Unravelling the Sedimentary Facies of the Tidal Channel and Tidal Flat Deposits within a Macrotidal Estuarine Setting: The Nanka Formation, South-Eastern Nigeria

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ABSTRACT

Selected outcrops of the Nanka Formation, Ameki Group especially the Umunya section and environs are re-interpreted as tidal channel and tidal flat deposits of a tide-dominated estuarine setting using detailed facies analysis which involves the integration of sedimentology, ichnology, as well as facies architecture. Detailed outcrop study reveals ten lithofacies that were interpreted and grouped into two major facies associations which include the tidal channels (subtidal) and the tidal flats (intertidal). The thickness of the intertidal deposits ranges from 4 m to a maximum of 15.5 m, thus suggesting a macrotidal range for the tide-dominated estuarine.

(Keywords: tide generated sedimentary structures, tidal range, hydrodynamic processes)

INTRODUCTION

Tidal channels and tidal flats are products of transgression and are associated with the tide-dominated or tidally influenced marginal marine or coastal environments such as estuaries, lagoons, embayments, open coasts, coastal plains and tidally influenced deltas ranging from sheltered environments to completely exposed to coastal sea or open ocean (Fan, 2012). Tidal channels can be described as large distributaries or cuts between tidal sand bars to small marsh creeks and shallow runnel across tidal flats (Hughes 2012).

Some physical sedimentary structures indicative of tidal processes which include herringbone cross-stratification, sigmoidal cross-stratification with mud drapes, wavy bedding, flaser bedding, lenticular bedding, reactivation surfaces, and tidal bundles (Nio and Yang, 1991; Dalrymple, 1992) are common in the Nanka Formation. Other diagnostic tidal signatures are heterolithic deposits, mud clasts and fluid mud deposits (McIlroy, 2004).

The Nanka Formation of the Ameki Group is about 305 m thick on the surface (Nwajide, 1980; Odumodu and Mode, 2014) and it is characterized by poorly consolidated sandstone, heterolithic deposit, mudrocks (which include claystone, gypsiferous, glauconitic or carbonaceous shales and mudstones) and lignites (Nwajide, 1980; Ekwenye, 2014).

Quite a number of works have been published on the Nanka Formation (Nwajide 1979, 1980; Nwajide and Reijers, 1996; Nwajide, 2006; Odumodu and Mode, 2014; Ekwenye et al., 2016). These works suggest tidal sedimentation for the Nanka Formation. The Umunya section which exhibits several reservoir properties has been a research tool as a reservoir analogy for the Niger Delta subsurface units (Nwajide, 2006). The section is subdivided into lower, middle and upper units representing subtidal shelf, lagoonal with fluvial incursion and mid-tidal flat respectively (Nwajide and Reijers, 1996 and Odumodu and Mode, 2014).

This study focuses on the detailed facies analysis of the Nanka Formation especially the Umunya and environs in order to re-interpret and reconstruct the depositional environments. In particular, this work aims at understanding the hydrodynamic processes that occurred during sedimentation and their application in re-interpreting the sub-environments of the Umunya section and environs.

REGIONAL GEOLOGY

The Nanka Formation (formerly referred to as Nanka Sandstone), is a lateral equivalent of Nsugbe Formation (formerly called Nsugbe Sandstone), and Ibeku Formation (formerly known as Ameki Formation) (Nwajide, 1980; Ekwenye, et al., 2014) (Figure 1).

These formations belong to the Eocene Ameki Group which lies within the Niger Delta. The Niger delta sedimentary basin is a regressive offlap sequence which prograded across the southern Benue Trough and spread out onto cooling and subsiding oceanic crust which had formed as Africa and South America separated (Evamy et al., 1978). The separation of the Afro-Brazilian plate initiated the opening of the South Atlantic during the Late Jurassic to Early Cretaceous times and reached Nigeria by Mid-Cretaceous (Fitton, 1980); this led to the evolution of the Benue Trough (Reyment, 1965; Murat, 1972; Nwachukwu, 1972; Kogbe ,1976; Benkhelil. 1982, 1989).

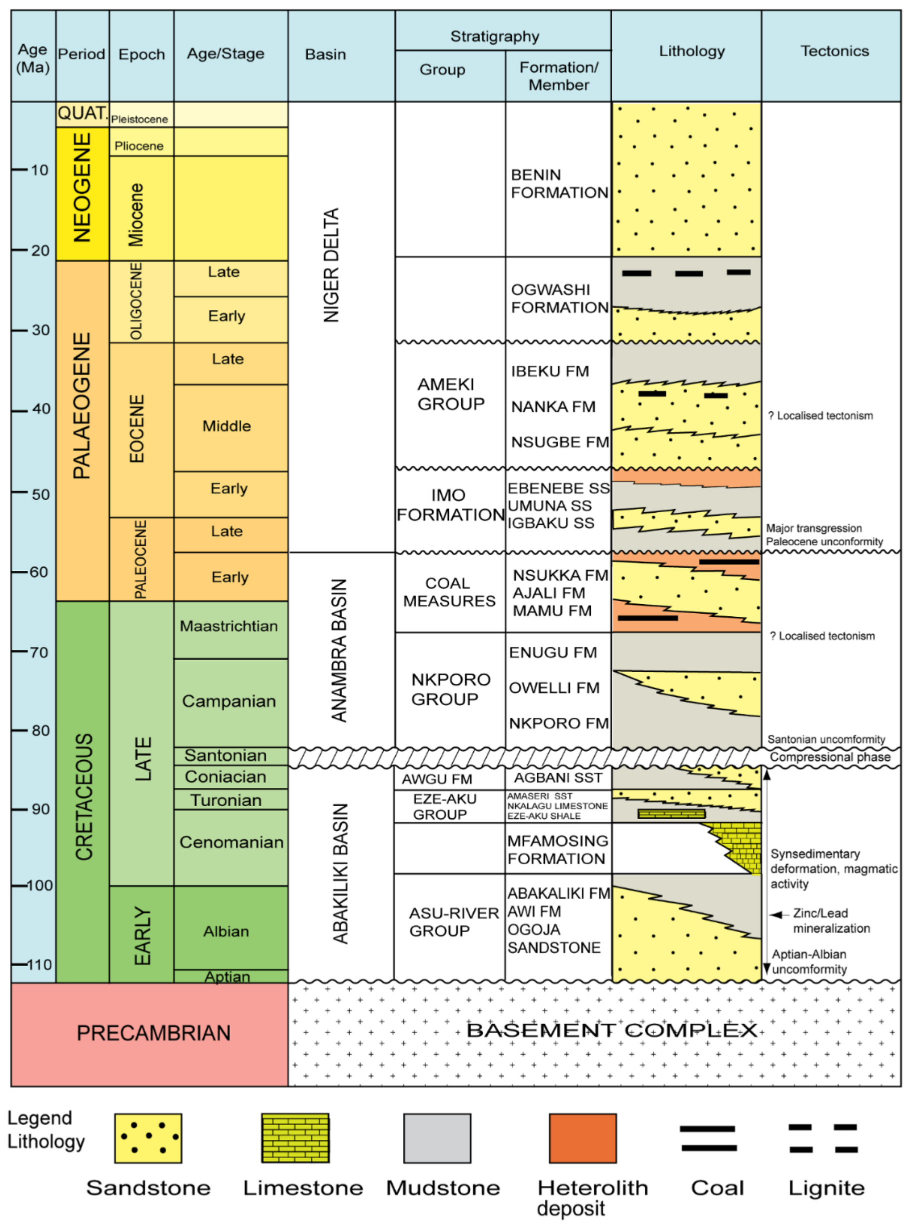


Figure 1: Stratigraphic Succession in the Anambra Basin and Outcropping Niger Delta (after Ekwenye and Nichols, 2016).

Table 1: Correlation of Subsurface and Outcrop Formations of the Niger Delta (redrawn and modified after Short and Stäuble, 1967; Avbovbo, 1978; Ekwenye et al., 2015)

Subsurface			Outcrop		
Youngest known age	Formation	Oldest known age	Youngest known age	Formation	Oldest known age
Recent	Benin	Oligocene	Recent	Benin Formation	Miocene
Recent	Agbada	Eocene	Miocene Eocene	Ogwashi Formation Ameki Group	Eocene Eocene
Recent	Akata	Paleocene	Lower Eocene	Imo Formation	Paleocene

Sedimentation commenced in the Abakaliki-Benue Trough during the Aptian-Albian, continued to the Conanian and was halted due to the Santonian thermo-tectonism (Murat, 1972; Nwachukwu, 1972; Hoque, 1984; Benkhelil, 1986, 1989; Umeji, 2007). Following the Santonian folding and uplift, the Abakaliki Basin, became flexurally inverted, displacing the depocentre to the west and northwest and to the east, resulting in the Anambra Basin and the Afikpo Syncline respectively. The Anambra Delta Complex was terminated by an extensive Paleocene transgression (Whiteman, 1982) and a Niger Delta sedimentation began in the late Paleocene (Short and Stäuble, 1967; Evamy et al., 1978).

