Journal of Natural Sciences Research
ISSN 2224-3186 (Paper) ISSN 2225-0921 (Online)
Vol.2, No.6, 2012

Tide-generated Sedimentary Structures, Lithofacies and Particle Size Distribution: Proxies to the depositional setting of the Ajali Sandstone in the Anambra Basin, Southeastern Nigeria.

*Onuigbo, Evangeline N., Okoro, Anthony U., Obiadi, Ignatus, I., Akpunonu, Eliseus O., Okeke, Harold C. and Maduewesi Victor U.
Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Nigeria
*E- mail:evangeline.onuigbo@yahoo.com

Abstract
Herringbone cross stratification, mud draped foresets, reactivation surfaces, tidal bundles, flaser beddings, ripple and horizontal laminations were identified on the Ajali Sandstone studied. The biogenic structures occur as dominantly vertical to sub-vertical and u -tubed burrows of the *Skolithos ichnofacies commonly Skolithos verticalis and Ophiomorpha nodosa.* Occasional *Thalassinoides* and *Teichichnus* isp burrows of the *Cruziana Ichnofacies* also occur. Three lithofacies were identified and these include; the medium to coarse grained cross bedded sandstone lithofacies, Fine grained cross bedded sandstone lithofacies and the mudstone lithofacies. The paleocurrent pattern from cross bed azimuths shows a bimodal – bipolar pattern indicative of tidal process. The grain size frequency histograms indicate both unimodal and bimodal asymmetrical patterns with shifting modes. The cumulative frequency curves suggest traction, saltation and suspension as the mechanisms of the sediment transport. The bivariate plots of the discriminant functions (Y_1, Y_2 and Y_3) for the sands suggest deposition in a shallow agitated marine environment. Intertidal to subtidal shallow marine depositional setting is proposed for the Ajali Sandstone.
Key word: Tide, Sedimentary structures, Particle size, Lithofacies, Subtidal, Depositional setting

1. Introduction

The paleoenvironments of the Ajali Sandstone is rather still controversial. The environments according to Reyment (1965) and Tijani *et al*., (2010) is fluvio-continental; for Hoque and Ezepue (1977) and Awalla and Eze (2004), it is fluvio- deltaic. Banerjee (1979) and Amajor (1986) in their works concluded that the environment is intertidal while Ladipo (1986) was of the view that it is subtidal.

The study of tidal flat sedimentation has received much attention. Malvarez *et al*., (2001) noted that the methodological approaches to the investigation of the tidal flat sedimentation are widely varied and focus commonly on the examination of forcing factors (tide, wave, wind) and the interplay with the morphology (e. g intertidal zone, channel, salt marshes). Sedimentary structures that reflect the periodic tidal current reversals separated by episodes of exposure or slack water have been used by geologists over a decade to recognize shallow water tidal facies (Kreisa and Moiola, 1986). These sedimentary structures include herringbone cross stratifications, reactivation surfaces, tidal bundles, lenticular and flaser beddings, bimodal-bipolar paleocurrent pattern etc. However, this approach to recognizing tidalities can be ambiguous since some other processes can generate the structures outside tidal environment.

This paper focuses on the tide- generated sedimentary structures, lithofacies and particle size distribution of the Ajali Sandstone. It however, integrated them in the interpretation of the depositional setting of the formation.

The methods and criteria for distinguishing environments of deposition from the grain size distribution used by the previous workers were based mainly on Folk and Ward (1957), Friedman (1961, 1979), Moiola and Weiser (1968) among others. Sahu (1964) noted that every environment of deposition may be assumed to have a characteristic range of energy conditions as functions of location and time. The bivariate plots of the discriminate functions of Sahu (1964) which were based on grain size parameters as well as his proposed scheme for classification of depositional environment were also employed here in the interpretation of the depositional setting.

2. Regional Tectonic and StratigraphicSetting

The origin of the Anambra Basin is intimately related to the development of the Benue Rift. The Benue Rift was installed as the failed arm of a trilate fracture (rift) system, during the breakup of the Gondwana supercontinent and the opening up of the southern Atlantic and Indian Oceans in the Jurassic (Burke *et al*., 1972; Olade, 1975; Benkhlil, 1982, 1989; Hoque and Nwajide, 1984; Fairhead, 1988). The initial synrift sedimentation in the embryonic trough occurred during the Aptian to early Albian and comprised of alluvial fans and lacustrine sediments of the Mamfe Formation in the southern Benue Trough. Two cycles of marine transgressions and regressions from the middle Albian to the Coniacian filled this ancestral trough with mudrocks, sandstones and limestones with an estimated thickness of 3,500m (Murat, 1972; Hoque, 1977). These sediments belong to the Asu River Group (Albian), the Odukpani Formation (Cenomanian), the Ezeaku Group (Turonian) and the Awgu Shale (Coniacian). During the Santonian, epeirogenic tectonics, these sediments underwent folding and uplifted into the Abakaliki- Benue Anticlinorium (Murat, 1972) with simultaneous subsidence of the Anambra Basin and the Afikpo Sub- basins to the northwest and southeast of the folded belt respectively (Murat, 1972; Burke, 1972; Obi, 2000; Mode and Onuoha, 2001). The Abakaliki Anticlinorium later served as a sediment dispersal centre from which sediments were shifted into the Anambra Basin and Afikpo Syncline. The Oban Masif, southwestern Nigeria basement craton and the Cameroon basement complex also served as sources for the sediments of the Anambra Basin (Hoque and Ezepue, 1977; Amajor, 1987; Nwajide and Reijers, 1996). Figure 1 is the geologic map of southeastern Nigeria showing the study area.

After the installation of the Anambra Basin following the Santonian epeirogeny, the Campanian- Early Maastrichtian transgression deposited the Nkporo Group (i.e the Enugu Formation, Owelli Sandstone, Nkporo Shale, Afikpo Sandstone, Otobi Sandstone and Lafia Sandstone) as the basal unit of the basin, unconformably overlying the Awgu Formation. This was followed by the Maastrichtian regressive event during which the coal measures (ie the Mamu, Ajali and Nsukka Formations) were deposited. Table 1 shows the stratigraphic sequences in the Anambra Basin.

3. Methodology

The outcrop sections of the Ajali Sandstone exposed at Inyi town and also near Onyeama Mine along Enugu- Onitsha expressway, Enugu were studied and logged from the base to the top (Figures 3 and 4) with emphasis on the distribution of the particle sizes, tide- generated sedimentary structures and lithofacies. Representative samples of the sands were collected for sieve analysis. In the laboratory the sand samples were dried and sieved for grain size analysis. The graphical computational method of Folk and Ward (1957) was employed in order to calculate grain size parameters, namely; Inclusive Graphic mean (MZ), Inclusive Graphic standard deviation (δ_1), Inclusive Graphic skewness (SK_1) and Graphic kurtosis (KG). The discriminate functions of Sahu (1964) together with his proposed scheme for the classification of the depositional environments, lithofacies and sedimentary structures formed the bases for the environmental interpretation.

