International Journal of Geology, Earth & Environmental Sciences ISSN: 2277-2081
Online, International Journal Available at http://www.cibtech.org/jgee.htm
2020 Vol. 10(1) January-April, pp. 37-54/Ekwenye et al.
***Research Article** (Open Access)*

DEPOSITIONAL FACIES AND SEQUENCE STRATIGRAPHY OF INCISED VALLEY-FILL IN THE 'BETA' FIELD OF THE COASTAL SWAMP DEPOBELT, NIGER DELTA

***O. C. Ekwenye [1], G. C. Obi [2], C. O. Okogbue[1] and M. I. Umeadi [3]**
[1]*Department of Geology, University of Nigeria, Nsukka*
[2]*Department of Geology, Chukwuemeka Odumegu Ojukwu University, Uli, Anambra State, Nigeria*
[3]*PTDF Professorial Chair, Department of Geology, University of Nigeria, Nsukka*
**Author for Correspondence: ogechi.ekwenye@unn.edu.ng*

ABSTRACT

This paper presents the results of sequence stratigraphic analysis carried out in the 'Beta' Field, Coastal Swamp depobelt of the Niger Delta. Wireline logs were integrated with high-resolution biostratigraphic data and core data to determine the depositional facies, identify the parasequence stacking patterns, key surfaces and systems tracts penetrated in the field. The results show that the stratigraphic succession penetrated in the field consists of a basal conglomerate unit that reflects a fluvial system that progressively becomes influenced by marine process; a medial sandstone and mudstone unit that represents deposition in the central part of an estuary and, a cross-stratified sandstone unit at the top, which represents the progradational filling of the bay-head of the estuary. The vertical arrangement of facies is typical of incised valley systems. The basal fluvial unit represents the aggradational deposit of a transgressive systems tract (TST). The medial material represents the backstepping or retrogradational deposit of the TST, while the upper unit represents the progradation of the bayhead during the highstand systems tract (HST). A conceptual model was proposed for the fluctuation in relative sea level which gave rise to the sedimentary cycle that accumulated between 10.6 Ma and 10.35 Ma. Sequence stratigraphic analysis reveals that the succession consists of two fourth-order sequences. Each complete sequence begins on type-1 sequence boundary and contains: a transgressive systems tract characterised by blocky to bell-shaped, fining upward which reaches its peak at the maximum flooding surface (MFS), and a highstand systems tract characterised by funnel-shaped or coarsening upward progradational stacking pattern. The basal uncomformity surfaces are dated 10.6 Ma and 10.35 Ma respectively, while the associated maximum flooding surfaces are dated 10.4 and 9.5 Ma respectively. The superimposition of these sequences document episodes of valley incision, marine flooding and sediment influx in response to cycles of basin subsidence and relative sea-level changes in the Niger Delta.

***Keywords**: Depositional Environment, Parasequence Stacking Patterns, System Tracts, Depositional Model, Incised Valley, Coastal Swamp, Niger Delta*

INTRODUCTION

Incised valleys commonly result from fluvial incision during relative sea-level fall and fill with sediments during the relative sea-level rise (Allen and Posamentier 1993). Sequence stratigraphic concept is applied in order to identify genetically related strata within a chronostratigraphic framework in the context of relative sea-level change (Posamentier and Vail 1988; Posamentier *et al.*, 1988; Mitchum *et al.*, 1993).

There has been increased documentation on the sedimentological and sequence stratigraphic development of modern and ancient incised valley estuarine fills in other sedimentary basins in the world (Van Wagoner *et al.*, 1990; Allen and Posamentier 1993; Zaitlin *et al.*, 1994). Incised valley estuarine fills are known to host reservoirs that produce economically significant quantities of hydrocarbon (Weimer and Posamentier 1993; Krystinik and Blakeney-DeJarnett 1997). This has therefore awakened interest in recognizing and interpreting the depositional systems of the ancient incised valley deposits in the Niger Delta.

This paper aims at describing the sedimentary facies of the incised valley fill using both sedimentology and ichnology. The ichnology is highly valuable in distinguishing distal and proximal part of sub-environments within the shallow marine. This work also demonstrates the effect of relative sea-level fluctuation on the stratigraphic succession of the IVF. The study is based on integrating wireline logs, high-resolution biostratigraphic data and core data, in order to further achieve a sequence stratigraphic interpretation of the 'Beta' field.

Geological Setting

The Beta field lies within the coastal swamp II depobelt of the Niger Delta (Fig.1). The incised valley fill occurs in the Agbada Formation which is one of the tripartite lithostratigraphic successions of the Niger Delta. The Agbada Formation forms the hydrocarbon prospective sequence in the Niger Delta. It consists of sands, silts, and clays of delta front and fluvio-deltaic environments and has a maximum thickness of more than 3000 m. The paralic sequence is present in all depobelts and it ranges in age from Eocene to Pleistocene.

The Agbada Formation is underlain by the marine shale of Akata Formation and overlain by the Benin Formation. Much of the geology of the Niger Delta can be found in a number of works such as Short and Stäuble (1967), Evamy *et al.*, (1978), Weber and Daukoru (1975), Doust and Omatsola (1990).

MATERIALS AND METHODS

Data Set/ Methodology

Sequence stratigraphic interpretation is based on the integration of four basic data sets, which are well logs and/or outcrops, seismic data, high-resolution biostratigraphic data and eustatic cycle chart. Availability of two or three of these data sets can be used for sequence stratigraphic interpretation. The data used for this study include core data, wireline logs, high-resolution biostratigraphic data and chronostratigraphic chart. Core data is highly valuable for high-resolution facies interpretation. The available data sets were easily accessible and highly reliable.

Three wireline logs which include gamma-ray logs, resistivity logs and neutron /density logs obtained from wells BT1, BT2 and BT3 were useful in discriminating lithologies. Figure 1 shows the locations of the wells. Cores (at 8651.8-8595ft; 10835.1-10773ft; and 11748-11691ft) from a representative well (BT2) were sedimentologically described for lithofacies interpretation at the laboratory of Location Sample Services (LSS) Port-Harcourt, Rivers State. Core diameters of 7.5cm were slabbed into one-third and two-third sections. The one-third section was laid out in core boxes (3 ft in each box) and studied for sedimentological description while the two-third section was digitally photographed. High–resolution biostratigraphic data were available for wells BT1 and BT2. The data were mainly derived from side-wall samples (type 2) than ditch cuttings (type 3). The former is more reliable.

Subsurface sequence stratigraphy relies on the recognition of keys surfaces of chronostratigraphic significance from logs. These key surfaces subdivide the strata into contemporaneous depositional systems within which reservoirs quality and sediment architecture becomes more predictable (Williams, *et al.,* 1997). The maximum flooding surfaces occur within marine shales and are best recognised by locating the point of maximum separation between the neutron and density logs and as well as lowest shale resistivity. It represents the time when the delta shoreline was at its further landward position relative to other flooding surfaces. It occurs between two adjacent sequence boundaries. The sequence boundaries (SB) represent times of maximum basinward shift of the shoreline position within the deltaic cycles. It is identified by analysing the stacking patterns between maximum flooding surfaces (Williams *et al.,* 1997). Sequence boundaries are located at the base of the thickest and shallowest sand between two adjacent maximum flooding surfaces. The surface is characterized by the lowest foraminiferal abundance and diversity. The abundance and diversity of the planktonic foraminifera were used for paleobathymetric determination. The Niger Delta chronostratigraphic chart (modified after Haq *et al.,* 1988) is used for correlating and assigning absolute ages to the identified sequence boundaries (SB) and maximum flooding surfaces (MFS) on the logs.

Figure 1: Map showing the area of interest and well locations within the Coastal Swamp Depobelt, Niger Delta

RESULT AND DISCUSSION

Facies Analysis

Ten lithofacies were recorded in the area of interest, based on the rock type, lithology, grain size, texture and sedimentary structures and their hydrodynamic processes (Table 1). These lithofacies are genetically grouped into three facies associations (FA) that were recognized based on vertical facies changes, the facies succession, lithology, texture, and sedimentary structures. The cored interval is tied to the wireline logs. The three facies associations depict sedimentary rocks deposited in the fluvial (FA 1), central estuarine (FA 2) and foreshore-shoreface (FA 3) depositional environments.