During the Paleocene, subsidence occurred south of the Anambra Basin and the Afikpo Syncline; down dip of the NW-SE trending faults of the Calabar Flank and the NE-SW trending faults of the Benin Flank give rise to the Niger Delta Basin (Umeji, 2010). The oldest formations in the Niger Delta are the Paleocene-Eocene Imo Formation; the Eocene Ameki Group, Oligocene Ogwashi Formation, and the Miocene-Recent Benin Formation (Petters, 1991). These formations are highly diachronous and extended into the subsurface where they have been assigned different formation names which are the Akata, the Agbada, and the Benin formations (Table 1).

METHODOLOGY

Good outcrop exposures in Umunya, Ogbunike, Nibo and Awka areas (Figure 2) allow detailed study of facies analysis and facies architecture of the rock units. The representative outcrops were systematically logged to unravel the rock types, textural features, sedimentary structures and nature of bedding. Measurement of bed thickness, the lateral extent of outcrops and for heterolithic deposits, the thickness variation of sand, silt or clay couplets were recorded. Photopanorama mapping was carried out for laterally extensive outcrops. The field observations/investigations were used to interpret the lithofacies units and facies assemblages, interpret the depositional environments.

RESULTS

Facies Analysis - Lithofacies

Field data obtained by sedimentological logging of selected outcrops from the study area is classified into lithofacies. A total of ten facies and seven subfacies were identified from the studied outcrop sections. Facies codes are designated to bed(s) based on their internal sedimentological features. Facies code S is for sandstone, while F is for finer grains such as siltstone, mudstone and shale. The sedimentary facies scheme used in the study area is modified after Miall (1996).

Tabular Cross-Bedded Sandstone Facies (Sp) Description

The tabular cross-bedded sandstone facies (Sp) is characterized by planar foresets with angular bases and curved foresets with asymptotic (tangential) or concave toesets. This facies is composed of three sub-facies (Sp1-3).

Sp1 is the planar cross-bedded sandstone sub-facies which comprises medium to very coarse-grained, moderately to poorly sorted sandstone. The sands are mostly unconsolidated, creamy white to light brown color on fresh surfaces and ferruginsed, reddish brown on weathered surfaces. This sub-facies is characterized by normal grading of the foresets from pebbly or coarse grains to finer grains. They are observed at Awka and Ogbunike.

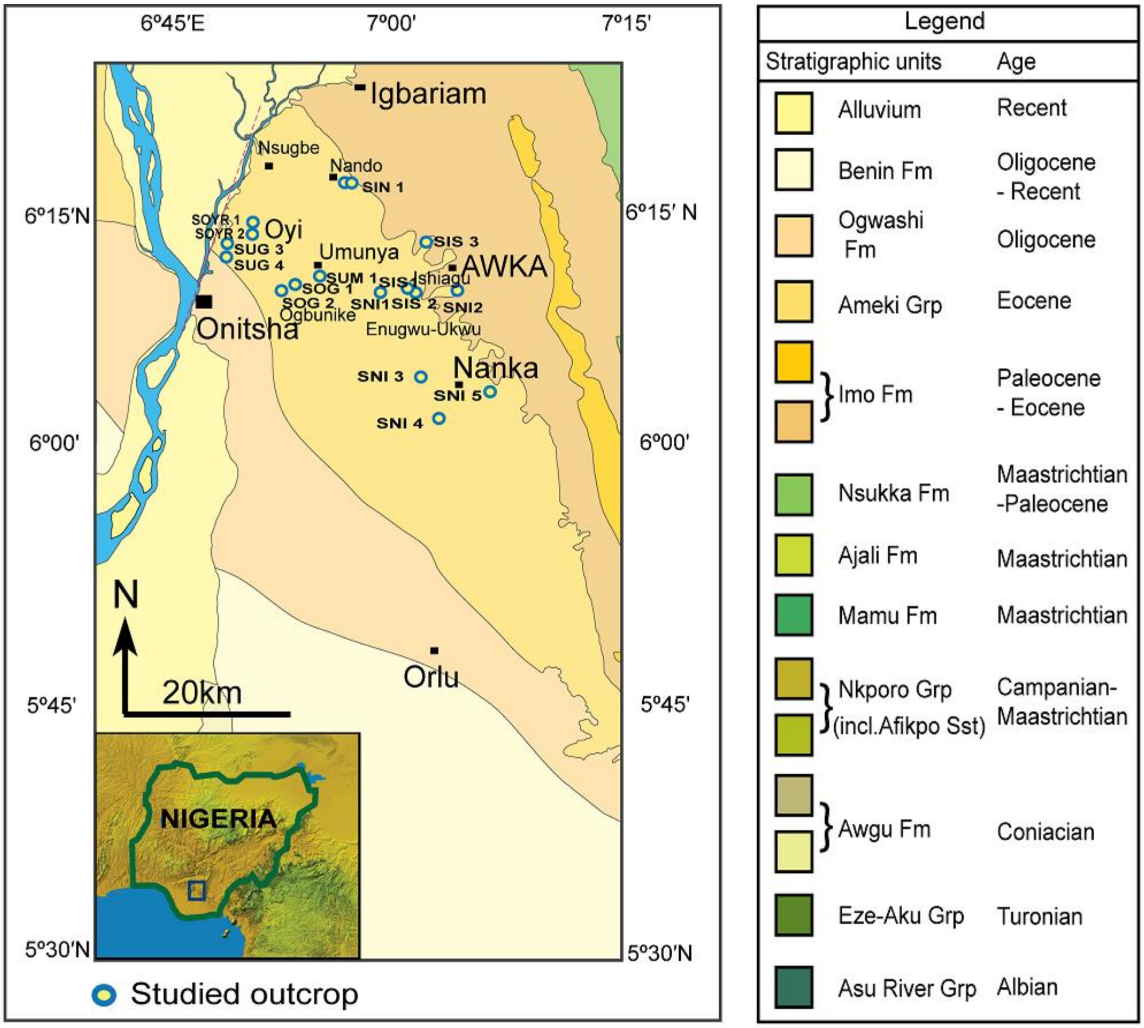
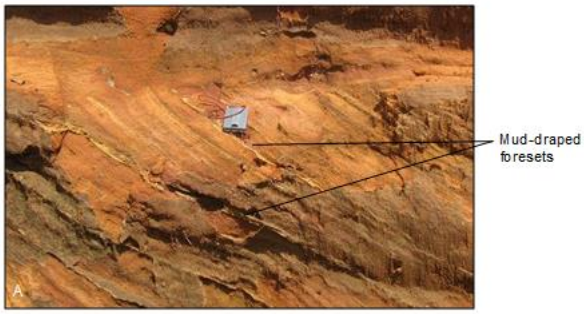


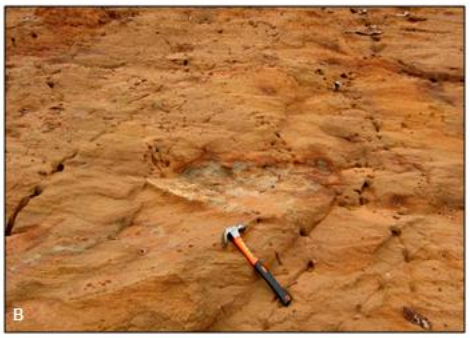
Figure 2: Geologic Map of the Study Area Showing Umunya and Environs.

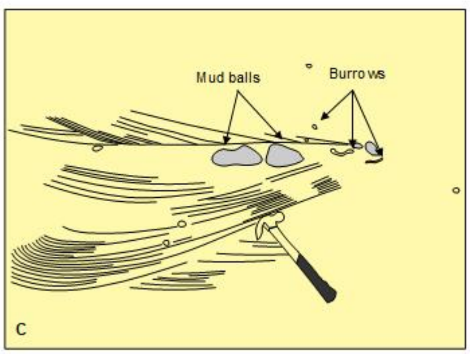
The foresets are planar (angular based), and they are bounded at base and top by sharp contacts, at Awka some of the bounding surfaces are draped with mud. Individual foreset ranges from few millimetres to several centimetres thick. Bed thickness ranges from 20 cm to1 m.

Sp2 is a mud draped tabular cross-stratified sandstone with single to double mud drapes on some foresets. The toesets would be asymptotic or planar (Figure 3a). The sands are fine to coarse-grained, moderately to poorly sorted and creamy to light brown color. The bed thickness ranges from 40 cm to 1 m and the bed contacts are sharp to gradational bases and tops. This sub-facies consists of mud clasts and saucer-shaped mud lenses as observed in Ugwu-Akpi at Enugwu-Ukwu. The Sp2 occur as sheets covering about 20 to 50 m or as channel fills in Oyi, Nibo, Ugwu-Akpi and Umunya sections.

Sp3 represents tabular cross-stratified sandstone with asymptotic (tangential) or concave base. This sub-facies consists of coarse-grained, poorly sorted, creamy to light brown colored sands. The bed thickness range between 20 cm to 1.5 m and has a tangential or curved basal contact and a sharp to gradational top contact. It is uncommon and occurs in Awka and Ifite-Awka.







