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Sedimentary facies characterization and depositional settings of the ajali sandstone, anambra basin, southeastern Nigeria

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ABSTRACT

Sedimentary facies characterization was carried out on the Ajali Sandstone of southeastern Nigeria in order to deduce its depositional settings. Twelve lithofacies identified from the formation were grouped into subtidal channel facies and subtidal sandwave facies based on association. Grain size ranges from fine to coarse and pebbly sandstones with minor clay content in places. Textural analysis shows that on the average, the sandstone is moderately well sorted, near symmetrically skewed and mesokurtic. Cross bedding is characteristics. Tide generated sedimentary structures such as herringbone cross beddings, tidal bundles, reactivation surfaces, clay drapes and clay flasers suggest tidal dominance over wave process. Vertical burrows of Ophiomorpha and Skolithos show colonization of only suspension feeders typical of high energy environment. Clasts of clay occur and can be attributed to reworking of the sediments by tidal currents. The bivariate scatter plots of the discriminate functions calculated from grain size data indicate deposition of the sandstones in a predominantly shallow marine/subtidal environment. Ajali Sandstone is deposited in subtidal channel and subtidal sandwave environments.

Keywords: Sedimentary, Facies, Subtidal, Shallow marine structures, Sandstone

INTRODUCTION

The Maastrichtian Ajali Sandstone in the Anambra Basin of southeastern Nigeria has been described by Agagu et al. (1985) and Nwajide, (2013) as an areally extensive sand body with sheet- like multi – storey geometry. It underlies an extensive area of southeastern Nigeria (Nwajide, 2013) and belongs to the Coal Measure Group (middle coal measure) of Reyment (1965). Ajali Sandstone is underlain by the paralic Mamu Formation (Lower Coal Measure) and overlain by the Nsukka Formation (Upper Coal Measure). The subsurface thickness of the formation estimated by Agagu et al. (1985) from several oil wells drilled west of Enugu was at 500 m.

Although much work has been carried out as regard the depositional environment of the Ajali Sandstone, but it is still a debate. The interpreted depositional environments range from fluvial (Reyment, 1965; Tijiani *et al*., 2010), fluvio-deltaic (Hoque and Ezepue, 1977; Awalla and Eze, 2004), intertidal (Banerjee, 1979), a spectrum of environments ranging from continental through marginal marine to shallow marine (Amajor, 1984), tidally influenced regime in a shelf/shoreline environment (Ladipo,1986), intertidal through tidal channels to continental setting (Bassey and Djieutchue, 2000), tidal/littoral (Adeigbe and Salufu, 2009), shallow marine littoral/fluvial (Adekoya et al., 2011) and marginal marine setting (Nwajide, 2013). The spectacular cross bedded units in the sands were also intrepreted by Nwajide (2013) as tidally propagated sandwaves on a shallow (inner) shelf easily affected by even small sea level fluctuations which caused both fluvial incision, channel filling and the development of tidal subenvironments.

Ancient sedimentary environments can be reconstructed using a combination of sedimentary facies and facies associations including the sedimentary structures particularly primary physical and biogenic (trace fossil assemblages) types. This is because a sedimentary facies is a product of depositional environment. Each sedimentary environment is characterized by a particular suite of physical, chemical and biological parameters that operate to produce a body of sediment characterized by specific textural, structural, and compositional properties (Boggs, 2006) which constitutes a sedimentary facies. Environmental interpretations follow after sedimentary facies analysis and characterization (Middleton, 1978). It is worth noting that unique environmental interpretation cannot be actualized using a single depositional facies. Facies associations and successions which are groups of facies that occur together and are genetically or environmentally related provide a better tool for environmental analysis (Boggs, 2006).

The sedimentary facies characterization of the Ajali Sandstone exposure in various localities in southeastern Nigeria was carried out in this work in order to deduce the depositional settings of the extensive friable sandy unit that constitute the formation.

Regional tectonics and stratigraphic setting

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 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 mudrock, sandstones and limestones with an estimated thickness of 3,500 m (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 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.

