Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol 2, No.6, 2012

Lithofacies and Pebble Morphogenesis: Keys to Paleoenvironmental Interpretation of the Nkporo Formation, Afikpo Sub-Basin, Nigeria

Okoro Anthony. U*, Onuigbo Evangeline N., Akpunonu Eliseus O and Obiadi Ignatius I.
Department of Geological Sciences, Nnamdi Azikiwe University, P. M, B. 5025, Awka. Nigeria.
*anthonyuokoro@yahoo.com

Abstract
The Nkporo Formation in the Afikpo Subbasin, Nigeria, is dominantly shaly but contains two sandstone members within it. These sandstones host vein quartz pebble beds and dispersed clasts which have been used for pebble morphometric analysis. As independent functions and dependent variables, pebble morphometric indices of Coefficient of Flatness, Elongation Ratio, Maximum Projection Sphericity, Oblate-Prolate Index, Roundness and Form suggest deposition of the sandstones in fluvio-deltaic to littoral settings. Lithofacies analysis identified six lithofacies, grouped into estuarine delta and marine offshore lithofacies associations. These include trough cross-bedded sandstone, *ophiomorpha* burrowed, wave/rippled and planar cross-bedded lithofacies, Inclined heterolithic lithofacies, fine grained, silty sandstone, lignite/coals, shales/mudstone, interbedded with limestones and oolitic ironstones lithofacies. The estuarine lithofacies association shows a tripartite subdivision into meandering estuarine and tidal point bars overlain by estuary funnel tidal creek sandstones, carbonaceous beds; and estuary mouth tidal and barriers bars and shallow marine shales in a drowned incised valley. The fining upwards lithofacies pattern suggests deepening and transgression of the sea in a tidal estuarine setting.

Keywords: Lithofacies, Lithofacies association, Pebble morphogenesis, Paleoenvironments, Tidal estuary

1. Introduction

The Afikpo Sub-basin in southeastern Nigeria was installed after the Santonian to early Campanian thermo- tectonic event which folded and uplifted the Albian – Coniacian sediments of the Benue Trough into the Abakaliki Anticlinorium/Afikpo Synclinorium. The Nkporo Formation (Campanian – Maastrichtian) is the basal lithostratigraphic unit of the Afikpo Sub-basin (Figure 1) and comprises dominantly of dark grey to black shales, sandstone, minor limestone and oolitic ironstone beds. The sandstones occur as two sandstone bodies (Simpson, 1954 and Reyment, 1965) representing the Afikpo Sandstone, embedded within the dominantly shaly sequence (Figure 2). The stratigraphically lower member lies unconformably on the Eze-Aku Group (Figure 1, Table 1) and underlies the hilly terrain of Afikpo town, trending eastwards across the Cross River at Ozizza and Ndibe Beach areas. The Upper sandstone member outcrops in Owutu Edda area trending east – west but turns southwards to Ohafia area (Figure 1). The Nkporo Formation and its sandstone Members in the Afikpo Sub-basin lie uncomfortably on the Turonian Amasiri Sandstone of the Eze-Aku Group (Simpson, 1954).

The paleoenvironments of deposition of the Nkporo Formation has variously been interpreted grossly as shallow marine and brackish water solely based on fossil and palynological evidences extracted from the shaly lithofacies of the formation (Reyment, 1965; Simpson, 1954; Mode, 1991; Petters and Edet, 1996; Odebode, 1986). The sandstone lithofacies designated as the Afikpo Sandstone by Shell D,arcy Geologist (Simpson, 1954) has hardly been investigated with respect to its depositional environments.

The purpose of this study is to reconstruct the paleodepositional environment of the Nkporo Formation by identifying and describing the different lithofacies and also analyze the shapes and forms of vein quartz pebbles in the sandstone lithofacies with diameters between 5.00 mm – 2.25 mm, and to use the results to evaluate the paleodepositional environment of the Nkporo Formation.

2. Geological Setting

The Anambra Basin and a smaller Afikpo Sub-basin was installed simultaneously as flexural basins relative to the Abakaliki Anticlinorium after the Santonian squeeze. The study area generally referred to as the "Afikpo Syncline" rests uncomfortably on the folded pre - Santonian Abakaliki Anticlinorium, filled with pre-Santonian sediments of the Asu River Group and the Eze-aku Group (Murat, 1972). The syncline, a narrow asymmetrical depression, gently plunging southwards, is aerially flanked in the north and northwest by the Abakaliki Fold Belt (Anticlinorium), in the east by the Calabar Flank and in the south by the Niger Delta (Figure 2).

Reyment (1965) and Murat (1972) described the stratigraphy of the Anambra Basin and the Afikpo Syncline and noted that sedimentation was controlled dominantly by transgressions and regressions which led to deposition in a wide variety of environments ranging from fluvial through fluvio-marine to marine environments (Short and Stauble, 1967). The basal lithostratigraphic unit of the Afikpo Sub-basin is the Nkporo Formation, conformably overlain by the Mamu Formation, Ajali Sandstone and the Nsukka Formation. Table 1 shows the Lithostratigraphic framework of the sub-basin highlighting the sandstone members under study.

3. Methodology

Lithofacies characterization (analysis) method employed in this study involved the description and logging of well exposed sections. The lithotypes, sedimentary structures, textures, bed thicknesses and contact types as well as fossil contents were recorded. Lithologic logs of selected sections exhibiting important sedimentological features of the rocks were arranged as composite lithologs, highlighting the different lithofacies used for paleoenvironmental interpretation.

The pebble morphometric method of Sneed and Folk (1958) adopted by Dobkins and Folk (1970), Sames (1966), Lutig (1962), Nwajide and Hoque (1982) have been used in this study. In this method, measurements of the three mutually perpendicular diameters (axes) of each pebble using the veneer caliper were done. The method where the long axis (L), intermediate axis (I) and short axis (S) are imagined to represent the internal diameters of a rectangular box into which the pebble just fits into was used. Pebbles (vein quartz species 5.00 mm – 23.00 mm in size) collected from logged outcrop sections of the Afikpo Sandstone Member of the Nkporo Formation were used in this study. These pebbles were found to be very abundant as dispersed pebbles and thin beds in the pebbly, cross stratified sandstone units and *Ophiomorpha* burrowed cross bedded sandstone units of the Formation. Sampling was done in such a way as to represent all the two facies hosting pebbles (Figure3). Fifteen largest pebbles extracted from the sandstone beds were sampled out of which the best ten were selected to form a batch for analysis. Three hundred and forty (340) pebbles were assembled into thirty four (34) batches and studied for morphometric indices. Two hundred (200) pebbles assembled into twenty (20) batches were studied from the lower sandstone unit at Afikpo while one hundred and forty (140) pebbles (14 batches) were studied from the upper sandstone unit at Owutu Edda.