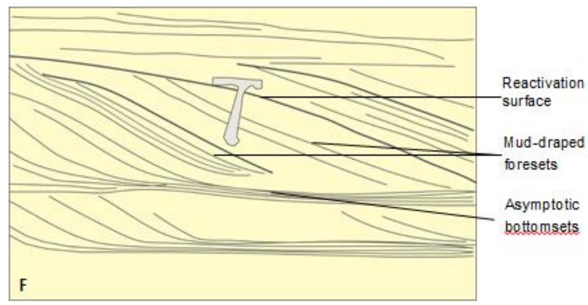


Figure 3: (A) Tabular Cross-Bedded Sandstone Facies (Sp) showing Mud Draped Tabular Cross-beds (Sp2 Facies) with Asymptotic Toesets (tangentially based) Observed at Nibo Section. **(B)** Large-Scale Trough Cross-Bed (St2) with Mud Drapes and Mud Balls, Moderately Burrowed at the Basal Unit of the Nibo Section (Nanka Formation). **(C)** Schematic Diagram shows the Scallop-Shaped Scour with Well Curved Forests. **(D)** Herringbone Cross-Stratification Facies (Sxh) Observed at Nibo Section. **(E)** Mud Draped Sigmoidal Cross-Beds (Sx) with Mud Draped Reactivation Surfaces (hammer head is on the reactivation surface), Umunya Section (Nanka Formation). **(F)** Schematic Diagram showing the Mud Draped Sigmoidal Cross-Beds.

Interpretation

Sp suggests the migration of straight-crested bedforms, in the middle part of the lower-flow regime. Flow strength over the crest can strongly influence the shape of the foreset, weak flow creates angular foresets as observed in Sp1 facies whereas, stronger flow leads to tangential foresets typical of Sp3 facies (Collinson et al. 2006).

Small-scale cross-bedding (10 to 30 cm) reflects the migration of small-sale bedforms with low relief. The presence of reactivation surfaces in Sp1 may result from reworking by waves during the emergence of a bedform between successive flood events that commences bedform migration (Collinson et al., 2006). It may also result from subordinate tidal flow due to reversals in flow direction such that a bedform's lee side is changed into the stoss side resulting in substantial bedform modification (Allen and Homewood, 1984).

Mud drapes on cross beds foresets in Sp2 are deposited during slack water conditions in response to semi-diurnal tidal fluctuation (Shanley et al., 1992). The high occurrence of iron mineral as observed in the ferruginised sandstone of Sp1 facies and iron-rich (hematite) concretions suggest post-depositional effect due to sub-aerial exposure and an oxidizing condition.

Trough Cross-Bedded Sandstone Facies (St)

Description: The trough cross-bedded sandstone facies (St) is characterized by three-dimensional dunes with spoon-shaped or scallop-shaped scours. This cross-stratification has also been referred to as festoon bedding. It is subdivided into two subfacies, St1, trough cross-bedded sandstone, and St2, trough cross-bedded sandstone with mud drapes. This facies occurred dominantly at the lower and middle part of the outcrop sections observed at Nibo and Umunya.

St1 is characterized by medium to very coarse grained and moderately to very poorly sorted sandstone. The sands are creamy to dark reddish brown colored, poorly to well consolidated and may be ferruginised. Trough sets have sharp tangential basal contacts and sharp concave top. Bed thickness varies from 20 cm to 40 cm.

St2 consists of medium to coarse-grained, moderately to poorly sorted sandstone. The sands are light brown in color and poorly consolidated. Trough sets occur as medium scale (20 to 30 cm thick) and large-scale (>40 cm thick) troughs. This subfacies is characterized by mud balls, mud drapes on foresets (Figures 3b and c) and thick mud plugs at the troughs. It is poorly to strongly bioturbated and dominated by *Skolithos* ichnofacies (robust *Ophiomorpha nodosa, Thalassinoides paradoxicus*, *Planolites montanus, Paleophycus tubularis)* as observed at Nibo.

Interpretation: The formation of trough cross-stratification suggests migration of lunate or sinuous-crested bedform, at a deeper and higher velocity flow than straight–crested dunes (Collinson et al., 2006). It occurs at the upper part of the lower-flow regime. Erosional surfaces may be induced by the fluctuation of flow velocity or depth during bedform migration.

Variable grain texture is controlled by variation in sorting due to fluctuating hydraulic conditions. The presence of mud drapes on foresets of St2 facies reflects fallout of suspended sediments at slack water periods. The accumulation of thick mud plugs/balls on foresets/troughs are accelerated by rapid flocculation, with decreasing current velocity, they often known as fluid (or water-rich) mud and are common in tidally influenced setting (McIlroy, 2004). The low diversity *Skolithos* and *Cruziana* ichnofacies suggest stressful conditions due to low and/or fluctuating salinity levels, common in the marginal marine realm (Taylor and Gawthorpe, 1993).

Herringbone Cross-Stratified Sandstone Facies (Sxh)

Description: Sxh facies consists of fine to medium, moderately sorted, brown color sandstone. Bed thickness is about 15 to 20 cm, with erosional or non-erosional bases and planar tops (Figure 3d). Sxh is characterized by small-scale bi-directional cross-beds as observed at Nibo. It is poorly or moderately burrowed. Sxh facies is associated with cross-ripple laminated sandstone facies (Sr). The sandstone bodies have lensoidal-shaped geometry.

Interpretation: Sxh signifies periodic reversals in the current direction as a result of tidal deposition. The formation of herringbone requires floods and ebb currents to occur at difference times where the rate of sedimentation is enough to preserve them (Visser, 1980).

The presence of bimodal rippled foresets with mud drapes implies migration of ripples formed by maximum tidal currents, followed by deposition of mud layer due to sediments fallout from suspension during slack water period (Visser, 1980; Dalrymple, 1992). The herringbone cross-stratification records bipolar flow (two opposite directions of flow) at Nibo (320^0 /150^0). This bedform is associated with variation in flow velocity and direction, typical of tidal currents (Visser, 1980).

Sigmoidal Cross-Stratified Sandstone Facies (Sx)

Description: Sigmoidal cross-stratified sandstone facies (Sx) exhibits a gentle, sigmoid to avalanche-type cross-bed foreset back to sigmoidal shape (Kreisa and Moiola, 1986). The foresets have convex-up topset and tangential toeset laminae.

This facies is a fine to medium grained, well to moderately sorted sandstone. It is creamy white to light brown on the fresh surface, but dark grey on weathered surface. Bed thickness is between 10 cm to 80 cm, with rippled or planar sharp bases and tops. This sub-facies is characterized by single to double mud draped foresets, with extensive mud draped rippled toesets that form asymptotic bottomsets.

The internal structure of the asymptotic bottomsets is characterized by wavy bedding and bifurcated wavy flaser bedding as observed at Umunya. Mud draped reactivation surfaces are very common (Figures 3e and f), and the sandstone is moderately bioturbated. Common ichnofossils are *Ophiomorpha nodosa*, *Paleophycus heberti*, *Planolites montanus*, *Beaconites*, *Cylindrichnus concentricus*, and *Skolithos*. These trace fossils represent the *Skolithos* ichnofacies. Sub-facies 2 forms a tabular or sheet-like geometry.

Interpretation: Sigmoidal cross-stratified sandstone facies is produced during migration of megaripples as flow velocity decelerates (Kohsiek and Terwindt 1981). The topset is generated during deceleration, and the full vortex action (tangential toeset) is formed during maximum high flow velocities (Kohsiek and Terwindt, 1981).

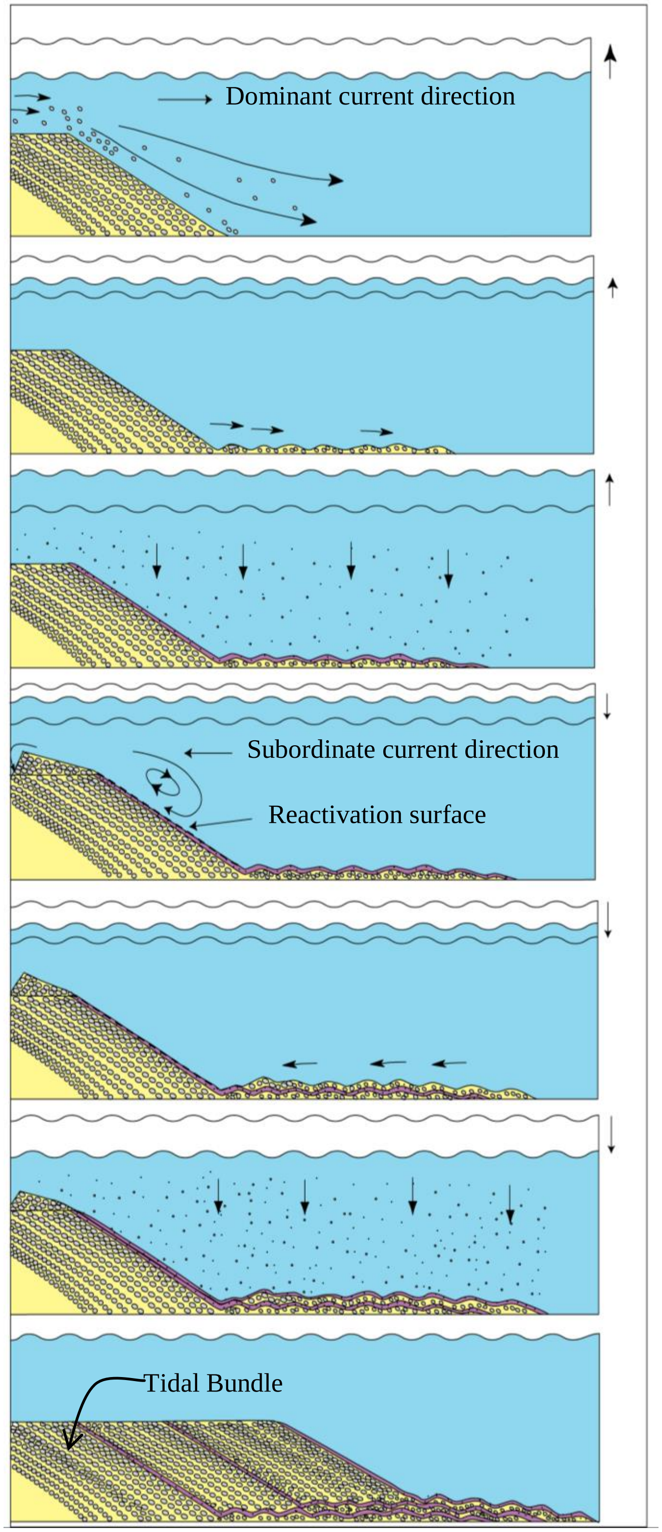
Sx is interpreted as tidal bundle, generated and modified in response to spring/neap tidal cycles during the migration of tidal current (Kreisa and Moiola, 1986; Shanley et al., 1992). The tidal bundles at Umunya display cyclic thickening and thinning of foresets that correspond to the neap/spring tidal fluctuations.

