# A Regional Evaluation of the Paleodepositional Environment of the Ajali Formation in the Anambra Basin, Nigeria

Odumodu, Chukwuemeka Frank and Ugwuona, Emmanuel Nwachukwu

**Abstract** --- Pebble morphometric, sand textural studies as well as lithofacies study and paleocurrent analysis were carried out so as to decipher the paleodepositional environment of the Ajali Formation, in the Anambra Basin. The lithofacies study suggests that the Ajali Formation consists of six sedimentary facies; coarse grained cross-bedded sandstone – sandflat, ripple laminated fine grained sandstone - tidal channel, ripple laminated heteroliths – mixed flat, ripple laminated mudstones – mudflat, interlaminated clay and thin pebbly sandstone – point bar and claystone facies – floodplain. Results of form indices calculated for pebbles indicate that the mean coefficient of flatness ranges from 32.74 to 49.53, the mean sphericity ranges from 0.532 to 0.723, the mean oblate – prolate index range from 0.159 to 4.505, while the mean roundness index varies from 0.311 to 0.498. These results suggest that means of coefficient of flatness and sphericity lies within and above the limits for fluvial pebbles, thus suggesting both fluvial and (beach) shallow marine influence. Bivariate plots of coefficient of flatness against sphericity and sphericity against oblate – prolate index suggest that the formation was deposited by both fluvial and (beach) shallow marine processes. Plots made on the sphericity form diagram do not show any significant trend between sphericity and pebble sizes. Bivariate plots of mean diameter against standard deviation and skewness against standard deviation favours a fluvial origin for the sandstones. Most sedimentary structures such as herringbone cross bedding, reactivation surfaces and bimodal paleocurrent pattern are suggestive of tidal origin. The sedimentary facies is suggestive of deposition in both fluvial and tidal settings. This study has shown that the Ajali Formation is a product of fluvial transport and tidal sedimentation in a shallow marine environment.

**Keywords***: Anambra Basin, Ajali Formation, Coefficient of flatness, Oblate-prolate index, Sphericity, Roundness, fluvial origin*

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## 1 Introduction

Previous interpretations on the paleo-depositional environment of the Ajali Formation have remained largely controversial. The Ajali Formation has been severally interpreted as formed in a fluvial / fluviodeltaic environment [28], [14] and / or a tidally influenced environmental setting [4], [2], [18]. These interpretations were based mainly on facies, sedimentary structures, trace fossils, petrography and paleocurrent patterns. Previous studies using pebble form indices for paleoenvironmental interpretations for the Ajali Formation [3], [25] supports the fluvial origin for the formation. These studies may however be biased, since they considered pebbles from only one or very few outcrops. The present study therefore reports and evaluates the results of measurements carried out on pebbles from five different outcrops of the Ajali Formation from several parts of the Anambra Basin (Fig. 1). The results of these studies are also corroborated with other evidence such as sand textural parameters, sedimentary structures / sedimentary facies and paleocurrent studies from several outcrops of the formation in the Anambra Basin.

- *Odumodu, Chukwuemeka Frank holds a Ph.D in Petroleum Geology from the University of Nigeria, Nsukka.. He is a Senior Lecturer in the Department of Geology at the Anambra State University, Uli. E-mail: raluchukwu@yahoo.com*
- *Ugwuona, Emmanuel Nwachukwu is currently pursuing doctoral degree in Petrology at the University of Nigeria, Nsukka, Nigeria. He is a Lecturer in Anambra State University, Uli, Anambra State, Nigeria. Email: marynwachukwu@yahoo.com*

## 2 Geological Background

The study area lies within the Anambra Basin in southeastern Nigeria, between longitudes 6°30′E and 8°00′E and latitudes 5°20′N and 7°50′N (Fig.1). The stratigraphic sequence in the Anambra Basin is well discussed in several literatures [28], [1], [26]. The oldest sedimentary formation in the Anambra Basin is the Nkporo Group (Nkporo Shale, Enugu Shale, the Afikpo Sandstone and the Owelli Sandstone). The Nkporo Group is Campanian to Lower Maastrichtian in age. It consists of dark gray shales and mudstones and occasionally thin beds of sandy shale, sandstone, shelly limestone and coal. The Nkporo Group is conformably overlain by the Mamu Formation. The Mamu Formation consists of an assemblage of sandstones, shales, mudstones and sandy shales, carbonaceous shales and coal seams. The Mamu Formation is conformably overlain by the Mid-Maastrichtian Ajali Formation. The Ajali Formation consists of thick, friable, poorly sorted, medium to coarse-grained sandstones, typically white in colour, with distinct mud drapes and burrows. It is one of the most extensive stratigraphic units in this basin. The Ajali Formation is conformably overlain by the Late Maastrichtian to Danian Nsukka Formation.

## 3 Materials and Methods

Ten lithologic sections were systematically logged at the following locations; Ugwuaba-Asaga Ohafia, Isiukwuato, Uturu, Ihube, Okigwe and Arochukwu all in Abia State, Mbiabong in Cross-River State, Abor near Ngwo, in Enugu State, Idah in Kogi State and Fugar in Edo State of Nigeria (Fig. 2). The log-

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ging also involved the collection of sedimentological, ichnological and paleocurrent data. Quartzose pebbles were randomly but carefully collected from pebbly units. The size of the pebbles collected vary from - 2ϕ to -5ϕ. Pebbles collected include only pebbles with isotropic constitution, high resistivity to wear and high abundance. Broken and feldspathic pebbles were carefully avoided. The pebbles were washed and labeled appropriately. The long (L), intermediate (I) and short (S) axes of each of the five sets of pebbles collected were measured using the vernier caliper, following the procedures described by [31], [6]. The pebbles were grouped into half phi size classes according to their intermediate axes, which are also referred to as "sieve diameter" (Table 1).Roundness of pebbles was determined through visual comparison with [29] image chart. This method was also utilized by [31], [22], [24], [25]. About 15 sandstone samples were also collected and studied using the conventional sieving method of [9]. The samples were disaggregated carefully and 50 gram of each sample was sieved using half phi intervals and a 15 minutes sieving time. Critical percentiles (5ϕ, 16ϕ, 25ϕ, 50ϕ, 75ϕ, 80ϕ and 95ϕ) were computed from plotted frequency and smoothed frequency curves.

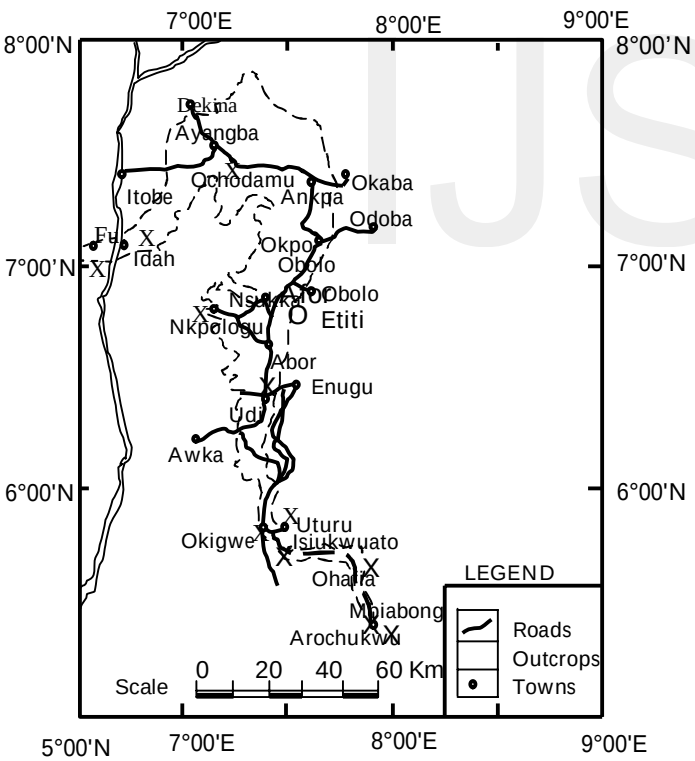


FIG. 1. – Outline Map of the Ajali Formation showing the locations of the outcrops studied

3.1. Computations

The values of the long, intermediate and short axes measured, were loaded into an excel spreadsheet. The following form indices were calculated by using the following formulas (Table 2) Means and standard deviations of morphometric indices were calculated for each set of pebbles, using known statistical formula as given below

$$\text{Mean} = \bar{x} = \frac{\sum x}{n} \text{ ---------- } (6)$$

$$\text{SD} = \sigma(n-1) = \frac{\sum x^2 - \frac{\left(\sum x\right)^2}{n}}{n-1} \text{ --- } (7)$$

Where $x$ = the deviations of each of the numbers $x$j from the mean, n = the number of samples in a population, σ = the standard deviation of a population. Textural parameters of sandstones such as graphic mean ($M_z$), inclusive graphic skewness ($S_{ki}$), inclusive graphic standard deviation or sortng ($\sigma_o$) and Kurtosis ($K_G$) were computed using appropriate formulae (Table 3) [20], [9].

