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Tidalite Facies and Depositional Environment of the Ajali Formation, Anambra-Afikpo Basin Complex of Southeastern Nigeria

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Abstract
Lithofacies study of tidalites in six localities within the Ajali Formation, Anambra-Afikpo Basin complex of southeastern Nigeria was carried out to interpret depositional environments and model for the unit. The study involved identification and description of outcrops, and lithofacies characteristics of tidalites noting sedimentary structures in the outcropping facies. Six lithofacies typically of tidally-influenced shelf setting and tidal current processes characterized the Ajali Formation. The medium to coarse grained planar and trough cross bedded sandstone lithofacies, fine to medium grained planar cross bedded sandstone lithofacies, herringbone cross bedded sandstone lithofacies are deposits of subtidal sandwaves under high energy phase associated with tidal flow regime. The cross/ripple laminated heterolithic facies and horizontal laminated/bedded sandstone lithofacies were deposited in tidal flats, shallow shelf setting under low current energy. The bioturbated sandstone lithofacies with *Skolithos* isp was deposited in low energy intertidal zone. These interpretations are corroborated by occurrence of tidally-influenced sedimentary structures in the studied formation. These include tidal bundles, herringbone cross stratification, mud draped foresets, reactivation surfaces, flaser beddings, ripple and horizontal laminations and biogenic trace fossil suites consisting dominantly of *Skolithos* ichnofacies. Overall, these lithofacies indicate deposition in tidal flat and tidal sandwaves in shallow shelf depositional environments.

1. Introduction

Tidalites represent a new process for sedimentary facies, deposited by tidal currents [1]-[2]-[3]. Reference [4] has now designated tidalites to all sediments and sedimentary structures that are tide-generated. Subtidal, intertidal, and supratidal subenvironments, can be distinguished based on the sedimentary structures, textures, lithologies, and vertical successions of such facies [5]. Tidalites occur in the Ajali Formation within the Anambra-Afikpo Basin Complex of southeastern Nigeria. The basin was formed during the mid-Santonian thermotectonic event which led to uplift of the Abakaliki Anticlinorium and subsidence at both western and eastern flank of the anticlinorium. Reference [6] described the Ajali Formation at the Ajali River, near Enugu as its type locality. He noted that the formation consists of thick friable, poorly-sorted sandstones, typically white in colour but sometimes iron-stained, characterised by large scale cross stratifications. The formation has been variously described as white false bedded sandstone unit [7]. The Ajali Formation outcrops on the crestal and towards the dip-slopes of the Enugu – Awgu – Okigwe Cuesta [8]. In the Enugu area, the formation is estimated to be 450m in thickness [6]. The Ajali Sandstone gets thinner southwards along strike to the axial nose of the Abakaliki Anticlinorium at Uturu and into the Afikpo Sub-Basin, where it caps the southwards and westwards-facing dip-slope of the Cuesta from Uturu to Arochukwu [8]. The Ajali Formation overlies the Mamu Formation in the basin complex (Table 1).

There is no consensus on the environments of deposition of the Ajali Formation in the basin. Reference [9] based on petrology and sedimentary structures interpreted the formation as fluvial. The environmentof deposition according to [6]-[10] is fluvio-continental. Reference [11] interpreted the sandstone formation as tidal shelf deposits and reworked shallow marine sands of littoral and sub-littoral environments.

Table 1. *Stratigraphic sequences of the Anambra Basin (after Nwajide, 2005).*

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

Carter (1965) and Nwajide, (1979) documented the formation as a tidal flat and tidal sandwave deposits in shallow marine shoreline setting. Reference [8] based on the study of the Afikpo Sub-Basin assigned tidal flat and shallow marine subtidal shelf setting to the lithostratigraphic unit. Reference [12] suggested a fluvio-deltaic environment. In the light of this underlying controversy, this paper focuses and describes the outcrops, lithofacies characteristics of the tidalites and sedimentary structures in the outcropping facies of the Ajali Formation within the Anambra-Afikpo Basin Complex. The aim is to integrate them and re-interpret the environments of deposition of the Ajali Formation in the basin in order to have a better understanding of tidal facies in such sedimentary formation.