4. Results

4.1 Lithofacies Characterization

Walker (1984) defined facies as a body of rock showing lateral variations in the aspects of defined lithological characteristics. On the basis of this, and to achieve simplicity, objectivity, repeatability and comprehensiveness, seven (6) lithofacies have been recognized in the Nkporo Formation as follows (1) trough cross-bedded sandstone, (2) *Ophiomorpha* burrowed, wave/rippled and planar cross-bedded lithofacies, (3) horizontal bedded/laminated sandstones and heterolithics, (4) Very fine grained, silty sandstone (5) coals/carbonaceous beds, (6) shales/mudstone with limestones and oolitic ironstones beds.. These lithofacies are described below with representative figures to illustrate their main lithological characteristics and sedimentary structures.

4.1.1. Cross – Stratified Sandstone lithofacies A

This consists of fine to very coarse, but dominantly medium to coarse grained sandstones with thick cross–stratified bedsets (Figures 3a & 3b). The main characteristic is cross-bedding and exhibits both upward fining grain size motifs. In the fining upward parts, sharp and scoured erosive basal contacts, most often lined with vein quartz pebbles and clay chips, are common. The cross-beds vary from trough to planar with graded foreset laminae and scattered vein quartz pebbles. Occasionally, this lithofacies exhibits bi-directional foreset beds (herringbone structures), clay draped foresets, graded foresets and reactivation structures with tidal bundles. Fine to very coarse but dominantly very coarse grained, massive to poorly stratified sandstone beds with scattered pebbles are associated with this lithofacies. They are poorly sorted with local admixed clay clasts. Internal erosional surfaces are common with subtle fining upward motifs. This lithofacies has been interpreted as tidal channel point bars in bayhead delta. This lithofacies dominates the lower sandstone body outcropping in Afikpo, Ndibe and Oziza areas.

4.1.2 *Ophiomorpha* burrowed, wave/rippled and planar cross-bedded lithofacies B

This lithofacies contains prominent O*phiomorpha isp* burrows as well as cross-stratified bedsets (Figure 4). The lithofacies is fine to very coarse grained with dispersed pebbles; poorly sorted and planar cross-bedded. Ripple bedforms and sandwaves (megaripples) exhibiting symmetrical geometry are common. The *Ophiomorpha isp* burrows vary from vertical to sub-horizontal with lengths from 5cm to 30cm and cross sectional diameter of 1.0 – 2.0 cm. This lithofacies exhibits both fining (with scoured basal contacts) and upward coarsening motifs. Occasionally, 5 – 30 cm thick lenticular-shaped claystone beds mark the rippled contacts of the sandstones. It has been interpreted as estuary mouth beach/barrier and tidal bar deposits. This lithofacies outcrops in Owutu area and characterizes the stratigraphically upper sandstone body.

4.1.3 Inclined Heterolithic Stratified (sand – dominant heterolithic) lithofacies C

This comprises friable, well sorted, very fine to medium but dominantly very fine to fine grained sandstones interbedded with thinner beds of dirty white and pinkish sand-dominant heterolithics. This lithofacies is dominantly inclined with mm – cm scale claystone laminations/beds as well as flasers (Figure 5). Few O*phiomorpha isp* burrows were recorded in this lithofacies. The bed thicknesses vary from 0.10 m to 0.50 m. The lithofacies is interpreted as tidal point bars in the proximal part of the estuarine funnel. Outcrops occur in the sandstone quarry at Ezi-Edda, near Owutu Edda

4.1.4 Coal/carbonaceous lithofacies D

Coal beds are ubiquitous in the lower sandstone unit. They occur as sandstones - carbonaceous shale - coal cycles sandwiched within the cross-bedded sandstone lithofacies at Ozziza and within a shaly facies at Wowo River (along the Afikpo – Unwana road). The presence of carbonaceous beds in this association suggests deposition in a lagoonal (or central) setting within the estuarine funnel.

4.1.5 Very fine grained, silty sandstone Lithofacies E

This lithofacies consists of 10 cm to 50 cm thick, poorly laminated, sometimes massive, silty to very fine grained sandstone. Distinct *monocreterion isp* burrows occur in this lithofacies. The absence of laminations may be possibly, due to reworking by wave/tides or burrowing by organisms (e.g *monocretarion isp* burrows). The lithofacies also contains large spherical siderite concretions/nodules and plant rootlets *(rhizoliths).* A 1.60 m thick bed of very fine to medium grained, grey to dark grey sandstone with intact bivalve and gastropod shells was described within this lithofacies (Figure 6). This lithofacies has been interpreted as estuary funnel tidal bars and sand sheets.

4.1.6 Shale and Mudstone lithofacies with interbedded limestones and oolitic beds F

This lithofacies consists of dark grey to black laminated shales and mudstones with pyrite framboids and gypsum veins and efflorescence (Figure7). They are fossiliferous, with dwarfed/juvenile bivalves, gastropods, ammonites and abundant foraminifera in some horizons. Cm-scale siderite nodules, mostly elliptical in shape, occasionally occur as nodular beds/lenses or sporadically scattered nodules within the bedding planes. Small burrows suspected to belong to the *Chondrites, Paleophycus and Teichichnus isp* occur in this lithofacies. Beds of brown micritic limestones (10 – 25cm thick) and siderite cemented chamositic oolitite (10 cm – 33cm) occur within the dominant laminated shale/mudstone lithofacies This facies outcrop in Asaga Amangwu, Itim Edda, Amaiyi, Akanu Ohafia and on the lower slopes of Enugu – Okigwe Cuesta. This lithofacies is interpreted as product of shallow, open marine shelf deposition in a transgressive setting

4.2. Pebble Morphogenesis

The results of pebble morphometric measurements of the vein quartz pebble suites of the Afikpo Sandstone are shown on Tables 2 and 3. The methods used in analyzing and presenting results from primary particle shape data have been controversial (Illenberger, 1991; Illenberger, 1992a and b; Benn and Ballantyne, 1992, 1993, 1995; Howard, 1992, 1993; Woronow, 1992; Sneed and Folk, 1958; Illenberger and Reddering, 1993). However, the precise method of result presentation is less important than the value of the results with respect to depositional processes that shaped the particles and their geomorphic environments of deposition.