Table 1: Grain size scales for pebbles [34]

| *mm* | *Phi* | *Class Term* |
|---|---|---|
| 48 - 64 | > - 5.5 | *Pebble* |
| 32 – 48 | > - 5.0 | |
| 24 – 32 | > - 4.5 | |
| 16 – 24 | > - 4.0 | |
| 12 – 16 | > - 3.5 | |
| 8 – 12 | > - 3.0 | |
| 6 – 8 | > - 2.5 | *Granule* |
| 4 - 6 | > - 2.0 | |

Table 2: Pebble morphometric Indices used for the study

| Morphometric Indices | Formula | Source |
|---|---|---|
| Flatness ratio<br>Coefficient of flatness | S / L<br>S / L * 100 | [19] |
| Elongation ratio | I / L | [19] |
| Maximum projection sphericity | $\left(\frac{S^2}{LI}\right)^{1/3}$ | [31] |
| Oblate – prolate index | $10\left[\frac{L-I}{L-S} - 0.50\right] S/L$ | [6] |
| Roundness (%) | Visual Estimation | [29] |

4 RESULTS

4.1 Pebble morphometric study

The computed form data and roundness data are given in Table 4 and 5 respectively. Pebble morphometric results (Table 4a) shows that the mean values of maximum projection sphericity range from 0.532 to 0.723 and mean values of oblate – prolate index range from 0.159 to 4.505. The mean values of the coefficient of flatness range from 32.74 to 50.82. The form

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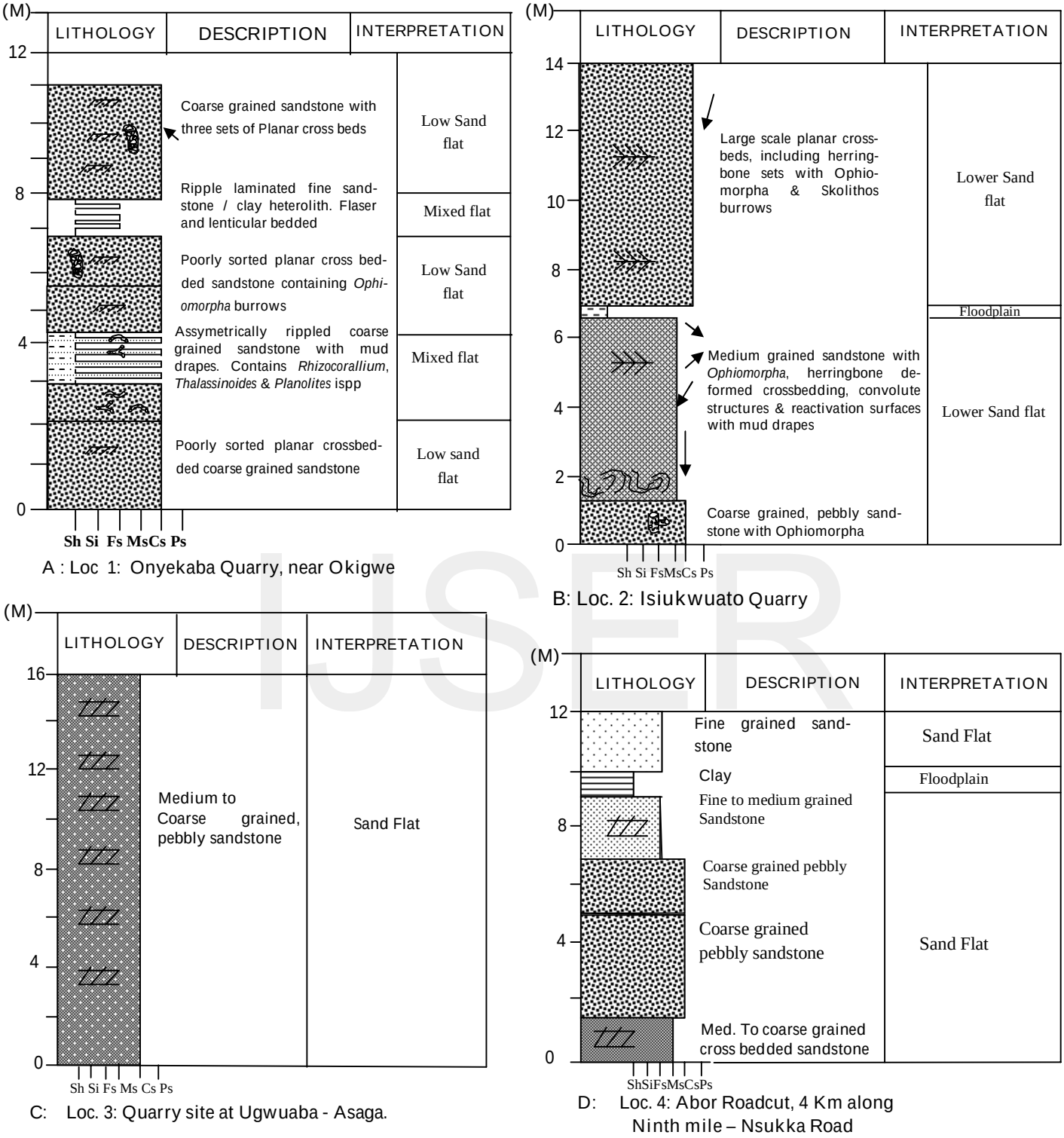


