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Facies and Paleoenvironmental Analysis of the Ajali Formation around Nkpologu-Ugbene Ajima, Southeastern Nigeria

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Abstract

Detailed facies and paleoenvironmental analyses were carried out on multiple outcrops of the Maastrichtian Ajali Formation in the Nkpologu to Ugbene-Ajima area of Enugu State, southeastern Nigeria. Three lithofacies were delineated in the Ajali Formation outcropping in the study area; Crossbedded Sandstone Facies, Grey Shale Facies and Laminated Sandstone Facies. Granulometric analysis sand samples show they are medium grained, moderately-poorly sorted, symmetrically skewed and platykurtic-very platykurtic. Pebble morphometric analysis shows predominantly bladed-very bladed shape indices, with Maximum Projection Sphericity ranging from 0.57-1.01, Oblate-Prolate Index ranging from -0.82-1.26, and Flatness Index ranging from, 25.53-72.73. The pebbles are mainly Very Bladed-Bladed. Paleocurrent analysis show a south-westerly unimodal direction of flow indicating a north-eastern provenance. Analysis of indicative sedimentary structures, bivariate and multivariate analysis of granulometric and morphometric indices point to a braided fluvial, transitioning to subtidal and tidal environment for the Ajali formation in the study area. Paleocurrent data points to sediment sourced from the uplifted Abakaliki Anticlinorium towards the east.

Keywords: *Ajali Formation; Anambra basin; Facies; Palaeoenvironment.*

1. Introduction

The Ajali Formation, formerly referred to as the Sandstone Series [1] or False-Bedded Sandstone [2], is one of the major lithostratigraphic units of the Campanian to Maastrichtian Anambra Basin. It overlies the coal bearing Mamu Formation and is succeeded by the Nsukka Formation. It is well established that this formation primarily comprises of dominantly cross-stratified, loosely to moderately packed quartz arenite of medium to coarse grain size, with subangular to subrounded grains [3–7]. The distinctive character, in addition to is extension throughout the Anambra Basin, and thickness reaching up to 550 meters makes the Ajali Formation the primary reservoir unit in the basin [6,8].

Facies and paleoenvironmental studies have been carried out on the Ajali Formation at basin wide and local scales by various authors. These studies have shown that there are important facies differences in the different areas where the Ajali Formation outcrops, related to a gradual progression from a continental to marine depositional environment, which characterized the Anambra Basin in the Late Cretaceous [9–12]. This study focuses on the area around Nsukka, Ugbene-Ajima and Nkpologu in Enugu State, Southeastern Nigeria, where the Ajali Formation is the predominant outcropping lithostratigraphic unit. A detailed facies and paleoenvironmental analysis, based on study of multiple outcrop sections, the analysis of paleocurrent indicators and granulometric analysis, is presented.

2. Geologic setting

The study area lies in the area bounded by latitude 6°45' 0''N and 6° 50' 0''N, and longitudes 7°13' 0''N and 7° 18' 0''N; areas around Nkpologu and Ugbene-Ajima on the outskirts of Nsukka in Enugu State (Fig. 1). The geography is generally streamless valleys and lowland areas, and flat top hills and mesas.