FA 1 – Fluvial channel

This facies is made up of a well-developed sand body that is characterized by blocky gamma-ray (GR) log motif and a very small separation from the neutron-density log combination (Fig. 2). Biostratigraphic data shows that this interval is generally barren and devoid of marine fauna. The thicknesses of the conglomerate unit in the three wells BT1, BT2 and BT3 are between 10 m and 40 m thick, proximally.

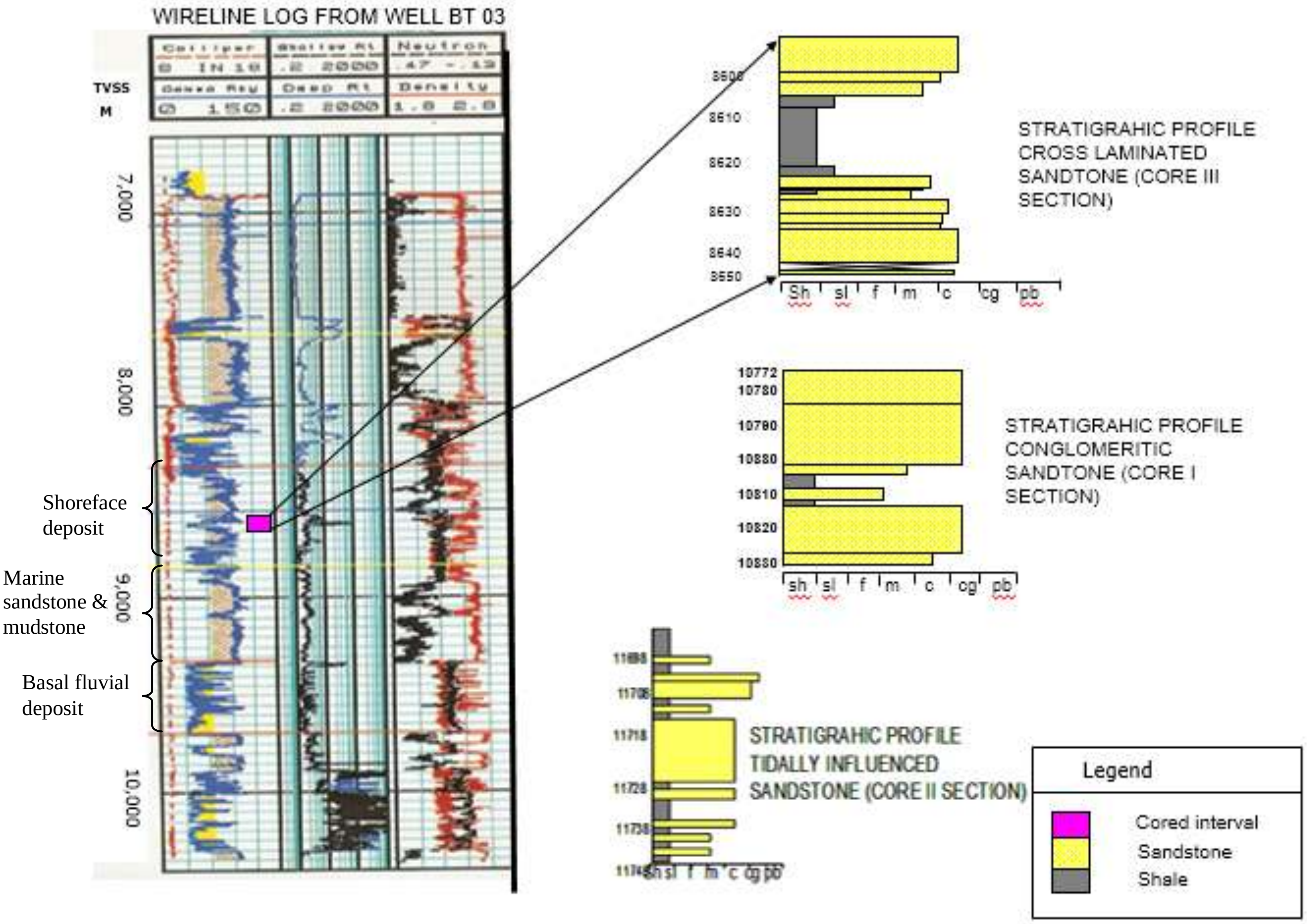

Figure 2: Representative stratigraphic log profile of the cored intervals and the wireline log of well BT 03

Table 1: Summary of the lithologic characteristics, ichnology and depositional processes of the lithofacies and the environment of deposition where they occur in the study area

Facies Code	Lithofacies	Texture	Lithologic Characteristics	Depositional Process	Depositional Environment	Ichnology
St	Trough cross-stratified sandstone	Clean, very coarse to coarse-grained, poorly sorted sandstone, woody fragments	Single to multistorey channels, erosive base	Migration of lunate or sinuous mega ripples	Fluviatile	None
Sp Sp 1 Sp 2	Planar cross-stratified sandstone	Clean, coarse-grained, poorly sorted sandstone, woody fragments	Single channels, erosive base	Migration of straight-crested bedforms	Tidally influenced fluviatile	*Ophiomorpha*

	Planar cross-stratified sandstone with occasional mud drapes	Clean fine to medium-grained well-sorted sandstone	Scanty plant fragments and occasional mud drapes	Migration of straight-crested bedforms. Deposits formed in the lower-flow regime and by the migration of mega-ripples. Mud drapes occur during slack water conditions	Foreshore	None
Sh	Horizontal bedding	Moderately to well-sorted clean fine to medium-grained sandstones with pebble layers	Erosional truncations	Lower flow-regime flat-bed produced by decelerating current.	Foreshore	None
Shl	Parallel laminated sandstone	Moderately to well-sorted fine to medium-grained sandstone	Parallel to undulating laminations with erosional truncations	Deposited under upper flow-regime, typical of plane-bed conditions in deltaic settings	Upper shoreface	None
Sr	Rippled laminated sandstone	Clean fine to medium-grained sandstone	Low to moderately bioturbated	Formed by relatively low flow velocity currents (asymmetric) or waves (symmetric)	Upper shoreface	Monospecific *Planolites*
Shc	Hummocky cross-beds	Moderately to well-sorted fine-grained sandstone	Parallel to undulating laminations with erosional truncations	The combined flow of storm wave and storm-induced geostrophic currents	Proximal middle shoreface	Minor churned, *Planolites*?
Sw	Wave ripple lamination	Alternation of sandstone and mudstone	Presence of wave ripple lamination	Oscillatory waves or a combination of oscillatory waves and unidirectional currents	Proximal middle shoreface	Burrows of *Bergaueria* and *Palaeophycus*
Sbs	Bioturbated siltstone and sandstone	Fine-grained sand bodies with silt-sized materials	Burrowing increases downwards within the facies producing a mottled texture to the core and	Soft ground and substrate-controlled. Biogenic reworking in high and medium energy	Distal middle shoreface	*Skolithos* ichnofacies such as *Diplocraterion*, *Ophiomorpha*, *Arenicolites* and *Cruziana*

			obliterating the physical structures	marine environments, sediment fallout.		ichnofacies like *Siphonichnus Planolites, Palaeophycus* are common
Sbf	Bioturbated sandy heterolith	Intercalation of very fine-grained sandstone and mudstone	Intensely bioturbated heterolith	Fluctuation inflow velocity within a fair-weather wave base setting, sediment fallout	Lower shoreface	*Cruziana* ichnofacies such as *Chondrites, Teichichnus, Planolites, Asterosoma and Thalassinoides. Ophiomorpha, and Palaeophycus* occur as opportunistic trace fossils
Fbm	Bioturbated muddy heterolith	Intercalation of mudstone and very fine-grained sandstone	Intensely to moderately bioturbated	Relatively low flow velocity within a fair-weather wave base setting, sediment fallout	Proximal offshore	*Zoophycos* ichnofacies: *Zoophycos, Chondrites, Phycosiphon, Helminthopsis*
Fm	Dark grey mudstone	Dark grey shale with occasional partings of silt	Presence of lenticular partings, slightly fissile and sparsely burrowed	Hemipelagic settling in a low energy setting below storm wave base, sediment fallout	Distal offshore	*Chondrites, Phycosiphon*

The unit is dominated by single to multistorey conglomerate and coarse sandstone. Each sandstone is defined by basal erosion surface over which is accumulated poorly sorted pebbly sandstone. The characteristic features are trough cross-beds (St), with planar cross-beds (Sp1) at certain intervals (Fig. 3 A, B). Fossils include rare scattered wood fragment and isolated *Ophiomorpha* burrow traces.