2. Geologic Setting

The installation of the Anambra Basin and Afikpo Sub-Basin resulted from the mid- Santonian tectonism which caused the folding and uplift of the sediments of the first cycle in the southern Benue Trough of Nigeria [13]-[14]. The Santonian Orogeny dating back to 84 Ma was accompanied by widespread magmatism, folding and faulting which caused the Abakiliki area to become flexurally inverted to form the Abakiliki Anticlinorium [15]-[16]-[17]-[18]-[19]-[20]-[21]. References [15]-[22] noted that those forces led to the formation of Anambra Basin and Afikpo Sub-Basin to the west and southeastwards of the anticlinorium respectively. The initiation of Anambra Basin gained momentum in the Coniacian and climaxed during the Santonian thermotectonic event [26]. Over 2000 m sediment thickness were eroded from the uplifted Abakaliki Anticlinorium and deposited as Campano-Maastrichtian sediments in the Anambra Basin and the Afikpo Syncline [27] both of which are jointly called the Anambra-Afikpo Basin Complex [8]. Reference [15] regarded both the uplifted Abakaliki Anticlinorium together with the Benue trough as Abakaliki-Benue Trough. Sedimentation was generally controlled by transgressive and regressive cycles which actually led to the deposition of sediments in a wide variety of environments ranging from fluvial, fluvio-marine to marine environments [25]-[15]. Reference [15] documented three unconformity-bound trangressive – regressive cycles represented by the Albian – Cenomanian phase, Turonian – Coniacian phase and Campanian – Maastrichtian phase within the trough. The regional geologic map of southeastern Nigeria showing the position of Ajali Formation relative to other formations is shown in Figure 1.

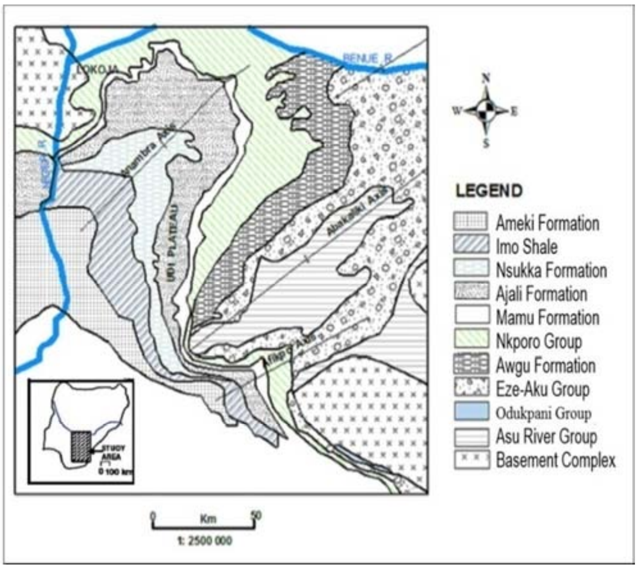

Figure 1. *Regional geologic map of southeastern Nigeria showing the position of Ajali Formation relative to other formations (modified from Hoque, 1977).*

3. Methodology

This study involved identification and description of outcrops, and lithofacies characteristics of tidalites noting sedimentary structures in the outcropping facies from six selected outcrop sections from the upper Maastrichtian Ajali Formation, Anambra-Afikpo Basin of southeastern Nigeria. The description of the outcrops was carried out and presented from Enugu, Nkpologu, Uturu and Abiriba-Ohofia. Some of the outcrops were represented in lithologs format using texture, sedimentary structures, fossil content and bed thickness designed to provide clues into vertical lithofacies variation pattern upon which lithofacies were recognized. The lithofacies were grouped into lithofacies associations (Table 2). Photographs of some of the described outcrops and other essentially sedimentary features were taken and the characteristic features of the lithofacies were superimposed with the lithologs. Subenvironments were distinguished on the basis of sedimentary structures, textures, lithologies, and facies interpretations of tidalites from the formation.