Dobkins and Folk (1970) used large particle properties (morphometric indices) of form, sphericity and roundness from Tahiti Nui to characterize pebbles shaped in various sedimentary environments. Graham and Midgley (2000) noted that morphometric parameter of form, roundness and sphericity provide means of differentiating facies, providing clues about the transport history of the sediment, and characterizing depositional environments. In this study, morphometric indices of maximum projection sphericity, oblate prolate index, coefficient of flatness and elongation indices regarded as environment - sensitive have been employed in the interpretation of the paleoenvironments of the Sandstone units of the Nkporo Formation. The relevant parameters used are:

- Coefficient of Flatness, S/L (Stratten, 1974; Els, 1988).
- Elongation Ratio, I/L (Sames, 1966; Lutig, 1962).
- Maximum Projection Sphericity $(S^2/LI)^{1/3}$ (Sneed and Folk, 1958) .
- Oblate – Prolate Index. (OPI) 10{(L – I)/L – S) - 0.50} / {S/L} (Dobkins and Folk, 1970)

- Form, (L – I / L – S) (Sneed and Folk, 1958). The shapes were obtained using the triangular Sphericity - Form Diagram of Sneed and Folk (1958).
- The roundness of each pebble was estimated using Sames (1966) Pebble Image Set.
- The mean and standard deviation for the morphometric indices were calculated using the statistical formulae as follows

Pebble suites from the stratigraphically lower unit at Afikpo have coefficient of flatness ratio (FR) varying from 0.46 – 0.61 with a mean value of 0.51±0.08; elongation ratio (ER) of 0.62 – 0.81 with mean of 0.71±0.10; form with dominant compact bladed (CB) shapes and values varying from 0.44 – 0.73 with a mean of 0.58±0.15. The maximum projection sphericity (MPS) varies from 0.64 – 0.78 with a mean of 0.71±0.07; oblate- prolate index (OPI) range from -1.42 – 3.26 with a mean of 1.67 while roundness (ρ) varies from 30% - 46% with a mean of 39.95%.
For the upper Sandstone Member at Owutu Edda, the pebble suites measured have coefficient of flatness (FR) of 0.35 - 0.50 with a mean of 0.42; elongation ratio (ER) of 0.67 - 0.78 with a mean of 0.73 and form index of 0.38 - 0.58 with a mean of 0.47 and dominant bladed (B) shapes. The maximum projection sphericity (MPS) varies from 0.56 - 0.70 with a mean of 0.63; the oblate-prolate index (OPI) varies from -3.13 - 2.04 with a mean of -0.69 while roundness (ρ) ranges from 50% - 71% with a mean value of 56%.

5. Interpretation and Discussion

S5.1 Lithofacies Association

Based on the lithofacies and their characteristics, the entire Nkporo Formation has been grouped into two lithofacies associations – the estuarine lithofacies association and partially anoxic shallow marine shelf association. Figure 8 shows a composite lithologic log (450 m thick) with the lithofacies and the associations. The estuarine lithofacies association clearly shows a tripartite subdivision into a lower section of estuary tidal channels and point bars, middle section of estuary funnel dominated by estuarine subtidal point bars, silts and lagoonal (carbonaceous) shales and an upper section of estuary mouth complex and inlet deposits (Dalrymple et al., 1992; Allen and Posamentier, 1993; Miall, 2000; Shanmugam et al, 2000; Catunuanu, 2006 and Nicols, 2009). The lower sandstone units have been interpreted as tidal channel point bars in upper estuarine delta setting. The presence of herringbone and tidal bundles with reactivation structures support this interpretation. The inclined bedded / laminated sand –dominant heterolithic lithofacies (IHS), the carbonaceous/coals and very fine silty sandstone facies were deposited in the estuarine funnel (Nicols, 2009, p. 210). The *Ophiomorpha* isp burrowed and planar cross-bedded lithofacies with wavy beds, ripples and dunes bedforms were deposited as beach/barrier and tidal sand bars deposits in the estuary mouths (Catenuanu, 2006, p. 149). The presence of wave and tide structures is noteworthy in this lithofacies. The coal and carbonaceous beds association, with the very fine grained and silty lithofacies belong to central estuarine funnel setting. The association of dark grey to black shales with micritic limestone and oolitic (sideritic) ironstone is interpreted as products of shallow marine shelf deposition in a transgressive setting (Nwajide and Reijers, 1996). The presence of siderite nodules, pyrites, dwarfed ammonites and chamosite oolitic ironstones, supported deposition in partially anoxic marine settings (Maynard, 1983, p. 42, 46).

5.2. Pebble Morphometric interpretation.

Several authors have demonstrated the usefulness of pebble morphometric parameters in paleoenvironmental interpretations (Dobkins and Folk, 1970; Lutig, 1962; Sames, 1966; Stratten, 1974; Els, 1988; Illenberger and Reddering, 1993 and Barret, 1980). As independent functions, the coefficient of Flatness (FR), Elongation Ratio (ER), Maximum Projection Sphericity (MPS), Oblate-Prolate Index (OPI), Roundness (ρ) and Form have been used as indices for environmental diagnosis. As dependent variables, scatter plots of maximum projection sphericity (MPS) versus oblate-prolate index (OPI) and roundness (ρ) versus elongation ratio (ER) are also useful in discriminating the environments of deposition.
Dobkin and Folk (1970) studied pebbles shaped by river and beach processes in Tahiti-Nui and noted that the mean sphericity of fluvial pebbles is 0.684 while mean sphericity of pebbles in low energy and high energy beaches are 0.0.640 and 0.584 respectively. On the basis of this study, they suggested that pebble suites with mean sphericity of 0.65 and less indicates beach processes while those with sphericity values above 0.65 are shaped by fluvial processes. The pebble suites from the lower unit of the Afikpo Sandstone with maximum projection sphericity varying from 0.67 – 0.78 and a mean of o 0.71 are therefore interpreted as product of a fluvial process.
The OP-Indices ranging from -1.02 – 5.06 are also suggestive of fluvial transport. Stratten (1974) used coefficient of flatness (% Flatness ratio) to discriminate between fluvial and beach pebbles. He noted that fluvial pebbles have coefficient of flatness of 45% and above. On this basis, the coefficient of flatness for the Afikpo Sandstone pebble

suites range from 45% - 61% with a mean of 51% corroborate fluvial action as the dominant depositional process. Dobkin and Folk(1970) identified shape classes (Form) of Sneed and Folk (1958) that are diagnostic of certain environments. Compact (C), compact bladed (CB), compact elongate (CE) and elongate (E) pebbles are diagnostic of fluvial environments, while platy (P), bladed (B), very bladed (VB) and very platy (VP) are more common in beach environments. The mean form index of 0.58 and compact bladed (CB) forms (and Table 2) of the pebble suites studied in the Afikpo Sandstone further support dominant fluvial shaping with for the grains.