Interpretation: Strata of FA 1 are interpreted as fluvial channels based on the blocky nature of the GR log motif. The fluvial channels represent deposition in a coastal plain setting landward of the tidal zone, after models of McCabes and Shanley, (1992). The blocky log pattern is common in the incised valley fill of Gironde type described by Allen and Postermentier (1993). The trough cross-strata are formed by the migration of three-dimensional megaripple of sinuous, lunate or crescentic crestline dunes with trough-shaped scour pit. The pebbly sandstone signifies debris flow which suggests bedload transport of granules over a low to moderate slope (Allen, 1985), generally in a channelised flow and it forms the channel lag. The mono-specific trace fossil suite of *Ophiomorpha* burrows is indicative of high energy, shallow marine environment, or estuarine point-bars and tidal channels (Ekdale *et al.*, 1984). The escape burrows of *Ophiomorpha* implied an increase in the rate of sedimentation (Pemberton *et al.*, 1992). Similar features have been described in numerous fluvial models that are summarized by Cant, (1982) and Collinson, (1986).

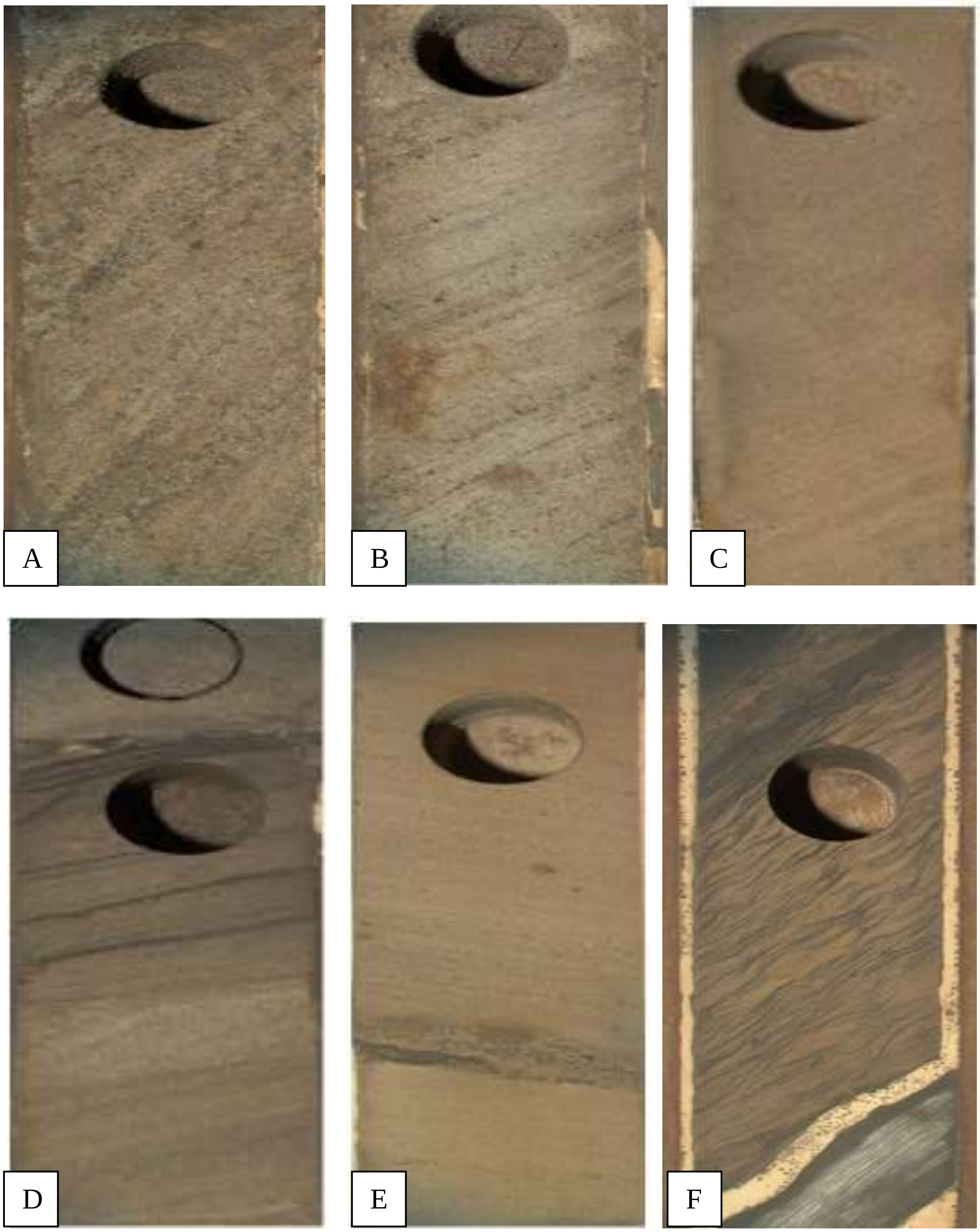

Figure 3 A. Trough cross stratified, coarse-grained sandstone [Depth: 10794ft; with of core 7.8 cm], and B. Planar cross stratified, coarse-grained sandstone, showing alternation of granular and coarse grained foresets [Depth:10771ft]. C. Medium to fine grained planar cross-beds and D. wedge-shaped cross-beds of foreshore deposit. E. Horizontal bedding with pebble layer and isolated pebbles of upper shoreface deposit. F. Wavy flaser bedding of the sandstone/mudstone unit of the middle shoreface [Depth: 11708ft].

FA 2 – Central estuarine

The interval is characterised by poorly developed coarsening and fining upward sandstone that exhibits an overall retrogradational stacking pattern from the wireline log. The GR log pattern of the sandstone/mudstone unit is characteristically serrated with high GR whereas the neutron/density log shows large separation.

The interval is dominated by foraminiferal assemblages that show a radical upward increase in the planktonic population based on the biostratigraphic chart. Bathymetric analysis of the fauna population indicates progressive deepening from middle neritic (MN) to outer neritic (ON).

Interpretation: The sandstone-mudstone unit is interpreted as the central basin based on the signature of the well-logs and biostratigraphic data. Core data was not obtained from this zone because it is dominated by mudstone. The net composition of the sand to shale is about 30% to 70%. This horizon corresponds to the area occupied by the drowned-valley estuary at the end of transgression (Zaitlin, *et al.*, 1994). According to MacEachern and Bann (2008), trace fossil assemblage for central basin reflects a high diversity with intense burrowing.

FA 3 – Foreshore-Shoreface Deposit

This unit consists of an alternation of fine to medium-grained sandstone, heteroliths and mudstone that exhibit a general coarsening and thickening upwards pattern (Fig. 2). It shows a progressive core analysis reveals the presence of well-sorted fine-grained cross-laminated sandstone, small-scale trough cross-bed, wave ripple laminated, bioturbated sandstone and soft-sediment deformation structures (SSDS). Sideritic concretions occur mostly in the laminated mudstone. The trace fossils comprise a diverse open marine trace suite that includes mainly *Cruziana* and *Zoophycos* ichnofacies with less common opportunistic *Skolithos* burrows. Biofacies data indicate a regressive upsection decrease in forams diversity and population. The foreshore-shoreface unit is further discussed below:

Foreshore

The foreshore facies is observed within the depth of 8642ft to 8651ft. The sands are clean, fine to medium-grained, well-sorted with planar cross-stratification (Sp 2) and horizontal bedding (Sh) (Fig. 3C, D). Scanty plant fragments and occasional mud drapes are observed. This zone is interpreted as foreshore, dominated by wave swash. It is also referred to as beachface. No trace fossils were observed.