4. Results and Interpretation

4.1. Description of Outcrops

4.1.1. Locality 1: Ihube Junction, Uturu

The outcrop is located at Ihube junction along Uturu – Okigwe road, uturu. It consists of milky white to whitish, fine to coarse grained sandstone with mottled reddish bands of mud chips within large scale foresets (Figure 2). The sandstones are sand dominant, poorly to moderately sorted and exhibits fining upward sequence. This sandstone outcrop is characterized by planar tabular cross stratification, clay drapes, flaser beds and tidal bundles. The foreset beddings/laminations display sharp, concave upward geometry (Figure 2). The lowermost part of the outcrop is bioturbated. The burrows which are vertical include *Skolithos* and *Orphimorpha* ichnospecies.

Figure 2. Outcrop of Ajali Formation at Ihube Junction along Uturu – Okigwe Road, Uturu.

4.1.2. Locality 2: Sand Mining pit 3 km from Ihube Junction, Uturu

The sand mining pit exposed fine to coarse grained, cross bedded sandstone. The lower middle part of the exposure is composed of parallel laminated and bioturbated sandstone that is mud dominant with reactivation surfaces when compared to the entire section which is sand dominant. The sandstone of the lower section is intercalated with clay/silt parallel laminations which are occasionally discontinuous, wavy, convoluted. The middle to upper section is characterized by medium to coarse grained sandstones that are moderately sorted with planar-tabular cross stratification. The cross-beddings at the middle part are mainly bidirectional (herringbone features) (Figure 3). The sandstone is generally friable to semi-consolidated and contains minor subordinate clay with subangular to subrounded grains.

4.1.3. Locality: Section 400 m from Abia State University Along Okigwe-Uturu-Afikpo Road

The outcrop consists of milky white, fine grained cross bedded sandstone with clay intervals at lower portions and reactivation surfaces. The foreset occur in several tidal bundles separated by reactivation surfaces (Figure 4). The clay draped foreset beds are graded. The beds appear ripple /convoluted and wavy with flaser bedding characterized by clays. The bioturbated lower section contains burrows of *Skolithos* and *Orphimorpha* isp.

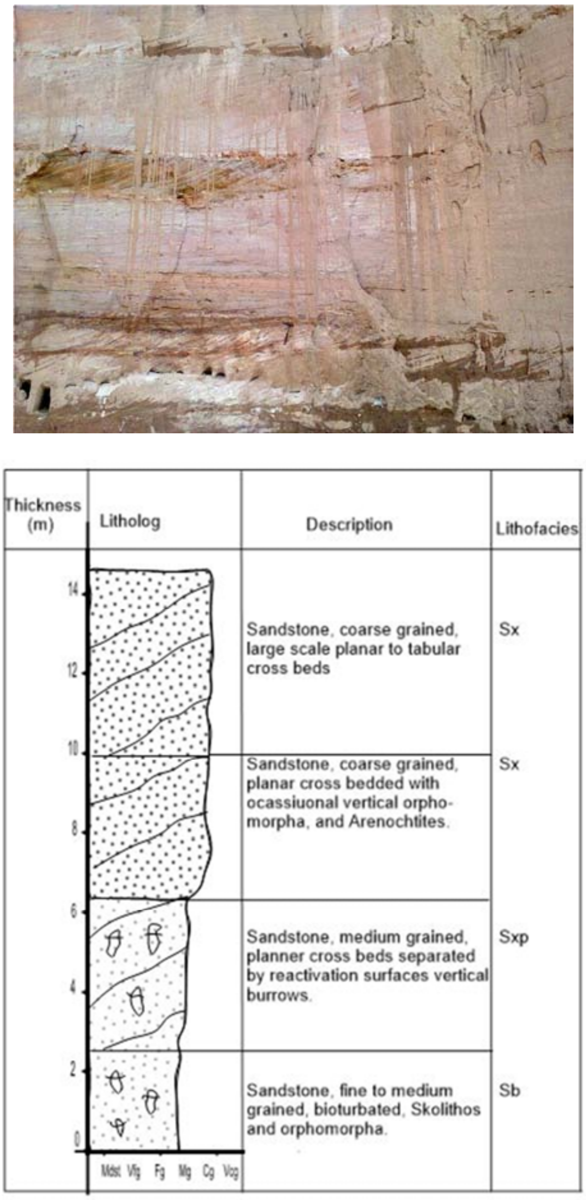

Figure 3. Outcrop of Ajali Formation in a sand mining pit 3 km from Ihube Junction, Uturu.