Fig. 2: Lithologs of the studied sections of the Ajali Formation

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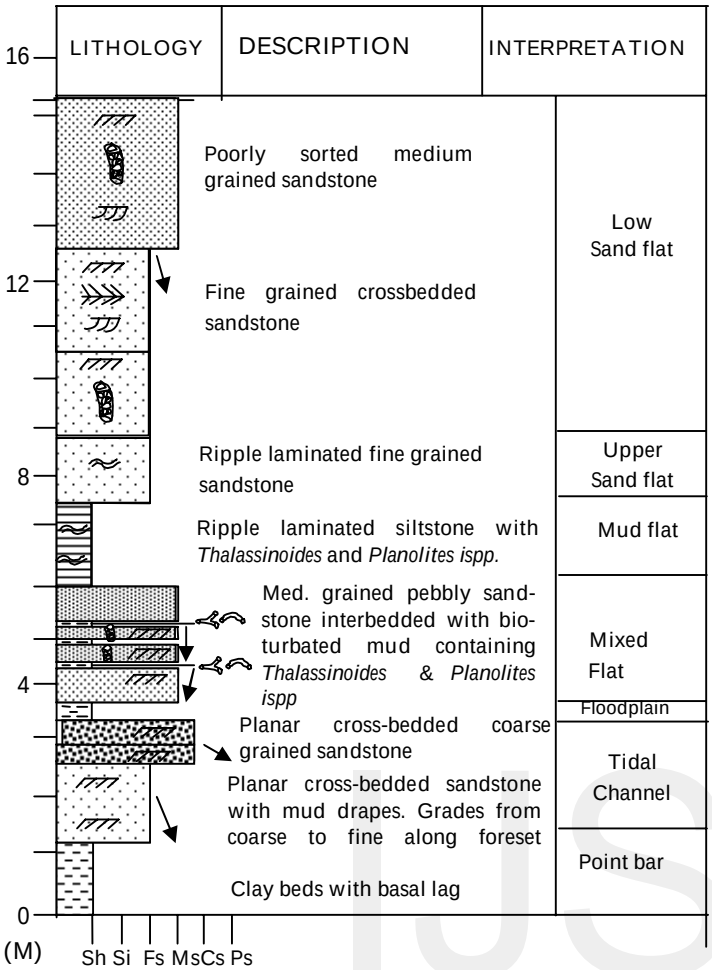
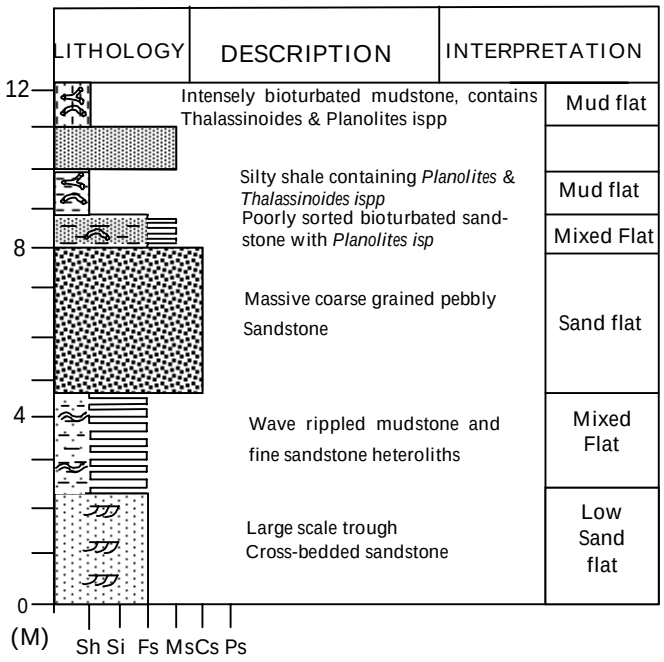
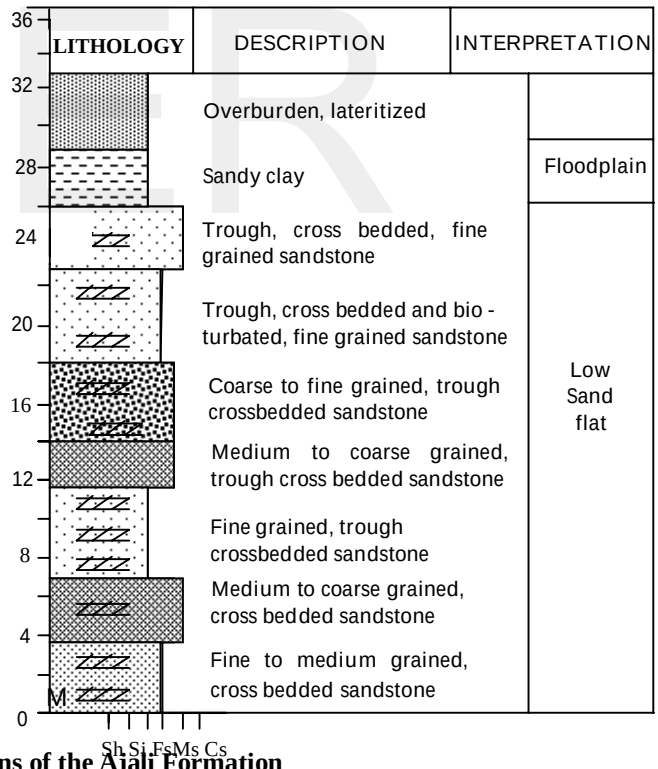



E: Loc. 5: Uturu Quarry




F: Loc. 6: Ihube Roadcut




G: Loc. 7: Mbiabong Quarry

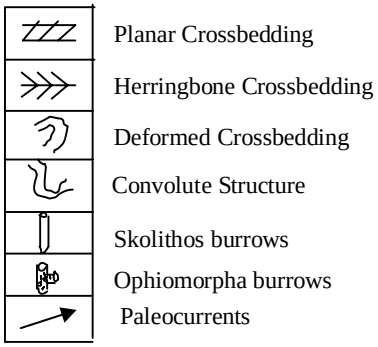



**Fig. 2: Lithologs of the studied sections of the Ajali Formation**

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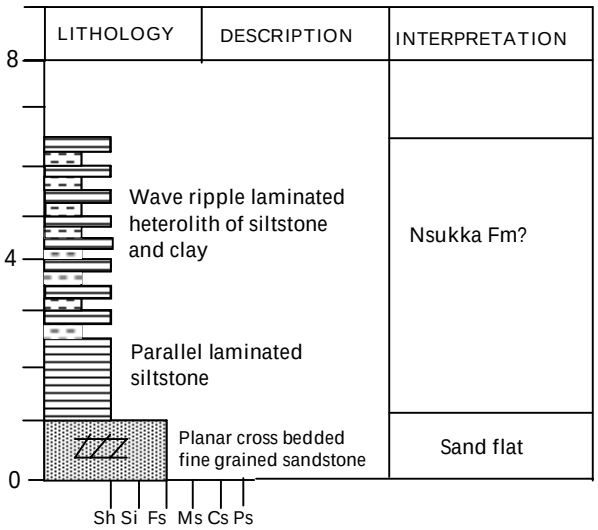
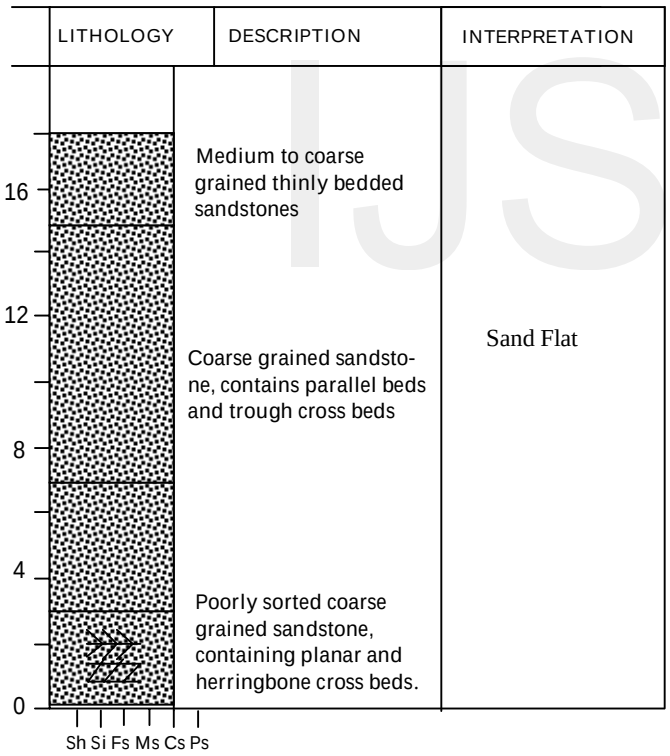
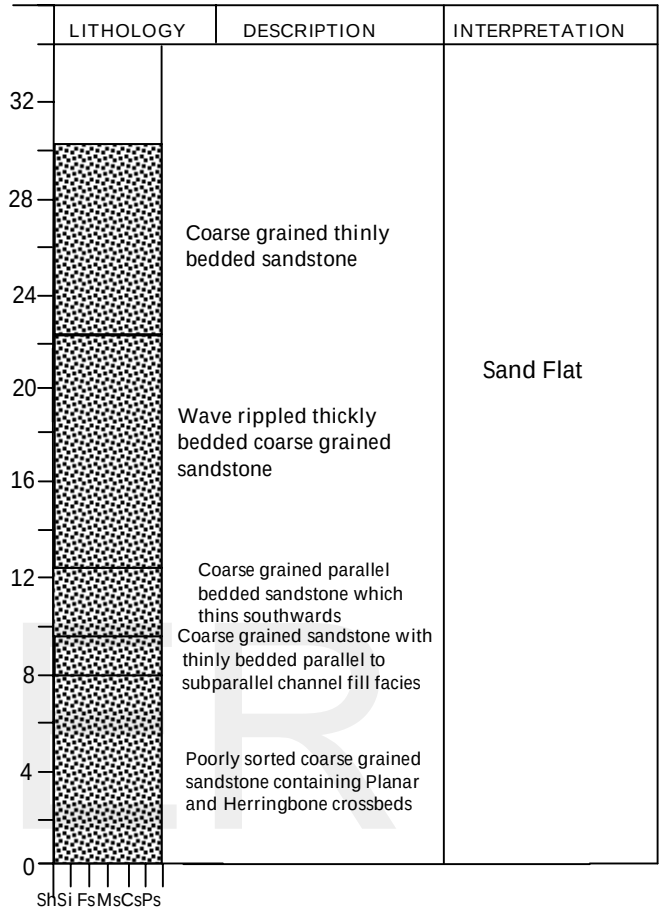