Upper Shoreface

The upper shoreface covers a depth of 8641ft to 8635.5ft. It is characterized by fine to medium-grained sandstone with two pebbly layers (Fig. 3E). The sand units are parallel laminated (Shl) and rippled (Sr) at the top. The sands are clean, fine to medium-grained. Moderate bioturbation is observed in the ripple laminated unit. Traces of monospecific *Planolites* were preserved as horizontal burrows in the upper shoreface.

Proximal Middle Shoreface

The middle shoreface is subdivided into distal and proximal units. The proximal middle shoreface falls between 08634ft and 08624ft. It is moderately to well sorted with fine-grained sandstone. Parallel to undulating laminations with erosional truncations and few burrows- *Bergaueria* and *Palaeophycus* are observed. Flaser bedding and (see Fig. 3F) wave rippled sandy heterolith (Sw) (Fig. 4A) are common. This facies is characterized by soft-sediment deformation structures (SSDS) such as microscale dish-and-pillar structure and load cast (Fig. 4B).

This facies association is considered to lie within the normal (fair-weather) wave base. The parallel to undulating laminations with erosional truncations are interpreted as hummocky cross-beds (Shc) (Fig. 4C). Within the middle shoreface, the trace fossil assemblage illustrates a clear break in behavioral pattern between the lower shoreface and the upper shoreface (Pemberton et al., 1992).

Distal Middle shoreface

The distal shoreface falls between 08596ft and 08600ft. The sand bodies are fine-grained with silt-sized material. Burrowing increases downwards within the unit producing a mottled texture to the core and obliterating the physical structures (Fig. 4D-F). Distal *Skolithos* ichnofossils such as *Diplocraterion*, *Siphonichnus*, *Ophiomorpha*, *Planolites*, *Palaeophycus* and *Arenicolites* dominates this facies. The burrows are dominantly the dwelling burrows of suspension feeders. This facies association lie within normal (fair-weather) wave base.

Lower Shoreface

The lower shoreface facies is observed within the depth range of 08625ft to 08623ft and 08605ft to 08601ft. It is characterized by rapid deposition of well-sorted very fine-grained sandstone and mudstone. Bioturbation increased upwards in both sandy and muddy substrates (Fig. 4G-H). Physical structures were obliterated by intense bioturbation (B.I. 4-6). The remnant of parallel lamination and wave ripple lamination, as well as sideritic nodules were observed. The heteroliths indicate rapid deposition by storm and fair-weather conditions. The trace fossil assemblage consists of the moderate diversity and population of *Cruziana* ichnofacies such as *Chondrites*, *Teichichnus*, *Planolites*, *Rhizocorallium*, *Asterosoma* and *Thalassinoides and* low diversity and high population of *Zoophycos* ichnofacies, dominated by *Helminthopsis, Neonereites, Phycosiphon*. *Diplocraterion* occurs as opportunistic trace fossils associated with storm sedimentation.

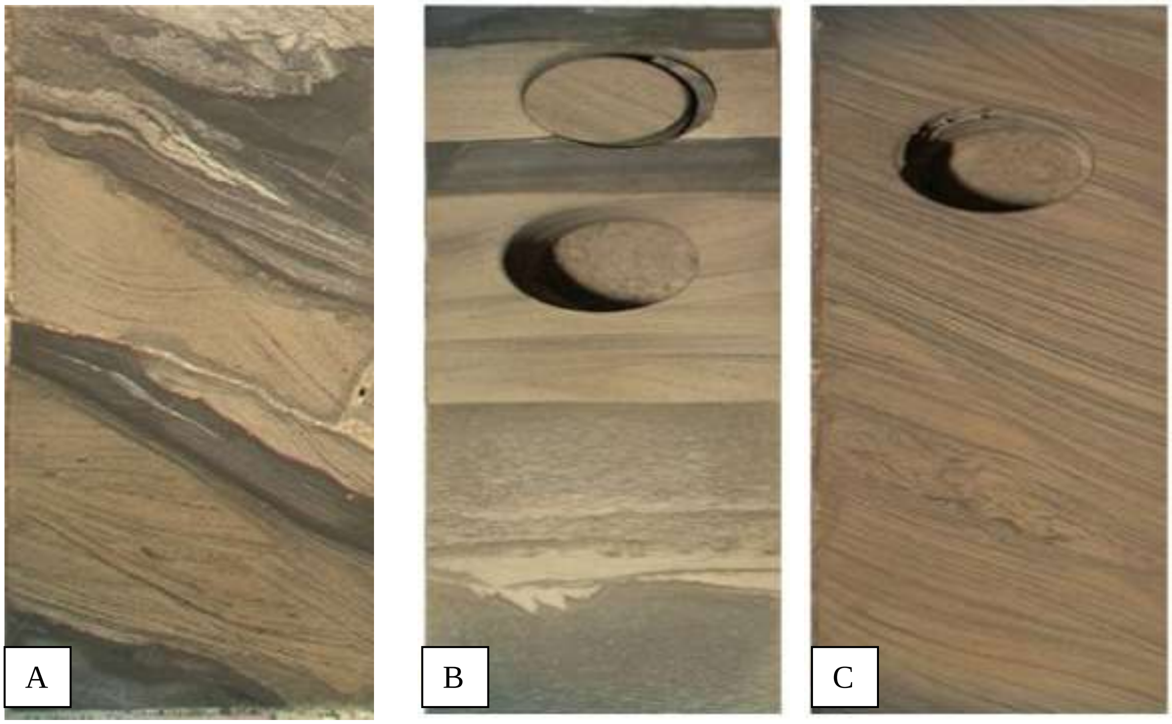

Figure 4 A. Wavy bedded sandy heterolith, showing chevron and bundled upbuilding and unidirectional cross lamination B. Micro-scale dish-and-pillar structure and load structures at the lower part of the core and tempestites (alternating mudstone and hummocky cross-stratified sandstone). C. Hummocky cross-stratified sandstone within the proximal middle shoreface (*Planolites*?).