Roundness is a poor indicator of environment. The roundness of pebbles under hydrodynamic transport has been observed to be a function of both inherited and acquired (environmental) factors (Sneed and Folk 1958; Lutig, 1962; Sames, 1966 and Dobkins and Folk, 1970). Sneed and Folk (1958) observed that pebble roundness increases downstream from rivers to the beaches for vein quartz pebbles. Roundness of less than 35% typifies fluvial environments while roundness greater than 45% characterizes littoral environments (Sames, 1966). Therefore an upper limit for roundness index in fluvial environments has been placed at 45%. The mean roundness index for the lower unit of the Afikpo Sandstone pebble suites is 39.95% with 80% of the pebble suite having roundness varying from 30 – 43%. This strongly suggests deposition in fluvial a environment (see Table 2).

Dobkin and Folk (1970) and Sames (1966) used plots of maximum projection sphericity (MPS) versus oblate - prolate index (OPI) and roundness (P) versus elongation Index (ER) respectively to discriminate environments. Plot of MPS versus OPI confirms that the lower sandstone unit was deposited in essentially fluvial setting (Figure 9a). The plot of roundness (P) versus elongation ratio (ER) indicates deposition in transitional environment (Sames, 1966) (Figure 9b), possibly suggesting some marine influence. In all, morphometric indices show that the stratigraphically lower unit of the Afikpo Sandstone was essentially deposited by fluvial processes.

For the upper sandstone unit outcroping in Owutu Edda area, the maximum projection sphericity (MPS) of 0.56 – 0.64 with a mean of 0.63± suggest that the pebbles were largely shaped by surf (beach) processes. The coefficient of flatness (% FR) of 35% - 45% and all bladed (B) suites of pebbles confirm deposition in environments dominated by beach processes (Stratten, 1974; Dobkins and Folk, 1970). The mean roundness index (P) indicated for the sandstone is 56% (Table 3). According to Sames (1966), this indicates deposition in littoral (beach) environment.

Plot of roundness (P) versus elongation ratio (ER) supports deposition of the sandstone in littoral (beach) environment (Figure 10b). However, plot of maximum projection sphericity (MFS) versus oblate - prolate index (OPI) is not diagnostic but indicates that 36% of the pebble suites were shaped by beach processes, 36% by fluvial processes while 28% are non-diagnostic (Figure 10a).

6. Depositional Model

Based on the depositional environments interpreted from pebble morphometry, lithofacies/associations, and their vertical facies distribution, an estuarine delta depositional model is proposed for the Nkporo Formation. The stratigraphically lower sandstones buried in the estuary muds represent tidal channel point bar and tidal creeks.

The stratigraphically upper sandstones interbedded within marine shales represent beach/barrier bars, tidal sand bars and inlet deposits in a tide-wave influenced estuary mouth Complex (Figure 11). The dark grey to black shales interbedded with limestones and oolitic beds were deposited as partially anoxic shallow marine shelf deposits.

The Nkporo estuarine delta may have developed, possibly due to falling eustatic sea levels and basin-ward shift of base level resulting in fluvial incision and erosion of the sub-aerially exposed shelf, following the Santonian uplift (Murat, 1972). The transgressions (base level rise) during the late Campanian resulted in submergence of the incised valleys and deposition of estuarine facies of the Nkporo Formation. As base-level rise slowed, the net rate of sediment supply dominated over eustatic rise, and coarse sediments were trapped at the estuary mouths while the shelf was starved of sediments. The Afikpo Sandstone Member and indeed the entire Nkporo Formation therefore represents estuarine and tidal point bars, tidal inlets, carbonaceous beds, estuary mouth barriers and tidal sand bars in a submerged/drowned river valley system (Figures 3 & 4) (Nicols, 2009).

7. Conclusions

Pebble morphometric indices of sphericity (MPS), oblate-prolate index (OPI), flatness index (FR), elongation index (ER), roundness (P) and form have proved useful, together with lithofacies characteristics, in deciphering the depositional environments of the sandstone lithofacies of the Nkporo Formation. The stratigraphically lower sandstone Member was deposited dominantly by fluvial/tidal systems with minor marine influence, possibly as estuarine tidal/fluvial point bars in the lower delta plain setting. The upper sandstone Member, on the other hand, was deposited under marine environmental conditions, possibly in the surf zone or littoral setting as beach/barrier bars and tidal delta sandbodies. The upper Sandstone Member exhibits finer grain size for its pebbles than those of the lower Sandstone unit. This may support deposition in a more distal environmental setting, downstream of rivers that transported the pebbles from the hinterland source regions.

References

Allen, G. P., and Posamentier H. W. (1993). Sequence stratigraphy and facies model of an icised valley fill, the Girond estuary, France. *J ournal of Sedimentary Petrology*, **63** (3), 378 – 391.

Barrett, P. J., (1980). The shape of rock particles: a critical review. *Sedimentology,* **27**, 291 – 303.

Benn, D. I, Ballantyne, C. K. (1995). Grain-shape indices and isometric graphs – discussion. *Journal of Sedimentary Research,* **A65** (4), 719 – 721.

Benn, D. I and Ballantyne, C. K. (1992). Pebble shape (and size!) – Discussion. *Journal of Sedimentary Petrology,* **62** (6), 1147–1150.

Benn, D. I, Ballantyne, C. K. (1993). The description and representation of particle shape. *Earth Surface Processes and Landforms*, **18** (7), 665–672

Catuneanu, O., (2006). *Principles of sequence stratigraphy*. Elsevier BV, Amstadam, Netherlands, (Chapter 4).

Dalrymple, R. W, Zaitlin, B. A and Boyd, R. (1992). Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology **62**, 1130 - 1146.