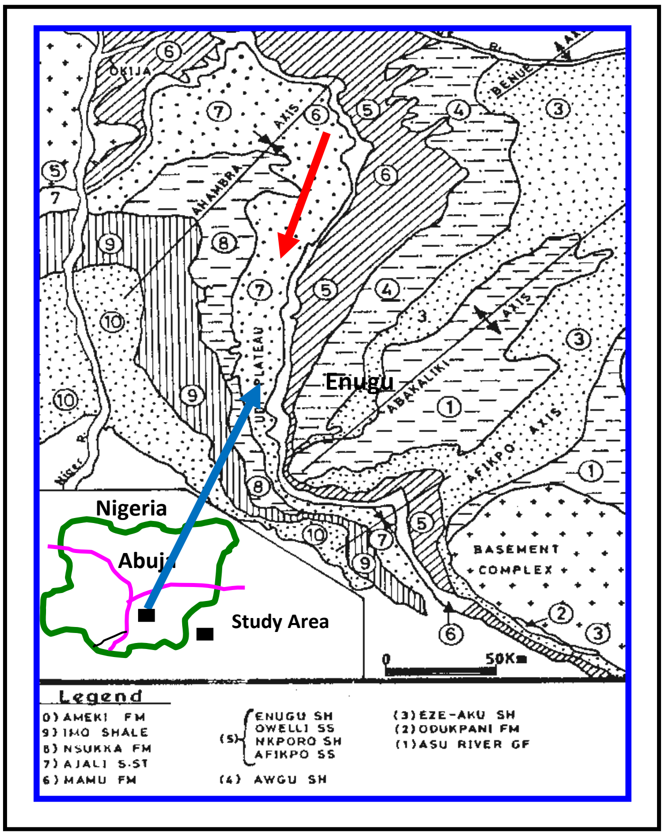
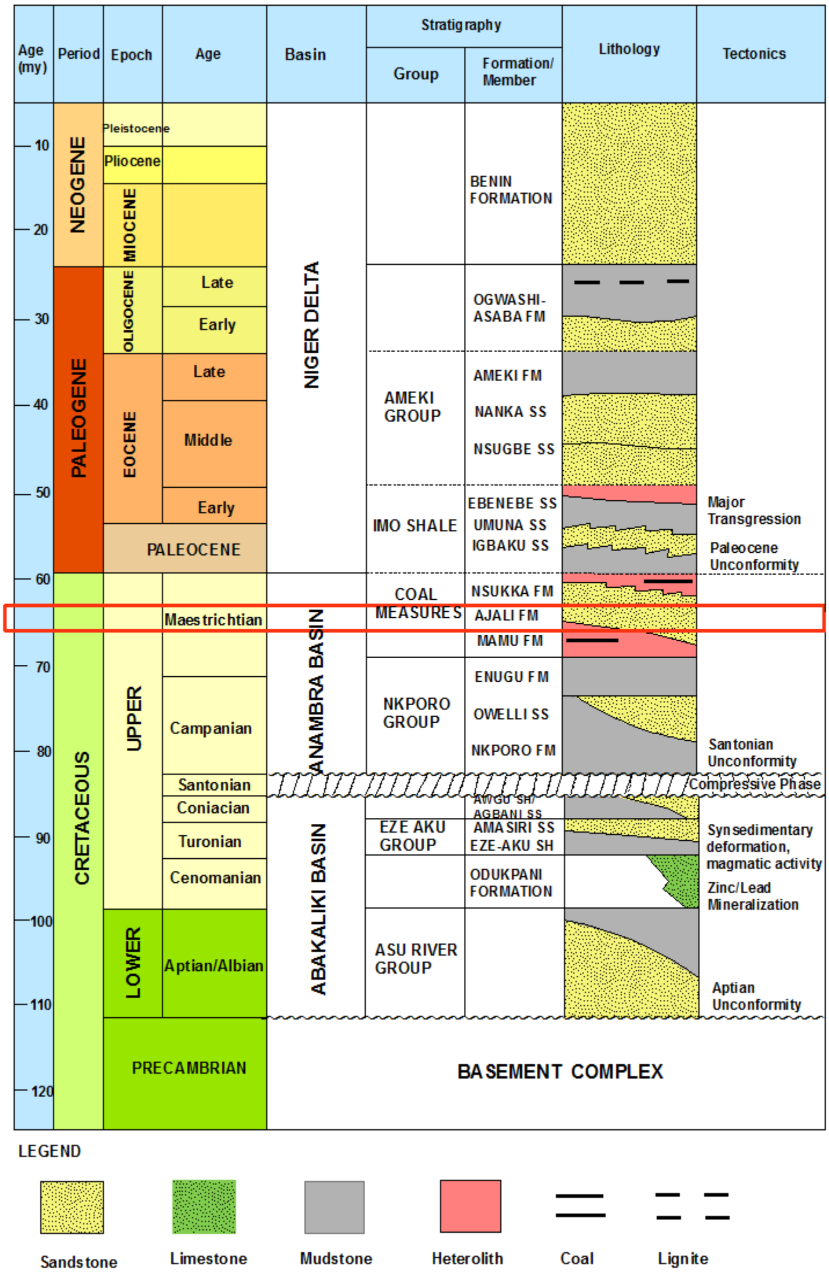


Figure 1: Geologic map of southeastern Nigeria showing the study area (modified from Hoque, 1977).

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 (i.e the Mamu, the Ajali and the Nsukka Formations) were deposited. Table 1 shows the stratigraphic succession of the Cretaceous and Tertiary basins of southern Nigerian with the Anambra Basin sandwiched between the Abakaliki Basin and the Niger Delta.

Table 1: Summarized Stratigraphy of the Benue Trough and Anambra Basin (after Reyment, 1965; Short and Stauble, 1967 and Nwajide, 2005).



METHODS AND MATERIALS

Selected outcrops of the Ajali Sandstone exposed in various parts of southeastern Nigeria were studied. Outcrop sections in Isukwuato, Obuluno, Okigwe and Enugu areas were logged from base to the top. Lithologies were identified and described. The mineralogical composition and texture (grain size, shape and sorting) were studied using hand lens and comparator (checklist). Sedimentary structures were identified. The type, varieties, mode of occurrence, attitudes, wall fills and distribution of the burrows were documented and azimuths of cross beds were measured using compass. Details of rock successions and their characteristic structures were sketched in the field notebook and thicknesses of individual beds were taken using meter tape. Representative samples of sandstone were collected and properly labelled for laboratory analysis. Photographs of important features were also taken.

The lithologs of the outcrops were finally produced, sedimentary facies were characterized based on lithology and sedimentary structures. Facies associations were also identified.

Forty sand samples collected from the field were sieved using the method described by Tucker (1988) and the grain size statistical parameters were calculated based on Folk and Ward (1957).

The discriminate Functions (Y_1, Y_2 and Y_3) of Sahu, (1964) were applied to the grain size data in order to characterize the depositional settings. For discrimination between Aeolian processes and littoral (intertidal) environments, the discriminate function used is given as $Y_1 = -3.5688MZ + 3.7016\delta_1^2 - 2.0766\,SK_1 + 3.1135\,KG$. 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.

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

$$Y_2 = 15.6534MZ + 65.79091\delta_1^2 + 18.1071SK_1 + 18.5043KG$$

If the values of Y_2 is less than 65.360 beach deposition is suggested whereas if it is greater than 65.3650 a shallow agitated marine environment is likely.

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

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

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.

Depositional settings were deduced by integration of the sedimentary facies associations and bivariate scatter plots of the discriminate functions calculated from the grain size data.

RESULTS AND INTERPRETATION

Outcrop descriptions

Isiukwuato Sandstone Quarry

This quarry is located along the Uturu- Ovim road in Isiukwuato, Abia State. The outcrop is dominantly sandstone, variously cross bedded (Figure 2a). The cross bedded sandstone is generally matrix free, fine to coarse grained and pebbly in places. Few Ophiomorpha burrows and dispersed clasts of kaolinitic clay are characteristics. Herringbone cross stratification, tidal bundles, reactivation surfaces, clay drapes, planar and trough cross beds, convolute laminations are some of the sedimentary structures associated with the sandstone. The lower part displays a coarsening upwards of succession of fine to coarse sandstone and is classified as subtidal sand wave facies association. The units above the lower part of the section exhibit a fining upwards of successions of fine to pebbly sandstone typical of channel deposit and was interpreted as subtidal channel facies association. Association of the units with tide generated structures suggest tidal setting whereas the matrix free nature of the sandstone can be attributed to minor wave action. The lithologic section of part of the outcrop logged is shown in Figure 2 (b).