H: Loc 1 ; Idah – Nsukka Road




**I: Loc. 1: River section, behind Ega Market, Idah**




J: Fugar section

| Textural parameters | Formula | Source |
|---|---|---|
| Mean (Mz) | $\frac{1}{3}(Ø16 + Ø50 + Ø84)$ | [9], [10] |
| Standard Deviation or sorting ($\sigma$) | $\left(\frac{Ø84-Ø16}{2}\right) + \frac{Ø95-Ø5}{3.3}$ | " |
| Skewness ($Sk_i$) | $\frac{1}{2}\ \frac{Ø16+Ø84-2Ø50}{Ø84-Ø16} + \frac{Ø5+Ø95-2Ø5}{Ø95-Ø5}$ | " |
| Kurtosis ($K_G$) | $\frac{Ø95-Ø5}{2.44(Ø75-Ø25)}$ | " |

**Fig. 2: Lithologs of the studied sections of the Ajali Formation**

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Table 3: Textural Parameters

Table 4 : Pebble Form Indices for the Ajali Formation pebbles

| | n | Coefficient of flatness × | Coefficient of flatness s | Sphericity × | Sphericity s | Oblate -Prolate Index × | Oblate -Prolate Index s |
|---|---|---|---|---|---|---|---|
| (A) Combined form Data for pebbles larger than – 2.0 phi | | | | | | | |
| Locality | | | | | | | |
| 1. Ohafia | 50 | 50.82 | 7.38 | 0.723 | 0.055 | 2.818 | 3.775 |
| 2. Mbiabong | 50 | 32.74 | 14.31 | 0.532 | 0.131 | 0.159 | 7.506 |
| 3. Arochukwu | 40 | 49.53 | 11.56 | 0.694 | 0.095 | 1.295 | 3.737 |
| 4 Isiukwuato | 50 | 41.33 | 11.45 | 0.646 | 0.093 | 4.505 | 5.825 |
| 5 Enugu | 50 | 47.08 | 9.38 | 0.702 | 0.082 | 0.885 | 0.929 |
| (B) Form Data for Location 1 (Ohafia) | | | | | | | |
| Phi Class | | | | | | | |
| > - 2.5 | 7 | 45.77 | 3.52 | 0.721 | 0.036 | 6.836 | 2.680 |
| > - 3.0 | 38 | 51.61 | 7.60 | 0.723 | 0.056 | 2.174 | 3.642 |
| > - 3.5 | 5 | 51.83 | 0.08 | 0.723 | 0.079 | 2.088 | 0.286 |
| (C) Form Data for Location 2 (Mbiabong) | | | | | | | |
| > - 2.0 | 7 | 27.27 | 13.30 | 0.504 | 0.150 | 9.367 | 9.308 |
| > - 2.5 | 24 | 36.07 | 17.06 | 0.567 | 0.138 | 0.961 | 4.725 |
| > - 3.0 | 19 | 30.57 | 9.85 | 0.497 | 0.107 | - 4.603 | 6.213 |
| (D) Form Data for Location 3 (Isiukwuato) | | | | | | | |
| > - 2.0 | 4 | 44.34 | 14.21 | 0.717 | 0.118 | 9.488 | 3.635 |
| > - 2.5 | 22 | 37.11 | 9.43 | 0.624 | 0.089 | 6.705 | 6.262 |
| > - 3.0 | 21 | 45.43 | 12.43 | 0.665 | 0.092 | 2.103 | 3.714 |
| > - 3.5 | 3 | 39.49 | 6.06 | 0.598 | 0.033 | - 1.461 | 6.710 |
| (E) Form Data for Location 4 (Enugu) | | | | | | | |
| > - 2.5 | 12 12 | 46.31 | 8.61 | 0.725 | 0.072 | 1.548 | 0.620 |
| > - 3.0 | 36 36 | 47.55 | 0.10 | 0.694 | 0.086 | 0.645 | 0.926 |
| > - 3.5 | 2 | 43.35 | 3.59 | 0.689 | 0.043 | 0.386 | 0.386 |
| (F) Form Data for Location 5 (Arochukwu) | | | | | | | |
| > - 3.5 | 9 | 52.47 | 11.72 | 0.727 | 0.077 | 2.353 | 3.165 |
| > - 4.0 | 20 | 49.04 | 11.45 | 0.691 | 0.092 | 1.528 | 3.088 |
| > - 4.5 | 6 | 50.36 | 9.23 | 0.705 | 0.074 | 1.074 | 5.632 |
| > - 5.0 | 5 | 45.20 | 15.95 | 0.633 | 0.146 | - 1.274 | 4.483 |

indices are represented graphically by plots of coefficient of flatness against sphericity (Fig. 3) [32], and plots of sphericity versus oblate – prolate index (Fig. 4) [6].

### 4.2 Grain size analysis

Sieve analysis results for sandstones from Ajali Formation using graphic method are given in Table 6. Certain parameters such as graphic mean, inclusive graphic skewness, inclusive standard deviation, and kurtosis were calculated so as to use the standard plots of [11], [12], [13] and [21] to infer the paleo-depositional environments of the Ajali Formation. Plots of skewness against standard deviation (Fig. 5a) and mean diameter against inclusive graphic standard deviation (Fig. 5b) favours a fluvial origin for the sandstones.

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Table 5 : Roundness indices for the pebbles from the Ajali Formation

A) Combined roundness indices for pebbles of sizes for the five locations studied

| Location | n | Roundness × | s |
|---|---|---|---|
| 1 Ohafia | 50 | 0.311 | 0.127 |
| 2 Mbiabong | 50 | 0.317 | 0.121 |
| 3 Arochukwu | 40 | 0.484 | 0.126 |
| 4 Isiukwuato | 50 | 0.459 | 0.202 |
| 5 Abor | 50 | 0.498 | 0.118 |

B) Roundness indices for different fractions at the five locations studied

| | 1 | | | 2 | | | 3 | | | 4 | | | 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n | × | s | n | × | s | n | × | s | n | × | s | n | × | s |
| > - 2.0 | | | | 7 | 0.294 | 0.087 | | | | 4 | 0.573 | 0.132 | | | |
| > - 2.5 | 7 | 0.244 | 0.072 | 24 | 0.321 | 0.142 | | | | 22 | 0.461 | 0.221 | 12 | 0.503 | 0.138 |
| > - 3.0 | 38 | 0.327 | 0.130 | 19 | 0.319 | 0.108 | | | | 21 | 0.454 | 0.179 | 36 | 0.503 | 0.111 |
| > - 3.5 | 5 | 0.286 | 0.286 | | | | 9 | 0.467 | 0.167 | 3 | 0.300 | 0.312 | 2 | 0.385 | 0.148 |
| > - 4.0 | | | | | | | 20 | 0.491 | 0.113 | | | | | | |
| > - 4.5 | | | | | | | 6 | 0.517 | 0.090 | | | | | | |
| > - 5.0 | | | | | | | 5 | 0.450 | 0.154 | | | | | | |

C) Combined roundness indices of all pebbles for the different size fractions

| | n | Roundness × | s |
|---|---|---|---|
| > - 2.0 | 11 | 0.395 | 0.103 |
| > - 2.5 | 65 | 0.393 | 0.160 |
| > - 3.0 | 114 | 0.405 | 0.120 |
| > - 3.5 | 19 | 0.396 | 0.182 |
| > - 4.0 | 20 | 0.491 | 0.113 |
| > - 4.5 | 6 | 0.517 | 0.113 |
| > - 5.0 | 5 | 0.450 | 0.154 |

× is the mean roundness; s is the standard deviation of the observations

Table 6: Sieve Analysis Result (Graphic method) for the Ajali Formation

| Samples | Mean size | Standard Deviation | Skewness | Kurtosis | INTERPRETATION / REMARKS |
|---|---|---|---|---|---|
| Onyekaba Quarry | 0.73 | 1.07 | 0.25 | 1.02 | c,ps,fs,M |
| Mbiabong | 0.29 | 0.70 | - 1.50 | 0.86 | c,mws,vns,P |
| Abor | 1.70 | 0.88 | 3.10 | 0.77 | m,ms,vps,P |
| Arochukwu 1 | 2.00 | 0.60 | - 0.38 | 1.0 | m,ms,vns,M |
| Arochukwu 2 | 2.38 | 0.43 | - 0.43 | 1.18 | f,ws,vns,L |
| Arochukwu 3 | 1.76 | 0.88 | - 0.10 | 0.77 | vc,ms,ns,P |
| Ohafia 1A2 | 1.06 | 0.77 | -0.13 | 0.92 | m,ms,ns,M |
| Ohafia 1A3 | 0.83 | 1.03 | 0.30 | 0.87 | c,ps,ps,M |
| Ohafia 1A4 | 1.58 | 0.97 | 0.24 | 1.14 | m,ms,ps,L |
| Ohafia 1A6 | 1.43 | 0.81 | 0.15 | 0.94 | m,ms,ps,L |
| Ohafia 2A6 | 0.52 | 0.91 | 0.49 | 1.67 | c,ps,ns,M |
| Ohafia 1A9 | 0.62 | 1.07 | 0.02 | 0.98 | c,ms,ns,P |