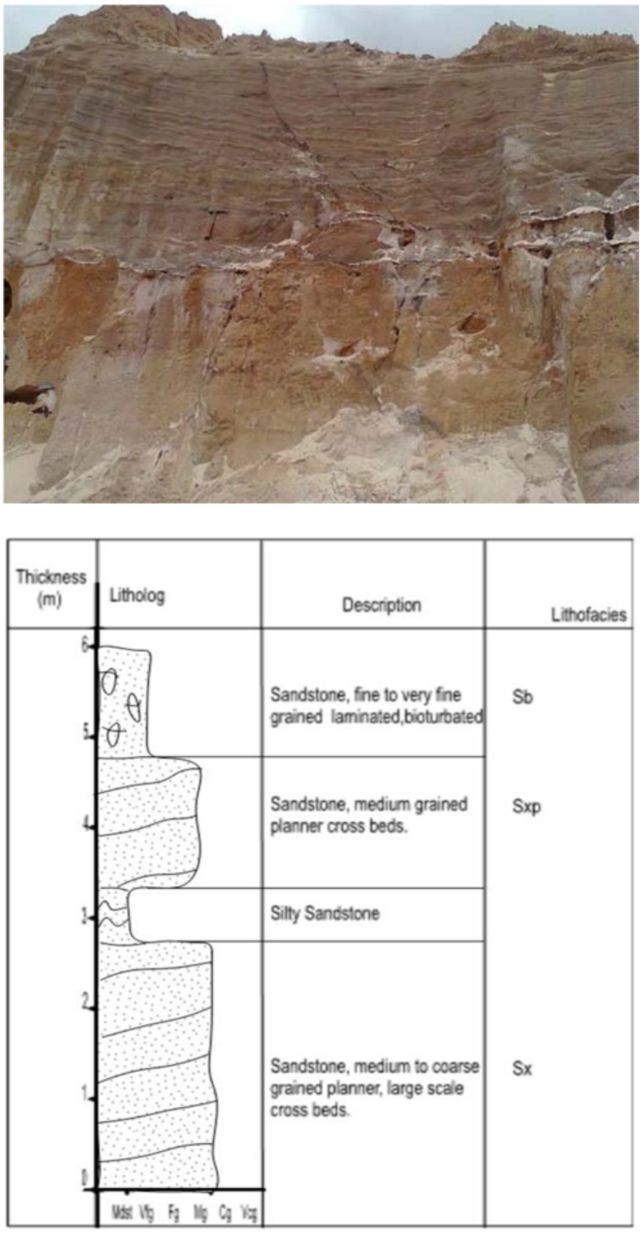

Figure 4. *Sandstone outcrop section 400 m from Abia State University along Okigwe-Uturu-Afikpo Road.*

4.1.4. Locality 4: Section of Ajali Formation in Gully Site Near Iva Valley, 4.8km from 9th mile Corner, Enugu

The section which was exposed by gully erosion is very loose at the upper part. The exposure is about 6.8 m of sandstones which consist of whitish, very fine to medium grained but dominantly fine grained sandstone with occasional pebbles. The sandstones are weakly consolidated, moderately to well sorted. The characteristic sedimentary structures include herringbone cross stratification, clay draped planar cross beddings mainly festoon types (Figure 5), flaser beddings and ripple/wavy lamination and liesegang structures. There is also occurrences of vertical burrows mainly *Skolithos* ichnospecies.

4.1.5. Locality 5: Nkpologu Burrow Pit Section

This lithofacies is a 15 m section of fine to coarse grained cross stratified sandstone (Figure 6). The lower part of the section consists of about 1.5m thick sequence of medium to coarse grained, moderately sorted, tabular planar cross-stratified sandstone. This is overlain by a medium grained to coarse grained trough cross-stratified sandstone with the thickness measuring about 5m. The overlying sequence consists of cosets of tabular planar cross-stratifications with clay bands. Generally, the sandstone is fine to coarse grained milky white to whitish sandstone with occasional clay and pebbles occurring towards the top of the section. The section exhibits fining upward sequence. Often, the beds at the top of the section appear rippled and wavy with occasional clay flaser beds.