4. Result and Interpretation

4.1 Outcrop Locations and Description

4.1.1 Locality: Inyi I

An outcrop of about 80 m thick was exposed inside a bush about 380 m away from the Mamu River Bridge along Ufuma- Inyi Road, Inyi (Figure 2). The outcrop consists of fine to coarse grained whitish sandstone with reddish brown banding. The sandstones at some points are interbedded with thin beds of mudstone. The exposure exhibits fining upwards sedimentation pattern and lateral facies variation. Sedimentary structures include; abundant herringbone cross- stratification especially at the basal part, reactivation surfaces, clay drape, tidal bundles, flaser bedding, parallel and ripple laminations.

The mudstone units are intensely bioturbated. The horizontal burrows of *Thalassinoides isp.* and *Teichichnus isp.* were found on the mudstone unit while the vertical to sub- vertical u tubes of *Skolithos* isp, *Ophiomorpha* isp. and *Arenicolite* isp. were seen on the sandstone units (Figure 6).

4.1.2 Locality: Inyi II: Agu Alum Inyi

The outcrop consists of massive friable fine to very coarse sandstone that is generally whitish in colour with minor stains of iron oxide in form of banding in the sandstone units. The iron oxide banding is more pronounced at the base of the outcrop. The sequence displays a fining upward motif with very coarse whitish to light brown sandstone at the base. The beds of very coarse sandstone are thin. The sandstone generally contains minor clay. They are poorly to moderately well sorted and the grains are subangular to subrounded. Sedimentary structures include current ripples, parallel laminations and herringbone cross stratification. The azimuths of the cross beds measured are essentially bi- directional and in the northwestern and southeastern directions. The outcrop is about 3.4 m thick (Figure 3).

4.1.3 Locality: Near Onyeama Mine, Enugu

The exposure is about 7 m thick and consists of whitish fine sandstone with minor clay pebbles. Sedimentary structures include abundant clay drape, tidal bundles, festoon cross- beds and ripple lamination. Vertical u- tubes of *Skolithos* are common (Figure 4).

4.1.4. Locality: Abriba burrow pit.

The exposure is 24 m thick and consists of white to milky white profusely cross-stratified sandstones with horizontally clayey intervals (Figure 5d). The sandstones are dominantly fine to medium but coarse and pebbly grains are common. Siltstone beds and claystones are also present in the lower part of the exposed section. The characteristic cross-bedding of the Ajali Sandstone is strikingly displayed. Planar cross-beds, with graded and clay draped foresets dominate over the trough types. Reactivation surfaces are common in the lower part of the outcrop section. The horizontal bedded and laminated sets vary from 5cm – 20cm in thickness. Clay beds varying from 3cm to 12cm in thickness also occur in these parallel bedded sets. Often these beds appear wavy and rippled with abundant clay flaser beds. Abundant *Ophiomorpha isp.* burrows characterize the beds in the lower part of the section (Figure 5e).

4.2 Lithofacies

*4.2.*1. Cross bedded medium to coarse sandstone facies (A): It consists of medium to coarse grained silty sandstone. The unit is whitish to brownish in colour and displays some colour bandings. Sedimentary structures include abundant herringbone cross- bedding, tidal bundles, reactivation surfaces and mud drape. Vertical and sub vertical burrows of *Ophiomorpha* and *Skolithos* characterised this facies unit. According to Boggs (1995), this unit belongs to both subtidal and sand flat (lower intertidal zone) which lie below and above the low tide level respectively. The sediments were possibly deposited by bedload transport during higher velocity phase of tidal cycle. The general absence of finer particles in this unit could be as a result of winnowing by wave energy at work in this zone.

4.2.2. Cross bedded fine sandstone facies (B): The unit is dominantly fine grained whitish sandstone with minor clay pebbles. Festoon cross beds (both planar and trough types), mud drape, tidal bundles, reactivation surfaces, ripple laminations and *Skolithos isp* burrows are common in the sandstone (Figures 4 and 5). These structures suggest high energy agitated shallow marine environment affected by tidal flows.

4.2.3. Ripple laminated mudstone facies (C): Thin beds of this facies unit were interbedded with the medium to coarse sandstone at some points within the exposure (Figure 1b). The unit is intensely bioturbated (Figure 6c). *Thalassinoides, planolites* and *Teichichnus* were identified. Boggs (1995) noted that mixed sand and mud together with flaser and wavy beddings characterize the mixed flat (middle intertidal zone) environments. In intertidal zone, organisms live where they are best adapted to the variations in substrate character and fluctuating salinity. The most tolerant thrive at the upper end of the intertidal flat and the less tolerant live closer to the low tide mark. The effects of wave and current energies are minimal in mixed flat zone and thus it supports greater population of organisms compared with the sand flat. The sediments were transported and deposited by both bedload and suspension. The mud settled from the suspension as discrete particles during the period of low water slack.

4.3 Tide - generated Sedimentary Structures

Tidally generated sedimentary structures identified from the base to the top of the three outcrop sections of the Ajali Sandstone studied include; abundant herringbone cross stratification, reactivation surfaces, tidal bundles, mud drape, small scale ripple laminated mudstone interbedded with medium to coarse sandstone and trace fossil suites consisting dominantly of skolithos ichnofacies (*Skolithos* and *Ophiomorpha*) and cruziana ichnofacies (*Arenicolites, Thalassinoides* and *Planolites*).

4.3.1. Clay drape and Flaser bedding

Boggs, (1995) noted that clay drapes are formed during slack- water stage by the deposition of suspended mud over eroded ripple crests. Figure 5a shows the fine grained sandstone unit of the Ajali Sandstone with abundant clay drape.

4.3.2 Tidal Bundles

Tidal bundles are set of cross laminae formed by the stronger set of currents in an asymmetric tidal cycle. The Ajali Sandstone exposed at Inyi area displays variations in the thickness of the foreset laminae in the cross- beds. The variation has been attributed to flow strength in the neap- spring cycles (Nicols, 1999). The tidal current strength being weakest during the neap tide deposited the smaller quantities of the finer sands and mud. With the increasing tidal variation towards the spring tide, coarse grained sands were deposited. The thicker beds were formed during the spring tide and the thinner ones during the neap tide. The tidal bundles were enclosed within a pause plane (Figure 5c). At Enugu area, the fine sandstone unit has abundant clay drape, tidal bundles and reactivation surfaces (Figure 5b).