LEGEND

f = fine grained, m = medium grained, c = coarse grained, vc = very coarse grained, ms = moderately sorted, mws = moderately well sorted, p = poorly sorted, fs = fine skewed, ns = nearly symmetrical,ns = negatively skewed vns = very negatively skewed, ps = positively skewed, M = mesokurtic, L = leptokurtic, P = platykurtic

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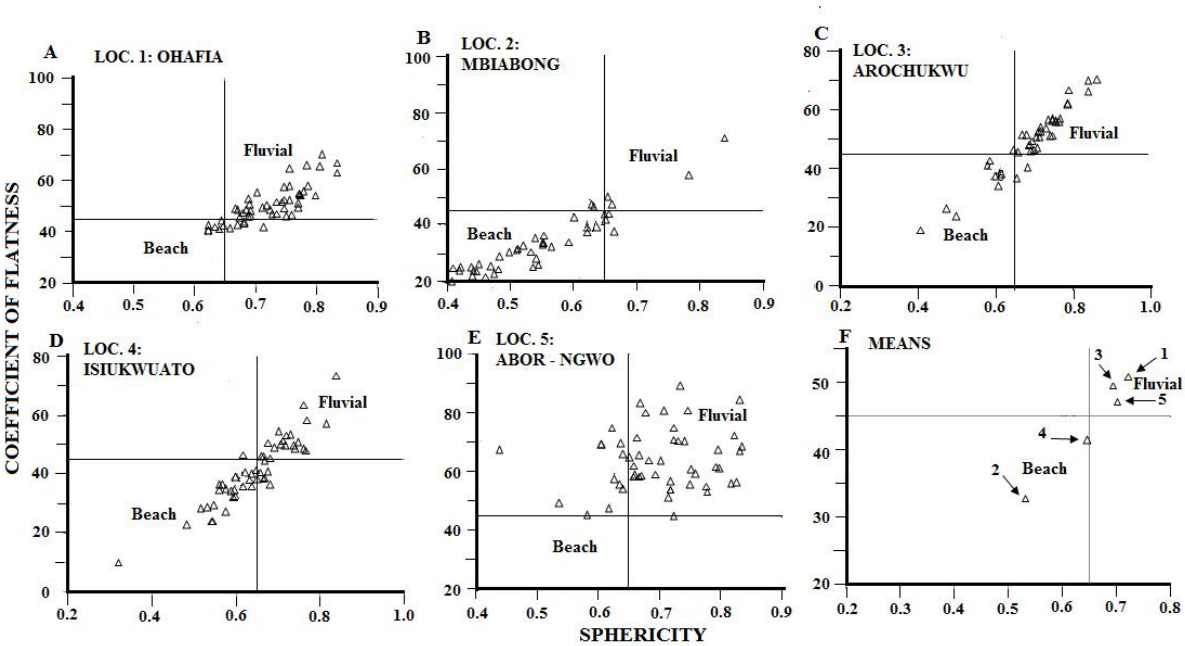


**FIG. 3 . - Graphical plots of coefficients of flatness and sphericity for individual pebbles at the five loactions studied ( A to E) and the means of these (F). Broken lines on these diagrams indicate the empirical lower limits of 0.65 for sphericity and 45 for coefficients of flatness of fluvial pebbles, determined by Stratten, 1974.**



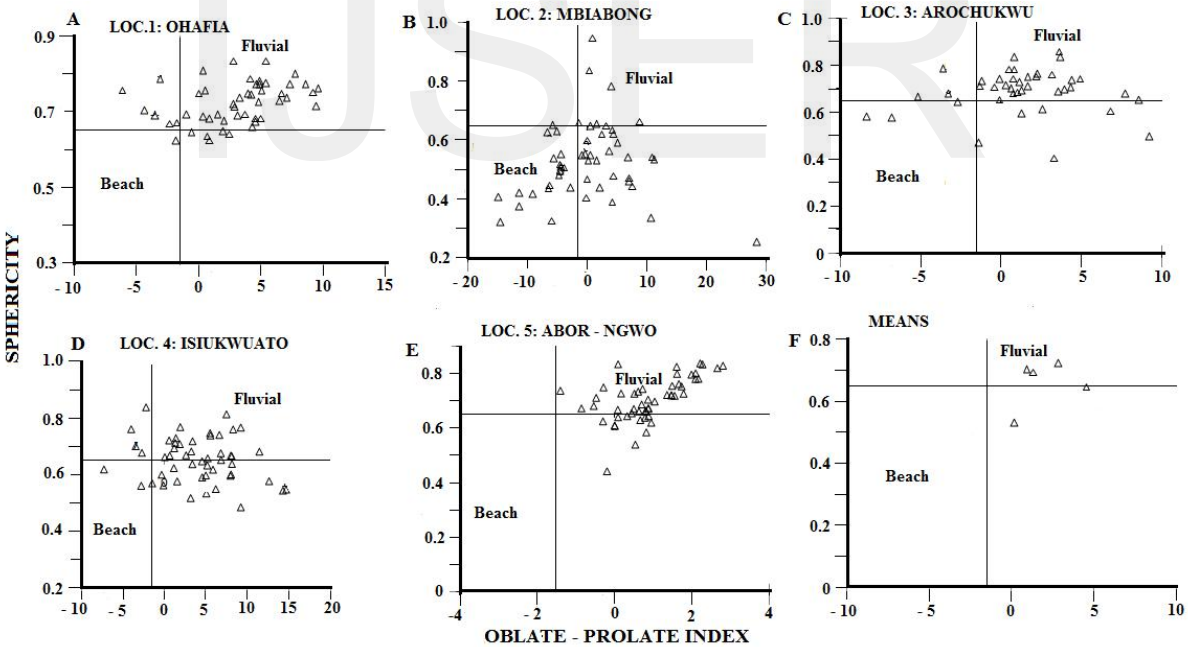


**FIG. 4 - Graphical plots of sphericity and oblate - prolate index for individual pebbles at the five locations studied ( A to E ) and the means of these (F). Broken lines on these diagrams indicate the empirical lower limits of - 1.5 for oblate - prolate index and 0.65 for sphericity for fluvail pebbles, determined by Stratten (1974).**

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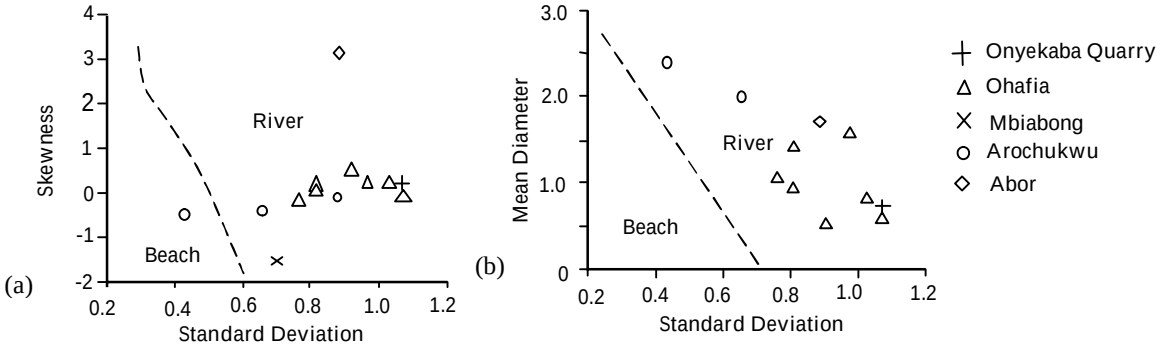


Fig. 5 (a): Bivariate plot of mean size against standard Deviation (After, Miola and Weiser, 1968) and (b): Bivariate plot of skewness against standard deviation (After Friedman, 1967 & Miola and Weiser, 1968)