The subtidal channel lithofacies identified include pebbly sandstone lithofacies (A), cross bedded medium to very coarse/pebbly sandstone lithofacies (B), cross bedded fine to medium grained sandstone lithofacies (C), parallel laminated fine grained sandstone lithofacies (D) and cross laminated fine grained sandstone lithofacies (E). Whereas the subtidal sandwave lithofacies consists of cross bedded fine grained sandstone lithofacies (G), cross bedded medium grained sandstone lithofacies (H) and cross bedded coarse grained sandstone lithofacies (I).

The description of the lithofacies as well as their environmental interpretations are treated under sedimentary facies characterization.

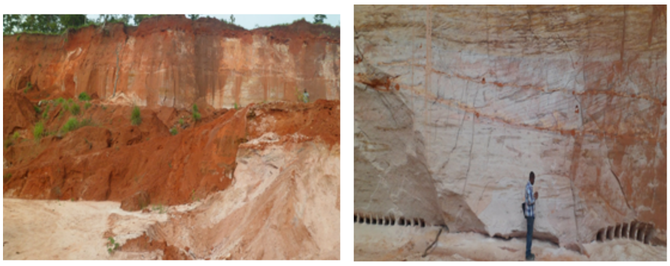


Figure 2a: Outcrop sections of the Ajali Sandstone exposed at Nkwonta along Uturu- Ovim road, Isiukwuato, Abia State..

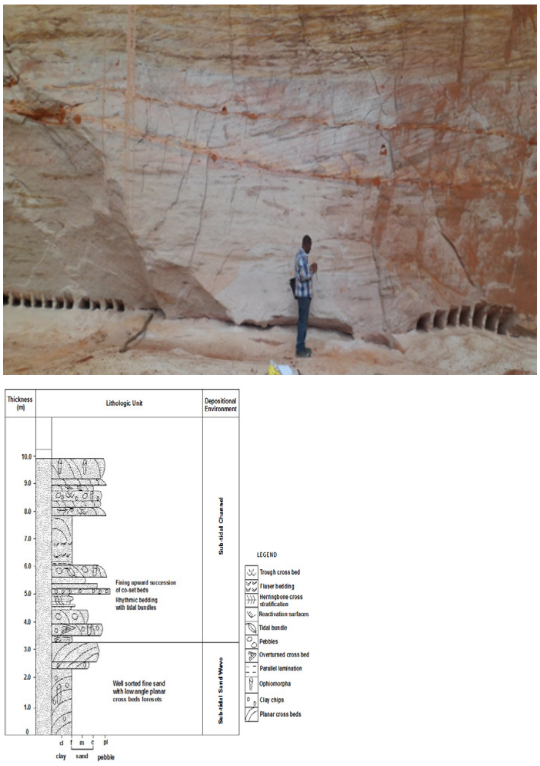


Figure 2b: Lithologic section of the Ajali Sandstone exposed at Nkwonta along Uturu- Ovim road, Isiukwuato, Abia State.

Okigwe/Umulolo Sandstone Quarry

Outcrops of the Ajali Sandstone were described in a sand quarry along the Enugu- Port Harcourt express way near the Umulolo junction. The exposure consists of fine to coarse and pebbly clayey sandtone with dispersed clasts of clay in places. Planar and trough cross beddings as well as clay flasers occur but bioturbation is rare. Facies association identified include the cross bedded coarse to pebbly clayey sandstone lithofacies (F) and cross bedded fine to medium sandstone lithofacies (C). The facies association exhibits a fining upwards characteristics and is interpreted as subtidal channel deposits. This is based on the association of the lithofacies with claystone flaser and dispersed clay clasts in this outcrop. The lithologic section of the outcrop is shown in Figure 3.

Obuluno Sandstone Quarry

This quarry is located off the Leru - Ngodo road in Umunnochi Local Government Area, Abia State. The exposure represents over 20 m thick section of Ajali Sandstone comprising sandstone beds interbedded with claystone facies (Fig iva). Lithofacies identified in this outcrop include cross bedded fine grained sandstone lithofacies (G), cross bedded medium grained sandstone lithofacies (H), cross bedded medium to coarse grained sandstone lithofacies (K), cross bedded coarse grained sandstone lithofacies (I) and grey-whitish claystone lithofacies (L) .

Rhythmic bedding, herringbone cross bedding, flaser bedding, clay drape, reactivation surfaces, planar cross beds with clay draped foresets, wavy and ripple laminations are common.

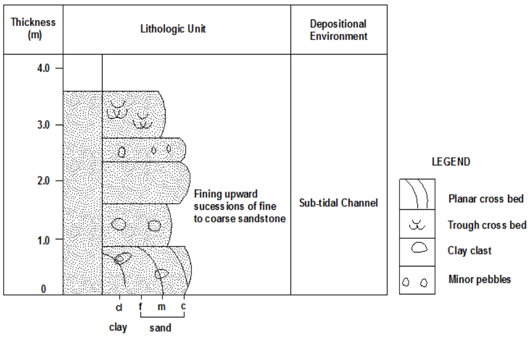


Figure 3: Lithologic section of the Ajali Sandstone exposed near Umulolo junction along Enugu- Port Harcourt express way.

Figure 4(b) is a lithologic section of part of the exposure logged about 30 m away. The facies association shows a coarsening upward characteristics and is interpreted as subtidal sandwave facies association.

Figure 4a: Panoramic view of outcrop section of the Ajali Sandstone at Obuluno, Abia State.

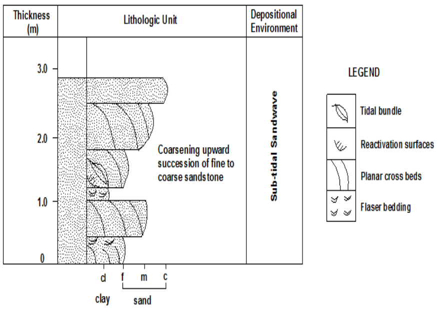


Figure 4b: Lithologic section of the Ajali Sandstone at Obuluno sandstone quarry.