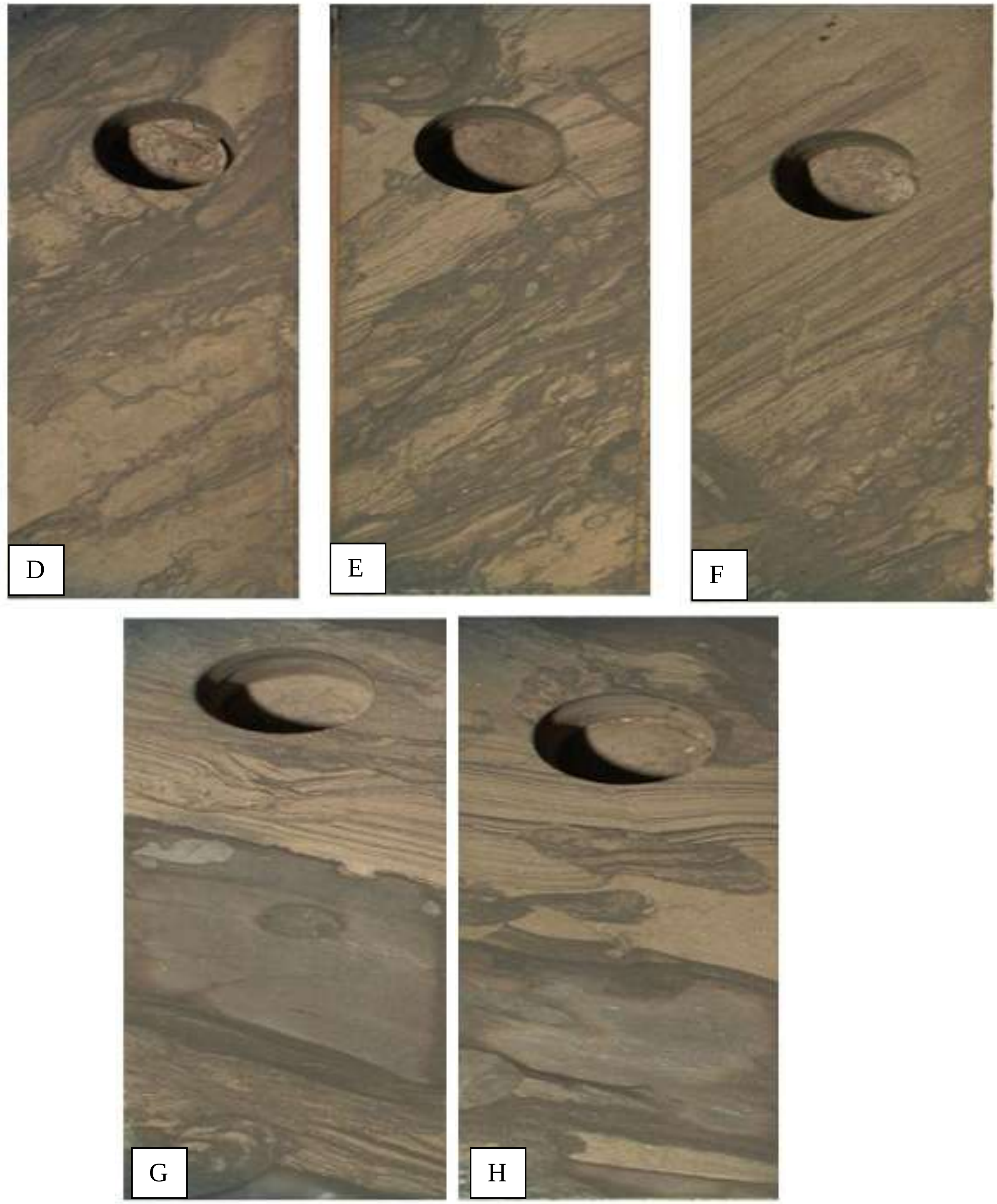

Figure 4D-F. Bioturbated fine grained sandstone, with relics of wavy to parallel lamination of distal middle shoreface. G-H. Lower shoreface. Sharp based burrowed sandstone beds alternate with mudstone (*Asterosoma, Thalassinoides, Rhizocorallium, Bergaueria*).

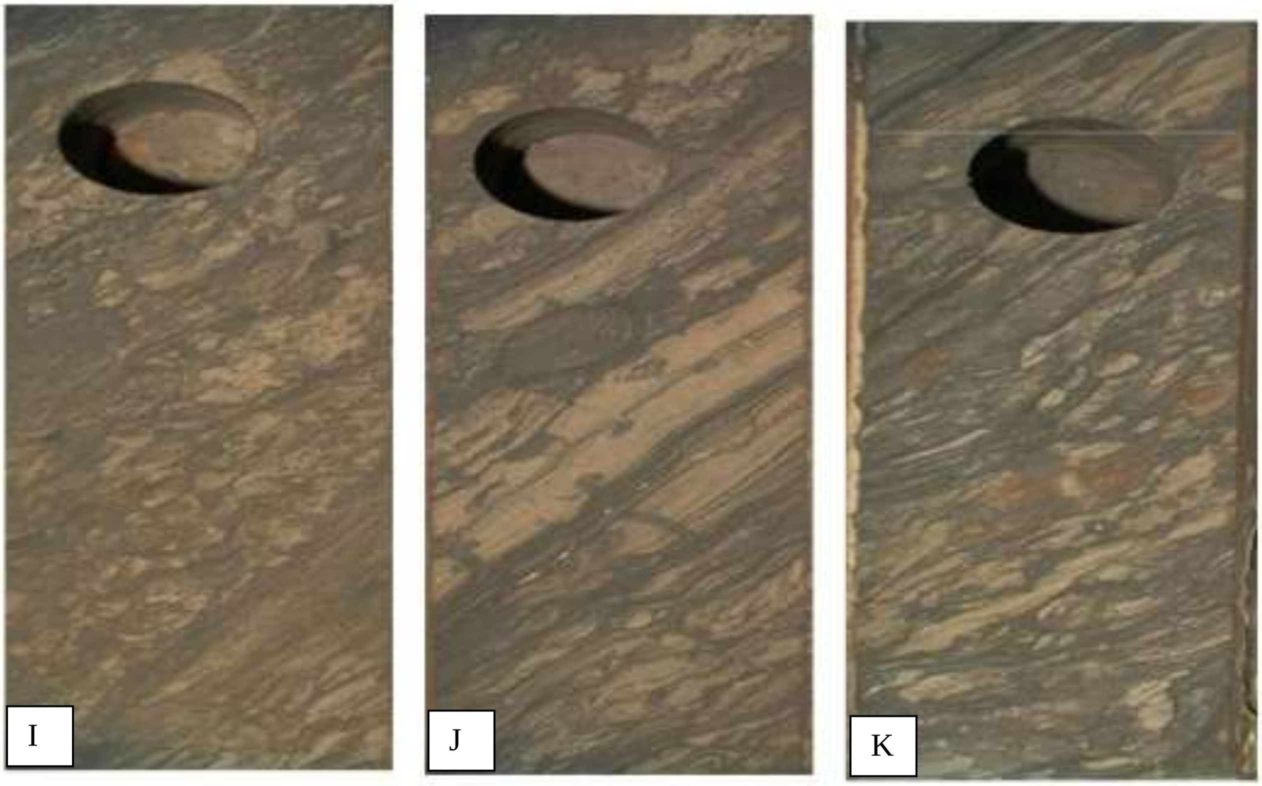

Figure 4. I-K. Rapid alternation of fine grained sandstone and mud laminae. Intensely burrowed with highly populated trace fossils suites of *Cruziana* (*Planolites, Palaeophycus, Chondrites, Teichichnus*) and *Zoophycos* (*Neonereites, Helminthopsis*) ichnofacies and opportunistic *Skolithos* ichnofacies such as *Diplocraterion*.

Offshore Facies

The offshore is further subdivided into distal and proximal offshore facies.

The proximal offshore is observed within the depth range of 08622ft to 08618ft and 08614ft to 08610ft. This unit is characterized by well burrowed, siltstone, very fine-grained sandstone and dark grey mudstone. Sideritic nodules are common. The sedimentary structures are nearly obliterated due to strong bioturbation, with a bioturbation index of 4-6. The FA is dominated by *Zoophycos* ichnofacies such as *Zoophycos, Phycosiphon, Chondrites, Teichichnus*, which are the resident traces and low diversity *Cruziana* ichnofacies such as *Scolicia, Palaeophycus* and *Thalassinoides* fossil assemblages (Fig. 5). The trace fossil assemblages represent horizontal to subhorizontal grazing and feeding traces in a soft substrate. They suggest a slow rate of sedimentation. The traces exhibit a complex shape in response to competition for food.

The distal offshore facies falls within the depth of 08615ft to 08617ft. This facies shows characteristic dark grey shale with occasional partings of silt and lenticular partings which are interpreted as starved wave ripples (Fig. 5). The dominant trace fossil is *Chondrites* which is indicative of an anoxic condition. In the lower horizon, a sideritic, sparsely burrowed, slightly fissile, dark silty shale is identified as a condensed section. This concurs with Pemberton et al. (1992) suggestion for the recognition of a condensed section. They suggested that a condensed section, characterized by the anoxic condition is recognized by the presence of unburrowed or slightly burrowed dark carbonaceous shale lying between more intensely burrowed marine deposits. The stratigraphic units are summarized in table 1.