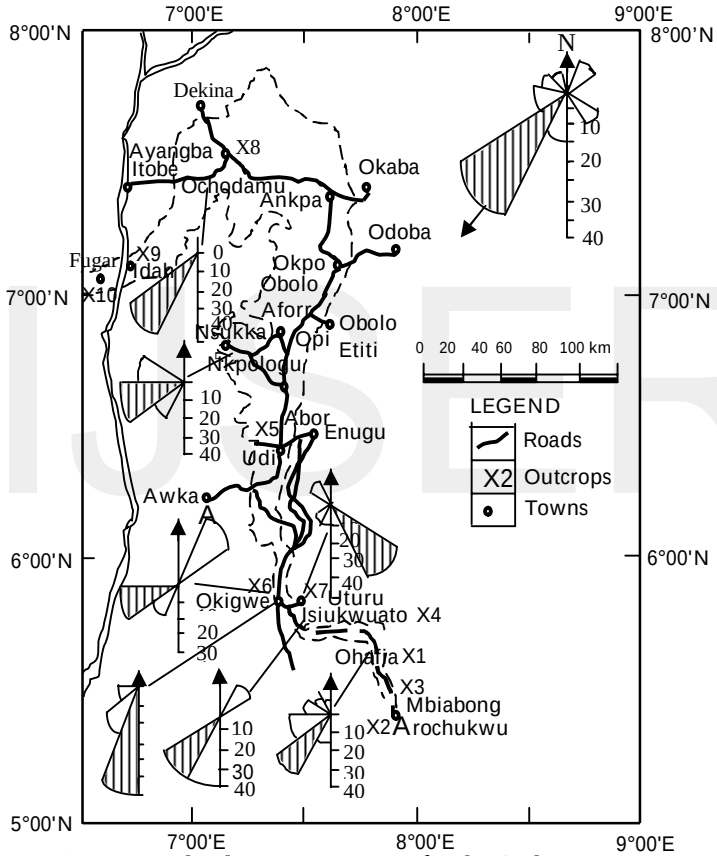


Fig. 6 – Regional paleocurrent pattern for the Ajali Formation

## 4.3 PALEOCURRENT ANALYSIS

The regional paleocurrent direction of the Ajali Formation was reconstructed using cross-bed data (Table 7) collected from several locations across the Anambra Basin (Fig. 6). These locations include (i) Ochodamu in Kogi State, (ii) Nkpologu in

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Enugu State, (iii) Umulolo junction, and (iv) Onyekaba quarry, in Okigwe, (v) Uturu, (vi) Isiukwuato, (vii) Ohafia, and (viii) Arochukwu, all in Abia State and (ix) Mbiabong in Cross-River State, (x) Idah in Kogi State and (xi) Fugar in Edo State of Nigeria. Tilt correction was not done because the beds are nearly horizontal. The regional rose diagram shows a bimodal paleocurrent pattern with the principal mode between 210° and 239° modal class. The vector mean azimuth calculated trigonometrically is 221° with a variance of 378° and standard deviation of 15°.

### 4.3.1 Sedimentary facies

The sedimentary facies of the Ajali Formation were defined using sedimentological and ichnological criterion. Six sedimentary facies were recognized and they include the following;

**1. Coarse grained cross bedded sandstone facies – Sandflat**

This facies is the most common sedimentary facies of the Ajali Formation in the Anambra Basin. It consists of poorly sorted medium to coarse grained sandstone with planar (Figs. 7h,8b,8e &8f), trough, herringbone (Figs. 7d, 7e & 8a) and convolute or deformed (Figs. 7a, 7b, 8c & 8h) cross beddings. The trace fossils present here include *Ophiormorpha* and *Skolithos* burrows (Figs. 7c, 7f, 8i & 8j), belonging to the *Skolithos* ichnofacies. It is characterized by bimodal-bipolar paleocurrent pattern. This facies were observed at Onyekaba quarry, Asaga-Ohafia, Isiukwuato quarry, Abor, Uturu, Ihube, Mbiabong, and at Idah and Fugar.

- Interpretation

The coarse grained crossbedded sandstone facies is interpreted as a sandflat using [5] model. Sandflats occur within the lower parts of most tidal flats and commonly contain dune cross bedding in areas with high current speed and ripple cross-lamination in areas where the current speed is lower [5]. Sandflats are commonly subject to subequal ebb and flow tidal current velocities, as indicated by common herringbone cross-bedding and reactivation surfaces. Soft sediment deformation structures such as convolute crossbeds are a common bedding feature in the intertidal parts of the sandflat.

2. Ripple laminated fine sandstone facies – Tidal channel

The ripple laminated fine sandstone facies is not very common in the Ajali Formation. It consists mainly of wave ripple laminated fine grained sandstones. Sedimentary structure present is mainly wave ripple lamination. This facies were observed at Uturu quarry and its thickness is about 1.5 metres.

- Interpretation

The tidal channel is indicated by a scoured or erosional base with pebble lag overlain by a fining upward succession of sandstone beds which ranges from coarse to fine grained and is interpreted as a tidal channel incised into the intertidal flat environment. The sedimentary structures ranging from ripples in coarse-grained sand, to flat bedding in the succeeding fine-grained sandstone beds is indicative of lower to upper flow regime conditions; and this indicates increasing flow velocity within the tidal channel [34].

3. Ripple laminated heteroliths – Mixed flat

The ripple laminated heterolithic facies were observed at Uturu quarry, Ihube road-cut, and Onyekaba quarry, near Okigwe. It consists of ripple laminated heteroliths of clayey - mud with fine to coarse grained sandstones. The sedimentary structures observed include wave ripple lamination, flaser and lenticular laminations. Biogenic structures observed include *Rhizocorallium* (Figs. 7i & 7k), *Thalassinoides*, *and Planolites* (Figs. 7i, 7j & 7k)and *Ophiomorpha* burrows (Figs. 7c & 7f), all belonging to the *Glossifungites* ichnofacies. The thickness of bed varies between 1 and 3.5 metres.

- Interpretation

The ripple laminated heterolithic facies is interpreted as a mixed flat environment following [5] model. The mixed flat environment is indicated by parallel laminated heteroliths of sandstones and mudstones with an upward increasing mud content and occurrence of flaser bedding. The interbedded sandstone and mudstones represents roughly equal periods of suspension and bedload deposition with bedload deposition increasing seaward [27].

4. Ripple laminated mudstones – Mud flat

The ripple laminated mudstone facies occurs at Uturu and Ihube. The lithology consists of siltstone, silty clay and mudstones. The thickness varies from 1cm to 40 cm. It is intensely bioturbated, containing *Planolites* (Fig. 7g) and *Thalassinoides* burrows (Fig. 7i, 7j & 7k), belonging to the *Cruziana* ichnofacies.

- Interpretation

The ripple laminated mudstones suggests deposition in a mud flat environment. According to [5], the transition from mixed flats to mud flats is marked by flaser bedding passing landward into lenticular bedding.

5. Interlaminated clay and thin pebbly sandstone facies – Point bar.

It consists of a rhythmic succession of clay bands and some thin basal lags. The clay bands are about 10 to 30 cm in thickness, while the basal lags are about 5 cm in thickness. The clay bands are purple to dark grey in colour. It also contains some conglomerates at the base. The clay bands are sparsely burrowed with some evidence of some unidentifiable burrows. This facies were observed at Uturu.

- Interpretation

The interlaminated clay and thin pebbly sandstone facies is interpreted as a point bar environment. The point bar environment is indicated by thin interlaminated clay-silt and sandstones, sometimes occurring as tidal rhythmites which form lateral accretion bedding or inclined heterolithic stratification [27]. The point bar is also subdivided into discrete wedges by some inclined erosion surfaces.

6. Claystone facies – Floodplain

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This consists of massive sandy clays, with thickness from to cm. It is commonly lateritized and typically overlies the cross bedded sandstone facies.

- InterpretationThe claystone facies is interpreted as a floodplain. The floodplain environment is indicated by the unfossiliferous clay and the presence of some leaf impressions. The various sedimentary structures observed in the Ajali Formation are shown in Fig. 7 and 8.