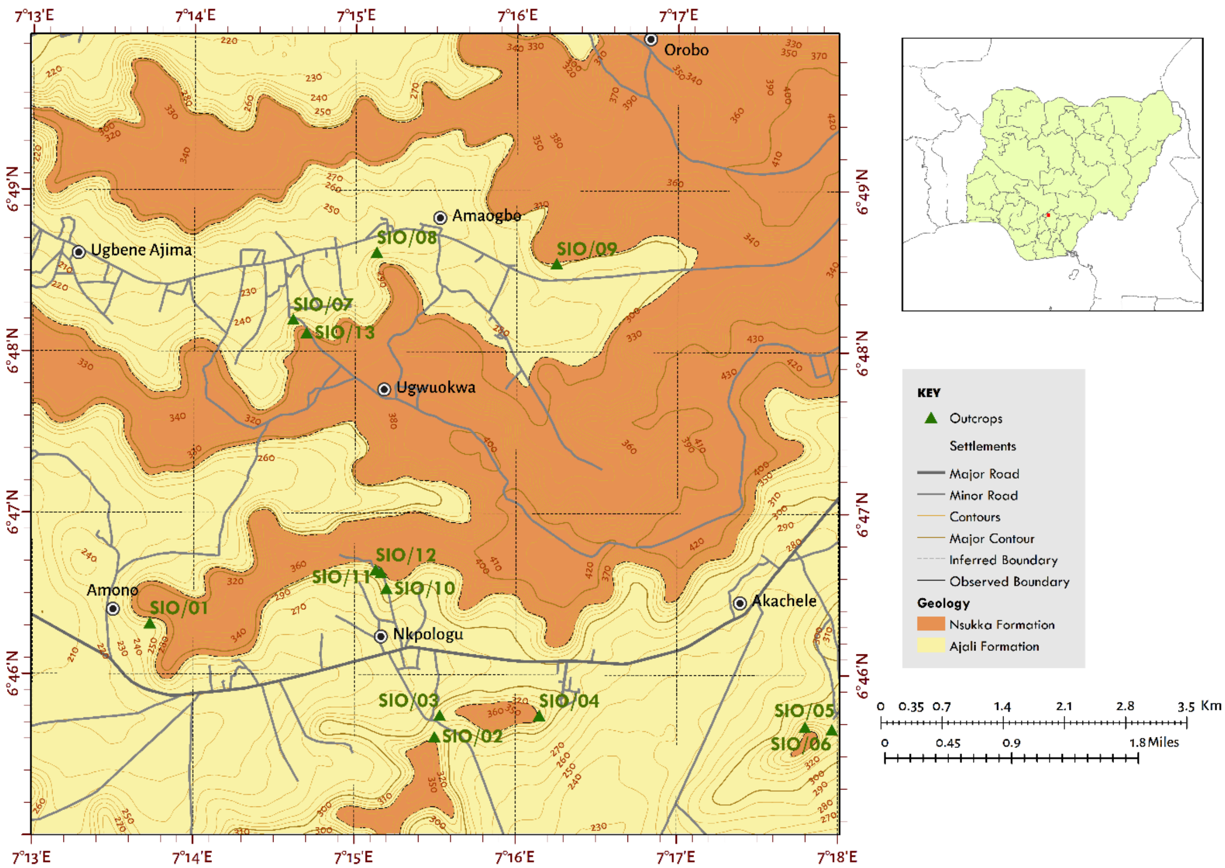


Figure 1. Geological map of the study area showing the locations of studied outcrops.

2.1. Tectonic setting

The Anambra Basin is an arcuate southward plunging synclinal structure [13–15] (Fig.2). It formed in the aftermath of the inversion and folding of the Southern Benue Trough during the Santonian Tectonic event [16-17]. The Benue Trough is a NE-SW trending wrench related rift basin, whose origin is related to the opening of the Equatorial Atlantic Ocean [13,18]. Its Albian to Santonian basin fill, as well as that of the succeeding Anambra Basin formed above the passive margin of the Equatorial Atlantic. The broad synclinal structure of the Anambra Basin, formed from the western to the southern flank of the uplifted Abakaliki Anticlinorium structure of the Southern Benue Trough became a centre of deposition of approximately more than 3000m in the central parts of the basin [6,19-20].

The Anambra Basin plunges to the south and southwest beneath the Palaogene to Recent Niger Delta Basin which is seen as the present day continuation of Cretaceous to Recent deltaic build out on the Atlantic Passive Margin of Nigeria.

The entire region of the Anambra basin was uplifted in the Oligocene-Miocene Period to form a 500km long cuesta [21-22]. The study area is located at the crest of the cuesta where elevations are more than 200 meters on average and reach up to 500 meters at the top of flat topped residuals hills and mesas [23].

2.2. Stratigraphy

The Anambra Basin has accumulated up to 3Km thick Campanian to Maastrichtian clastic sediments in regressive and transgressive cycles (Fig. 2).

The basal stratigraphic unit in the Anambra Basin is the Nkporo Group [24-25]. The Nkporo Group comprises of the Nkporo Formation with dark grey shales and thin layers of sandstones and limestone; the Enugu Formation with black carbonaceous shales interbedded with thin layers of sandstone and siltstone; and the Owelli Formation with massive medium to coarse grained sandstones with pebble bands. The Mamu Formation consists of sandstones, sandy shale, sand-silt-shale heteroliths and coal seams [6,8,21,26-27].

The Ajali Formation consists of friable, white, cross bedded sandstones with thin beds of white mudstone. It is characterized by large scale crossbedding with foreset dips as high as 25°. Bands and lenses of intra-formational breccia and pebbles occur. The thickness of the Ajali Formation is highly variable along the Anambra Basin but seems to be thickest around the study area, where it is estimated to be more than 500m thick. The Ajali formation contains very rare fragmentary plant remains and burrows but has been dated to the Maastrichtian from its stratigraphic position [3]. It is the continental sequence that, in combination with the paralic Mamu Formation and the marine Nkporo Group forms the Anambra Basin regressive delta complex [16].

The Nsukka Formation consists of alternations of sandstones shales and coals seams similar to the Mamu Formation. In the study Area it occupies the top of flat topped hills and mesas with a clear contact with the Ajali Formation. The Nsukka Formation marks a return to paralic conditions at the end of the Maastrichtian into the Danian [28-29].