Ajali Sandstone exposure at Enugu

The outcrop occurs as a gully erosion site beside the Enugu - Onitsha dual carriage express way in Uwani Ubogi near Onyeama Coal Mine, Enugu. The exposure consists of approximately 15 meters of Ajali Sandstone with sharply demarcated tabular cosets, 30 – 100 cm thick, composed of fine to medium grained, moderately sorted, weakly consolidated framework material with clay-draped planar cross-beds, flasers, ripples and herringbone structures. A fine grained conglomerate facies, about 0.25 m thick, is sandwiched within the succession (Figure 5,6). Biogenic structures are dominated by vertical *Skolithos* isp burrows and rare O*phiomorpha* isp burrows. Three lithofacies identified in this outcrop section are the very fine – medium grained, planar cross bedded lithofacies (C) with vertical skolithos ichnofacies burrows, fine grained conglomerate facies (M) and medium tp very coarse grained/pebbly cross bedded sandstone lithofacies (B). The sandstone was probably deposited as shallow marine subtidal sandwaves in tidally influenced shallow marine (inner shelf) setting.

Sedimentary facies characterization

The various lithofacies and associations identified in the Ajali Sandstone are described below. Subtidal Channel Facies

The subtidal channel facies generally display a fining upwards of successions of fine to coarse and pebbly sandstone.

Clay matrix is absent in IsIukwuato sandstone but minor in Okigwe facies. Six sedimentary lithofacies were identified and interpreted as follow;

Figure 5a: Outcrop section of the Ajali Sandstone exposed near Onyeama Mine along Enugu- Onitsha Expressway, Enugu. 5b: Tabular cosets, of fine to medium grained, sandstone beds with clay -draped planar cross-beds, flasers, ripples and herringbone structures

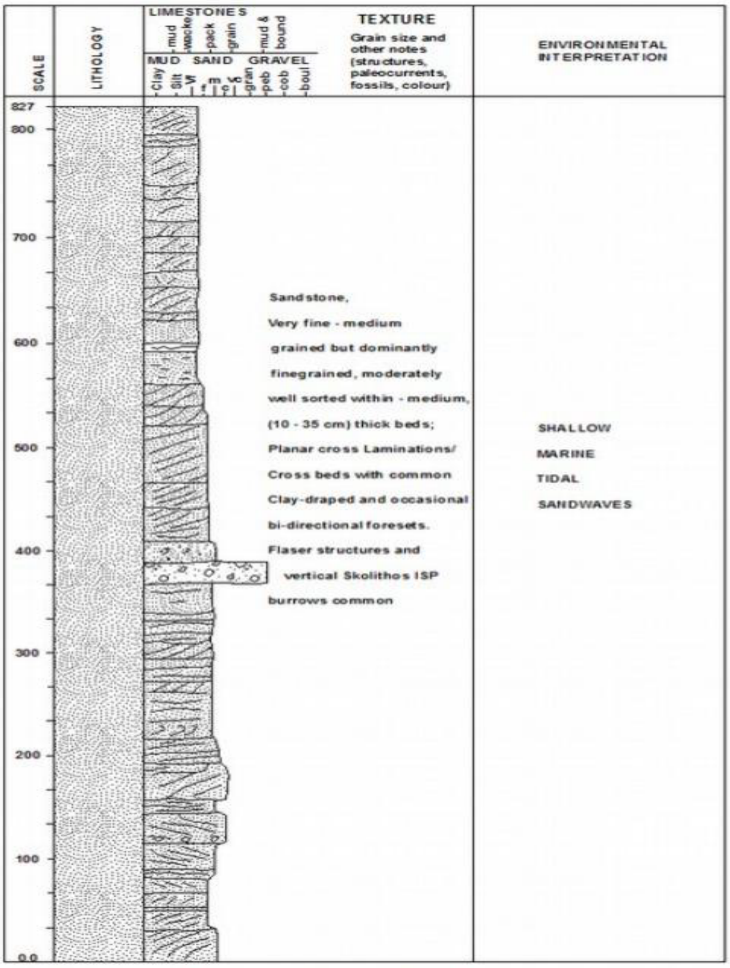


Figure 6: Lithologic section of the Ajali Sandstone exposed near Onyeama Mine along Enugu- Onitsha Expressway, Enugu.

Pebbly sandstone lithofacies (A):

This consists of grain supported matrix free cross bedded pebbly sandstones with sharp basal contacts which constitute the channel lag materials. In Isiukwuato section, thickness of the unit varied and averaged 0.2 m. The pebbly base towards the top of the lithologic section (Figure 2b) is overlain by medium to very coarse cross bedded sandstone lithofacies. Sedimentary structures include trough cross beds and herringbone cross bedding. However, structureless pebbly bases also occur in places. Burrows are rare in the pebbly units.

Interpretation

Association of the pebbly sandstones with herringbone structures is suggestive of tidal process. Herringbone cross bedding is a product of tidal cyclicity characterized by two vertically adjacent cross- beds with opposing foresets dip directions. It has been noted as one of the sedimentary structures typical of tidal setting (Klein, 1970; Visser, 1980; Allen. 1980; Clifton, 1983; Smith, 1988; Dalrymple et al., 1992). Tidal currents tend to be channelized into largely bidirectional currents in nearshore areas. Such bi-directional currents always show some degree of asymmetry (i.e flow in one direction is stronger than that in the other direction) during tidal cycle. This is interpreted as reflecting ebb- flood tidal current flow in a single ebb- flood cycle.

Tidal cross bedding (planar and trough) has been interpreted by Ashley (1990) as the product of large flow- transverse bedforms (sandwave or medium to very large subaqueous dunes) and forms one of the best known ancient subtidal sandstone facies (Narayan, 1971; Anderton, 1976; Nio, 1976; Allen and Homewood, 1984; Teyssen, 1984; Richard, 1986; Surlyk and Noe- Nygaard, 1991).

The pebbly nature of the sandstone as well as lack of bioturbations are suggestive of high energy depositional setting. The colonization window for organisms was possibly closed by sediment mobility which was in form of migration of bedforms and thus inhibiting bioturbation (Pollard et al., 1993; Desjardins et al., 2012).

Cross bedded medium to very coarse grained sandstone lithofacies (B):

This consists of several co-sets of 30 – 50 cm thick planar cross bedded sets which generally fines upwards from medium to coarse to very coarse/pebbly. It is characterized by sharp basal contact. Towards the top, trough and planar cross beds as well as herringbone cross stratification, dispersed clay clasts, large pebbles, *Ophiomorpha* isp burrows and tidal bundles are characteristics of this facies (Figure 2b).