4.3.3 Reactivation surfaces

These result from unsteady flow velocities produced in the unidirectional flow system by migration of a faster-moving mega ripple over a slower one (Mowbray and Visser, 1984). Boggs, (1995) attributed them to tidal reversal during an asymmetrical tidal cycle under which the ripple crests can be eroded and re-deposited during the next tidal cycle thereby giving rise to reactivation surfaces. Figure 5b shows reactivation surfaces on the sandstone of the Ajali Sandstone exposed near Onyeama Mine, Enugu.

4.3.4 Herringbone Cross Stratification

This results from current reversals (Kreisa and Moiola, 1986). The cross laminated sandstone deposited during flood tide dip in the opposite direction to those formed during ebb tide (Figure 5c).

4.3.5 Festoon cross- beds

These are cross- beds which are created when more rounded ripples and dunes cut back and forth into each other. Both the planar and trough types were present and alternate each other in the fine sandstone (Figure 5d). The cross bed thickens upwards suggesting progradation of the sea.

4.4 Biogenic Structures

Trace fossils are more on the lower part of the outcrop at Inyi. The mudstone units are intensely bioturbated. The ichnofacies identified include; Skolithos (*Ophiomorpha* and *Skolithos)* and Cruziana (*Arenicolite, Thalassinoides* and *Teichichnus*). The sandstone units documented the vertical to sub- vertical u tubes of *Ophiomorpha* and *Skolithos* while the mudstone preserved the assemblage which include; the *Skolithos, Arenicolites, Teichichnus* and *Thalassinoides* (Figures 6).

4.5 Paleocurrent Analysis

The azimuths of cross- beds measured from two outcrop location were analyzed (Table 3) and plotted on the rose diagram (Figure 7).

4.5.1 The Rose Diagram

The rose diagram from the azimuths of the cross- beds is bimodal and bi- polar. The bi- directional paleo- flow suggests sediment transport from the southeastern, southwestern and northwesterly directions.

4.6 The Particle Size Distribution

Environments of deposition can be discriminated using various statistical measures. The scattergraphs of grain size parameters have been employed by sedimentologists for years. The use of bivariate plots of the grain size parameters in environmental discrimination was based on the assumption that the statistical parameters reliably reflect differences in the fluid- flow mechanisms of sediment transportation and deposition (Sutherland and Lee, 1994). Table 4 shows the statistical parameters and discriminating functions (Y1, Y2 and Y3).

4.6.1 Bivariate Scattergraphs of Grain Size Parameters

Combinations of grain size parameters have been advocated by a number of authors as a method suitable to distinguish between sediments deposited by different processes. This method is based on the assumption that different processes of transportation result in variations in grain size distribution. These are reflected in the statistical parameters which when plotted as scatter graph, produce bivariate clusters of samples affected by the same process, and separation of those samples influenced by different processes.

Fig. 8a shows the relationship between the mean grain size and the sorting. Tucker (1990) noted the covariance between mean grain size and sorting. Sorting values increase (i.e for progressively poorer sorting) as mean grain size increases. Fine- grained sediments are almost moderately to well sorted. This is the case with the Ajali Sandstone studied. Majority of the coarse sands are poorly sorted while the medium sands are dominantly moderately sorted.

Figure 8b is the plot of skewness vs sorting for the sands. The sands are generally moderately sorted and near symmetrical to negatively skewed. The plot of skewness against kurtosis (Figure 8c) served as a powerful tool for the interpretation of the genesis of the sediments. This was done by quantifying the degree of normality of its size distribution. Most of the sands lie within near symmetrical/platykurtic and negatively skewed/platykurtic to leptokurtic fields. This suggests the dominance of medium grained size population and the presence of a subordinate population of coarse grained sands which are responsible for the negative skewness. The negative skewness of the sediments is attributed to higher energy conditions. Saravanan and Chandrasekar (2010) pointed out that sediments are medium grained and well to moderately sorted at low and high tide due to the high wave energy condition, causing the finer sediments to be winnowed away. Amos (1995) also acknowledged the role of waves in tidal- flat sedimentation and its importance in the intertidal area. The variation in the wave energy may also be responsible for the variation in the particle sizes (the medium and the coarser fractions) in the Ajali Formation.

4.6.2 The Cumulative Frequency Curves

The cumulative frequency curves of some of the sand samples recognized traction, saltation (in some case I and II are present) and suspension as the possible mechanisms of the sediment transport and deposition (Figure 9).

4.6.3 The Grain Size Histogram

The plots show unimodal and bimodal grain size distributions with shifting mode. The distribution is dominantly asymmetrical pattern (Fig. 10). A particular size fraction in the distribution is better sorted than others in each of the plots and thus suggests some variation in the energy of the current that deposited the sandstone as indicated by the shift in the modal class of the various samples plotted.

4.6.4 Environmental Discrimination

The discriminate functions (Y1, Y2 and Y3 of Sahu, 1964 cited in Alsharhan and El- Sammak, 2004) were applied to the grain size data from the Ajali Sandstone in order to characterize the depositional setting.

(a) For the discrimination between Aeolian processes and littoral (intertidal) environments, the discriminate function used is given below:

$$Y_1 = -3.5688\ MZ + 3.7016\ \delta_1^2 - 2.0766\ SK_1 + 3.1135\ KG$$

Where MZ is the grain size mean, δ_1 is inclusive graphic standard deviation (sorting), SK_1 is skewness and KG is the graphic kurtosis.

When Y_1 is less than -2.7411, Aeolian deposition is indicated whereas if it is greater than -2.7411, a beach environment is suggested. 100% of the sand samples from the Ajali Sandstone have Y_1 values that are greater than -2.7411 (Table 4) and thus suggest beach environment.

(b) For the discrimination between beach (back- shore) and shallow agitated marine (subtidal) environment, the discriminate function used include;

$$Y_2 = 15.6534\ MZ + 65.7091\ \delta_1^2 + 18.1071\ SK_1 + 18.5043\ KG$$

If the value of Y_2 is less than 65.3650 beach deposition is suggested whereas if it is greater than 65.3650 a shallow agitated marine environment is likely.

Over 85% of the sands from the formation have Y_2 greater than 65.3650 and thus suggests a shallow agitated marine (subtidal) environment.