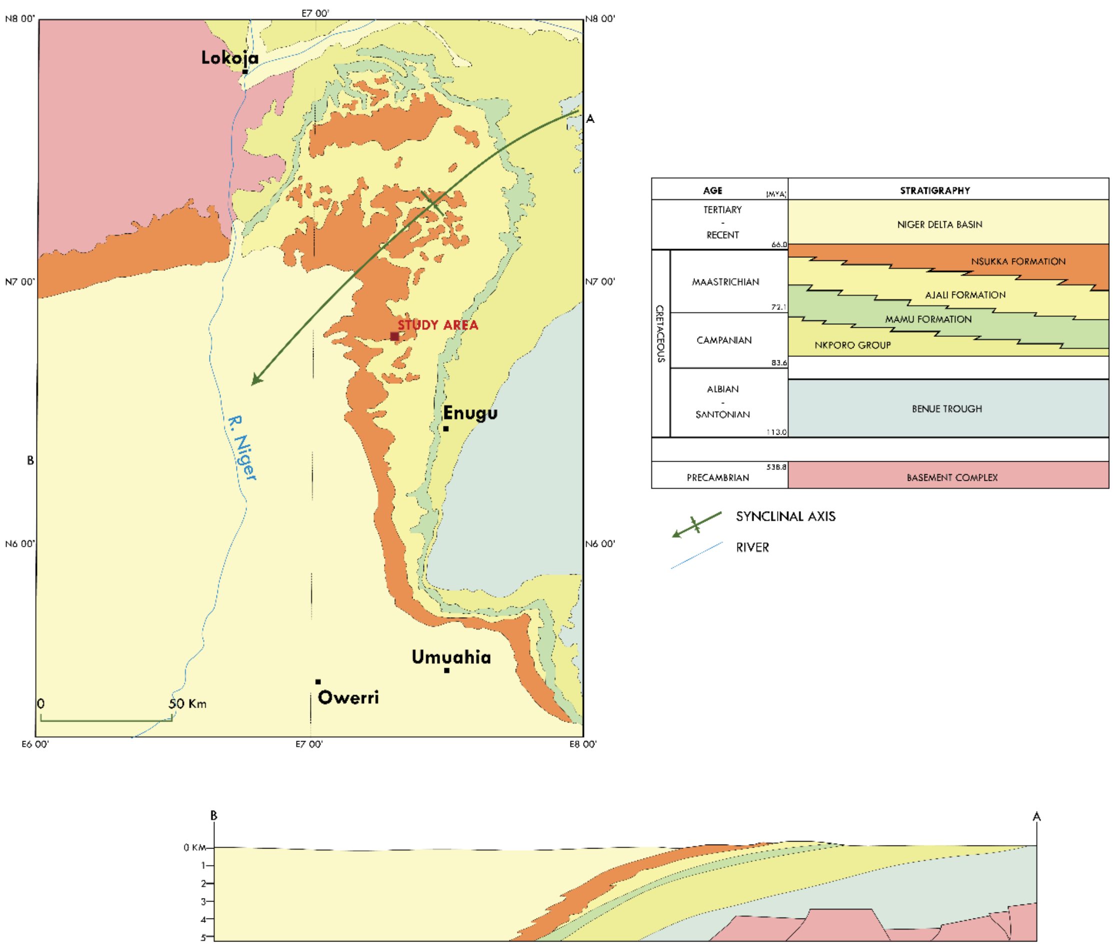


Figure 2. Geological map of the Anambra Basin, showing the stratigraphic units. Cross section shows relationship with the preceding Benue Trough and the succeeding Niger Delta Basin.

3. Methodology

3.1. Field observations

Outcrop observations and descriptions formed the basis of both facies and paleoenvironmental analyses that was carried out. Thirteen (13) outcrops were visited in the area, most of which were sand quarries where, due to the friable nature of the sandstones, extensive sand mining is taking place. Sedimentary logs were collected detailing gross sedimentary rock characteristics including: rock and sand grain characteristics and sedimentary structures. Sedimentary bedding relationships and outcrop scale architecture were also observed. Representative samples of unconsolidated sand, pebbles as wells as orientation data from cross beds were collected for granulometric, morphometric and paleocurrent analyses respectively.

3.2. Granulometric analysis

Eight (8) sandstone samples were collected from three locations; SIO03/ Twin Quarry 2 Owele-Ogbede road, Nkpologu, SIO04/ Inactive Quarry behind Gabvinco Foundation Limited, Nkpologu and SIO08/ Active Quarry 1, Ugbene-Ajima, TCC road were used for grain size analysis.

50 gram samples were sieved with a Rotap™ Shaker with mesh sizes 0.5 phi apart. The weights of the retained sieve fractions were normalized and their percentages and cumulative percentages calculated. These percentages were used to calculate univariate statistical parameters: mean size (M_z), sorting or standard deviation (σ^2), Skewness (Sk_1) and kurtosis (K_G), as defined by Folk and Ward [30]. These univariate statistical parameters were then used in bivariate discriminant plots [31-32] and to calculate a multivariate parameter which is used for further interpretation of depositional environment using the following formular after Sahu [33]:
$Y < 65.3650$ indicates beach deposition; and $Y > 65.3650$ indicates shallow marine deposition.
Y_U (Shallow marine: Fluvial) $= 0.2852\ M_Z - 8.7604\sigma^2 - 4.8932\ Sk_1 + 0.0482\ K_G$
$Y < -7.419$ indicates fluvial deposition; and $Y > -7.419$ indicates shallow marine deposition.