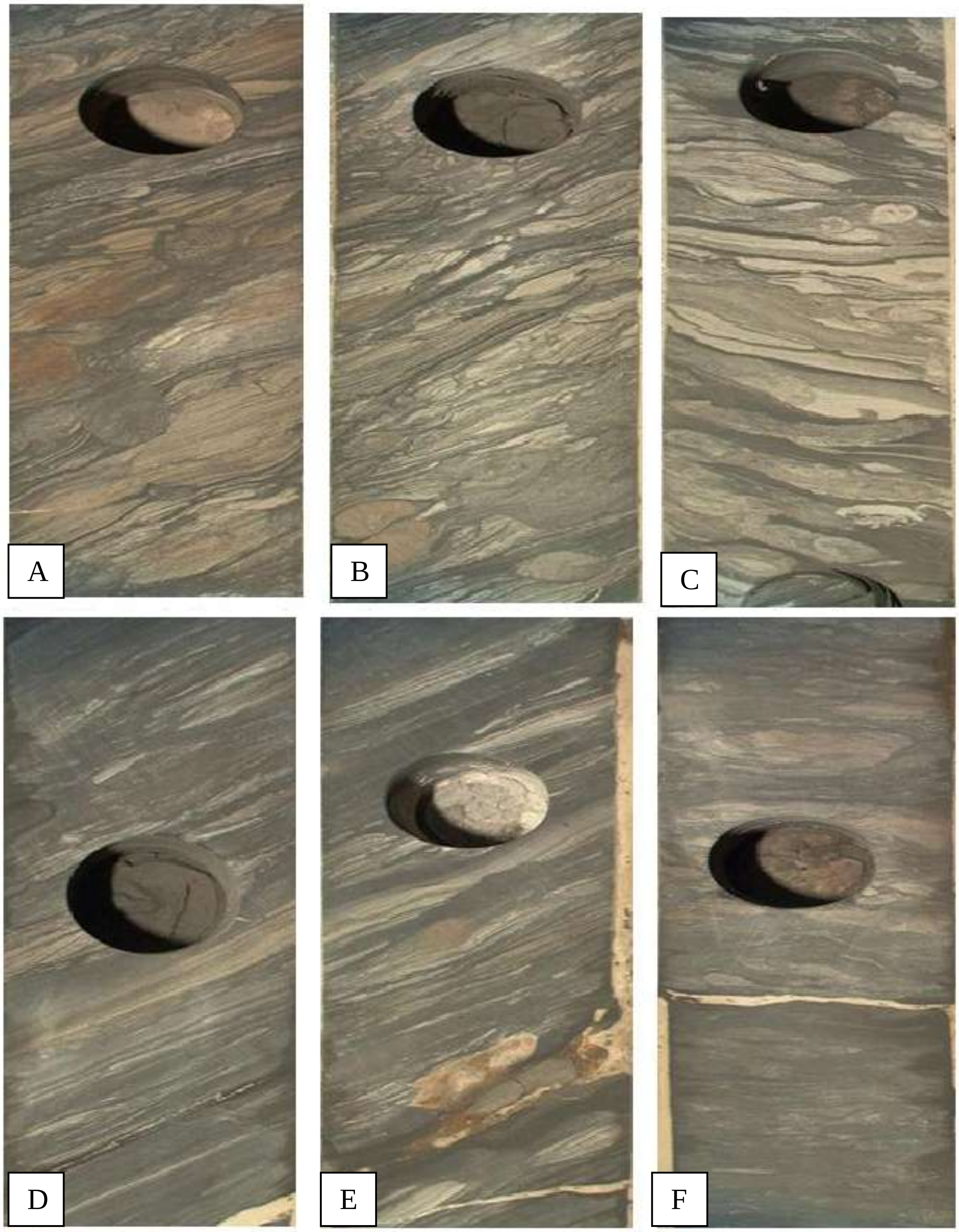

Figure 5: Offshore environment. A-C. Proximal offshore, characterized by bioturbated muddy heteroliths (paper lamination of mudstone, siltstone and very fine grained sandstone) sideritic nodules are observed. Dominated by *Zoophycos* (*Zoophycos*, *Scolicia*, *Phycosiphon*, *Neonereites*) and *Cruziana* (*Chondrites*, *Teichichnus*, *Palaeophycus*) ichnofacies. D-F. Dark grey shale with silty and lenticular partings, and sideritic nodules and bands; typical of distal offshore deposit. Low diversity and population of *Zoophycos* ichnofacies (dominantly *Chondrites* and *Phycosiphon*).

Sequence Stratigraphic Framework

Sequence analysis of the Beta field in the Coastal Swamp II depobelt Niger Delta indicates two incised valley-fill successions (Fig. 6). Each sequence is bounded by an unconformity.

Key Surfaces

Sequence boundary

Two significant basinward facies shift are identified from wireline logs and biostratigraphic data as type-1 sequence boundary which was formed as a result of relative fall of sea-level. In wells BT1 and well BT3, the first sequence boundary, Sb1 is located at 9850ft - 9700ft respectively, where coarse-grained fluvial deposit overlies tidal facies of the coastal plain. Sb1 is not encountered in well BT 2. The second sequence boundary, Sb2 is identified at 8480ft in well BT1 and well BT 2; and at 8325ft in well BT 3 (Fig. 6).

In well BT 1, the unconformity occurs where coarse-grained fluvial deposit overlies tidal heteroliths. In wells BT 2 and BT 3, the unconformity is marked by the juxtaposition of tidally influenced fluvial deposit over shoreface facies. Sb1 is dated 10.6 Ma on the Niger Delta chronostratigraphic chart (modified after Haq et al, 1988), while Sb2 is dated 10.35 Ma.

Maximum flooding surfaces:

This surface is marked by a maximum abundance in the population and diversity of foraminifera. In this study, two maximum flooding surfaces were identified from wireline logs (Fig. 6). The lowermost MFS occurs in wells BT -1, -2, and -3 at depths of 6700ft, 6800ft and 7070ft respectively. The surface is dated 10.4 Ma on the Haq et al's (1988) global cycle chart. The second MFS is located in wells BT -1, -2, and -3 at 8700ft, 8650ft and 8550ft respectively. The surface is dated 9.5 Ma on the global cycle chart (Haq et al's 1988).

Depositional System Tracts

Two transgressive systems tracts and two high systems tracts were recognised from the studied wells.

Transgressive systems tracts: Incised valleys occurred on the shelf during lowstand periods when there was a fall in sea level. The incised valley fills which are aggradational deposit of the transgressive systems tract (TST) were deposited during intervals characterised by subsequent slow relative sea rise.

Two transgressive systems tracts were identified within each wireline log (TST_1 and TST_2). Each overlies a type-1 sequence boundary. The aggradational deposit of the TST_1 occurs between 9880-9450ft; and 9700-9340ft in wells BT -01, and -03 giving an average thickness of approximately 400ft. The aggradational deposit of the TST_2 occurs between 8500-8100ft; 8510-8400ft and 9700-9350ft in wells BT -01, -02, and -03 respectively with a maximum thickness of approximately 400 ft. As the sea rises, back-stepping parasequences exhibiting upward fining sand/mud packages dominates the TST. The foraminifera assemblages become progressively of deeper water and more abundant toward the top of the systems tract and finally capped by the maximum flooding surface (MFS). This MFS marks the boundary between the transgressive systems tracts and the highstand systems tracts. The conglomerate and channelized sand and mud units characterize this systems tract.

Highstand systems tracts: Three highstand systems tracts are recognized in the wireline logs. The base of this systems tract is characterized by a condensed section which occurs as high gamma-ray/low resistivity in well-logs. The condensed section is also reflected by a maximum abundance peak of planktonic and benthonic microfossils. This enabled precise dating of the maximum flooding surface (i.e. the base of the HST). According to Allen and Posamentier (1993), a halt in relative sea-level rise led to a halt in the addition of new accommodation space. This led to a turn-around from transgression to regression in the incised valley as a prograding wedge or bayhead delta (consisting of prograding shoreface, tidal sand bars, tidal flats and upper sand bars, tidal flats and upper estuarine point bars) prograded into the head of the estuary.