(c) For the discrimination between shallow marine and the fluvial environments, the discriminate function below was used

$$Y_3 = 0.2852\ MZ - 8.7604\ \delta_1^2 - 4.8932\ SK_1 + 0.0482\ KG$$

If Y_3 is less than -7.419 the sample is identified as a fluvial (deltaic) deposit, and if greater than -7.419 the sample is identified as a shallow marine deposit.

About 78.5% of the samples have Y_3 greater than -7.419 (Table 4) which is suggestive of shallow marine environment.

The bivariate scatter plots of Y_2 against Y_1 and Y_3 against Y_2 (Figs. 11) provided a bases for better discrimination of the environments. In Figure 11a almost all the samples plot in the field of beach/shallow agitated marine environment (based on Sahu, (1964) proposed scheme for classification of the depositional environments).

A graphical plot of Y_2 vs Y_3 (Fig. 11b) shows distribution of the sands within three fields of depositional environments (based on the classification proposed by Sahu, 1964). The fields include;

(1) Shallow marine/shallow agitated marine environment (64.3%)

(2) Fluvial/shallow agitated marine environment (21.4%)

(3) Shallow marine/beach (14.3%)

Majority of the samples fall within the field shallow marine/shallow agitated marine environment.

5. Discussion and Conclusion

Ancient tidal processes are recognized on sedimentary rocks by the following criteria of Zimmarle and Zimmerle (1995);

1. Presence of paleocurrent patterns indicating bi- directional flow
2. The abundance of reactivated surfaces and clay drapes
3. Presence of sedimentary features indicating repeated, small scale alternations in sediment transport.

Ancient tidal environments are recognized based on the sedimentary structures association and sediments considered to indicate tidal processes and presence of fining upward cycles reflecting channel and fill and tidal - flat progradation.

The lithofacies and sedimentary structures of the Ajali Sandstone consisting of abundant herringbone cross stratification, mud drapes, reactivation surfaces, tidal bundles flaser bedding, parallel and ripple laminations are suggestive of tidal sedimentation. The occurrence of *Skolithos* isp. and *Ophiomorpha* isp. is suggestive of deposition in a high energy, intertidal flat environment (Nwajide and Hoque, 1979; Nwajide, 1980; Amajor, 1984; Mode, 1991). Mbuk *et al* (1985) attributed it to tide dominated shallow marine environment. Boggs (1995) noted that subtidal and the sand flat (lower intertidal) are characterized by deposition of cross bedded sand with other sedimentary structures as seen in the Ajali Sandstone. The alternation of sand and thin ripple laminated mud units are suggestive of mixed flat environment. The rose plot of the azimuths of the cross- beds indicates a bimodal and bi- polar paleocurrent pattern. Tucker (1982) however, noted that paleocurrent pattern in shallow marine shelf can be bimodal and unimodal (if one tidal current dominates). The bivariate scatter graphs of sorting vs mean grain size, skewness vs sorting and kurtosis vs skewness show that sorting increases as the grain size increases. Majority of the coarse sands are poorly sorted whereas the medium grained sands are dominantly moderately sorted. Skewness revolves around near symmetrical and negatively skewed while kurtosis ranges from platykurtic to leptokurtic. The distribution shows dominance of medium grain sand over the subordinate coarse sand population. The finer particles are rare and this is attributed to the winnowing by wave energy at work within these zones. The effects of wave on the sediments decreases from the subtidal (below low tide level) to the mixed flat (middle intertidal, below high tide level).The dominance of negative skewness is an indication of prevalence of higher energy. The Ajali Sandstone is sand dominated tidal flat environment. The cumulative frequency curves of the samples identified traction, saltation and suspension as the possible mechanisms of the sediment transport and deposition. The grain size frequency histograms show both unimodal and bimodal asymmetrical grain size distribution pattern with shifting mode. These suggest some variation in the energy of the current that deposited the sandstone. The bivariant plots of the discriminate functions (Y_1, Y_2 and Y_3) suggest deposition in shallow agitated marine environment. Subtidal to intertidal (sand flat and mixed flat) depositional setting is proposed for the Ajali Sandstone.

References

Adeigbe, O.C. and Salufu, A.E., (2009), “Geology and Depositional Environment of Campano- Maastrichtian sediments in the Anambra Basin, southeastern Nigeria: Evidence from field relationship and sedimentological study”. *Earth Sciences Research Journal* 13, (2)

Alsharhan, A.S. and EL- Sammak, A.A., (2004), “Grain- size analysis and characterization of sedimentary environments of the united Arab Emirates coastal area”. *Journal of coastal Research* 20 (2), 464- 477.

Amajor, L.C., (1984), “Sedimentary facies analysis of the Ajali Sandstone (Upper Cretaceous), Southern Benue Trough”. *Journal of Mining and Geology* 28, 7- 17.

Amajor, L.C., (1987), “The Eze- Aku sandstone ridge (Turonian) of southeastern Nigeria: A re- interpretation of their depositional origin”. *Journal of Mining and Geology* 23, 17- 26.

Amos, C.L., (1995), “Siliciclastic tidal flats” In: S.L. Yang *et al.* (Ed.), Spatial and temporal variations in sediment grain size in tidal wetlands, Yangtze Delta: on the role of physical and biotic controls. *Estuarine Coastal and Shelf Sci,* 77, 657- 671.

Awalla, C.O. and Eze, C.C., (2004), “Paleoenvironment of Nigeria’s Ajali Sandstone: A pebble morphometric approach”. *Global Journal of Geological Sciences* 2, (1), 37- 43.

Banerjee, I., (1979), “Analysis of cross bedded sequences: An example from the Maastrichtian Ajali Sandstone of Nigeria”. *Quart. Journ.of Geol., Min. and Met. Soc., India* 51, 69- 81.

Benkhelil, J., (1982), “Benue Trough and Benue Chain”. *Geology. mag*. 119, 155- 168.

Boggs, S., (1995), “Principles of sedimentology and stratigraphy”. Prentice Hall, Englewood Cliffs, New Jersey, 79- 93.

Burke, K.C.B., (1972), “Longshore Drift, Sub- marine Canyon and Submarine Fans in the development of Niger Delta”. *AAPG Bull*. 56, 1975- 1983.

Burke, K.C., Dessauvagie, T.F.J. and Whiteman, A.J., (1972), “Geological history of the Valley and its adjacent areas”. In Dessauvagie, T.F.J. and Whiteman, A.J. (eds.) African Geology, University of Ibadan Press, 187- 205.

Fairhead, J.D., (1988), “Mesozoic plate tectonic reconstruction of the central south Atlantic Ocean: the role of the West and Central African Rift Systems”. *Tectonophysics* 155, 181- 191.