Interpretation

Reactivation surfaces, herringbone cross stratification and tidal bundles in the unit are suggestive of tidal dominance. Tidal bundles show variations in bed thickness resulting from alternation of spring and neap tides. It is an important feature in subtidal environment with dominant flow component, ebb and flood tide (Boersma and Terwindt, 1980; Visser, 1980; Allen, 1981a &b; Yang and Nio, 1985). Reactivation surfaces are interpreted to have been formed by the migration of large bedforms under asymmetrically reversing currents (Boersma, 1969) in which the lee- face of the bed forms are modified by subordinate tidal currents (Elliot and Gardiner, 1981; Ladipo, 1986) followed by a further period of dominant flow (Collinson and Thompson, 1982). Nwajide (2013) attributed the mode of origin of reactivation surfaces to the overriding of one sandwave by another. It is among the characteristics of strongly asymmetric tidal flow with abundant supply of medium to coarse grained sand. Tidal bundles separated by erosional reactivation surfaces is suggestive of subtidal environment (Reineck and Singh, 1980). Particle size, dispersed Ophiomorpha burrows and lots of clasts of kaolinitic clay suggest high energy condition and rapid sedimentation. The density of bioturbation (benthic fauna in sand dominated subtidal sand bodies) is controlled by factors such as oxygen content of the water, food availability, salinity, sediment mobility and hydrodynamic energy, water turbidity and substrate type (Desjardins et al., 2012). Dispersed Ophiomorpha in the facies could be attributed to high energy or highly episodic sedimentation (Lewis and MacConchie, 1994). Clay clasts are reworked sediment.

Cross bedded fine to medium grained sandstone lithofacies (C):

This occurs at the middle part of the Isiukwuato exposure and consists of alternations of five thin beds of uniform thickness (each of the beds is 0.1 m thick). The sandstone is matrix free and whitish to pinkish in colour. Sedimentary structures include cross laminations, planar cross beds with tidal bundles in which the foresets commonly thin upwards and number varied between four and six. In Okigwe area, the facies is clayey and trough cross bedded (Figure 3).

Interpretation

This lithofacies is interpreted as products of moderate energy in subtidal channel setting.

Parallel Laminated, fine grained sandstone lithofacies (D)

This was described in Isiukwuato sandstone exposure. The lithofacies is pinkish to purplish in colour, well sorted, matrix free with parallel laminations. Herringbone structures are present. Convolute laminations occur towards the top of the facies (Figure 7b). Bioturbation is rare.

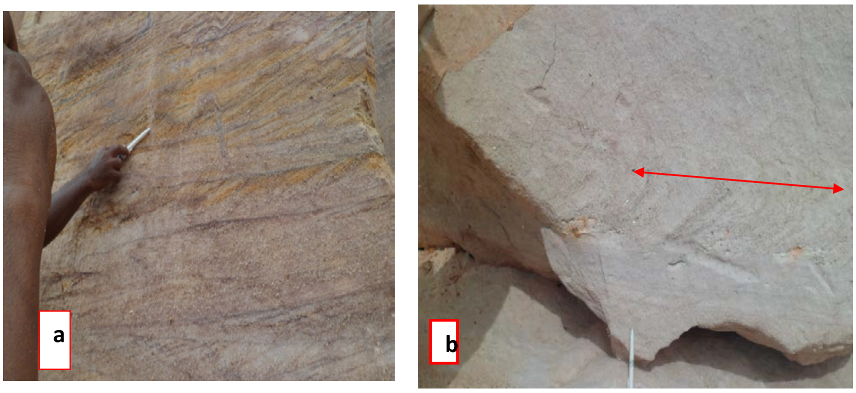


Figure 7: a) Cross bedded fine to coarse and pebbly sandstone lithofacies association of the subtidal channel exposed at Isiukwuato. Planar and trough cross beds, reactivation surfaces, tidal bundles, flaser bedding and dispersed clasts of clay are characteristics. The pen in (a) is pointing at long Ophiomorpha burrow. **b)** Convolute laminations above parallel lamination on the fine sandstone lithofacies at Isiukwuato. Pen and the red arrow are pointing to the parallel and convolute laminations respectively.

Interpretation

This lithofacies is interpreted as subtidal channel fill, deposited in shallow marine littoral setting based on the low angle cross beds and laminations and herringbone structures.

Cross laminated fine grained sandstone lithofacies (E)

This lithofacies occurs in the Isiukwuato quarry section and is interbedded with parallel laminated sandstone lithofacies. Planar cross laminations and claystones flasers are characteristics of the facies.

Interpretation

This lithofacies is interpreted as high energy, subtidal channel deposit in shallow marine littoral setting based on the low angle cross laminations, flaser structures and herringbone structures.

Cross bedded, coarse to pebbly clayey sandstone lithofacies (F)

This is exposed at Okigwe area. Planar and trough cross beds, mud flaser as well as clasts of clay were documented in the facies. Bioturbation is rare.

Interpretation

This lithofacies represents subtidal channel-fills with basal channel lag materials deposited under high energy conditions. Clay clasts were reworked and mud flasers formed during slack water periods due to subordinate tidal current phase.

Subtidal Sandwave Facies

The lithofacies association consists of coarsening upwards successions. The lithofacies identified are described below:

Cross bedded medium to very coarse grained/pebbly sandstone lithofacies (B)

This facies is planar cross bedded with clay draped foresets. Herringbone cross stratification also occur.

Cross bedded fine to medium grained sandstone lithofacies (C)

This lithofacies consists of fine to medium weakly consolidated sandstone. Sedimentary structures include tabular cosets, clay draped planar cross beds, herringbone structure, festoon cross laminations, clay flaser (Figure 8), convolute laminations, reactivation surfaces, ripples and parallel laminations. Skolithos burrows (9c) are common and bioturbation intensity increased from the base to the top.

Cross bedded fine grained sandstone lithofacies (G)

The lithofacies consists of low angle planar cross bedded fine sandstone of about 2.2 m thick. The sandstone is well sorted, matrix free and documented dispersed clay chips. In Obuluno exposure, this facies documented tidal bundles (commonly 7- 14 per cycle). Thinning upwards of cross bed foresets, accordion structure and reactivation surfaces occur. Flaser bedding is common (Figure 8a, b & e). The facies is clay laminated in places and few subvertical to vertical burrows of Ophiomorpha occur (Figure 9).