3.3. Pebble morphometric analysis

One hundred and ten (110) pebbles were selected from distinct pebble horizons in the sandstones at 2 outcrop locations. Pebble with fresh breaks and cracks were avoided or discarded while sampling as a precaution. Three mutually perpendicular axes: the long (L), the intermediate (I), and the short (S) axes of each pebble is measured with the veneer callipers. These measurements were used to calculate form indices for each pebble:

- Maximum Projection Sphericity (MPS): $\sqrt[3]{S^2/_{LI}}$
- Oblate Prolate Index (OPI): $\dfrac{\left({}^{(L-I)}/_{(L-S)} - 0.5\right)}{{}^{S}/_{L}}$
- Flatness Index (FI): $(S/L)\%$

These indices were used in bivariate discriminant plots: MPS against OPI, and FI against MPS, following the methods of Dobkins and Folk [34] and Stratten [35]. The parameters were plotted on the Sphericity-Form Ternary Diagram of Sneed and Folk [36] in order to determine the form classes of the pebbles found at the different outcrop locations.

3.4. Paleocurrent analysis

Azimuth and inclination of mainly planar crossbed sets were measured at 2 outcrop locations. The azimuth of the crossbeds were used to plot rose diagrams with class intervals of 30°, in order to determine either uni- or bi- directional flow patterns.

A measure of the distribution of the orientation of the azimuth of crossbeds can be described by computing relevant statistics. The Mean Vector Azimuth (MVA) is a measure of the mean direction of the depositional agent and is used to infer regional slope and source direction. Each crossbed azimuth measurement is represented as a unit vector and its directional components in a coordinate system. The MVA is the resultant of these vectors given by: $MVA = \tan^{-1}(\sum_{i=1}^{n}\cos\theta_i / \sum_{i=1}^{n}\sin\theta_i)$.
Vector strength ($\bar{R}$) is a measure of the direction and the magnitude of the depositional agent of sediment. High values of vector strength indicate low dispersion and low values indicate

high dispersion. $\bar{R} = \frac{\sqrt{\sum_{i=1}^{n} \cos\theta_i^{\,2} + \sum_{i=1}^{n} \sin\theta_i^{\,2}}}{n}$

The variance (σ^2) is a measure of the variability of the paleocurrent pattern and hence the flow direction. It can be used to interpret environment of deposition. $\sigma^2 = \frac{\sum(A_i - A)^2}{n-1}$
where: Ai= individual measurements and n = total number of measurements

Variance values of less than 2000 are indicative of a fluviatile environment, 2000-6000 indicates fluviatile-deltaic environment, 6000-8000 signifies shallow marine environment and greater than 8000 show a marine environment.

4. Results

4.1. Facies description

3 lithofacies were described from descriptions of outcrops of the Ajali Formation in the study area.

Crossbedded Sandstone Facies is the predominant facie is all the exposures. It consists of medium to fine grained (and sometimes pebbly) sandstones. The sandstones are white when fresh but iron stained to yellow, purple and even deep red. The are characterized by extensive cross stratification; a feature that is diagnostic of this facies. The cross beds are typically planar or trough with evidence of current reversals (herringbone crossbed structures) as well as reactivation surfaces (Fig 3A). Some of the cross bed forsets show millimetre thin mud drapes (Fig 3B). This is the characteristic facies of the Ajali Formation, observed across the Anambra Basin.

The Grey Shale Facies is found associated with the Crossbedded Sandstone Facies in several outcrops in the study area, where it forms thin (10cm – 20cm) layers interbedded with the sandstones (Fig. 3C). The rocks of this facies are light grey shales and mudrocks which may sometimes be discoloured by ferruginization. They are more predominant towards the topmost sections of the sandstone outcrops.

The Laminated Sandstone Facies consists of white, poorly sorted and clayey sandstone. The sandstones of this facies are characteristically parallel laminated (Fig. 3D). At the outcrop locations where this facies is present, it is located on top of the Crossbedded Facies and marks the transition of the Ajali Formation to the finer grained facies of the overlying Nsukka Formation.

Facies relationships observed from the correlation of outcrop logs show a transition from the Crossbedded Facies in the southeast of the study area to Laminated Sandstone Facies towards the northwest (Fig.4).

4.2. Granulometric analysis

Determined univariate and multivariate parameters from the grain size distribution data are summarized in Table 1. The results show that the sandstones of the cross bed facies are medium grained, moderately to poorly sorted, symmetrical and platykurtic to very platykurtic

Calculated multivariate parameter values for the samples show majority of values that classify as fluvial depositional environment. This is also apparent in sorting vs mean size bi-variate plot where all of the samples plot in the fluvial section of the chart (Fig 5). There is greater variability in results in the sorting vs skewness chart, with half the samples plotting in the beach section of the chart and the other half in the fluvial section.

Table 1. Summary of univariate and multivariate parameters determined from granulometric analysis.

Sample	Mz	σ^2	Ski	Ku	YU	Environment
SIO/3.1	1.172	0.905	0.160	1.79	-8.2967496	Fluvial
SIO/3.3	0.884	1.408	0.054	0.554	-12.3200564	Fluvial
SIO/3.5	1.578	0.941	0.068	0.695	-8.09273294	Fluvial
SIO/4.1	1.556	0.905	0.056	0.637	-7.7277066	Fluvial
SIO/4.3	1.513	0.867	0.289	0.548	-8.5514804	Fluvial
SIO/4.7	1.084	1.347	-0.086	0.616	-10.9767108	Fluvial
SIO/8.1	1.308	1.066	0.098	0.621	-9.4151462	Fluvial
SIO/8.3	1.838	0.922	-0.131	0.940	-6.866572	Shallow marine

Figure 3. A. Crossbedded Sandstone Facies of the Ajali Formation. Planar and trough crossbeds, and reactivation surfaces are visible. B. Close-up view of the crosbedded showing mud drapes and particles. C. Thin bands of Grey Shale Facies forming more resistant interbeds with the Crossbedded Sandstone Facies. D. Outcrop of the Laminated Sandstone Facies of the Ajali Formation.