4.1.6. Locality 6: Abriba Burrow Pit Section

The outcrop consists of milky white to white, highly cross bedded (Figure 7) sandstone interbedded with clay beds. The sandstone is friable to semi-consolidated with horizontally bedded intervals. The lower part of this section consists of bioturbated sandstones which is overlain by alternating sequence of fine to medium grained sandstone and heterolithic bedded sequence (siltstone, claystone beds) about 0.8 m thick. The middle to upper section consists generally of milky white to whitish, moderately to poorly sorted with prominent cross beds. The characteristic cross stratification of the Ajali Formation is occurring in all beds. The tabular planar cross-beds and clay draped foresets dominate over the trough type cross-beds. The foresets are occasionally rippled or wavy. There is occurrence of festoon-type cross beds, reactivation surfaces and cross laminations in the lower part of section (Figure 7). The laminated horizontal bedded sequences have thickness range from 8 – 30 cm. Generally, the laminated beds appear wavy/rippled with surbordinate mud flasers. The biogenic structures in this lower part of the outcrop include trace fossils belonging to *Skolithos* ichnogenera and *Orphimorpha i*sp.

Figure 5. *Outcrop of Ajali Sandstone exposed by gully near Iva valley, Enugu.*

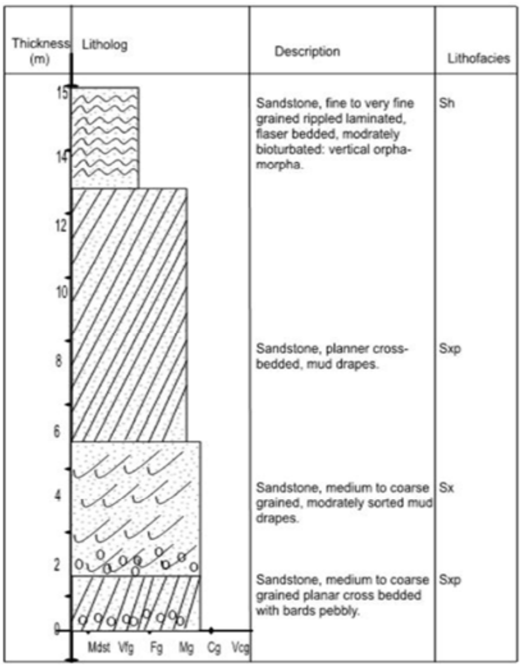

Figure 6. *Litholog of Ajali Formation at Nkpologu.*

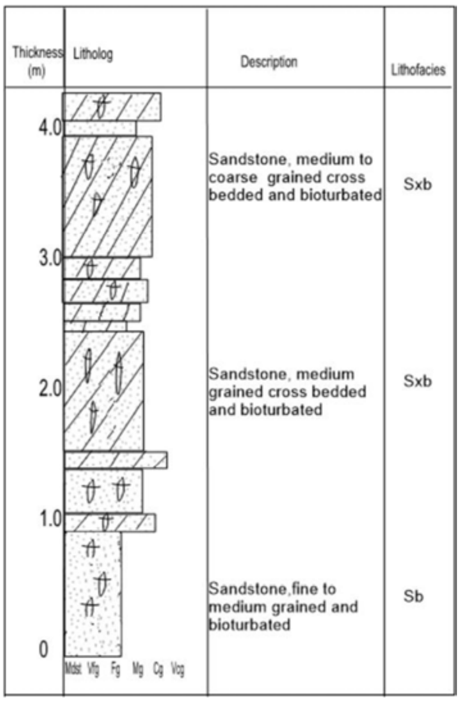

Figure 7. *Outcrop of Ajali Formation exposed in a burrow pit Abiriba, Ohafia.*

4.2. Tidalite Facies

Six lithofacies of tidalites within the Ajali Formation of southeastern Nigeria were identified in this study: (1) medium to coarse grained planar and trough cross bedded sandstone lithofacies (Sxc), (2) fine to medium grained planar cross bedded sandstone lithofacies (Sxp), (3) herringbone cross bedded sandstone lithofacies (Sxh), (4) cross/ripple laminated heterolithic facies (Hl), (5) bioturbated sandstone lithofacies (Sb), Horizontal laminated/bedded sandstone lithofacies (Sh). This lithofacies which were further divided into three lithofacies association (Table 2) are discussed as follows:

4.2.1. Medium – Coarse Grained Planar and Trough Cross Bedded Sandstone Lithofacies (Sxc)

This lithofacies outcrops in all the studied localities. It consists of medium to coarse grained, poorly to moderately sorted sandstone that is occasionally fine to silty. Its colours range from white to light brown with patches of yellowish red. It is characterized by thick cross bedded sets (Figure 8). The cross beds include planar and trough but dominantly tabular planar with graded foresets, clay draped foresets and clay/mud chips. Other sedimentary features include tidal bundles and reactivation surfaces. Trace fossil suites in this facies include *Skolithos* isp and *Orphimorpha* isp. This lithofacies display subtle fining upward sequence with gradational, sharp and scoured erosive contacts which are mainly mudstone. The lithofacies is interpreted as subtidal sandwaves deposited under the influence of high energy phase of tidal regime. The coarse detrital materials corroborate deposition in shallow shelf setting while the winnowing influenced by wave energy deposited the finer material in a deeper environmental setting.

4.2.2. Bioturbated Cross Bedded Sandstone lithofacies (Sxb)

This Lithofacies outcrop in Enugu, Uturu and Nkpologu. It consist of fine to medium but dominantly fine grained, white to light brown, moderately to well sorted, semi-consolidated sandstone with bioturbations, clay draped planar cross beds, tidal bundles and reactivation surfaces (Figure 9). Flasers, ripple laminations. The burrows that characterized this lithofacies include *Orphimorpha* and *Skolithos* ichnospecies. The *Orphimorpha* isp burrows vary from vertical to sub-horizontal. This lithofacies is interpreted as deposits of near shore under influence of high energy associated with tidal flow regime.

4.2.3. Planar Cross Bedded Sandstone with Herringbone Structure (Sxh)

This lithofacies comprise fine to medium grained white to brownish yellow, poorly to moderately sorted with gradational but sharp contact. This facies unit is characterized by planar cross beds with abundant herringbone structures (Figure 10). It is interpreted as deposits of subtidal subenvironment and sandwaves under high energy regime of tidal cycles (Nwajide and Reijers, 1996).

Figure 8. *Medium to coarse grained planar and trough cross bedded sandstone lithofacies at Ihube axis along Uturu – Okigwe Road, Uturu.*

Figure 9. *Bioturbated Cross bedded sandstone lithofacies 400 m form ABSU, along Okigwe-Uturu-Afikpo Road.*

Figure 10. *Planar cross bedded sandstone with herringbone structure in a sand mining pit 4 km off Ihube Junction, Uturu.*

4.2.4. Horizontal Laminated/Bedded Sandstone Lithofacies (Sh)

This lithofacies consist of beds/laminae of very fine to fine but dominantly fine grained sandstone, occasionally medium grained. It is friable to weakly consolidated. The sands within the horizontal bedded unit are well graded and moderately to well sorted but sands are generally sorted. Laminations are commonly horizontal to subhorizontal (Figure 11), clay draped laminations and flasers. This lithofacies occur in association with the cross bedded facies units in Uturu, Ohofia and Enugu localites. It is interpreted as deposits of intertidal subenvironment.

4.2.5. Cross/Ripple Laminated Heterolithic (Hl)

This lithofacies is thin bedded unit of mudstones/siltstones interbedding with fine to coarse grained sandstone in lower to middle portions of outcrops studied especially in Uturu and Ohofia locality. This lithofacies is commonly characterized by flaser beddings, wavy/ripple laminations, cross laminations (Figure 12a) within the interbedding sandstone unit with conspicuous structuration of leisegang rings (Figure 12b). This lithofacies is interpreted as tidal flats, shallow shelf deposits under low current energy.