Dobkins, J. E. and Folk, R. L., (1970). Shape development in Tahiti Nui. *Journal of Sedimentary Petrology,* **40,** 1167 – 1203.

Els, B. G., (1988). Pebble morphology of an ancient conglomerate: The Middelvlei Gold Placer, Witwatersrand, South Africa. *Journal of Sedimentary Petrology*, **58,** 894 – 901.

Genik, G. J., (1993). Petroleum geology of Cretaceous – Tertiary basins in Niger, Chad and Central African Republic. *American Assocition Petroleum Geologists Bulletin*., **77,** 1405 – 1434.

Graham D.1.J and Midgley N.G., (2000). Graphical representation of particle shape using triangular diagrams: an excel spreadsheet method. *Earth Surface Process and Landforms* , **25**, 473–1477.

Howard J. L., (1992). An evaluation of shape indices as palaeoenvironmental indicators using quartzite and metavolcanic clasts in Upper Cretaceous to Palaeogene beach, river and submarine fan conglomerates. *Sedimentology*, **39** (3), 471– 486.

Howard J. L. (1993). An evaluation of shape indices as palaeoenvironmental indicators using quartzite and metavolcanic clasts in Upper Cretaceous to Palaeogene beach, river and submarine fan conglomerates – reply. *Sedimentology,* **40** (5), 1020 –1021.

Illenberger W. K, Reddering J.S. V., (1993). An evaluation of shape indices as palaeoenvironmental indicators using quartzite and metavolcanic clasts in Upper Cretaceous to Palaeogene beach, river and submarine fan conglomerates – discussion. *Sedimentology*, **40** (5), 1019 –1020.

Illenberger W. K. (1991). Pebble shape (and size!). *Journal of Sedimentary Petrology*, **61** (5), 756–767.

Illenberger W. K. (1992a). Pebble shape (and size!) – reply. *Journal of Sedimentary Petrology*, **62** (3), 538–540.

Illenberger W. K. (1992b). Pebble shape (and size!) – reply. *Journal of Sedimentary Petrology*, **62** (6), 1151–1155.

Lutig, G. (1962). The shape of pebbles in the continental, fluviatile and marine facies. *International. Association. Science. Hydrology*. **59,** 253 – 258.

Maynard, J. B., (1983). *Geochemistry of sedimentary ore deposits*. Springer – Verlag Publ., NY. 285p (chapter 2)

Miall. A. D. (2000). *Principles of sedimentary basin analysis*. Springer. Berlin. 616p (chapter 4)

Mode, A. W., 1991. Assemblage zones, age and paleoenvironment of the Nkporo Shale, Akanu area, Ohafia, southeastern Nigeria. *Joural. Mining & Geoogy.,* **27,** (1), 107 – 114.

Murat, R. C., (1972) Stratigraphy and Paleogeography of the Cretaceous and Lower Tertiary in Southern Nigerian. In Dessavaugie, T. F. J & Whiteman, A. J. (Eds.) *African Geology*, (pp. 251–266). University of Ibadan Press, Nigeria

Nicols, G. (2009). *Sedimentology and stratigraphy*. (2^{nd} Edition). Wiley and Blackwell, (chapter 13).

Nwajide, C. S and Hoque, M., (1982). Pebble morphometry as an aid in environmental diagnosis: an example from the Middle Benue Trough, Nigeria. *Journal Mining and Geology*, **19**(1), 114 – 120.

Nwajide, C. S and Reijers, T. J., (1996). The geology of the southern Anambra Basin: in Reijers, T.J. A (Ed.) *Selected Chapters on Geology: Sedimentary geology and sequence stratigraphy of the Anambra Basin,* (pp. 133 – 148) SPDC Corporate Reprographic Services, Warri, Nigeria.

Odebode, M. O., (1986). Occurrence and geological significance of Afrobolivina afra Reyment in the Upper Cretaceous of Calabar Flank, S.E Nigeria. *Ife Journal of Science*. **1**, 1 – 9.

Okoro, A. U. (2009). The sedimentological and stratigraphic analysis of the Campanian –Maastrichtian depositional sequence in the Afikpo Sub-basin, southeastern Nigeria. *Unpublished. Ph.D Thesis,* University of Nigeria, Nsukka, 389p

Petters S. W and Edet, J., (1996). Shallow shelf and anoxic facies in the late Campanian – early Maastrichtian of SE Nigeria. *Geoloe de I' Afrique et L' Atlantique sud: Actes colloques Angers*. 220 - 227

Reyment, R. A., (1965). *Aspects of the Geology of Nigeria*. Ibadan University Press. 145p

Sames, C. W., (1966). Morphometric data of some recent pebble associations and their application to ancient deposits. *Journal of Sedimentary Petrology*, **36**, 125 – 142.

Shanmugam, G., Poffenberger, M. and Alava, I. T. (2000). Tide dominated estuarine faciesin the Hollin and Napo ("T" and "U") Formations (Cretaceous) Sacha Field, Oriente Basin, Ecuador. *American Association of Petroleum Geologist Bulletin,* **84** (5). 166 – 215.

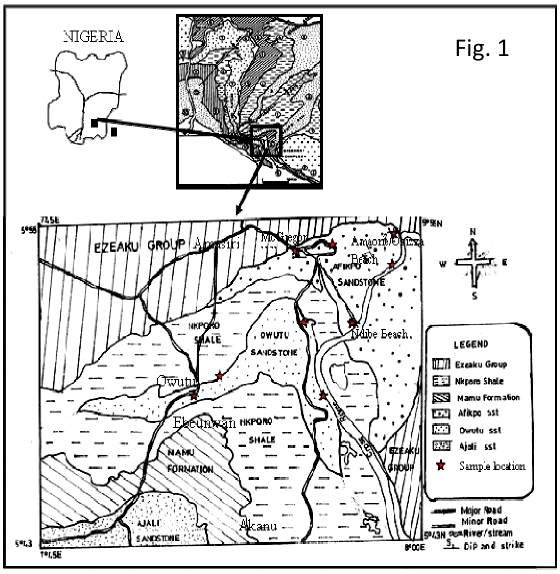
Short, K. C and Stauble, A. J., (1967). Outline of Nigeria Delta. *American. Association Petroleum Geologist. Bulletin,* **5**, 761-779.

Simpson, A., (1954). The Nigerian Coal Field: The geology of parts of Onitsha, Owerri and Benue Provinces. *Geological Survey Nigeria Bulletin*., **24**, 1- 67.