The tidal bundle sequence is characterised by thick and thin mud draped foresets, bounded by mud drapes and/or reactivation surfaces (Yang and Nio, 1985). The sandy thick foresets and bottomset lamina which were deposited by a dominant tidal current; followed by mud drapes on foresets deposited during relatively slack water periods (Figure 4). Whereas, the thin sandy layers were deposited during subordinate current flow, while subsequent mud drapes were deposited during slack water periods following the subordinate current stage (Visser, 1980; Yang and Nio, 1985).

A mud draped reactivation surface reflects a strong subordinate current. The gently dipping to more steep dipping and back to gentle dipping of the sigmoidal foreset represents acceleration changing to full vortex flow conditions, followed by deceleration with a single tide (Kreisa and Moiola, 1986).

Asymptotic bottomsets reflects continuous deposition of thin rippled sands and muds in the downdip direction of the toesets of the tidal bundles, during deceleration phase (Figure 4). The thick asymptotic bottomsets and the ripple cross-bedding reflect decelerating flow conditions during neap-spring tidal cycles (Martinius and Van den Berg, 2011).

The neap-spring-neap tidal bundle has an average number of 27, reflecting a semi-diurnal tidal cycle (Figure 5). Kreisa and Moiola (1986) referred it as pause plane and interpreted the mud drape as fallout from suspension during the slackening phase of tidal flow. Tidal bundles develop on channel margins and floors where burial can be rapid as a result of relatively strong currents (Davis, 2012). They are common in tidal channels, channel margins or intertidal flats where mesoscale bedforms occur (Davis, 2012).



Flood tide current: Onshore flow as tide rises. Traction development of foresets due to maximum flow velocity.

Increasing (accelerating) tide: As flow velocity reduces (decelerating flow), fine sand-size clastics move along the toeset by rolling.

High tide (slack water): Suspension fallout of mud drapes due to low flow velocity.

Ebb tide current: Subordinate current flowing the offshore direction.

Decreasing (decelerating) tide: Decelerating flow resulting to fine sand-size clastics move along the toeset.

Low tide (slack water): Suspension fallout of mud drapes due to low flow velocity.

Deposits of subordinate flows are easily eroded by dominant flows. Tidal bundles are formed from repeated cycles of low and high tide (neap-spring tidal cycles).

Tidal bundles with rippled asymptotic bottomsets are formed from repeated cycles of low and high tide (neap-spring tidal cycles).

Figure 4: Formation of Tidal Bundles and Rippled Asymptotic Bottomsets during Semi-Diurnal Tidal Cycle (redrawn and modified after Visser, 1980; Dalrymple, 1992).

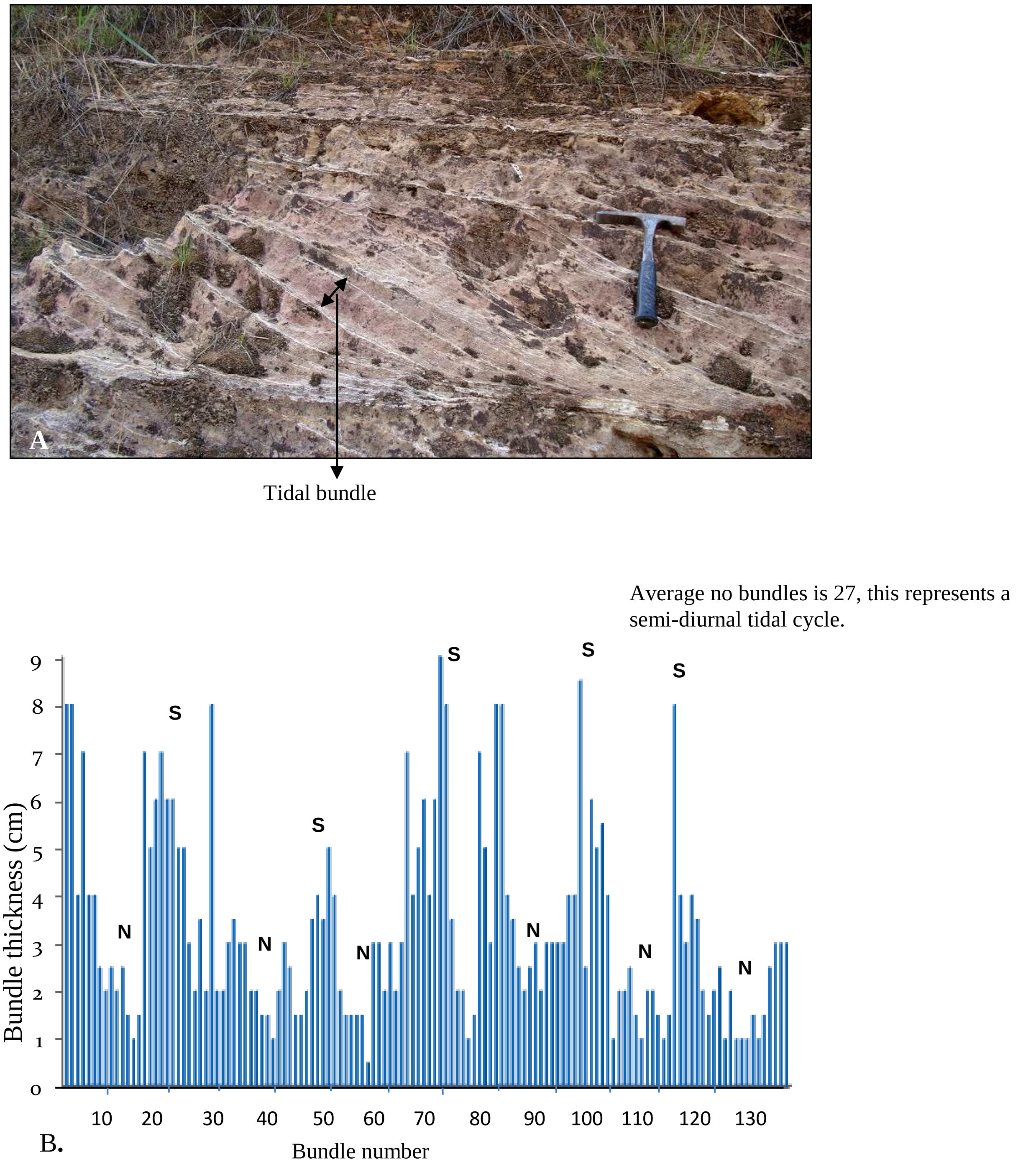


Figure 5: Tidal Bundle in the Umunya Section. **(A)**. Outcrop Photograph showing Variation in the Thickness of the Tidal Structure. **(B)**. The Neap-Spring-Neap Tidal Bundle has an Average Number of 27, Reflecting a Semi-Diurnal Tidal Cycle.

Bioturbated Sandstone Facies (Sb)

Description: Sb facies comprises fine to medium grained, well to poorly sorted, brown to reddish/yellowish brown colored sandstone. Some weathered surfaces are dark grey colored. Bed thickness ranges from 20 cm to more than 2 m and has erosive or gradational basal and planar top contacts.

The fine to medium grained bioturbated sandstone (Sbf) is micaceous; most of the internal structure is obliterated, but contains relics of ripple lamination. At Umunya and 33 Junction, Nsugbe, a moderately to strongly bioturbated fine to medium grained sandstone exhibits trace fossil suites of *Skolithos-Cruziana* ichnofacies. Systematic description, physiological conditions and environmental interpretations of these trace fossils are discussed in Ekwenye et al. (2016). Burrows such as *Ophiomorpha nodosa, Cylindrichnus*, *Teichichnus*, *Asterosoma, Beaconites, Paleophycus* and *Planolites* are observed in Umunya (Figure 6).