Table 7a: Paleocurrent Analysis for the Ajali Formation

| Location | Number of observations | Average foreset dip | Mean azimuth | Variance | Standard Deviation |
|---|---|---|---|---|---|
| Ohafia | 25 | 23 | 216 | 330 | 18 |
| Onyekaba quarry | 30 | 25 | 212 | 145.7 | 12 |
| Mbiabong quarry | 40 | 24 | 240 | 145.7 | 12 |
| Uturu | 9 | 16 | 168 | 2964.5 | 54.4 |
| Nkpologu | 6 | 26 | 254 | 7.2 | 2.6 |
| Isiukwuato | 5 | 16 | 193 | 62.5 | 7.9 |
| Ochodamu | 5 | 27 | 224 | - | - |
| Fugar | 8 | 27 | 225 | 740 | 27 |
| Regional mean | 128 | 24 | 221 | 378 | 15 |

Table 7b: Distribution of dip azimuths in 29 sectors

| Sectors | Frequency % |
|---|---|
| 360 - 29 | - |
| 30 - 59 | 2.3 |
| 60 - 89 | - |
| 90 - 119 | - |
| 120 - 149 | 5.3 |
| 150 – 179 | 4.5 |
| 180 – 209 | 20.3 |
| 210 – 239 | 36.8 |
| 240 – 269 | 15.8 |
| 270 – 299 | 7.5 |
| 300 – 329 | 4.5 |
| 330 - 359 | 1.5 |

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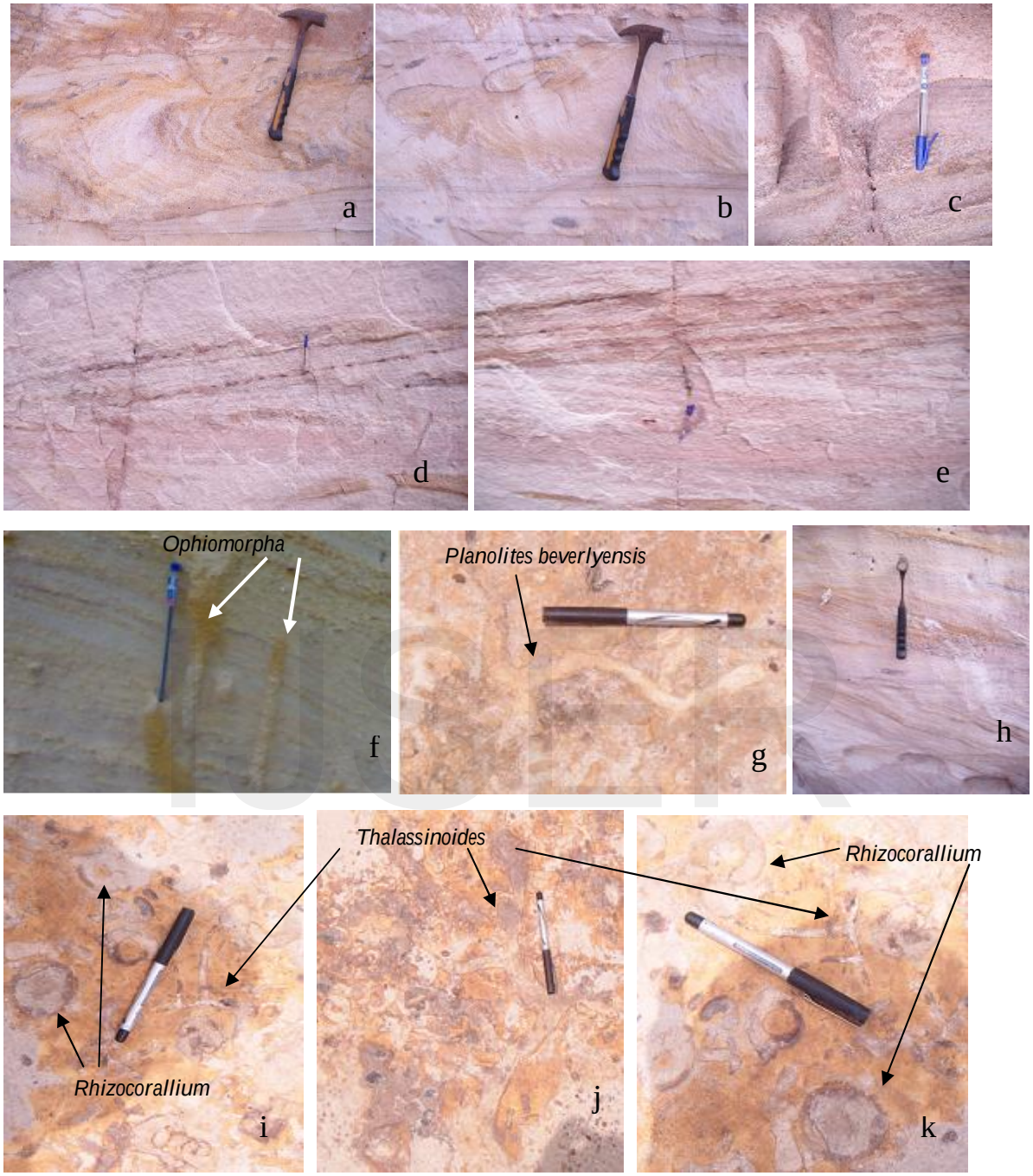


Fig. 7: Sedimentary structures and trace fossils from the Ajali Formation, (a & b) convolute crossbeds (c & f) *Ophiomorpha nodusa* burrows, (d & e) Herringbone crossbeds (g) *Planolites* burrows (h) Planar crossbeds (i, j & k) *Thalassinoides* and *Rhizocorallium* burrows.

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Fig. 8: Sedimentary structures and trace fossils of the Ajali Formation, a. Herringbone crossbeds (Fugar), b,e & f. Planar crossbeds (Fugar, Idah & Ohafia), c. deformed crossbeds (Ohafia), d. Idah, g. wave rippled sandstone beds (Idah), h. convolute crossbeds (Ohafia), I & j. Skolithos isp. (Ohafia).

## 5 DISCUSSION OF RESULTS

### 5.1 Pebble morphometric study

Pebble morphometric studies have been successfully used in paleoenvironmental interpretation [29], [8], [22]. Certain index limits have been established for pebble form indices. [32] es-

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tablished that fluvial pebbles have lower index limits of 45 and 0.65 for coefficient of flatness index and mean sphericity respectively, while [6] suggested a lower limit of 0.66 for the mean sphericity of river pebbles. Dobkins and Folk [6] indicated that the mean oblate – prolate index for river pebbles are above – 1.5, while beach pebbles have lower values. The appropriate lower index limits of form indices for fluvial pebbles are thus; sphericity = 0.65 / or 0.66, coefficient of flatness = 45, and oblate – prolate index = -1.5.The calculated form indices are shown in Table 4 and the roundness data in Table 5. Table 4a shows that the means of two of the three indices (sphericity and coefficient of flatness) are above the lower limits for fluvial pebbles, for only three of the locations studied, while they are below these limits at the other two locations. Table 4 also shows that the means for the oblate – prolate index are above the lower limits for fluvial pebbles for all the locations. Plots of coefficient of flatness against sphericity show that pebbles from three locations lie in the fluvial field, while pebbles from the other two locations plot in the beach field of [32] (Fig. 3a – e). All the means, too, plot likewise (Fig. 3f). The mean values of maximum sphericity of the pebbles range from 0.532 to 0.723. The mean values of coefficient of flatness obtained for the pebbles in this study range from 32.74 to 50.82. These values plot across the fluvial and beach fields, which is suggestive of an influence of both fluvial and shallow marine (beach) processes. Plots of sphericity against oblate – prolate index (Fig. 4), following [36] method suggest that the majority of the pebbles fall in the fluvial field. The oblate – prolate index calculated for pebbles in this study range from 0.159 to 2.818, which is above the – 1.5 minimum, required for pebbles formed in fluvial environments. Sneed and Folk [31] and Els [8] suggested that the sphericity of quartz pebbles decrease with increasing size. The sphericity values listed in Table 4B-F; do not appear to follow this pattern. Plots on the sphericity form diagram of Sneed and Folk (1970) (Fig. 9) for the – 2.0, - 2.5, - 3.0, - 3.5, - 4.0, - 4.5, - 5.0 and – 5.5 phi classes for the five locations studied do not give any significant trend. This may be explained from the fact that the pebbles are very close to their source area and have not experienced much shaping by fluvial action.[6] suggested the values of 0.375 and 0.508 as the mean value of roundness for river and beach environments. In this study, the [17] visual method was used in estimating roundness. Thus results of roundness from this study were not compared with that of [6]. The roundness values from this result ranges from 0.311 ± 0.127 to 0.498 ± 0.118. Sneed and Folk [31], suggested that roundness increases in a downstream direction from a mean value of 0.542 upstream, 0.618 midstream and 0.633 in the downstream reaches. Thus, the roundness values of pebbles in this study suggest a very short distance of transport.