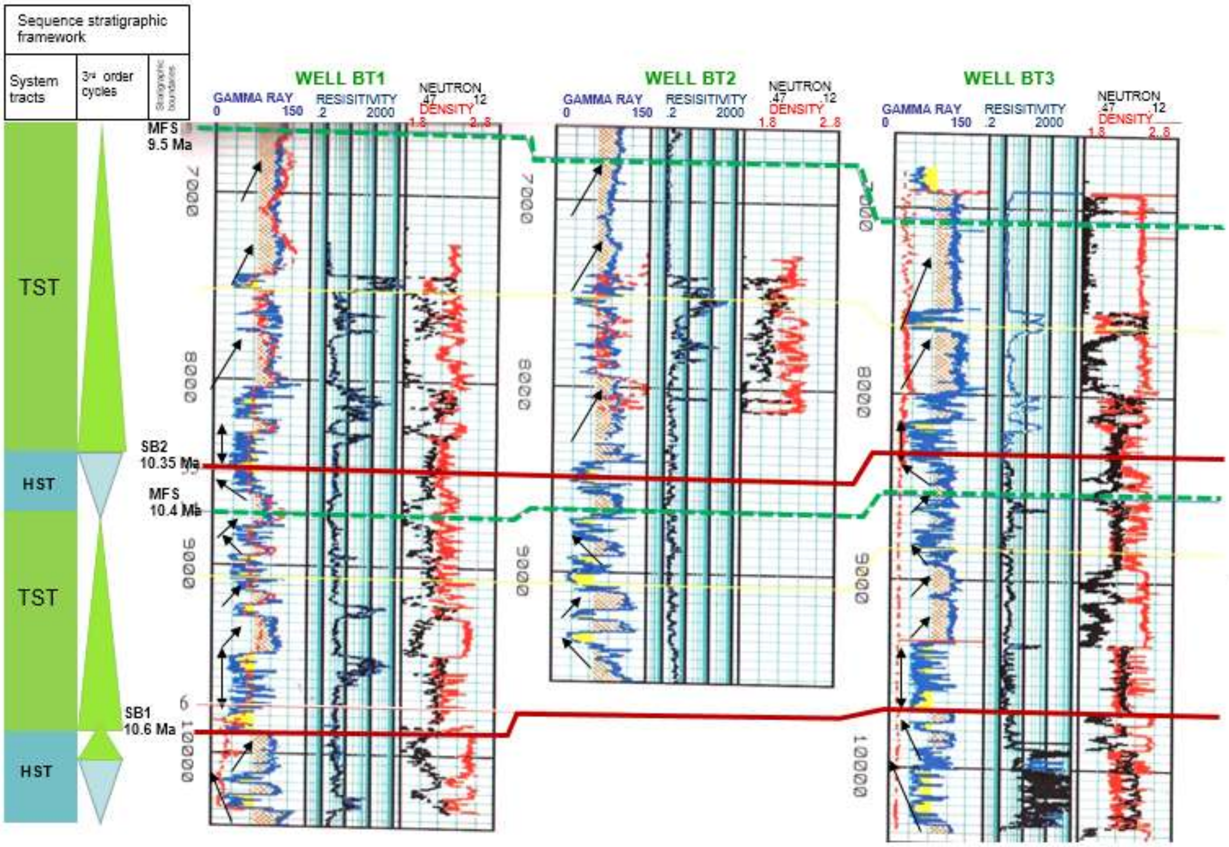

Figure 6: Wireline log correlation chart showing the sequence stratigraphic framework of the 'Beta' field in the Coastal Swamp Depobelt.

Conceptual Depositional Model

The deltaic succession penetrated in the study area comprises two 4th-order (Vail *et al*, 1990) sedimentary cycles that accumulated between 10.6 Ma and 10.35 Ma. Each cycle begins on a type-1 sequence boundary and contains the three-part vertical succession of facies that typifies an incised valley fill. From base upward these are:

(1) a basal fluviatile coarse sand and gravel that accumulated directly over the erosional sequence boundary and which progressively reflects more marine influence up the section;

(2) a central muddy interval comprising tidal sands and muds, formed in estuary-point bars, tidal bars/ tidal flats and estuary mouth, and

(3) cross-stratified sandstone and mudstone formed as shoreface sands, tidal sandbars, tidal flats and upper estuary point bars, representing the progradational filling of the bay-head of the estuary.

The following sequence of events is proposed for the development of each of the estuarine cycles in the study area:

Stage 1. *Valley incision and marine transgression:* Valley incision started (e.g. at 10.6 Ma, and 10.35 Ma respectively) as a result of relative fall in sea level consequent upon basin subsidence. Coarse fluvial sediments bypassed the incised valley and accumulated at the lowstand shoreline located at the continental shelf. The presence of the overlying tidal-estuarine facies implies that the valley was rapidly flooded by marine waters and that the rate of increase in accommodation space was greater than the

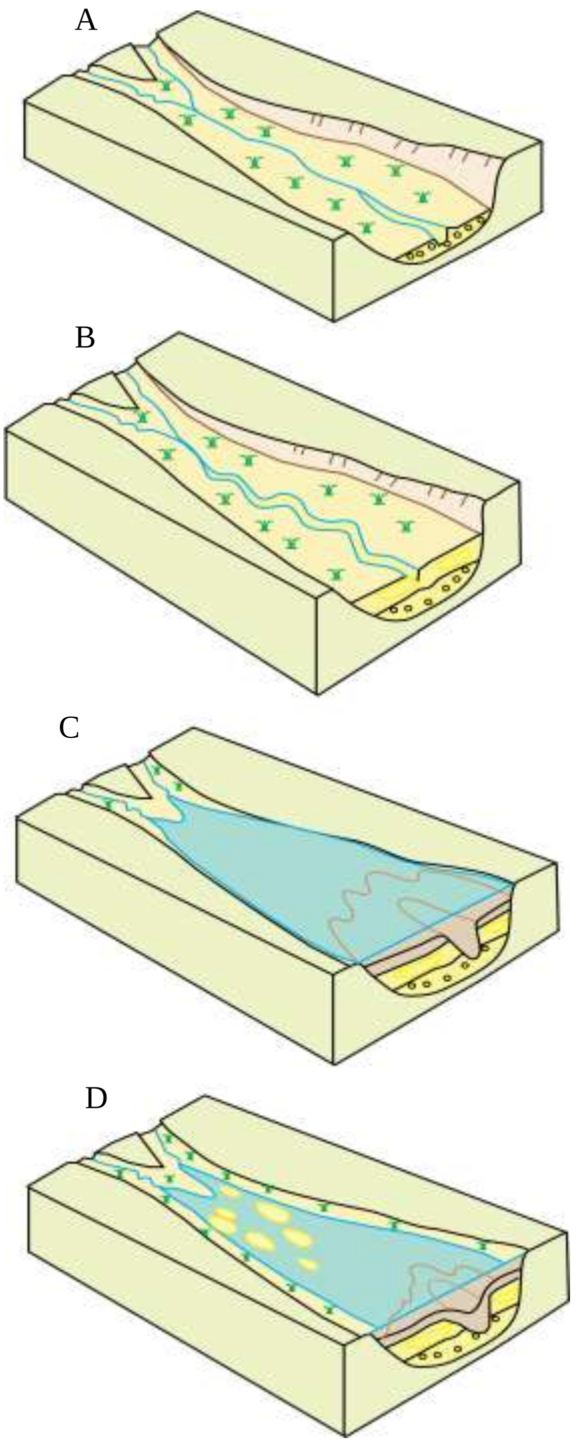

Figure 7. Depositional model of the incised valley fill displaying the sequence stratigraphic framework of the 'Beta' field, Coastal Swamp Depobelt (redrawn and modified after Plink-Björklund, 2005).

A. Valley incision:
Coarse fluvial sediment bypassed the incised valley on route to the lowstand shoreline at the continental shelf.

B. Marine transgression:
Incised valley was transgressed, became an estuary, with estuarine coastal plain deposits onlapping on to the alluvial plain as the bay line migrated up the valley.

C. Maximum marine flooding:
Estuary mouth sands in the form of the tidal inlet and flood-tidal delta complex migrate up the estuary.

D. Bayhead filling:
During the high-stand of relative sea level and progradation of a regressive tidal-estuarine bay head delta into the upper estuarine, the basin is gradually filled with sediments.

fluvial clastic influx. Consequently, these facies onlap on the lowstand fluvial profile as the valley transformed from a fluvial valley into an estuary (Fig. 7A).

Stage 2. *Maximum marine flooding:* As the valley became flooded to its maximum point (e.g., at 10.4 Ma, and 9.5 Ma respectively), the estuary-mouth sands in the form of a tidal inlet and flood-tidal delta complex migrated up the estuary (Fig. 7B; Fig. 7C). The base of the tidal inlet eroded deeply into the underlying tidal-estuarine sands and muds and formed a tidal ravinement surface. As the valley flooded, the adjacent open coast retreated landward because of drowning and wave-induced erosional shoreface retreat, forming a wave-ravinement surface.