Folk, R.L. and Ward, W., (1957), “Brazos river bar: a study in the significance of grain size parameters”. *Journal of Sedimentary Petrology,*. 27, 3- 26.

Friedman, G.M., (1961), “Distinction between dune, beach and river sands from their textural characteristics”. *Journal of Sedimentary Petrology,* 31, 514- 529.

Friedman, G.M., (1979), “Differences in size distributions of particles among sands of various origins”. *Sedimentology*, 26, 3- 32.

Hoque, M., (1977), “Petrographic differentiation of tectonically controlled Cretaceous sedimentary cycles, southeastern Nigeria”. *Sedimentary Geology,* 17, 235- 245.

Hoque, M. and Ezepue, M.C., (1977), “Petrology and Paleogeography of the Ajali Sandstone Nigeria”. Journal of Mining and Geology, 14, 16- 22.

Hoque, M. and Nwajide, C.S., (1984), “Tectono- sedimentological evolution of an elongate intracratonic basin (aulacogen): the case of the Benue Trough of Nigeria”. *Journal of Mining and Geology*, 21, 19- 26.

Kreisa, R.D. and Moiola, R.J., (1986), “Sigmoidal tidal bundles and other tide- generated sedimentary structures of the Curtis Formation, Utah”. *Geological Society of America Bull.,* 97, 381- 387.

Ladipo, K.O., (1986), “Tidal shelf depositional model for the Ajali Sandstone, Anambra Basin, southern Nigeria”. Journal of African Earth Sciences, 5, 177- 185.

Malvarez, G.C., Cooper, J.A.G. and Jackson, D.W.T., (2001), "Relationships between wave- induced currents and sediment grain size on a sandy tidal- flat". *Journal of Sedimentary Research,* 71(5), 705- 712.
Mbuk, I.N., Rao, V.R., and Kumaran, K.P.N., (1985), "The Upper Cretaceous- Paleocene boundary in the Ohafia Ozu Abam Area, Imo State, Nigeria". *Journal of Mining and Geology,* 22, 105- 119.
Mode, A.W., (1991), "Assemblage zones, age and paleoenvironment of the Nkporo Shale, Akanu area, Ohafia, southeastern Nigeria". In: A.W. Mode (Ed.), Ichnostratigraphy and paleoenvironments of the Benue Trough, Nigeria. *Journal of Mining and Geology,* 33 (2), 115- 126.
Mode, A.W. and Onuoha, K.M., (2001), "Organic matter Evaluation of the Nkporo Shale, Anambra Basin, from wireline logs". *Global Journal of Applied Sciences,* (7), 103- 107.
Moiola, R.J. and Weiser, D., (1968), "Textural parameters: an evaluation". *Journal of Sedimentary Petrology*, 38, 45- 53.
Mowbray, T. de and Visser, M., (1984), "Reactivation surfaces in subtidal channel deposits, Oosterscheide, southwest Netherlands". *Journal of Sedimentary Petrology,* 54,. 811- 824.
Murat, R.C., (1972), "Stratigraphy and paleogeography of the Cretaceous and Lower Tertiary in southern Nigeria". In: A.J. (Eds.), African Geology, University of Ibadan press Nigeria. 251- 266pp.
Nichols, G., (1999), "Sedimentology and Stratigraphy". Blackwell Science ltd. Oxford, 355p.
Nwajide, C.S., (1980), "Eocene tidal sedimentation in the Anambra Basin, southern Nigeria". S*edimentary Geology,* 25, 189- 207.
Nwajide, C.S., (2005), "Anambra Basin of Nigeria: synoptic basin analysis as a basis for evaluating its hydrocarbon prospectivity". In: Okogbue, C.O. (Ed.), Hydrocarbon Basin. In: Reijers, T.J.A. (Ed.), Selected chapters on Geology, SPDC., 133- 147.
Nwajide, C.S. and Hoque, M., (1979), "Trace fossils from the Nanka Formation, southeastern Nigeria". *Geologie en Mijnbouw*, 58, 85- 88.
Nwajide, C.S. and Reijers, T.J.A., (1996), "The Geology of the southern Anambra Basin", In: T.J.A. Reijers (Ed.) Selected chapters in Geology, sedimentary geology and sequence stratigraphy of the Anambra Basin, *SPDC* Publication, 133- 148.
Obi, G.C., (2000), "Depositional model for the Campano- Maastrichtian Anambra Basin, southern Nigeria". Unpublished Ph.D Thesis, University of Nigeria, 291p.
Olade, M.A., (1975), "Evolution of Nigeria's Benue Trough (Aulacogen): a tectonic model". *Geology Magazine*, 112, 575- 583.
Reyment, R.A., (1965), "Aspect of the Geology of Nigeria". Ibadan Univ. press
Sahu, B.K., (1964), "Depositional mechanisms from the size analysis of clastic sediments". *Journal of Sedimentary Petrology,* 34(1), 73- 83.
Saravanan, S. and Chandrasekar, N., (2010), "Grain size analysis and depositional environment condition along the beaches between Ovari and Kanyakumari, southern Tamilnadu Coast, India". *Marine Georesources and Geotech.,* 28, 288- 302.
Sutherland, R.A. and Lee, C.T., (1994), "Discrimination between coastal sub environments using textural characteristics". *Sedimentology*. 41, 1133- 1143.
Terwindt, J.H.J., (1981), "Origin and sequences of sedimentary structures in inshore mesotidal deposits of the North sea". In: Nio S.D. and others (Eds.), Holocene marine sedimentation in the North sea Basin. Special publication no. 5, International Assoc. of Sedimentologists, Buston, Blackwell Scientific Publ, p. 4- 26 .
Tijani, M.N., Nton, M.E., and Kitagawa, R., (2010), "Textural and geochemical characteristics of the Ajali Sandstone, Anambra Basin, SE Nigeria: Implication for its provenance". *Comptes Rendus Geosciences,*
Tucker, M., (1990), Techniques in sedimentology. Blackwell Scientific publications, 63- 86.