The medium grained bioturbated sandstone (Sbc) are structureless. Sb facies occurs as sheet-like geometry and covers an areal extent of about 50-500 m^2

Interpretation: The occurrence of monospecific and high faunal density suggest high environmental stress in a marginal-marine environment due to low and /or fluctuating salinity levels (Taylor and Gawthorpe, 1993). *Ophiomorpha, Arenicolites, Diplocraterion* and *Skolithos* are formed by formed by suspension-feeder dwelling burrows that reflect high-energy environments typical of shallow subtidal to intertidal deposits (Howard and Frey, 1984).

The dominance of *Ophiomorpha* burrows suggests condition of moderate to high energy sediment influx and predominance of the vertical shafts suggest that sedimentation was periodic causing a successive upward extension of shafts (Dam, 1990). *Lingulichnus* are languid dwelling traces typical of brackish and estuarine setting (Buatois et al., 2005). Escape structures and spatial adjustment traces are indicative of rapid sedimentation. The presence of deposit-feeders such as *Teichichnus, Rhizocorallium, Taenidium* and *Asterosoma* indicate a quiet and stable condition. Details on the trace fossils are discussed in Ekwenye, et al. (2016).

Sandy Heterolithic Facies (Sht)

Description: Sandy heterolithic facies occurs throughout the exposed units at 33 Junction, Nsugbe and at Paully petrol station at Ogbunike (Figures 7a and b).

Heterolithic facies consists of two sub-facies 1, and 2. Sub-facies 1 is represented by non-inclined heterolithic sub-facies, it is further sub-divided into 1a and 1b. Sub-facies 1a comprises well sorted, fine-grained sandstone of centimeter scale and mud of millimeter scale.

The sand color is reddish brown while the mud is light grey in color. Bed thickness is about 1.2 m and has sharp to gradational basal and planar top contact. It is characterized by parallel laminated sand with mud intercalation. Sub-facies 1b is represented by well sorted, very fine grained sandstone of mm-dm scale and mud of mm-dm scale. Sand color varies from yellowish brown to reddish brown, while the mud is light grey in color. The laminae thickness varies between 5 mm to 30 cm and has sharp contacts within the sand and mud laminae.

Other sedimentary structures associated with the sub-facies 1 include continuous and discontinuous wavy lamination, flaser bedding, and small-scale trough and planar cross laminations, with synaeresis crack. The heterolithic unit is moderately to strongly burrowed with suites of diminutive *Skolithos* ichnofacies that include *Paleophycus, Planolites, Cylindrichnus, Ophiomorpha nodosa*, *Conichnus,* and *Skolithos* are observed at 33 Junction, Nsugbe (Figure 7a).

Interpretation: Intercalation of non-inclined millimeter-centimeter scale sands, silt and mud denote cyclic accumulation of vertically and laterally accreted sediment, referred to as tidal rhythmites (Kvale, 2006).

Sand laminae are deposited by asymmetrical tidal currents during the period of falling tide and the rising limb of the following high tide whereas the silt/mud lamina represents deposition from suspension during slack water at high tide (Gibson and Hickin, 1997). Thicker sand layer represent flood or ebb tides during spring period, also thicker mud layer represent slack-water period during spring.

Figure 7: Bioturbated Sandstone Facies (Sb) at Umunya Section (Eocene Ameki Group) Shows Low Diversity *Skolithos-Cruziana* ichnofacies. **(A)** *Planolites,* **(B)** *Ophiomorpha nodosa,* **(C)** *Beaconites,* **(D)** *Cylindrichnus* (Cy), *Beaconites (B*e), *Paleophycus* (Pa).

Similarly, thinner sand lamina represents flood or ebb tides during neap period while thinner mud lamina suggests slack water periods during neap period. Lack of erosional contacts between layers and the presence of rippled and cross-laminated heterolithics, flaser bedding, and wavy bedding within the sandy intervals suggest that the sediments are formed under a relatively weak energy condition. The presence of *Skolithos* and *Cruziana* ichnofacies suggest a brackish condition.

Current Rippled Laminated Sandstone Facies (Sr)

Description: This facies occurs in the middle and upper part part of the outcrop exposure at Umunya and Nibo. Current rippled laminated sandstone facies is fine to medium grained, well to moderately sorted sandstone. Sands are brown to white colored, with subordinate mud that is light to dark grey. Bed sets vary from about 5 to 25 cm thick and cosets are about 1 m thick. Beds have a sharp or gradational base and wavy top contacts. Observed sedimentary structures include ripple lamination, flaser bedding, and wavy bedding (Figures 7b and c). This facies is poorly to moderately burrowed as observed at Nibo, with *Ophiomorpha nodosa* and *Planolites*.

Interpretation: Current rippled laminated sandstone occurs as a result of migration of unidirectional current in water or during deceleration of high-velocity current. Cosets of ripple cross lamination result from the migration of ripples combined with a net accumulation of sediment on the bed (Collinson et al., 2006).

The wavy and flaser bedding reflects fluctuations in flow velocity during deposition or occurs as a result of sediment supply due to fluctuation in current. During periods of current activity, the sand is deposited as ripples while mud is entrained in suspension. When the current wanes, the mud floccules are deposited in troughs or completely cover the ripples (Reineck and Singh, 1980). The sand ripple is can also be formed by the maximum current of the dominant tide, followed by deposition of mud layer during the slack–water period of the subsequent weaker tide (Visser, 1980).

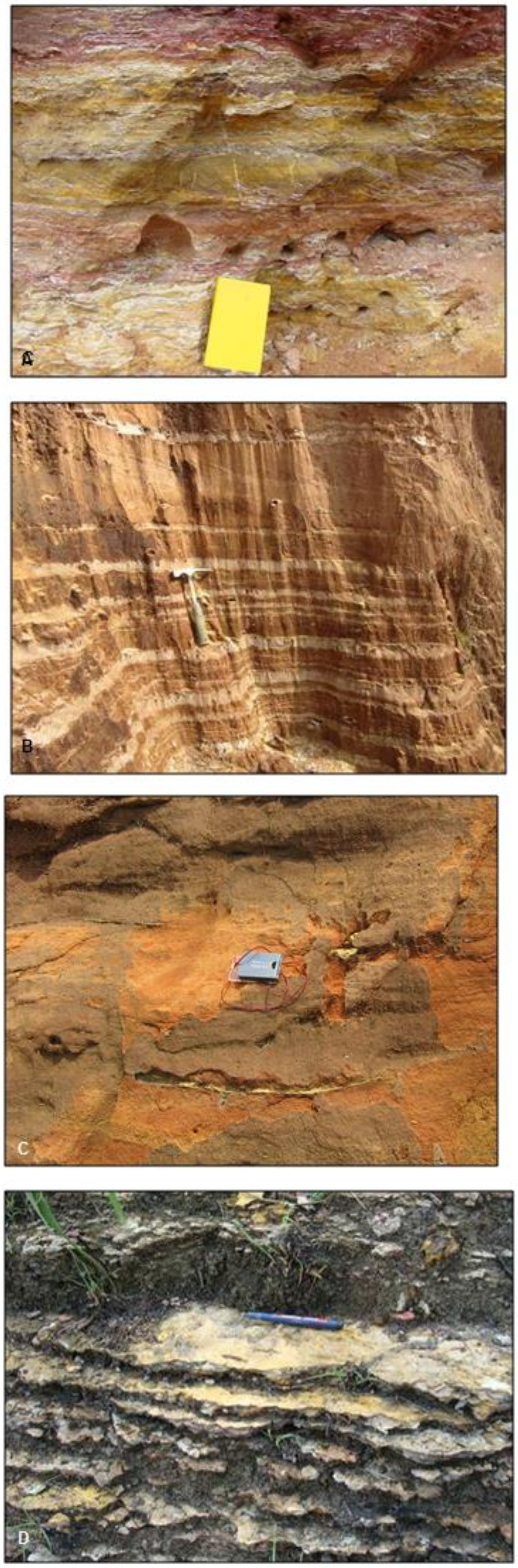


Figure 7: Sandy Heterolithic Facies (Sht). **(A)** Displays Continuous and Discontinuous Wavy Lamination, Flaser Bedding, and Small Scale Planar Cross Laminations (33-Junction, Nsugbe). **(B)** Centimetre-Decimetre Scale Heterolithic Bedding Interpreted as Annual Cyclicity. The Sandy Intervals Show Wavy and Flaser Bedding (Paully petrol station section, Ogbunike). **(C)** Flaser Bedding from Tidal Channel Deposit at Nibo. **(D)** Wave Rippled Laminated Sandstone Facies (Sw) Showing Intercalation of Wave Rippled Sandstone and Mudstone (uppermost interval of Umunya section) and **(E)** Symmetrical Wave Ripple Characterized by Interference Ripple Pattern (Umunya section).