Figure 11. *Horizontal laminated/bedded sandstone lithofacies ofAjali Formation at a gully near Iva valley, Enugu*

Figure 12. *(a) Crossss laminated/ripple laminated heterolithiclithofacies at sand mining pit Uturu (b) Leisesang structure (pen) at outcrop near Iva valley Enugu.*

4.2.6. Bioturbated Sandstone Lithofacies (Sb)

This lithofacies outcrops in Uturu and Abiriba localities. It consist of milky white to light brown, friable to semi-consolidated fine to coarse grained sandstone with bioturbation, burrowing with distorted physical sedimentary structures. The trace fossils (Figure 13) include *Skolithos, Orphimorpha* and *Teichichinus* isp. This lithofacies is overlain by cross/ripple laminated heterolithic facies. The sandstones are generally clayey, moderately to poorly sorted and contain relict of flaser and wave beddings. It is interpreted as deposits of intertidal zone under low energy associated with tidal system.

Figure 13. *Bioturbated Sandstone lithofacies in the section 400 m from Abia State University along Uturu-Afikpo Road.*

4.3. Tide-Influenced Sedimentary Structures

Tide-influenced sedimentary structures were noted in the studied outcrop sections of Ajali Formation within Anambra-Afikpo Basin Complex of southeastern Nigeria. They include: tidal bundles, herringbone cross stratification, mud drapes, reactivation surfaces, flaser beddings, ripple laminations and biogenic structures (trace fossil suites) (eg. Figs. 3, 5, 7 & 13). The trace fossil assemblage include: *Skolithos*, *Ophiomorpha* and *Teichichinus*.

Careful synthesis of the works of several authors [26]-[27]-[28]-[29]-[3] gave clues for the interpretation of depositional environments for the unit using sedimentary structures as presented in Table 2. Physical sedimentary are critical parameters of sedimentary rocks, important in the interpretation of sedimentary processes, environment and direction of flow [26]-[27]. Trace fossils are useful in determining the environment in which the organism lived, sedimentation rate and has proved to be a very index of sedimentary facies and water depth [27]. In general, trace fossils found in shallower water are vertical, those in deeper water are horizontal and patterned [30]. Biogenic structures differ from body fossils in that they are incapable of reworking or redeposition.

5. Discussion

Ajali Formation which overlies the Mamu Formation and underlies the Nsukka Formation in the studied basin outcrops on the crestal and towards the dip-slopes of the Enugu – Awgu – Okigwe Escarpment with estimated thickness of 450 m [6]. The formation has been studied and interpreted by [9]-[6]-[10]-[11] with varying interpretations of the environments of deposition for the formation. While [9] interpreted the sediments as fluvial deposits, Reference [6]-[10] regarded the unit as fluvio-continental. Reference [11] interpreted the sandstone formation as tidal shelf deposits and reworked shallow marine sands of littoral and sub-littoral environments. Table 2 summarizes the lithofacies of tidalites encountered in the six localities, their associated sedimentary structures and inferred depositional environmental setting. On the basis of these however, the paleodepositional setting depicts general of tidally-influenced shelf setting typical of a tidal flat and tidal sandwaves in shallow shelf environmental settings with strong evidences of tidal current processes.