Figure 8: a) Planar cross bed foresets on medium grained sandstone. The foresets are commonly clay draped. The upper and lower part is separated by very thin bed of mud flaser. Reactivation surfaces and tidal bundles are characteristics (b) Fine grained sandstone with planar cross bed foresets, reactivation surfaces, accordion structures, tidal bundles (counted 7- 14 per cycle) and thin flaser bedded unit (c) Deformed cross beds on the medium granedi sandstone at Obuluno. The foresets dip is over 60°and are commonly draped by clay (d) Convolute laminations and planar cross beds on the cross bedded medium to coarse sand facies (e) Abundant mud flaser on the fine sandstone facies (f) fine to medium grained sandstone facies with abundant mud flasers.

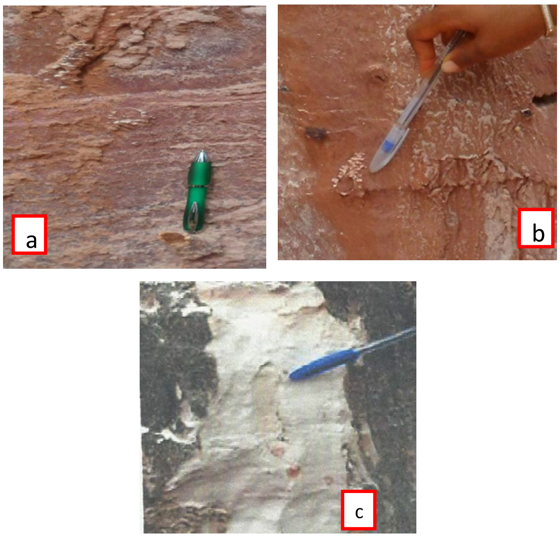


Figure 9: (a and b) Ophiomorpha burrows on the fine grained sandstone facies (c) Skolithos burrows and clay draped festoon cross laminations on the fine to medium grained sandstone facies.

Cross bedded medium grained sandstone lithofacies (H)

This lithofacies overlie the cross bedded fine sandstone lithofacies. It is matrix free and planar cross bedded. The foresets of the cross beds dip at higher angle. Dispersed clay chips occur but burrows are rare.

Cross bedded coarse grained sandstone lithofacies (I)

This lithofacies is also planar cross bedded and matrix free with thickness of about 0.7 m. The foresets of the cross beds have steep dip. Burrows are rare.

Medium to coarse grained sandstone lithofacies (J)

This lithofacies is planar cross bedded and the foresets of the cross beds are clay draped. Herringbone cross stratification, deformed cross beds (Figure 8c) and convolute laminations (Fig, 8d) also occur. The lithofacies is underlain by cross bedded fine sandstone lithofacies.

Claystone lithofacies (K)

This lithofacies occur as ripple laminated claystone and is overlain by fine grained sandstone.

Fine grained conglomerate lithofacies (L)

It consists of conglomerates which are fine grained and show no imbrication structure.

Interpretation

High energy, subtidal depositional setting with tidally propagated sandwaves in the inner shelf zone. Mud drapes on foresets are diagnostic features of a tidal environment (Visser, 1980; Boersma and Terwindt, 1981; Smith, 1988). Foresets of cross beds are draped by clay in an environment with abundant suspended clay. Convolute laminations and deformed cross beds are soft sediment deformation structures. Herringbone cross stratification has earlier been attributed to the presence of strong bi- polar currents as seen in ebb- flood channel systems (de Raaf and Boersma, 1971; Reineck and Singh, 1973). Reactivation surfaces indicate the erosion of the mud drapes by the subordinate current. The thinning upwards of foresets of the bundles or downcurrent thickening of the same is an indication of neap- spring tidal periods (Visser, 1980; Allen, 1981a and b). The neap tide bundles are thinner than the spring tide bundles (Reineck and Singh, 1980). They commonly show lateral thickness variations (and are referred to as tidal rhythmites (Smith et al., 1991). Mud drape and flaser bedding result from settling of suspended mud during slack water condition. Ophiomorpha and Skolithos burrows suggests high energy. Intense bioturbation was possibly inhibited by rapidly migrating bedforms (Baucon, 2008; Mángano and Buatois, 2004a; Reineck and Singh, 1980) and only the vertical burrows of suspension feeders were documented.

Particle size distribution

The results of the calculated grain size statistical parameters for the Ajali Sandstone as well as the discriminate functions (after Sahu, 1964) are shown in Tables 2 and 3 respectively. The grain size of the sands ranges from fine to coarse. On the average, the sand is moderately well sorted, near symmetrically skewed and mesokurtic.

Table 2a: The result of grain size statistical parameters calculated from the Ajali Sandstone.

LOCALITY	SAMPLE NO	Md	Mz	STD (δ_1)	SKI	KG
Nkwonta, Isiukwuato L.G.A., Abia State	AJN1A	2.30	2.30	0.51	-0.06	1.16
	AJN1B	2.40	2.42	0.58	-0.09	1.14
	AJN1C	2.60	2.60	0.55	-0.10	1.17
	AJN1D	0.3	0.53	1.31	0.29	0.98
	AJN2A	1.90	1.87	0.90	-0.20	1.42
	AJN2B	1.25	1.64	0.87	0.47	1.99
	AJN2C	1.55	1.58	0.72	-0.01	1.43
	AJN2D	2.00	1.92	0.67	-0.20	1.05
	AJN2E	1.90	1.77	0.72	-0.25	0.97
	AJN2F	1.40	1.30	1.10	-0.15	1.20
	AJN2G	2.10	2.03	0.51	-0.19	0.10
	AJN2H	1.50	1.48	0.62	-0.11	1.13
	AJN2I	0.70	0.53	0.32	-0.24	0.92
	AJN2J	0.80	0.60	0.64	-0.48	0.89
	AVERAGE	**1.62**	**1.61**	**0.72**	**-0.09**	**1.11**