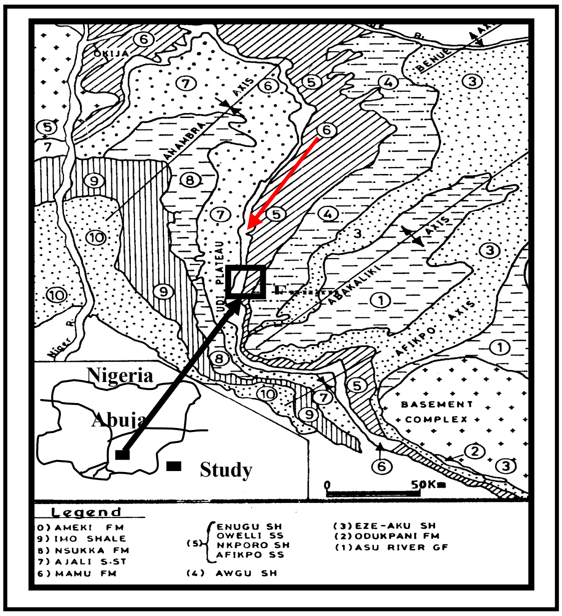


Figure. 1: Geologic map of southeastern Nigeria showing the study area (Modified from Hoque, 1976)

Table1: Stratigraphic sequences in the Anambra Basin (After Nwajide, 2005)

AGE	BASIN	STRATIGRAPHIC UNITS						
Thanetian	Niger Delta	Imo Formation						
Danian	Anambra Basin	Coal Measures	Nsukka Formation					
Maastrichtian			Ajali Sandstone					
			Mamu Formation					
Campanian			Nkporo Fm.	Enugu Fm	Owelli Sst.	Afikpo Sst.	Otobi Sst.	Lafia Sst
Santonian	Southern Benue Trough	Awgu Formation						

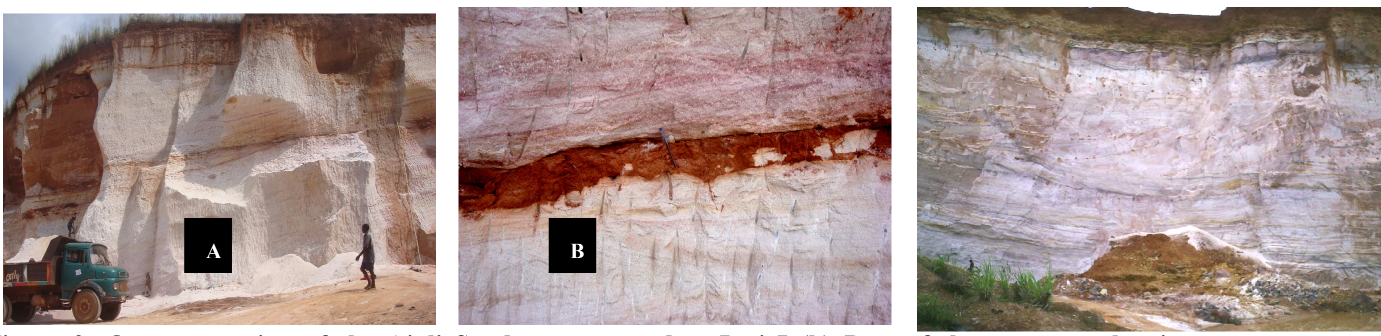
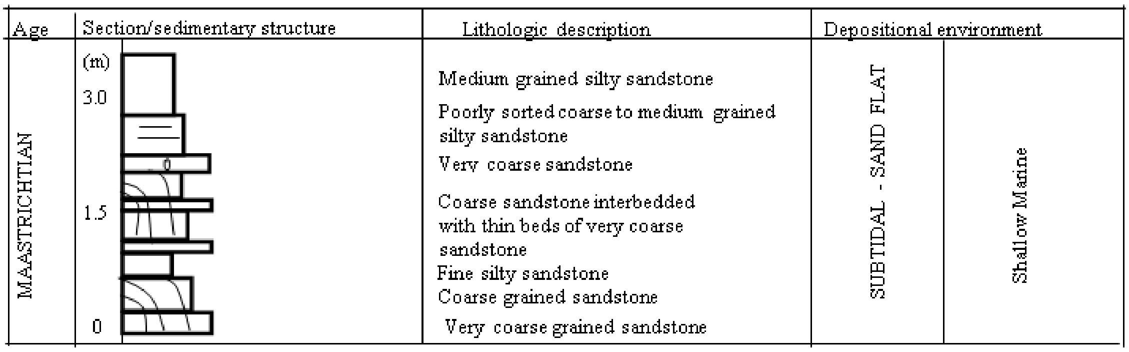


Figure 2: Outcrop section of the Ajali Sandstone exposed at Inyi I (b) Part of the exposure showing interbedded mud and sandstone unit



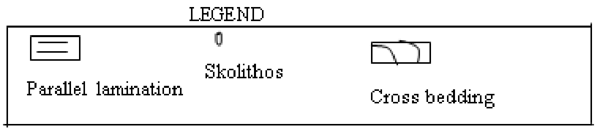


Fig. 3: Lithology and interpretation of an exposure of the Ajali Sandstone exposed at Inyi II

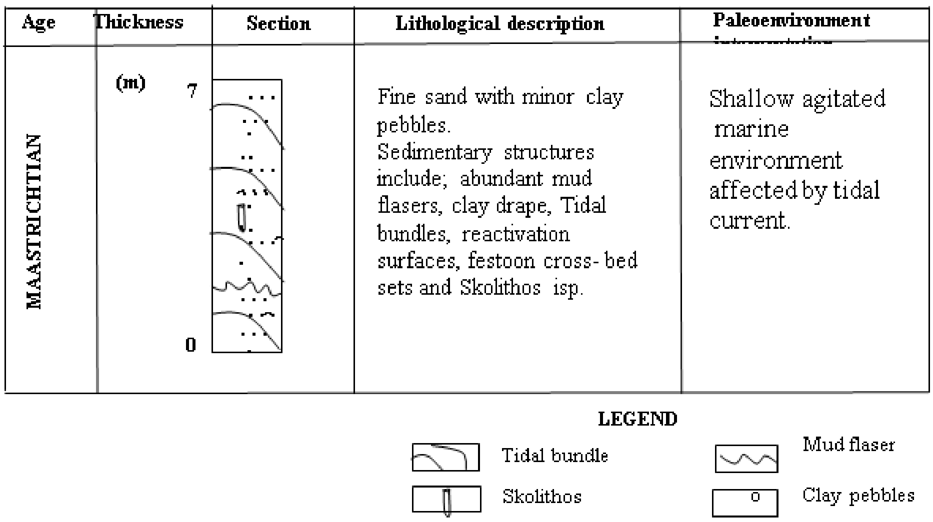


Figure 4: Lithologic section of the Ajali Sandstone exposed near Onyeama Mine, Enugu

Table 2: Classification of sedimentary structures from the Ajali Sandstone

	Physical	Chemical	Biogenic
Primary	**Parallel lamination , Ripple lamination, Herringbone cross stratification, flaser bedding, mud draped foresets, reactivation surfaces, tidal bundles and tidal channels**		***Ophiomorpha* isp. *Skolithos isp. Arenicolite* isp., *Thalassinoides* isp. and *Teichichnus* isp**
Secondary	**Joints**	**Colour bands, nodules and concretions**	.