Wave Rippled Heterolithic Facies (Sw)

Description: The wave ripple heterolithic facies is observed in the middle and uppermost part of Umunya section. The Sw facies includes well sorted, very fine to fine-grained, micaceous sandstone. Sands are light brown to yellowish brown in color. Bed thickness is millimeter to centimetre thick with sharp wavy base and top contacts. The wave ripples may be symmetrical (modified by interference ripple pattern) and asymmetrical (heterolithic) laminated (Figures 7d and e).

Other structures such as convolute lamination, load casts, wavy, flaser and lenticular bedding, slumping are observed at the upper part of the Umunya section. Sw facies forms a sheet-like geometry of about 1 km as observed in Umunya and Oyi River.

Interpretation: Wave action in the study area is indicated by the presence of symmetrical and asymmetrical ripples with rounded crest. The former is as a result of oscillatory waves while the latter is produced as a combination of oscillatory waves and unidirectional currents. Structures such as convolute lamination, load casts and slumping structures occur within the wave ripples facies in Umunya.

These are syndepositional soft sedimentary structures and their occurrence within the heterolithic bedding suggests liquefaction and fluidization of unconsolidated sediments in a discrete zone. They were more obvious at the lower part of the sections. Their occurrence may be aided by breaking waves during the emergence of the bed or by the rise and fall of the water table through the sediment (Collinson et al., 2006).

The flaser/wavy and lenticular bedding associated with the wave rippled heterolithic bedding may have resulted from variations in wave activity or sediment supply due to changing wave action. These wave ripples occur within tidal rhythmites, which is common in exposed tidal flats (Fan, 2012).

Structureless (Massive) Sandstone Facies (Sm)

Description: The structureless sandstone facies are observed only in Ogbunike at the Paully petrol station section. This sub-facies rarely occurs in the study area. The sandstone is medium grained and moderately sorted.

Interpretation: Structureless sandstone is suggested to originate from gradual aggradation of sediments beneath steady or near-steady flows (Johansson et al., 1998). Massive sandstone can also occur as a result of intense bioturbation or rapid deposition, through deceleration of a heavily sediment-laden current (Collinson et al., 2006).

Tidal Range: Intertidal deposit commences from the base of sand flats to the top of mudflats and it varies from 4 m thick (as observed at Ogbunike in a tidal flat to 15.5 m thick (as observed at Umunya in the tidal flat successions). At Ogbunike, the mixed flat succession is 4 m thick, whereas at Umunya the mixed flat succession is 6 m thick. At Umunya, the sand flat is about 6 m thick and the mudflat is more than 3.5 m thick. The thickness of the intertidal flat reflects the tidal range (Darlymple, 1992), and based on Davies (1964) classification, the tide-dominated estuarine is defined as macrotidal.

The tidal range is similar to the average semi-diurnal tidal range of 11.5 m in the Minas Basin (Yeo and Risk, 1981) and the maximum range of 16.3 m in the Cobequid Bay located at the head of the Bay of Fundy (Dalrymple et al., 1990). The presence of the deposit of tidal flats, supratidal flats, tidal channels and tidal bars further support a tide-dominated macrotidal estuary setting (Dalrymple et al., 1990; Pontén and Plink-Björklund, 2005).

Mudstone Facies (Fm)

Description: The mudstone facies is further sub-divided into two (Fm1-2) based on their internal structures and characteristics.

Fm1 sub-facies are exposed at the middle and upper units of the outcrop sections at Oyi and Ogbunike. The sub-facies is a carbonaceous mudstone that is characterized by abundant carbonaceous and plant matters. It is thickly laminated, dark yellowish brown, and medium to dark grey in color. It contains streaks of siltstone.

The medium dark grey mudstone is strongly bioturbated at certain intervals. Bed thickness is mm to cm and has a sharp to gradational basal and top contacts with underlying and overlying beds as observed at Oyi and Ogbunike. At Ogbunike, the dark grey mudstone is structureless is also observed; it contains fragments of lignite, plant and organic matters.

Fm2 sub-facies are observed within the middle and upper intervals of outcrops at Umunya, 33 and Ogbunike sections. This sub-facies is characterized by laminated mudstone that exhibits finely, parallel laminated mudstone sometimes with fine streaks of siltstones and sandstone forming lenticular bedding. The mudstones are white to very light grey colored and are observed at Umunya, 33 and Ogbunike sections.

Interpretation: The mudstone facies suggests the dominance of low energy conditions where the muds are deposited by suspension settling, episodic sedimentation and /or fallout during one or several slack-water periods. The presence of brownish black with plant matters suggest subaerial or supratidal conditions.

The lack of internal structure in Fm2 (massive or structureless mudstone) may be due to very homogeneous, continuous and possibly rapid deposition from suspension (Backert et al., 2010; Collinson et al., 2006), the presence of fossilized wood steam and leaves support rapid deposition and burial of vegetation. Laminated mudstone reflects episodic settling of mud/silt from suspension in quiet water. The dark grey to black color of the shale is caused by the high organic content of the shales.

Facies Association and Environment of Deposition

The ten lithofacies are grouped into two major facies associations that refer to rocks deposited in the tidal channel (subtidal) and tidal flat (intertidal) environments.

Facies Association 1: FA1 (Tidal channel)

Description: Facies association 1 comprises tabular cross-bedded sandstone sub-facies (Sp), mud-draped tabular cross-bedded sandstone sub-facies (Sp2), trough cross-bedded sandstone facies (St), bioturbated sandstone facies (Sb), sigmoidal cross-stratified sandstone facies (Sx), herringbone cross-stratified sandstone facies (Sxh), variegated facies (Fms) and mudstone facies (Fm). This outcrop section is observed at Umunya, Ogbunike, Nibo and Okpuno-Awka, along Onitsha-Awka express road and Enugwu-Ukwu.

Typical examples of the tidal channel deposits are the Umunya and Nibo sections (Figures 8 and 9). These tidal channels occur as large distributary, minor erosive channels or cut between tidal sand bars (Figure 10).

The lower unit of the Umunya section (SUM 1) is characterized by fine to medium-grained sandstone, which is well to moderately sorted, clayey, micaceous, and poorly consolidated. The sandstone unit is dominated by sigmoidal and tabular cross-beds, with mud drapes, rippled asymptotic bottomsets, reactivation surfaces, and flaser and wavy bedding. Each bed unit shows similar sedimentary structures from single to double mud draped sigmoidal, or tabular cross-beds with thick asymptotic bottomsets and cross lamination exhibiting wavy and flaser bedding.

Some intervals show gradual lateral changes from sigmoidal cross beds to co-flow cross-lamination in a north eastern direction. The dominant trend in the cross beds is to the north-east (070°). The beds vary in thickness from 30 cm to 1 m. The entire cross-stratified sandstone unit is about 4 m thick. The sandstone unit is characterized by low-diversity, opportunistic burrows of mixed *Skolithos-Cruziana* ichnofacies and monospecific, depauperate *Scoyenia* ichnofacies such as *Ophiomorpha, Planolites, Skolithos, Arenicolites, Paleophycus, Beaconites* and concentric vertical burrows of *Cylindrichnus.*

Interpretation: The mud-draped sigmoidal and tabular cross beds form tidal bundles which occurred during the neap-spring cycles. Cyclic variation in thickness of bundles was observed (Figure 5a), thicker bundles are known to form during stronger spring tides and thinner bundles occur during neap tides (Kreisa and Moiola, 1986; Dalrymple, 1992). The average number of the tidal bundles is 27; suggesting semi-diurnal tidal cycles (Figure 5b).

Lateral change in sedimentary structures from sigmoidal cross beds to co-flow cross lamination suggests a decrease in flow strength in the north-easterly direction. The lack of counter current ripples suggests the absence of vortices in the dune troughs. The dominant occurrence of tidal bundles and thick bottomsets is diagnostic of a subtidal sub-environment or inshore tidal domain (Dalrymple, 1992; Martinius and Van den Berg, 2011).

Facies Association 2: FA 2 (Tidal Flats)

Description: Facies association 2 is the most commonly occurring facies association in the study area. FA 2 encompasses current rippled laminated sandstone facies (Sr), wave-rippled laminated sandstone facies (Sw), mud-draped tabular cross-bedded sandstone sub-facies (Sp2), siltstone facies (Sl), bioturbated sandstone facies (Sb), and mudstone facies (Fm).