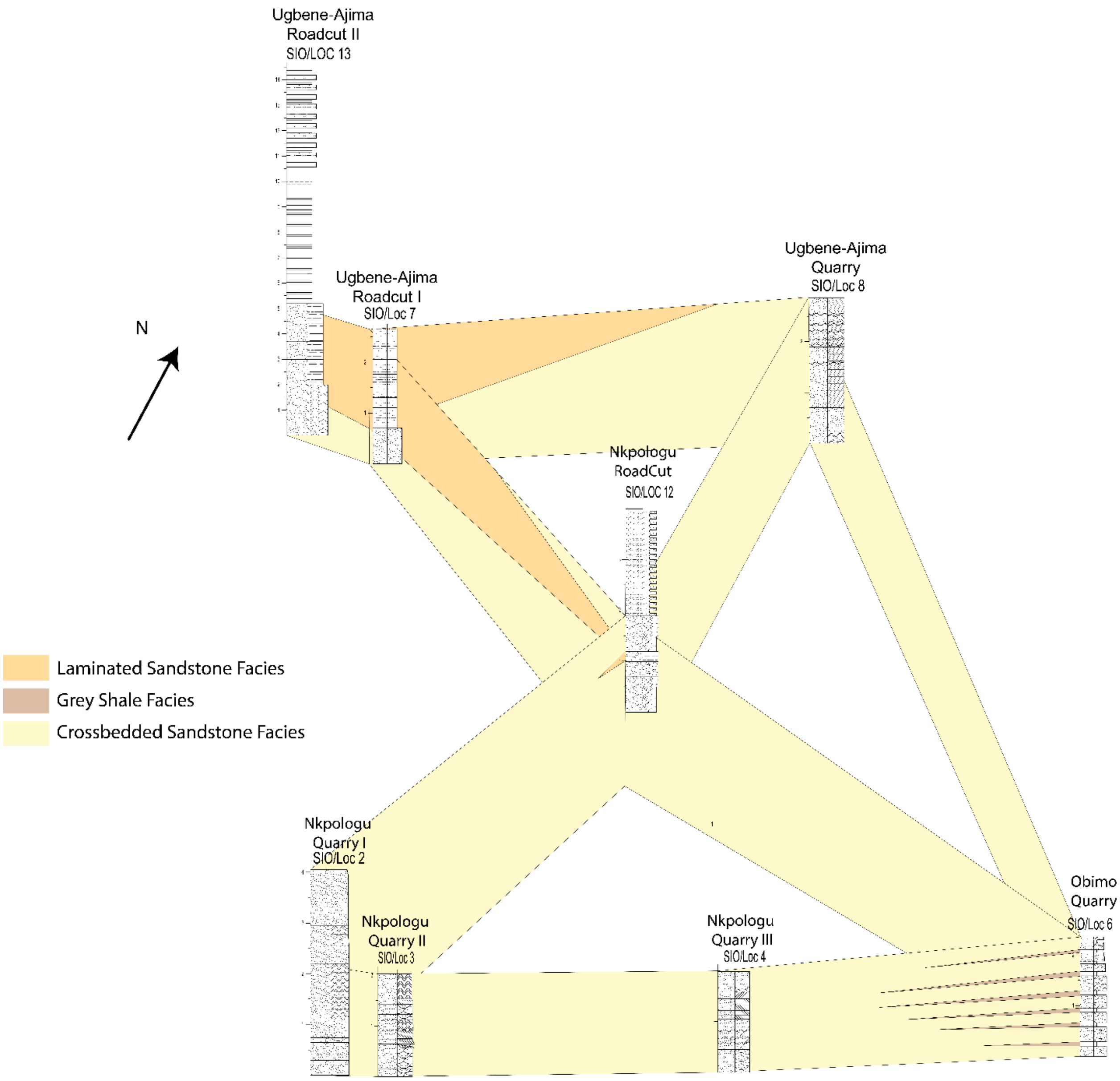


Figure 4. Fence diagram correlating log sections across the study area.