Sneed, E. D. and Folk, R.L., (1958). Pebbles in the lower Colorado River, Texas: a study in particles morphogenesis. *Journal. Geology*, **66**, 114 – 150.

Stratten, T. (1974). Notes on the application of shape parameters to differentiate between beach and river deposits in southern Africa. *Transactions Geological Society of South Africa*, **77**, 59 – 64.

Woronow A. (1992). Pebble shape (and size!) – Discussion. *Journal of Sedimentary Petrology*, **62** (3), 536 – 537.



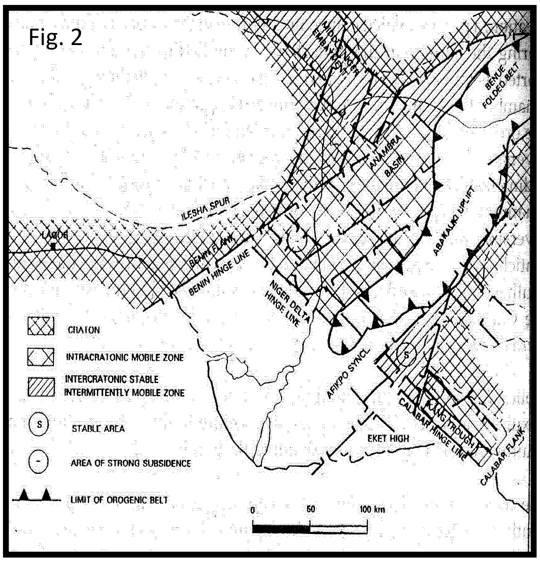


Figure 1: Geological Map showing the Nkporo Formation with the sandstone members

Figure 2: Structural framework of southeastern Nigerian sedimentary basin (After Murat, 1972)

Age		Lithostratigraphic Unit: Formations	Lithostratigraphic Unit: Members	Basin
Late Cretaceous	Late Maastrichtian	Nsukka Fm.		Afikpo Sub- basin
	Middle Maastrichtian	Ajali Fm.		
	Early Maastrichtian	Mamu Fm.		
		Nkporo Fm.	Nkporo Shale Afikpo Sandstone	
	Late Campanian		Nkporo Shale. Afikpo Sandstone	
	Santonian	angular unconformity		
	Turonian	Ezeaku Group		Benue/ Abakaliki Basin/ Calabar Flank
	Cenomanian	Odukpani		
Early Cretaceous	Albian	Asu River Group		
Precambrian	Precambrian Basement Complex			

Table 1 shows a lithostratigraphic framework for the Afikpo Sub-basin, southeast Nigeria

Figure 3a: Planar cross bedded sandstones with reactivation structures and tidal bundles (3b) and herringbone structures are sandstones on the Amaorie Beach road, Ozziza, Afikpo.

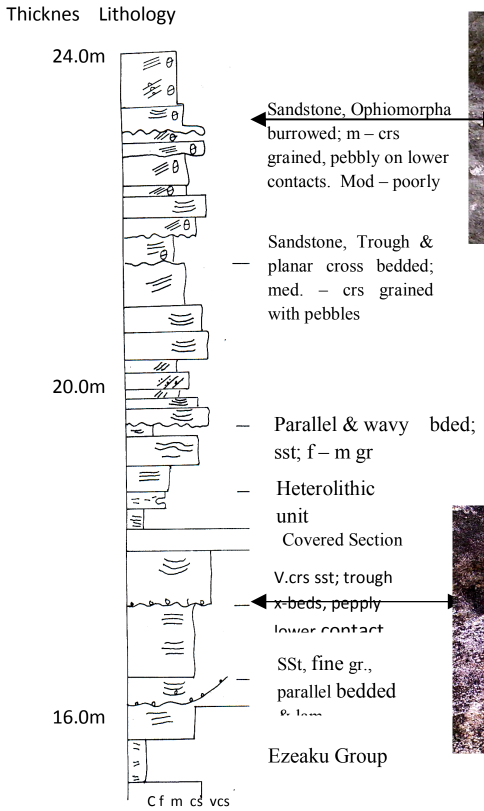


Figure 4: Outcrop section of Afikpo Sandstone on Mcgregor Hill with vein quartz pebbles

Figure 5: Sand-dominant heterolithic unit with wavy and ripple laminations, flaser structures, low angle cross-beds and rare *Ophiomorpha isp* burrows at the Ezzi Edda Sandstone quarry.

Figure 6: Fossiliferous Sandstone with intact bivalves and gastropod shells along Ndibe Beach Road

Figure 7: Dark grey to black shale with beds of brownish micritic limestone.

Table 2: Summary result of Pebble Morphometric Analysis for the Afikpo Sandstone

Sample No.	L	I	S	S/L	I/L	$\frac{L-I}{L-S}$ Form	$(S^2/LI)^{1/3}$ Maximum projection sphericity	Oblate Prolate Index	Form Name	Roundnes s (ρ) (%)
AF01P	1.37	0.92	0.70	0.53	0.69	0.64	0.74	3.11	CB	46
AF02P	1.33	0.1	0.74	0.57	0.81	0.44	0.74	-1.02	CB	41
AF03P	1.29	0.95	0.78	0.61	0.74	0.67	0.78	2.80	CE	43
AF04P	1.88	0.27	0.97	0.53	0.68	0.68	0.74	3.54	CE	34
AF05P	1.68	1.22	0.79	0.48	0.73	0.54	0.68	0.54	B	30
AF06P	1.70	1.24	0.79	0.48	0.75	0.49	0.67	-0.09	B	42
AF07P	1.54	1.18	0.74	0.48	0.78	0.44	0.67	-1.42	B	38
AF08P	1.69	1.23	0.74	0.46	0.74	0.45	0.64	0.32	B	30
AF09P	1.89	2.36	0.94	0.52	0.74	0.57	0.72	1.11	CB	42
AF10P	1.96	1.49	1.04	0.55	0.77	0.53	0.72	0.21	CB	40
AF11P	2.00	1.43	0.96	0.48	0.72	0.55	0.68	0.75	B	30
AF12P	2.25	1.55	1.18	0.53	0.70	0.67	0.74	2.95	CE	48
AF13P	2.26	1.38	1.09	0.48	0.62	0.73	0.73	5.06	E	40
AF14P	2.11	1.41	1.07	0.50	0.68	0.64	0.72	2.96	CB	38
AF15P	2.30	1.45	1.02	0.45	0.63	0.68	0.69	3.87	E	39
AF16P	2.11	1.39	0.02	0.49	0.66	0.64	0.71	3.26	B	49
AF17P	1.57	1.03	0.73	0.47	0.67	0.63	0.70	2.69	B	46
AF18P	1.47	1.08	0.77	0.53	0.75	0.53	0.72	2.88	CB	38
AF19P	1.55	1.12	0.73	0.48	0.66	0.51	0.67	0.12	B	43
AF20P	1.54	1.11	0.73	0.49	0.73	0.53	0.69	0.67	B	42
Mean				0.51	0.71	0.58	0.71	1.67	CB	39.95%

