofacies and sedimentological analyses, allowing for the interpretation of their formative paleoenvironments. A total of six lithofacies were recognized and grouped into four facies associations. These include: The mudstone and heterolith lithofacies are storm wave-dominated shelf deposits (FA1). The planar laminated sandstone facies is characterized by planer bed flow, deposition under upper flow-regime, plane-bed conditions in marine setting (FA2). The planar cross-bedded and wave ripple sandstones comprise of shorefaces deposits (FA3) above fair-weather wave base. The structureless sandstone and conglomeritic sandstone lithofacies indicates fluvial channel deposits (FA).

In the granulometric analysis, the histogram plots, supports a fluvial environment interpretation. The sandstones are predominantly medium- to coarse-grained and poorly sorted, indicating high-energy depositional conditions. Furthermore, their symmetrical skewness suggests the depositing medium operated at a steady velocity over a prolonged period, a characteristic feature of fluvial systems.

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