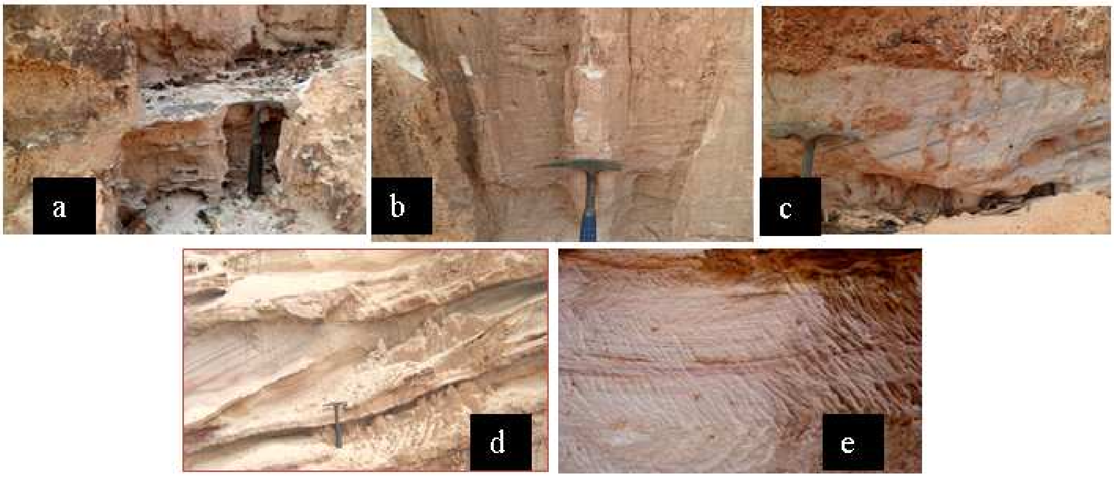


Figure 5: Physical Sedimentary Structures from the Ajali Sandstone in the study area
(a) Mud flaser and Ripple lamination (b) and (c) Clay draped foresets and tidal bundles (d) tidal bundles and reactivation surfaces (e) Herringbone cross- stratification and planar bounding surface

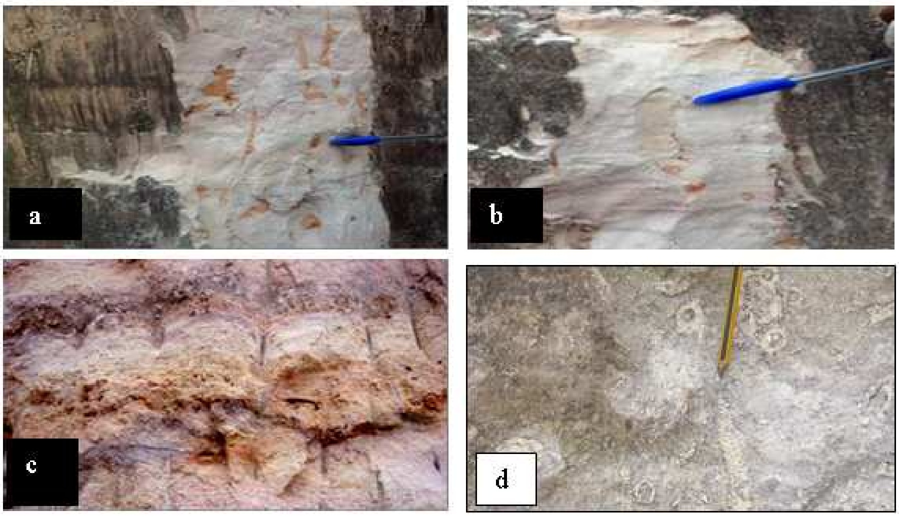


Figure 6: Biogenic Sedimentary structures from the Ajali Sandstone in the study area
(a) and (b) Vertical *Skolithos* burrows (*Skolithos* verticalis) . (c) Intensely bioturbated mudstone unit with some *Cruziana* isp horizontal burrows. (d) *Ophiomorpha* nodosa burrows in bioturbated sandstone

Table 3: Tally of cross- beds azimuths into 15˚ class Intervals

Azimuth Range	Frequency	Total %
90- 105	7	10.00
105- 120	13	18.57
120- 135	8	11.42
135- 150	2	2.86
150- 165	-	-
165- 180	-	-
180- 195	-	-
195- 210	-	-
210- 225	-	-
225- 240	-	-
240- 255	1	1.43
255- 270	6	8.57
270- 285	17	24.29
285- 300	7	10.00
300- 315	8	11.42
315- 330	-	-
330- 345	1	1.43
345- 360	-	-
Total	77	100

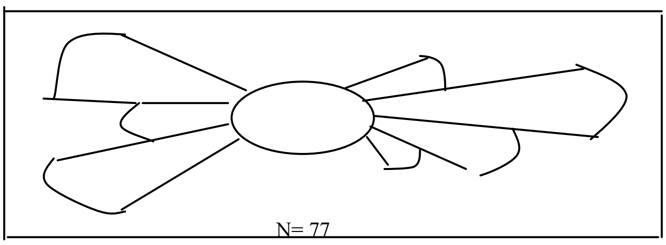


Figure 7: Paleocurrent pattern from cross beds in the Ajali Sandstone showing a bimodal – bipolar pattern in the NW and SE directions typical of flood and ebb flows in tidal environmental setting

Table 4: Results of sieve analysis of sand samples from the Ajali Sandstone

Sample no	Graphic Mean Φ	Median Φ	STD	SKI	KG	Y_1	Y_2	Y_3
AJ1	1.55	1.50	0.67	0.07	0.98	-0.964	73.161	-3.786
AJ2	1.43	1.70	0.67	-0.47	0.96	0.523	61.135	-1.179
AJ3	1.07	1.05	0.87	-0.02	0.82	1.578	81.296	-6.188
AJ4	1.82	1.92	0.52	-0.38	1.42	-0.2840	65.652	0.078
AJ5	1.15	1.20	0.86	0.00	0.71	0.844	79.738	-6.117
AJ6	0.93	0.90	0.98	-0.05	0.77	2.737	91.008	-7.867
AJ7	1.18	1.40	0.91	-0.31	0.77	1.895	81.520	-5.364
AJ8	1.32	1.45	0.95	-0.19	1.21	2.863	98.915	-6.542
AJ9	1.38	1.95	0.82	-0.61	1.34	3.635	79.535	-2.448
AJ10	0.85	0.95	1.12	-0.16	0.73	5.149	98.194	-7.727
AJ11	0.83	1.00	1.27	-0.29	0.86	6.288	129.637	-12.432
AC_1	0.90	1.40	0.80	-0.62	0.79	9.328	59.534	-2.278
AC_2	-0.3	0.59	0.81	0.61	1.60	7.214	79.068	-2.771
AC_3	0.07	0.19	0.91	-0.07	3.70	14.481	122.708	-6.714