CB = Compact bladed. B = Bladed. CE = Compact elongate. E= Elongate
L = Long axis. I = Intermediate axis. S = Short Axis. S/L = Coefficient of Flatness. I/L = Elongation Index

S/NO	L	I	S	S/L	I/L	L-I/L-S Form	$(S^2/LI)^{1/3}$ Maximum projection Sphericity	Oblate Prolate Index	Form Name	Roundness (ρ) (%)
OW01P	0.98	0.74	0.46	0.42	0.76	0.47	0.66	0.74	B	71.00
OW02P	0.56	0.36	0.23	0.42	0.67	0.58	0.64	2.04	B	55.00
OW03P	0.52	0.40	0.22	0.41	0.76	0.43	0.61	-1.65	B	53.00
OW04P	0.54	0.40	0.20	0.39	0.76	0.47	0.58	-2.48	B	52.00
OW05P	0.63	0.48	0.25	0.40	0.78	0.38	0.60	-2.84	B	56.00
OW06P	0.64	0.45	0.22	0.35	0.72	0.44	0.57	-1.15	B	58.00
OW07P	0.61	0.44	0.25	0.43	0.73	0.50	0.62	-0.66	B	57.00
OW08P	0.80	0.58	0.37	0.46	0.72	0.55	0.68	0.38	B	62.00
OW09P	0.67	0.50	0.29	0.41	0.76	0.42	0.61	1.36	B	53.00
OW10P	0.56	0.44	0.24	0.46	0.72	0.42	0.63	-1.51	B	47.00
OW11P	0.79	0.58	0.40	0.50	0.73	0.53	0.70	0.86	B	62.00
OW12P	0.86	0.61	0.31	0.35	0.72	0.44	0.56	-1.31	B	51.00
OW13P	0.61	0.44	0.30	0.50	0.73	0.54	0.70	0.75	B	50.00
OW14P	0.63	0.48	0.25	0.40	0.70	0.39	0.59	-3.13	B	57.00
Mean				0.42	0.73	0.47	0.63	-0.69	B	56%

B = Bladed. L = Long axis. I = Intermediate axis. S = Short Axis. S/L = Coefficient of Flatness. I/L = Elongation Index

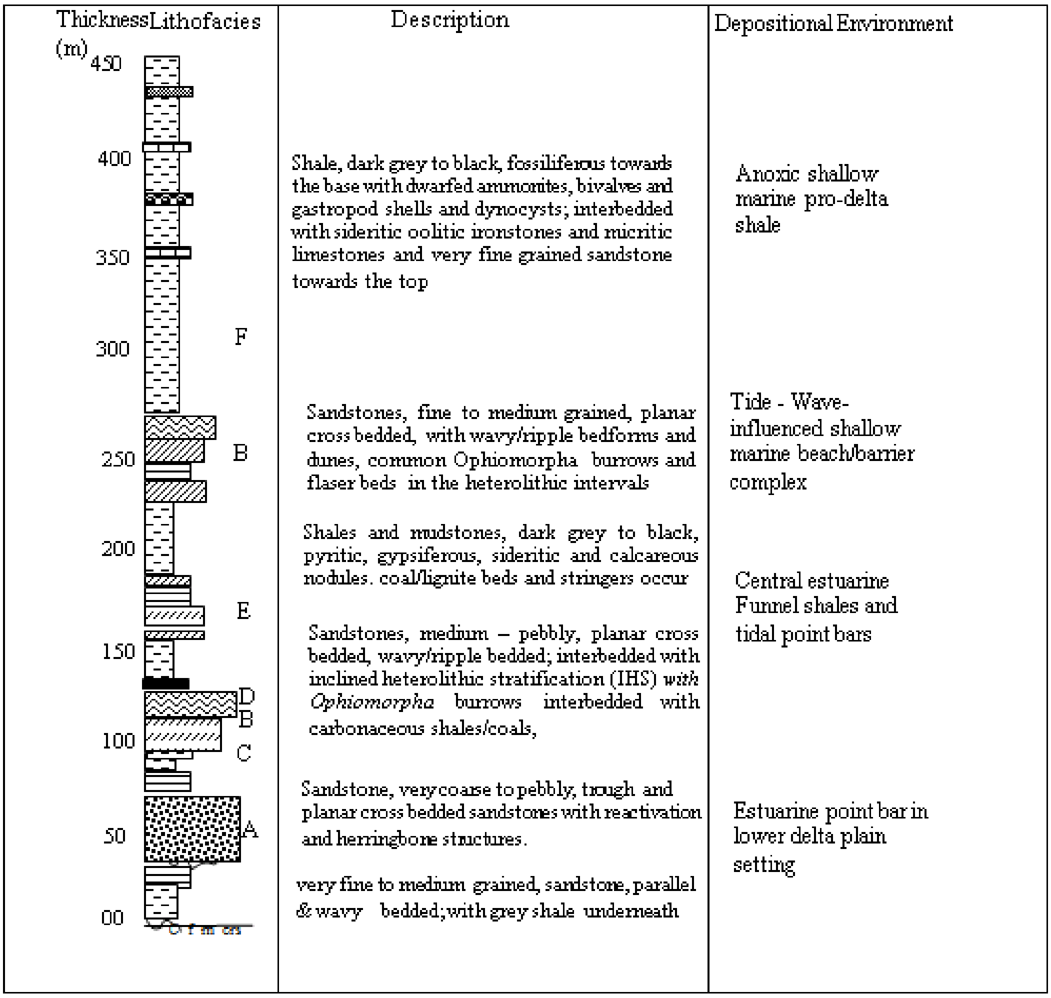


Figure 8: Composite lithologic section of the Nkporo Formation in the Afikpo Sub-basin