Near Onyeama Mine along Enugu- Onitsha Expressway, Enugu.	AEN1	2.70	2.63	0.41	-0.13	0.68
	AEN2	1.80	1.83	0.43	0.10	1.23
	AEN3	2.70	2.68	0.35	0.05	1.2
	AEN4	2.70	2.68	0.28	0.00	1.13
	AEN5	2.60	2.62	0.34	0.12	1.09
	AEN6	2.80	2.78	0.36	0.00	1.33
	AEN7	2.20	2.23	0.74	0.03	0.89
	AEN8	2.80	2.70	0.58	-0.24	1.02
	AEN9	2.60	2.72	0.50	0.27	1.00
	AEN10	2.50	2.80	0.41	1.36	1.00
	AEN11	2.60	2.58	0.38	-0.05	1.02
	AEN12	2.80	2.85	0.44	0.07	1.15
	AEN15	2.80	2.80	0.61	-0.02	0.92
	AEN18	2.90	2.80	0.35	-0.37	0.94
	AEN19	2.90	2.82	0.31	-0.29	1.02
	AEN20	2.85	2.83	0.38	-0.05	1.02
	AEN21	2.90	2.93	0.33	0.09	1.08
	AEN222	1.80	2.77	0.99	-0.04	0.88
	AEN23	2.80	2.80	0.37	-0.04	1.07
	AEN24	2.90	2.88	0.32	-0.06	0.96
	AEN25	2.50	2.52	0.51	-0.02	1.20
	AVERAGE	**2.63**	**2.67**	**0.45**	**0.04**	**1.04**
Okigwe/Umulolo	AJO1	1.60	1.60	0.83	0.01	1.11
	AJO2	1.75	1.78	0.95	-0.03	1.13
	AJO3	2.20	2.08	0.79	-0.48	1.15
	AJO4	1.50	1.47	1.01	-0.09	1.09
	AJO5	1.90	1.92	0.73	-0.06	1.18
	AVERAGE	**1.79**	**1.77**	**0.86**	**-0.13**	**1.13**

Table 2b: Average values of the textural parameters for the localities.

TEXTURAL PARAMETERS	AVERAGE VALUES	INTERPRETATION
Mode (Md)	2.01	Fine sand constitutes the dominant class
Graphic mean (Mz)	2.02	Fine sand
Inclusive Standard Deviation (STD)	0.68	Moderately well sorted
Inclusive Graphic Skewness (SK1)	-0.06	Near symmetrical
Graphic Kurtosis	1.09	Mesokurtic

Table 3a: Discriminate functions calculated from the Ajali Sandstone.

LOCALITY	SAMPLE NO	Y1	Y2	Y3
Nkwonta, Isiukwuato L.G.A., Abia State	AJN1A	-3.50 Aeolian	73.46 shallow agitated marine	-1.27 Shallow marine
	AJN1B	-3.67 Aeolian	79.44 Shallow agitated marine	-1.77 Shallow marine
	AJN1C	-4.31 Aeolian	80.42 Shallow agitated marine	-1.36 Shallow marine
	AJN1D	6.91 Beach	144.44 shallow agitated marine	-16.25 Fluvial (deltaic)
	AJN2A	1. Beach	105.16 Shallow agitated marine	-5.52 Shallow marine
	AJN2 B	2.17 Beach	124.07 Shallow agitated marine	-8.37 Fluvial (deltaic)
	AJN2C	0.75 Beach	85.08 Shallow agitated marine	-3.92 Shallow marine
	AJN2D	-1.50 Beach	75.36 Shallow agitated marine	-2.35 Shallow marine
	AJN2E	-0.86 Beach	75.19 Shallow agitated marine	-2.77 Shallow marine
	AJN2F	3.89 Beach	119.35 Shallow agitated marine	-9.43 Fluvial (deltaic)
	AJN2G	-5.58 Aeolian	47.28 Beach	-0.77 Shallow marine
	AJN2H	-0.11 Beach	67.35 Shallow agitated marine	-2.36 Shallow marine
	AJN2I	1.85 Beach	27.70 Beach	0,47 Shallow marine
	AJN2J	3.14 Beach	44.08 Beach	-1.03 Shallow marine
	AVERAGE	**0.02 Beach**	**82.03 Shallow agitated marine**	**-4.05 Shallow marine**

Near Onyeama Mine along Enugu- Onitsha Expressway, Enugu.	AEN1	-6.38 Aeolian	52.49 Beach	-0.05 Shallow marine
	AEN2	-2.23 Beach	46.44 Beach	-1.53 Shallow marine
	AEN3	-5.47 Aeolian	73.12 Shallow agitated marine	-0.49 Shallow marine
	AEN4	-5.75 Aeolian	68.01 Shallow agitated marine	0.12 Shallow marine
	AEN5	-5.78 Aeolian	70.95 Shallow agitated marine	-0.80 Shallow marine
	AEN6	-5.30 Aeolian	76.65 Shallow agitated marine	-0.29 Shallow marine
	AEN7	-3.22 Aeolian	87.90 Shallow agitated marine	-4.27 Shallow marine
	AEN8	-4.72 Aeolian	78.88 Shallow agitated marine	-0.96 Shallow marine
	AEN9	-6.23 Aeolian	82.40 Shallow agitated marine	-2.72 Shallow marine
	AEN10	-9.07 Aeolian	98.01 Shallow agitated marine	-7.27 Shallow marine
	AEN11	-5.40 Aeolian	67.84 Shallow agitated marine	-0.24 Shallow marine
	AEN12	-5.72 Aeolian	79.87 Shallow agitated marine	-1.17 Shallow marine
	AEN15	-5.70 Aeolian	84,94 Shallow agitated marine	-2.32 Shallow marine
	AEN18	-5.85 Aeolian	45.23 Beach	1.59 Shallow marine
	AEN19	-5.92 Aeolian	64.07 Beach	1.43 Shallow marine
	AEN20	-6.29 Aeolian	71.41 Shallow agitated marine	-0.17 Shallow marine
	AEN21	-6.89 Aeolian	74.63 Shallow agitated marine	-0.54 Shallow marine
	AEN222	-3.44 Aeolian	129.32 Shallow agitated marine	-7.56 Fluvial (deltaic)
	AEN23	-6.07 Aeolian	71.71 Shallow agitated marine	-0.15 Shallow marine
	AEN24	-6.79 Aeolian	68.48 Shallow agitated marine	0.26 Shallow marine
	AEN25	-4.25 Aeolian	77.73 Shallow agitated marine	-1.31 Shallow marine
	AVERAGE	**-5.55 Aeolian**	**74.77 Shallow agitated marine**	**-1.35 Shallow marine**
Okigwe/Umulolo	AJO1	0.28 Beach	75.68 Shallow agitated marine	-5.58 Shallow marine
	AJO2	0.57 Beach	107.53 Shallow agitated marine	-7.20 Shallow marine
	AJO3	-0.53 Beach	86.16 Shallow agitated marine	-2.48 Shallow marine
	AJO4	2.11 Beach	108.58 Shallow agitated marine	-8.03 Fluvial (deltaic)
	AJO5	-1.08 Beach	64.04 Beach	-3.77 Shallow marine
	AVERAGE	**0.27 Beach**	**88.40 Shallow agitated marine**	**-5.41 Shallow marine**

Table 3b: Average values of the discriminate functions for the localities.