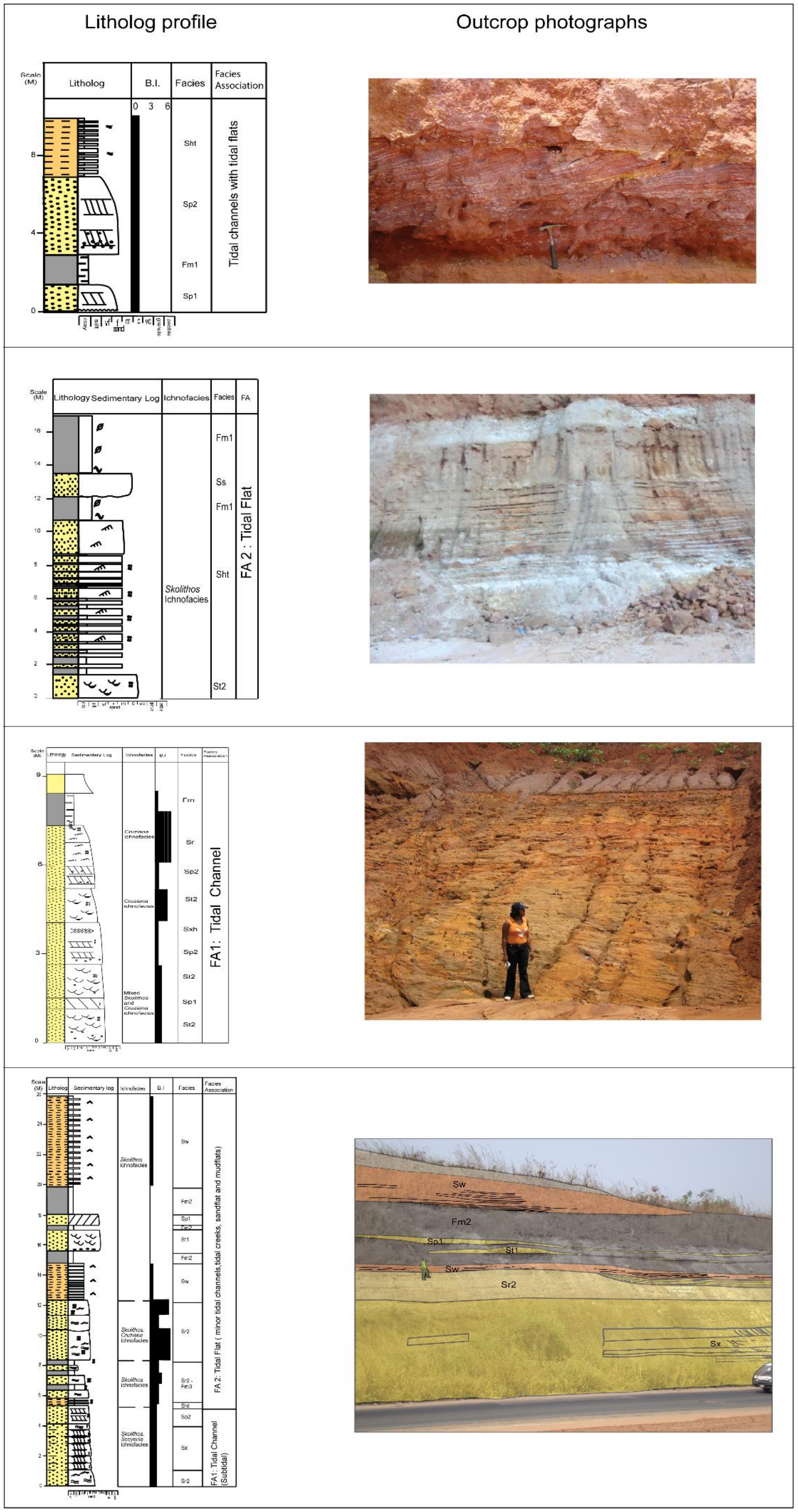


Figure 8: Catalog of Selected Lithologs and Outcrop Photographs of the Tidal Channel and Tidal Flat Deposits (Nanka Formation).

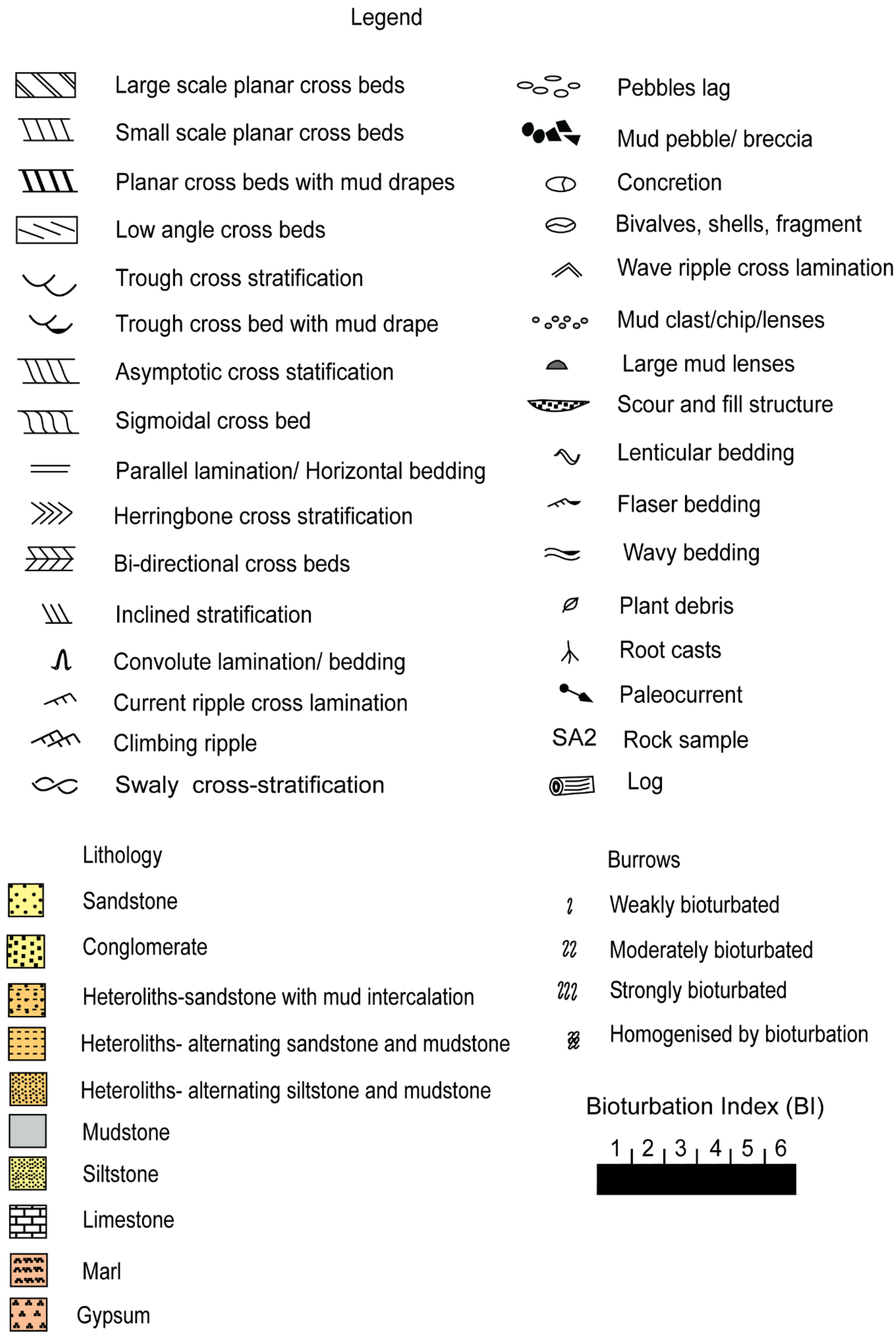


Figure 9: Legend for Lithologs.