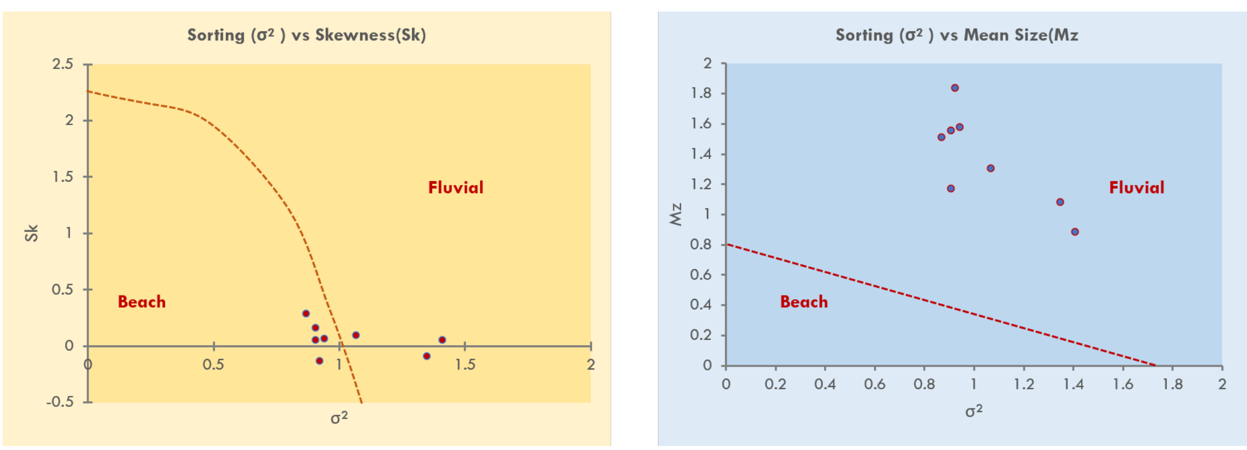
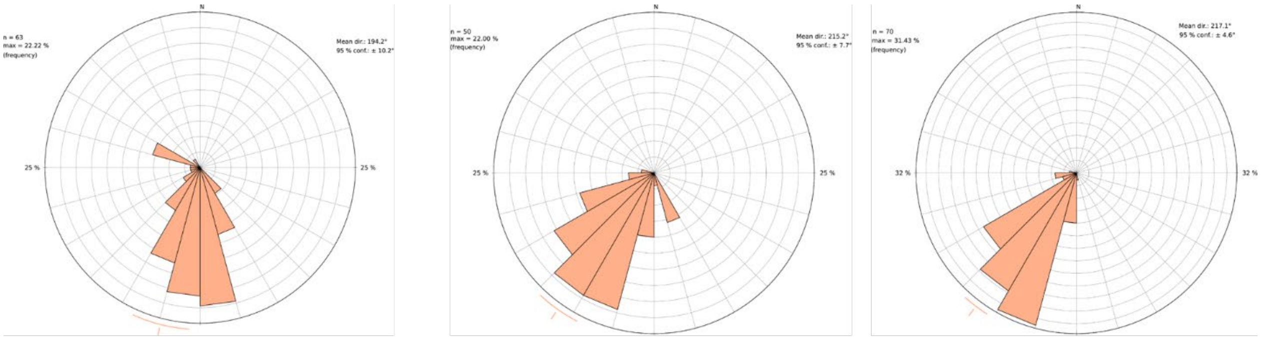


Figure 5. Bivariate discriminatory plots: Sorting vs Skew [31], and Sorting vs Mean Size [32].

4.3. Palaeocurrent analysis

A summary of the paleocurrent results from the 3 outcrops are shown in Figure 6. MVA values show a paleocurrent direction to the SSW, Vector Strength values of approaching 1 show a unimodal direction of flow. Variance values (less than 2000) show low dispersion and, in combination with the vector strength values, point to a fluvial system.



Location	Vector Strength (R)	Circular Standard Deviation	Circular Variance	Mean Vector Azimuth (MVA)	Confidence Interval (95%)	Variance
SIO01/Amono	0.7791	0.4399	0.0922	194.2	+/- 10.2	1763.911164
SIO06/Boundary	0.8962	0.1211	0.0073	215.2	+/- 7.7	730.8512816
SIO08/Ugbene-Ajima	0.9462	0.1517	0.0114	217.1	+/- 4.6	370.1405181

Figure 6. Rose diagram of crossbed forset orientations for the sampled locations. Table shows a summary of calculated paleocurrent statistics.

4.4. Pebble morphometry

Pebble morphometry shows that the Maximum Projection Sphericity ranges from 0.57-1.01, Oblate Prolate Index ranges from -0.82-1.26, and the Flatness Index from, 25.53-72.73. Ternary plot of pebble morphometry values of locations SIO07/ Roadcut 1 Ugbene-Ajima (Fig.7) and SIO08/ Quarry 1 Ugbene-Ajima (Fig. 8), show 12% and 16% of the pebbles are classified as very bladed (VB) and 88% and 84% as bladed (B) respectively. All the pebbles from the 2 locations plot in the fluvial portion of the maximum projection sphericity vs. flatness index and oblate prolate index vs. maximum projection sphericity binary plots.

5. Discussion

5.1. Environment of deposition

There have been varying interpretations of the depositional environment of the Ajali Formation ranging from fluvial [7,12] to fluvio-deltaic [9] to tidal [3,10-11]. The white colour and medium grain size and poor sorting of the sandstones of the Crossbedded Sandstone Facies plus its distinctive sedimentary structures (the planar and trough cross bedding) suggests a fluvial channel deposition environment. The extensive reactivation surfaces and channelization are as result of shifting fluvial channels within its sandy bedload bedload, a characteristic of braided river systems. The thin interbedded grey shale layers of the Grey Shale Facies represent overbank muds associated with braided fluvial systems. They light grey colour of the shales are indicative of aeration and shallow water.