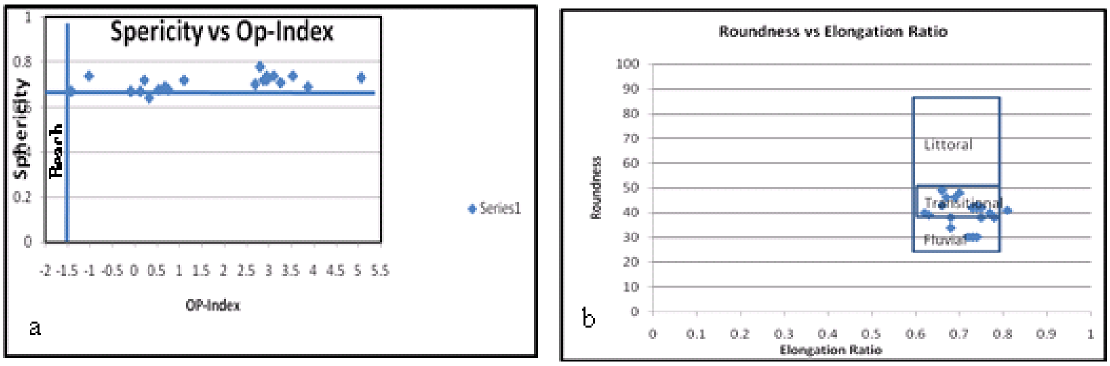


Figure 9a: Plot of Maximum Projection Sphericity vs. OP-Index for Afikpo Sandstone
Figure 9b: Plot of Roundness vs Elongation Ratio for Afikpo Sandstone

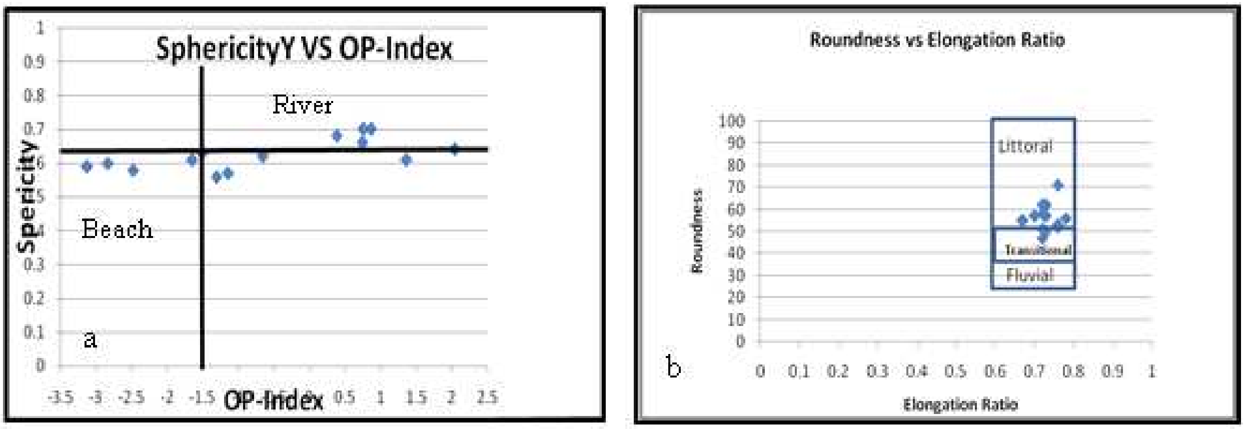


Figure 10a: Plot of Maximum Projection Sphericity versus OP-Index for the Upper Sandstone units
Figure 10b: Roundness vs Elongation ratio for upper Sandstone unit

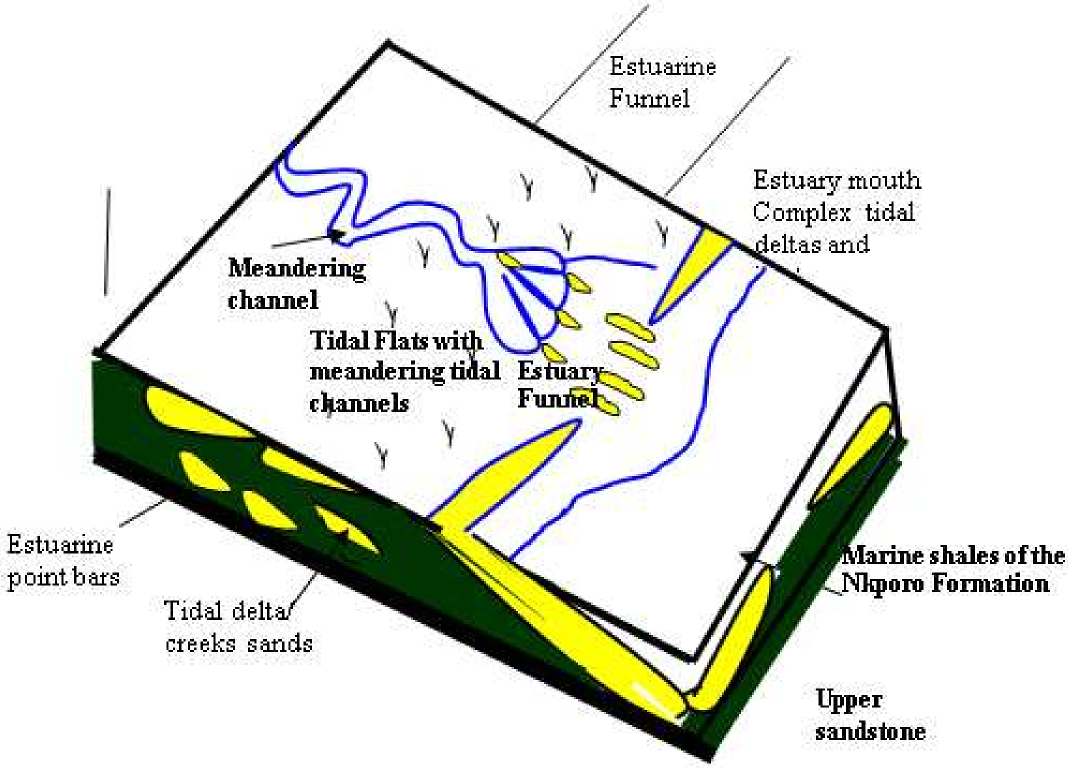


Figure 11: Depositional model of the Nkporo Formation in the Afikpo Sub-basin, southeastern Nigeria