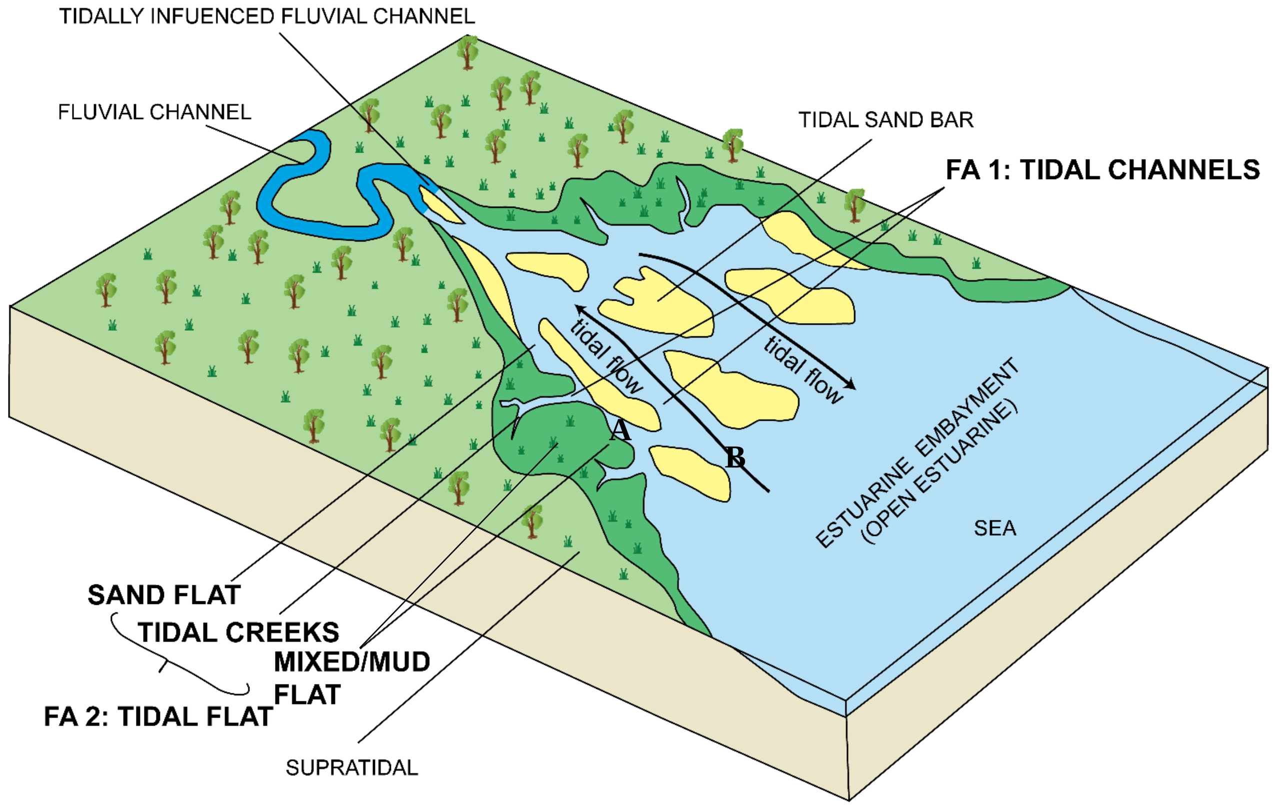


Figure 10: Schematic Diagram of Tide-Dominated Estuarine Depositional Environment Showing the Tidal Channels and Tidal Flat. The Tidal Channels Occur as Large Distributary **(A)**, Minor Erosive Channels or Cuts between Tidal Sand Bars **(B)**.

The outcrop sections are at Umunya, Ogbunike, Enugwu-Ukwu, Awka, Sandaff quarry, about 3 km from 3-3 junction in Onitsha, Ifite-Awka, Ishiagu and Nkwelle Ezunaka along the Onitsha-Awka express road (Figure 2).

The Umunya section (SUM 1) unveils a typical tidal flat environment, as it exhibits well preserved sedimentary structures that characterise deposits in subtidal and intertidal zones such as mixed flats, mudflats, tidal creeks and minor tidal channels (Figure 8a). The characteristic of the tidal flat is similar to those of the modern intertidal sediments of the Minas Basin, a macrotidal estuary at the head of Bay of Fundy (Yeo and Risk, 1980).

Sand Flat

The sand flat is characterized by a cross-bedded unit that grades into alternations of fine to very fine-grained sandstone and thin burrowed mudstone. The sandstone exhibits mud-draped planar cross bedding, flaser and wavy bedding. The burrowed mudstone varies from 5 - 35 cm thick, with increasing thickness upward whereas the sandstone beds vary from 35 cm - 4 m thick.

Thalassinoides burrows dominate the mudstone beds. The succeeding units are strongly burrowed, fine-grained, micaceous, clayey sandstones, characterized by the presence of mud flasers, and wavy bedding, with low diversity ichnofacies which includes abundant large *Ophiomorpha nodosa*, *Thalassinoides, Planolites, Asterosoma, Protovirgularia,* and *Teichichnus* burrows.

Tidal Gullies

Scour and fill channels occur cross the sand flat. The lower channel fill is about 2 meters thick and

8 meters wide. It comprises fine grained to silty sandstone, with cross-laminated and concentric fill. The upper channel-fill is characterized by lateral accreting heterolithic units that consist of interbedded lensoidal shaped silts/sandstone and mudstone, probably influenced by tidal currents and waves. The heterolithic channel-fill increases seaward in a southwards direction from 80 cm to 1.8 m thick and more than 15 m across. Succeeding the channel-fill heterolithic unit is white colored parallel laminated claystone with silt stringers that are slightly burrowed with *Planolites* burrows.

Mixed Flat

The mixed flat setting is characterized by fine-grained, rippled sandstone and heterolithic beds with wavy and flaser bedding. It interfingers with sand flat deposits and overlies the light grey claystone interpreted as mud flat deposits. Mixed flats are common in intertidal environments (as observed at Umunya, Paully petrol station 1 and 2 sections, Ogbunike in Figure 8c).

The heterolithic beds range in thickness from 1 to 6 m and show rhythmic alternation of cm–mm scale mudstone and fine grained rippled sandstone. The sandstone may be wave-rippled (symmetrical) laminated and highly micaceous as observed at Umunya section. On the bedding planes, the wave ripples show interference ripples with sinuous bifurcating crestlines (Figures 7d and e). Convolute lamination, slumping and other soft sediment deformations were observed within the heterolithic beds.

Mud Flat

The mud flat is characterized by laminated claystone or mudstone with thin continuous to discontinuous silty stringers. The thickness can vary from 50 cm to 3.5 m. At Umunya, the claystone of about 3.5 m thick is parallel laminated, light grey to white colored and it is dissected by coarse to medium grained sandstones (35 to 70 cm thick) with a scoured base. Mud chips, rip-up clasts and pebbles occur at the base of the sandstone beds. The sandstone beds may be structureless, planar or trough cross-stratified.

The sandstone bodies occur as a lens in the claystone with a length from about 20 to 50 m long. At Nibo and Awka, the mud flat occurs on top of tidal channels as dark grey mudstone. The mudstones may be bioturbated as observed at Nibo, or contain fossil molds as observed as Awka.

Interpretation: The sandstone unit of sand flats characterized by cross-bedded sandstone formed at high current velocities while the ripple cross lamination occurred when the current velocity is lower (Dalrymple, 1992). Upward increase in mud content resulted in wavy bedding and high bioturbation in the sand flat. These sand flat deposits interfinger with the deposits of the overlying mixed flat setting, reflecting localized environmental changes.

In the tidal gullies, a sudden change from cross-laminated to concentric fill as observed, indicates fluctuation in energy from relatively higher flow velocity and migration of ripples to lower flow energy. The concentric deposit represents vertical aggradation within a slowly migrating tidal creek (Dashtgard and Gingras, 2005).The laterally accreted heterolithic units represent tidal creek point bar deposition associated with channel migration (Dashtgard and Gingras, 2005). They are also referred to as tidal gullies (Dalrymple, 1992, Hughes, 2012), and they increase in depth and width seawards. The heteroliths are less burrowed because deposition is more rapid than in the surrounding mud flats.

The alternation of sand and mudstone layers displayed in the mixed flat is interpreted to reflect fluctuations in tidal currents (Nio and Yang, 1991). In each sand-mud couplet, the sand represents deposition from higher flow velocities followed by suspension fallout of mud during the stillstand slack water period: this reflects a single tidal fluctuation in a diurnal or semidiurnal system (Archer, 1995). The wavy and flaser bedded heterolithic mudstone and sandstone suggest deposits in wave-influenced relatively low energy mixed flat environment (Tirsgaard, 1993). The influence of waves suggests shallow water deposition.

The parallel laminated claystone represents mud flats in an intertidal flat. Tidal currents are relatively weak in the mud flats, thus, the deposit is muddy. The laminated claystone and thin discontinuous silty stringers suggest dominant deposition occurring from suspension settling with limited bedload transport caused by weak current (Ghazi and Mountney, 2009). The sandstone beds with scoured bases represent minor tidal channels incised onto the mud flats. These minor tidal channels are referred to as shallow runnels across tidal flats (Hughes, 2012).

DISCUSSION

Hydrodynamic Processes and their Implications for the Eocene Depositional Setting

Tidal processes, basin morphology, sediment influx and relative sea-level changes controlled sedimentation of the Nanka Formation. The morphology of the coastline is used as a proxy for tidal influence (Ainsworth, et al., 2011); highly embayed or funnel-shaped coastal morphologies can amplify the tidal wave as it moves into an area, resulting in increased tidally generated current velocities and sediment influx due to tides.

The dominance of tide in the studied succession was amplified most probably due to the basin morphology during the Eocene. The tidal channels and tidal flats strata are associated with a tide-dominated estuarine system which has funnel-shaped or highly embayed shoreline morphology (Ekwenye, 2014).

The estuary occurred during a regional transgression in the Eocene period, whereby the ancient river (which occurred during a sea level fall) deposited the fluvial strata of the Nsugbe Formation. The fluvial deposit became tidally influenced and later formed an estuarine setting depositing strata of Nanka Formation (Ekwenye, 2014). The transgressive period led to the deposition of tidal channels, tidal flats and other sub-environments of a typical tide-dominated estuarine setting such as tidal sandbars.

Although the tidal process is dominant in the study area, wave process was observed in the occurrence of wave ripple lamination within an intertidal flat at Umunya outcrop section. This structure was formed as wave action acted on shallow waters during deposition. This support the fact that tidal successions can be affected by other processes like wave or storm actions in a typical open-coastal setting (Lee et al., 2004).

CONCLUSIONS

Deposits of Umunya and environs within the study area shows mainly tidal signatures with minor wave-generated sedimentary structure. The occurrence of depauperate *Scoyenia*, and mixed *Skolithos* and *Cruziana* ichnofacies suggests a stressful condition that is typical of brackish water setting.

The tidal bundles and tidal rhythmites display cyclic thickening and thinning of foresets and laminae that corresponds to the neap/spring tidal fluctuations. The maximum tidal range of 15.5 m defines the tide-dominated estuarine as macrotidal. Factors that influenced this dominance of tidal action in the Nanka Formation include coastal morphology, sediment influx and transgression.

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