Reversal in cross bed direction, herringbone crossbeds and mud drapes on cross bed foresets in the Crossbedded Sandstone Facies is indicative of the influence of tides. This influence becomes more marked with the transition to the Laminated Sandstone Facies. The fine grained nature and poor sorting of the sands, as well as the planar lamination points to greater tidal influence as the braided fluvial setting passes into an estuarine coastal setting.

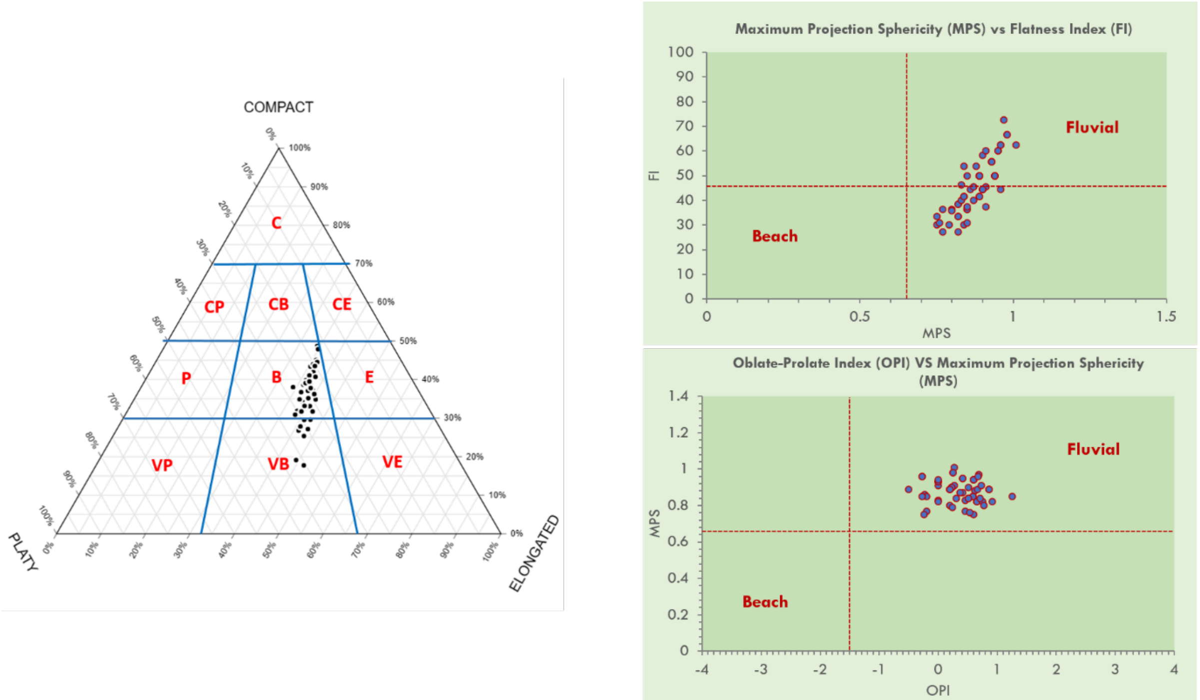


Figure 7. Summary of morphometric analyses of pebble collected from Ugbene-Ajima Hill (SIO/07). Ternary diagram (left) showing form classification and bivariate discriminatory plots (right) after the method of Dobkins and Folk [34]