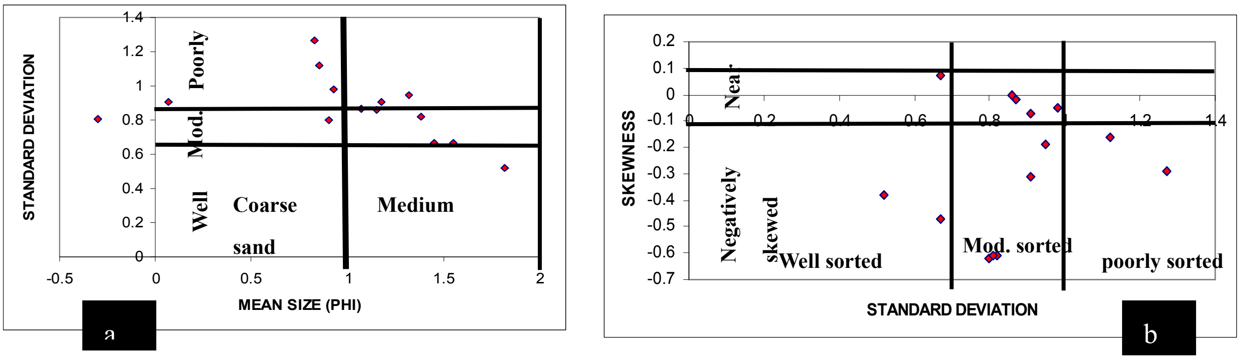


Figure 8: The bivariate plots of the sand samples from the Ajali Sandstone using the template of Alsharhan and El- Sammak (2004). (a) Standard deviation vs Mean grain size (b) Skewness vs Standard deviation

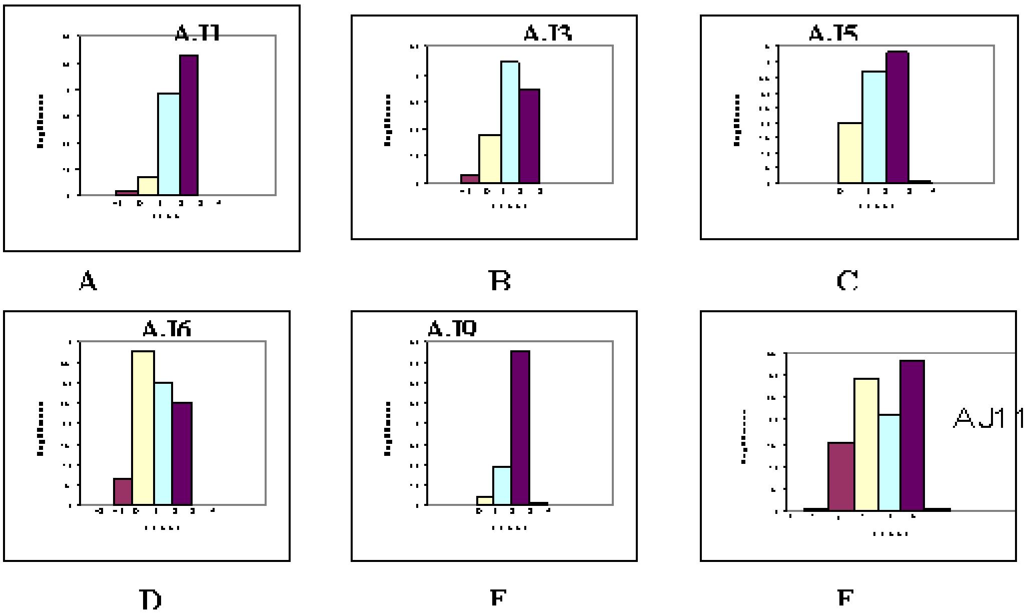


Fig. 9: A - F show the grain size frequency histograms for six sand samples from the Ajali Sandstone.

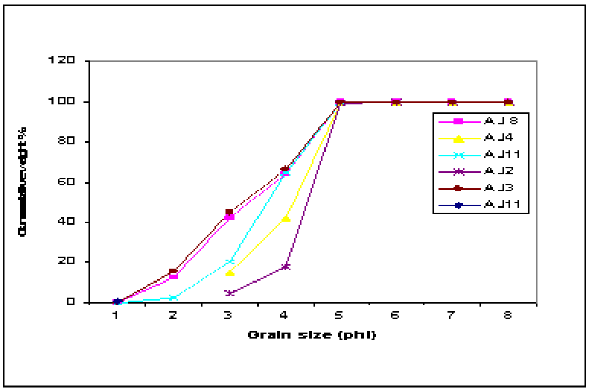


Fig. 10: Cumulative Frequency curves of selected sandstone samples of the Ajali Sandstone

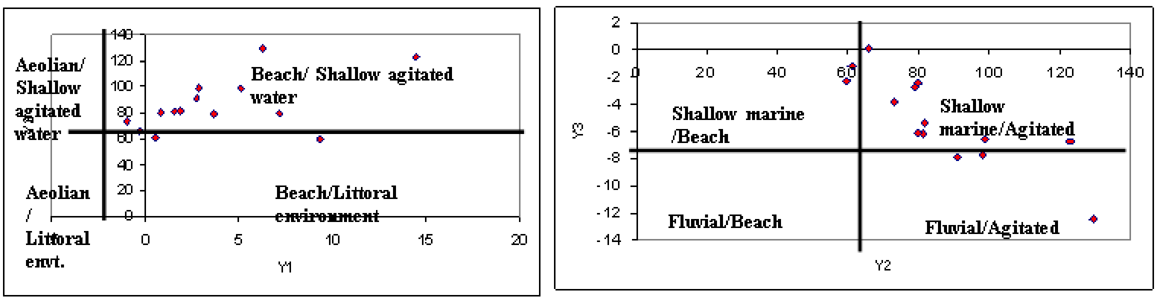


Fig. 11a: Bivariate plot of Y_2 vs Y_1 for the Ajali Sandstone using the template of Alsharhan and El- Sammak (2004).
Fig. 11b: Bivariate plot of Y_3 vs Y_2 for the Ajali Sandstone using the template of Alsharhan and El- Sammak (2004).