Reference [28] suggested that cross bedded sandstones with other sedimentary features as observed in the Ajali Formation are deposits within subtidal and sand flat (tidal setting). These are in agreement with [31]-[11]-[32] on the interpretations made on the sedimentary facies of the formation. More so, the sedimentary facies identified in study area part of the sedimentary lines of evidence within tidalites classified by Shanmugam [33]in his study of deep-marine tidal bottom currents and their reworked sands in modern and ancient submarine canyons. The facies he classified include heterolithic facies, rhythmites of sandstone-shale, thick-thin bundles, alternation of parallel and cross-laminations, climbing ripples, double mud layers (mud couplets), cross-beds with mud drapes, superposed bidirectional cross-bedding, sigmoidal cross-bedding with mud drapes, (10) reactivation surfaces, crinkled laminae, elongate mudstone clasts, flaser beds, wavy bedding, and lenticular bedding. Reference [5] in comparison of tidalites in siliciclastic, carbonate, and mixed siliciclastic-carbonate systems from Cambrian and Devonian Deposits of East-Central Iran suggested that siliciclastic sediments contain more preserved sedimentary structures than carbonates; therefore, it is easier to identify subenvironments. They noted that sedimentary textures and structures of tidalites are the most important factors in interpretation of tidal deposits. The occurrence of tidal bundles, herringbone cross stratification, mud draped foresets, reactivation surfaces, flaser beddings, ripple and horizontal laminations in the lithofacies of tidalites within the studied Ajali Formation indicates presence of different flow regimes in tidal systems. The environmental settings fall within tidal flat and tidal sandwaves in shallow shelf environmental settings [26]-[27]-[31]-[28]-[29]. The presence of trace fossil suites consisting dominantly of *Skolithos* ichnofacies (*Skolithos* isp. and *Ophiomorpha* isp.) corroborates the interpretation of tidally influenced shallow shelf environmental setting [34]-[35]-[36]. Herringbone cross stratification and reactivation surfaces which are common in the studied tidalites (see Figure 10) occur in lithofacies Sxc, Sxb and Sxh. These are characteristic structures of an intertidal zone and were formed by the movements of ripple marks and wave-shaped dunes [37]. While reference [38] believed that bidirectional cross-laminations or cross-beds, flaser, wavy, and lenticular beds are normally observed in tidal deposits. Reference [39] noted that these sedimentary structures can be formed by both turbidity and contour currents. Reference [3] in the analyses of recent tidal cycles reveals that tidal currents are more important in the formation of tidalites than other currents. The dominant current resulted in the formation of wavy bedforms and subsequent formation of cross beds. The current from the opposite direction was lower in energy and therefore it could not lead to formation of cross beds in opposite direction. It only eroded the sediments from the ripple surface. This process could result in formation of tidal bundles and cross-beds separated by mud drapes [5] observed in the tidalite facies Sxb, Sxc of the the studied Ajali Formation. The presence of herringbone cross-beds in sandstone lithofacies Sxh as well as mud drapes in the upper parts of fining upwards cycles reflects deposition of sediments in different depth and tidal current energies in an intertidal subenvironment [1]-[40]-[41]. The flaser and wavy structures in cross/ripple laminated heterolithic lithofacies HI (see Figure 12) also occur in tidal flat environmental setting.

Table 2. *Lithofacies, localities and interpreted depositional processes and environments for the studied tidalites of Ajali Formation.*

Lithofacies	Lithofacies Association	Locality occurrence	Depositional processes	Depositional environments
1. Medium to coarse grained planar and trough cross bedded sandstone (Sxc) 2. Bioturbated cross bedded sandstone (Sxb) 3. Planar cross bedded sandstone with herringbone structure (Sxh)	Cross bedded sandstone facies association (FAa): planar, trough and herringbone cross stratification	Enugu, Uturu, Abiriba, Nkpologu	High en ergy phase associated with tidal flow regime	Subtidal sandwaves
4. Horizontal laminated/bedded sandstone (Sh) 5. Cross/ripple laminated heterolithic (Hl) 6. Bioturbated sandstone (Sb)	Laminated sandstone facies association (FAb): cross, wavy/ripple occurring with flasers and drapes	Uturu, Ohofia and Enugu	Low current energy	Intertidal subenvironment Tidal flat, shallow shelf environmental setting
	Bioturbated facies association (FAc): *Skolithos* and *Orphimorpha* isp	Abiriba, Uturu	Low energy associated tidal systems	Intertidal subenvironment, tidal channels

6. Conclusion

Tidalites lithofacies and sedimentary structures have provided essential and unequivocal clues for interpreting the depositional environments and model for the Ajali Formation in Anambra-Afikpo Basin, SE Nigeria. Six lithofacies belonging to three lithofacies associations were identified, described and interpreted. The lithofacies were typically of tidally-influenced shelf setting and tidal current processes deposited in an environmental setting characteristic of tidal flat and tidal sandwaves in shallow shelf depositional environments. The Ajali Formation is composed of sedimentary structures characteristic of tidal systems. The tide-generated structures in the formation are tidal bundles, herringbone cross stratification, clay-draped planar foreset beds, reactivation surfaces, flaser beddings, cross/ripple laminations andtrace fossil suites of *Skolithos* ichnofacies. Subenvironments for tidalites were distinguished based on the sedimentary structures, textures, lithologies, and vertical successions of such facies.

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