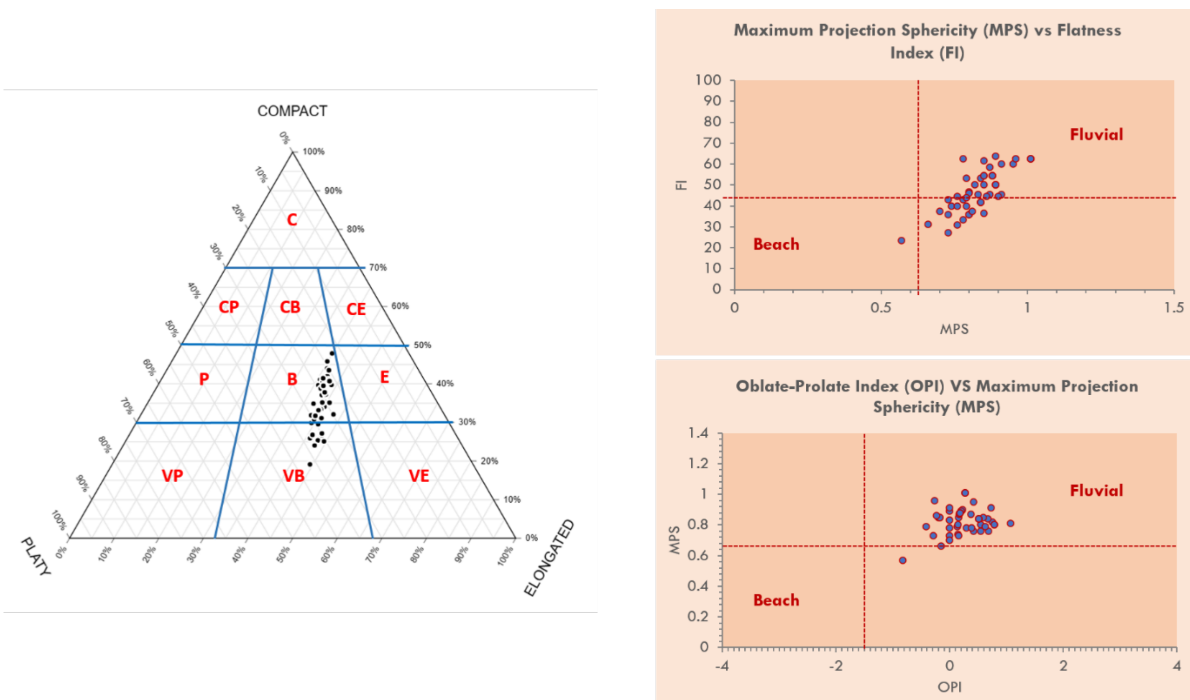


Figure 8. Summary of morphometric analyses of pebble collected from Ugbene-Ajima TCC Road (SIO/08). Ternary diagram (left) showing form classification and bivariate discriminatory plots (right) after the method of Dobkins and Folk [34].

5.2. Provenance and geologic history

Unidirectional south-westerly paleocurrents point to a north eastern provenance. Sediments that formed the Ajali formation in the study area came from the uplifted Abakaliki Anticlinorium containing Albian to Santonian clastics. The textural and mineralogical maturity of the Ajali formation in the study area is evidence that the sandstones are reworked.

The uplift of the Abakaliki Anticlinorium during the Santonian created the synclinal Anambra basin to the west. A major transgression in the Campanian led to the creation of an extensive shallow marine shelf trending NW-SE in the study area. The Campanian to Maastrichtian Age saw a gradual regression of the coastline towards the southwest as eroded sediments from the Abakaliki Anticlinorium created a fluvio-deltaic complex forming the basin fill of the Anambra basin. In the study area complex braided rivers flowed southwestwards to a tidally influenced marginal marine coastline (Fig. 9). The shallow nature of the shelf made the area sensitive to sea level fluctuation leading to fluvial incision and channel filling as well a tidal reworking.

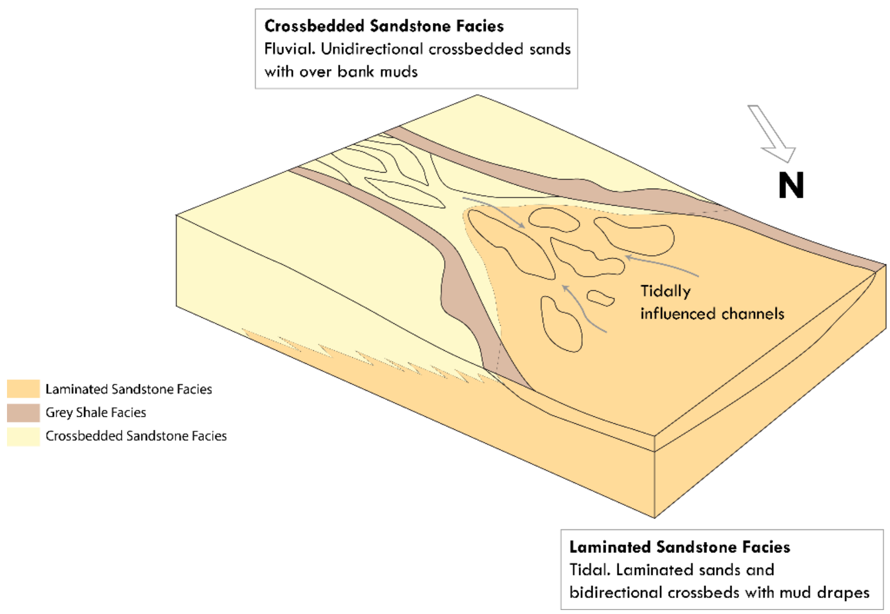


Figure 9. Depositional model showing the relationships between the observed facies.

6. Conclusion

Detailed facies and paleoenvironmental analysis, based on study of multiple outcrop sections, the analysis of paleocurrent indicators and granulometric analysis, was carried out on the Maastrichtian Ajali Formation in the Nkpologu-Ugbene Ajima area of southeastern Nigeria. 3 lithofacies were delineated: The Crossbedded Sandstone Facies from a fluvial environment, Grey Shale Facies formed from overbank muds interbedded with the Crossbedded Sandstone Facies, and the Laminated Sandstone Facies from a tidal environment.

Granulometric analysis on selected sand samples show that they Ajali Formation is medium grained, moderately to poorly sorted, symmetrically skewed and platykurtic-very platykurtic. The pebble forms sampled and analysed are mostly bladed to very bladed. Bivariate plots and multivariate statistical calculations also buttress a tidally influenced fluvial paleoenvironmental interpretation. Paleocurrent analysis show very strong unimodal directions towards the southwest. This suggests a northwestern provenance. The Ajali Formation is interpreted to have been deposited in braided rivers, carrying sediment eroded from the Abakaliki Anticlinorium and emptying into a tidally influenced shallow shelf towards the southeast of the study area.

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