### 5.2 Grain size analysis

Bivariate plots of skewness against standard deviation (Fig. 5a) and mean diameter against standard deviation (Fig. 5b) supports a fluvial origin for the sandstones of the Ajali Formation.

### 5.3 Paleocurrent analysis

The paleocurrent direction is generally southwesterly with a dominant SSW mode and subordinate WSW, WNW, ENE and ESE modes (Fig. 6). The southwesterly paleocurrent suggests a northeasterly provenance of source area, which has been attributed mainly to igneous and metamorphic complex of the Cameroun highlands, with little contribution from the Abakaliki Folded belt [14], [15]. Ladipo [18] suggested that the dominant SSW mode as being discordant to the northeasterly source area, which he attributed to tidal processes within the depositional basin. The minor ENE, ESE, WSW and WNW modes are indicative of reversals in current directions during the depositional history of the sandstone. Such current reversals are signatures of tidal settings.

### 5.4 Sedimentary facies and Depositional environments

The sedimentary structures observed in the Ajali Formation are indicative of tidal deposition in a shelf setting [16], [5]. These features include bimodal – bipolar paleocurrents, abundant occurrence of reactivation surfaces, common occurrence of herringbone cross bedding which is indicative of current reversals, laterally extensive low relief erosion surfaces overlain by thin granule or pebble lags or silt / mud drapes, paucity of mudrocks and their high mineralogical maturity and considerable lateral extent as shown by regional studies [2], [18]. The sedimentary facies of the Ajali Formation is suggestive of deposition in both tidal (sand flats, mixed flats, mud flat, and tidal channel) and fluvial (point bar and floodplain) settings. The *Skolithos* and *Cruziana* ichnofacies are indicative of a high energy depositional environment, in the tidal and sub tidal parts of beaches, while the *Glossifungites* ichnofacies suggests deposition in a shallow water setting.

### 5.5 Paleogeography

This study has shown that the Ajali Formation is a product of fluvial transport and tidal current energy. The paleocurrent analysis suggests that the sediments were sourced from the Abakaliki Anticlinorium and Cameroun highlands and transported by rivers to the coastline where they are shaped by tidal current energy (Fig. 10). According to [23] major critical factors that initiated the tidal currents include the shape of the coastline, shelf bathymetry and wave dynamics, governed by the prevailing wind direction and determined by the nature of the longshore drift. During the Maastrichtian times, the Anambra shelf was funnel shaped and has an extremely wide, low gradient slope. Elliot [7] and Schopt [30] have suggested the width and slope of paleo-shelves as critical paleogeographic factors influencing tidal effects. Nwajide and Reijers [23] attributed the tidal currents generated during the Maastrichtian times to have originated by a convergence of two drift cells, a southwest to northeast directed drift cell and a southeast to northwest directed drift cell, towards the apex of the funnel shaped Anambra shelf. Again the structural grains brought in by the rivers might have constricted and enhanced sedimentation dominated by tidal current energy during those times when circulation is controlled by transgressive tendencies. During the regressive phases, the input from the proto-rivers dominates, leading to a gradual closing and smoothing out of the

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funnel shaped estuary.

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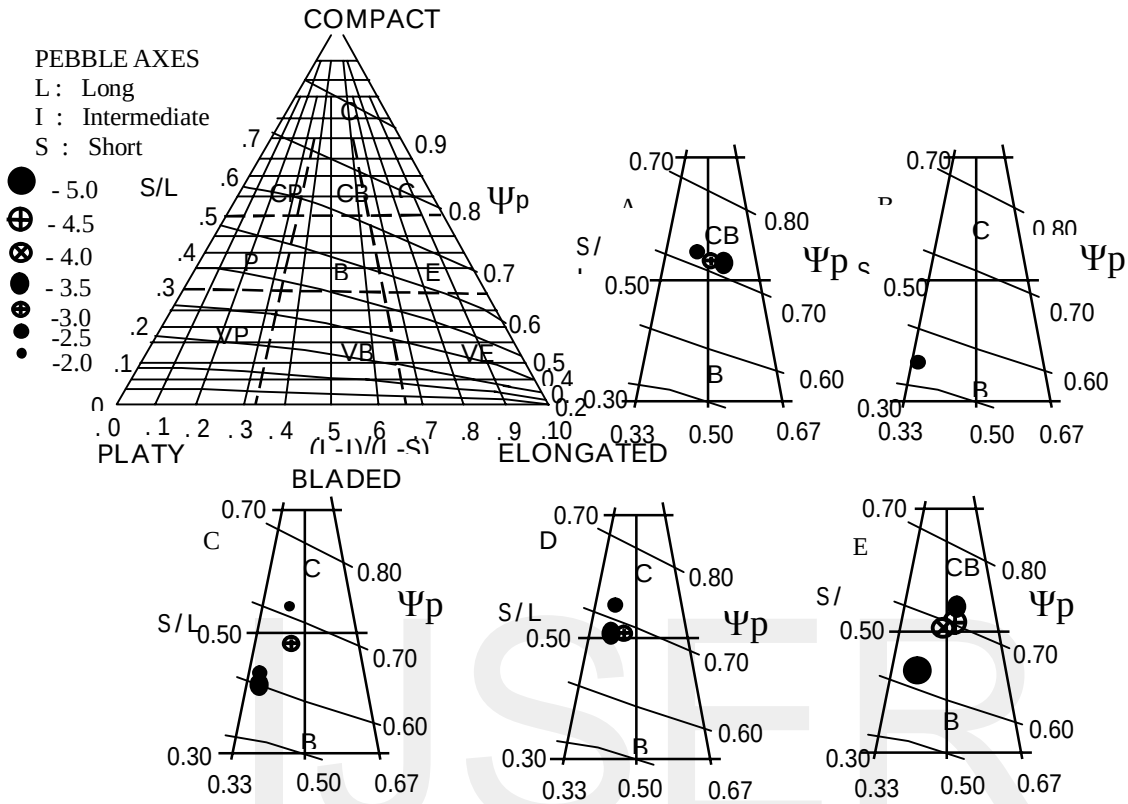


Fig. 9: - Sphericity – form diagram of Sneed and Folk (1958), Sphericity – form plots of mean indices of the – 2.0, - 2.5, - 3.0, - 3.5, - 4.0, - 4.5 and – 5.0 phi size classes for the five locations studied.

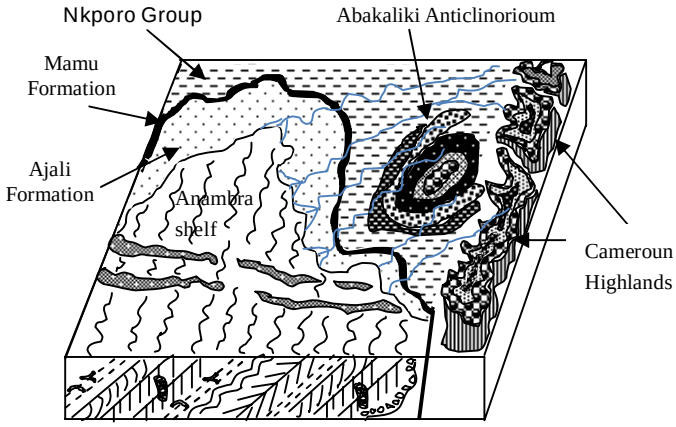


Fig. 10: 3 – D Paleogeographic model of the Ajali Formation

## 6 CONCLUSIONS

On the basis of the mean sphericities and coefficient of flatness obtained for the five sets of pebbles of the Ajali Formation, it is concluded that the pebbles were shaped in both fluvial and marine environments. Plots of coefficient of flatness against sphericity, and sphericity against oblate – prolate index indicate that the pebbles were formed in both fluvial and beach settings. Mean roundness indices computed for the pebbles are suggestive of a short transportation distance. The results of

the grain size or textural analysis are suggestive of a fluvial origin for the sandstones of the Ajali Formation. The paleocurrent analysis suggests a northwesterly provenance of source area. The sedimentary facies is indicative of a mixed tidal / fluvial setting. The tidal subenvironments include sand flats, mixed flats, mud flats and tidal channel, while the fluvial subenvironments are point bars and floodplain deposits

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