DISCRIMINATE FUNCTIONS	AVERAGE VALUES	INTERPRETATION
Y1	-1.75	Beach
Y2	81.73	Shallow agitated marine
Y3	-3.60	Shallow marine

Grain size histograms

The grain size histograms for the sands of the Ajali Sandstone show both unimodal and bimodal distribution patterns (Figure 10) with either 2 or 3 phi class (fine to medium grained sand) or both constituting the modal class. Both symmetrical and asymmetrical distribution pattern occur.

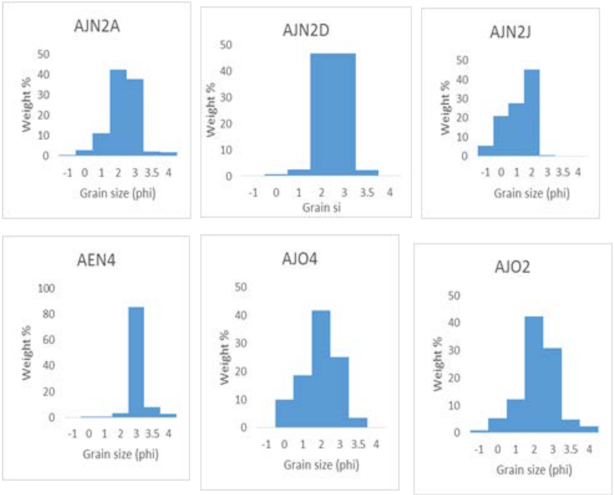


Figure 10: Grain size histograms of the Ajali Sandstone.

Environmental discrimination

Better discrimination of the environment was achieved using the bivariate scatter plots of the discriminate functions (Figure 11). Figure 11(a) shows that 85% of the samples were deposited in a shallow agitated water while littoral accounted for the remaining 15%. In Figure 11b, 87.50% of the sands plot in the field of shallow marine and 12.50% are fluvial.

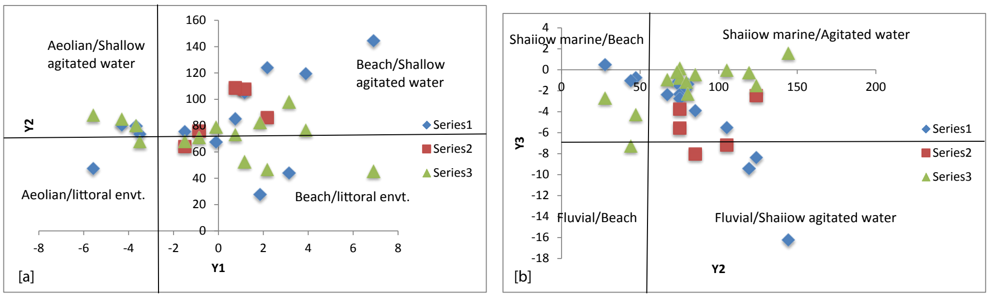


Figure 11a: Bivariate scatter plot of Y$_1$ *vs.* Y$_2$ from the grain size data of the Ajali Sandstone (xib): Bivariate scatter plot of Y$_2$ *vs.* Y$_3$ from the grain size data of the Ajali Sandstone.

DISCUSSION

The twelve lithofacies identified in the Ajali Sandstone are classified into two based on association. These include; the subtidal channel facies and subtidal sandwave facies.

The channel facies exhibits a fining upwards characteristics consisting of pebbly sandstone with sharp basal contacts, very coarse to coarse grained, medium grained and fine grained sandstone at the topmost part of the succession. Association of this lithofacies with structures such as tidal bundles suggest deposition in a subtidal setting (Boersma and Terwindt, 1980; Visser, 1980; Allen, 1981a and b; Yang and Nio, 1985). Large scale cross beddings which is an attribute of the lithofacies has been recorded as an important structure in ancient subtidal sandstone facies (Narayan, 1971; Anderton, 1976; Nio, 1976; Allen and Homewood, 1984; Teyssen, 1984; Richard, 1986; Noe- Nygaard, 1991). The occurrence of clay clasts in the sandstone can be attributed to the reworking by tidal current. The role played by ebb and flood tide in the deposition and reworking of the sandstones is evidenced on the occurrence of bipolar/ bimodal paleoflow structures (e.g herringbone cross bedding). Reactivation surfaces reflect the asymmetric nature of the two opposing tidal currents. Button and Vos (1971) attributed trough cross bedding in subtidal channel sandstone facies to migration of megaripple in ebb dominated domain. The overall abundance of cross bedding probably indicate strong tidal currents (Levell, 1980). This is supported by low density vertical burrows of Ophiomorpha and an unbioturbated thick cross bedded sandstone which reflects progressive higher energy conditions (Mangano et al., 1996). Ophiomorpha is an indication of colonization by suspension feeders. The matrix free nature, minor clay content and the degree of sorting of the sandstones suggest minimal wave process.

The subtidal sandwave facies shows a coarsening upwards of succession. The various kinds of cross beddings which show evidence of reversing currents documented on the sandstone as well as the sheet like pebble layer sandwiched in between the sandstone can be interpreted as product of subtidal sandwave (shallow marine shelf) (Levell, 1980). Eriksson and Simpson (2011) interpreted tabular cross bed sets and cosets (0.5- 0.3m thick) consisting of planar and trough cross strata as sandwave deposit. Large scale trough cross bed cosets reflect migration of sinuous-crested sandwaves. Sigmoidal reactivation surfaces is related to fluctuation in tidal current velocities (Boersma and Terwindt, 1981; Kreisa and Moiola, 1986). Low to high density vertical burrows of Skolithos represent colonization by suspension feeding organisms. Mangano et al., (1996) attributed it to subtidal sandwaves characterized by high energy.

CONCLUSION

Subtidal channel and sandwave (shallow marine shelf) depositional settings is assigned to the Ajali Sandstone of southeastern Nigeria. This is based on facies association and tide generated structures. Fining upwards of facies succession is typical of channel facies whereas the subtidal sandwave facies are characterized by coarsening upwards of succession. Large scale cross beddings which occur in the facies is attributed to migration of megaripples or sandwaves. Herringbone cross bedding suggests the involvement of both ebb and flood tide in the deposition of the sediments. Tidal influence is very high whereas wave action is minimal.

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