Stage 3. *Bay-head filling*: Infilling of the estuary started with fluvially scoured tidal-estuarine sand and mud, and a regressive bay-head prograded into the upper estuary, gradually filling it with sediment. These deposits prograded over the transgressive tidal estuarine sands and muds in the upper and middle estuary, and the estuary-mouth sands inn the lower estuary (Fig. 7 D) Another episode of basin subsidence and relative sea-level fall abruptly terminated the cycle at the sequence boundary.

CONCLUSION

The integration of wireline logs, core and high-resolution biostratigraphic data was used in the identification of a three-part vertical succession of facies in the studied field, which typifies an incised valley fill and two 4th-order sedimentary cycles.

The sedimentary succession includes:

A basal conglomerate unit, comprising fluviatile coarse sand and gravel formed as a result of valley incision and subsequent marine flooding.

A central channelized sandstone and mudstone unit consisting of tidal sands and muds, which accumulated during major marine flooding, and

the topmost cross-laminated sandstone unit which represents the progradational filling of the bayhead of an estuary.

This succession forms a complete sedimentary cycle that began during falls in relative sea level which initiated the type-1 sequence boundaries at 10.6 Ma and 10.35 Ma. The fluvial channel deposits (aggradational deposit of TST), the tidal sand bars (TST) of the channelized sandstone unit and shoreface sands and tidal sand bars (HST) of the cross-laminated sandstone unit are good reservoirs in the ‘Beta’ field. The mudstone units may act as source and seal rocks.

In conclusion, this incised valley-fill reflects a coastal plain setting affected by fluvial, tides and marine systems and all these typify a coastal swamp depocentre.

REFERENCES

Allen JRL (1985). Principles of physical sedimentology. George Allen & Unwin publication limited, 272 p.

Allen GP and Posamentier HW (1993). Sequence stratigraphy and facies model of an incised valley fill: the Gironde estuary, France. *Journal of Sedimentary Petrology* **63** 378-391.

Cant DJ (1982). Fluvial facies models. In: *Sandstone depositional environment*, edited by Scholle PA and Spearing D (American Association Petroleum Geologists), 115-138.

Collinson J D (1986). Alluvial sediments. In: *Sedimentary environments and facies*, 2nd ed., edited by Reading HG (Oxford Blackwell Scientific Publication), 20-62.

Doust H and Omatsola EM (1990). Niger Delta. In: *Divergent/passive margin basins*, Memoir 45, edited by Edwards JD and Santogrossi PA (American Association Petroleum Geologists, Tulsa Oklahoma), 201-238.

Ekdale AA, Bromley RG and Pemberton SG (1984). Ichnology: Trace fossil in sedimentology and Stratigraphy. *SEPM Short Course* **15** 54 - 60.

Evamy DD, Haremboure J, Kamerling P, Knaap WA, Molloy FA, and Rowlands PH (1978). Hydrocarbon habitat of Tertiary Niger Delta. *American Association Petroleum Geologists Bulletin* **62** (1)

39.

Haq BU, Hardenbol J and Vail PR (1988). Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In *Sea-level changes: an integrated approach*, Vol 42, edited by Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, and Van Wagoner JC (SEPM Special Publication), 71-108.

Kamola DL (1984). Trace fossils from the marginal-marine facies of the Spring Canyon Member, Blackhawk Formation (Upper Cretaceous), east-central Utah. *Journal of Paleontology* **58** 529 -541.

Kreisa RD (1981). Storm-generated sedimentary structures in subtidal marine facies with examples from the Middle and Upper Ordovician of southwestern Virginia. *Journal of Sedimentary Petrology* **51** 823 848.

Krystinik LF and Blakeney-DeJarnett BA (1997). Developing a compound Morrow valley fill Reservoir heterogeneity and implications for reservoir management and field expansion, State Line trend, Colorado/Kansas. Notes Core Conference, *Canadian Society of Petroleum Geologists–Society of Economic Paleontologists and Mineralogists Joint Convention*, Calgary, 201–222.

Leetaru HE (2000). Sequence Stratigraphy of the Aux Vases Sandstone: A major oil producer in the Illinois Basin. *American Association Petroleum Geologists Bulletin* **84** 399-422.

MacEachern JA and Bann KL (2008). The role of ichnology in refining shallow marine facies models; Recent advances in models of siliciclastic shallow-marine stratigraphy. Special Publication, *Society for Sedimentary Geology* **90** 73–116.

McCabe PJ and Shanley KW (1992). An organic control on shoreface stacking patterns-bogged down in the mire. *Geology* **20** 741-744.

McCubbin DR (1982). Barrier-island and strand-plain facies. In: *Sandstone Depositional Environment* edited by Scholle PA and Spearing D (American Association Petroleum Geologists Memoir) 247-279.

Miall AD (1991). Stratigraphic sequences and their chronostratigraphic correlation. *Journal of Sedimentary Petrology* **61** 497-505.

Mitchum RMJr, Sangree JB, Vail PR and Wornardt WW (1993). Recognizing sequence and systems tracts from well logs, seismic data and biostratigraphy: Examples from the Late Cenozoic of the Gulf of Mexico. In: *Siliciclastic sequence stratigraphy: Recent development and applications*, Memoir 58, edited by Weimer, P and H.W. Posamentier, (American Association Petroleum Geologists) 163-197.

Obi GC (2000). Depositional model for the Companian-Maastrichtian Anambra Basin, Southern Nigeria. Ph.D. Thesis, University of Nigeria, Nsukka, Nigeria. 291p.

Pattison SAJ (1995). Sequence stratigraphic significance of sharp-based lowstand shoreface deposits, Kenilworth Member, Book Cliffs, Utah. *American Association Petroleum Geologists Bulletin* **79** 444-462.

Pemberton GS, MacEachern JA, and Frey RW (1992). Trace fossil models: Environmental and allostratigraphic significance. In: *Facies models: response to sea-level chang*e, edited by Walker RG and James NP (Geological Association of Canada) 195-218.

Plink-Björklund P (2005). Stacked fluvial and tide-dominated estuarine deposits in high frequency (fourth-order) sequences of the Eocene Central Basin, Spitsbergen. *Sedimentology* **52** 391–428.

Posamentier HW, Jervcy MT and Vail PR (1988). Eustatic controls on clastic deposition I- conceptual framework. In: *Sea-level changes: an integrated approach*, Vol 42, edited by Wilgus CK, Hastings BS, Kendall CGStC, Posamentier HW, Ross CA, and Van Wagoner JC (SEPM Special Publication) 109-124.

Reading HG (1986). Sedimentary Environments and Facies. Blackwell Science Publication, 569pp.

Reineck HE and Singh IB (1980). Depositional sedimentary environments, 2nd ed. New York, Springer-Verlag, 521.

Reineck HE and Wunderlich F (1968). Classification and origin of flaser and lenticular bedding.

Sedimentology **11** 99-104.

Short KC and Stauble AJ (1967). Outline of geology of Niger Delta. *American Association Petroleum Geologists Bulletin* **51** 761-779.

Smith GJ and Jacobi RD (2001). Tectonic and eustatic signals in the sequence stratigraphy of the Upper Devonian Canadaway Group, New York State. *American Association Petroleum Geologists Bulletin* **85** 310-325.

Vail PR, Audemard F, Bowman SA, Eisner PN, and Perez-Cruz G (1990). The stratigraphic signatures of tectonics, eustasy and sedimentation – an overview. In: *Cyclic stratigraphy*, edited by Einsele G, Ricken W and Seilacher A (Springer-Verlag, New York) 617-659.

Van Wagoner JC, Posamentier HW, Mitchum RM, Vail PR, Sarg JF, Loutit TS, and Hardenbol J (1988). An overview of the fundamentals of sequence stratigraphy and key definitions: In sea level change - an integrated approach. *SEPM Special Publication* **42** 39-45.

Van Wagoner JC, Mitchum RMJr, Campion KM and Rahmanian VD (1990). Siliciclastic sequence stratigraphy in well logs, cores and outcrops-Concepts for high – resolution correlation of time facies. *American Association Petroleum Geologists Methods in Exploration Series* **7** 55p.

Visser MJ, (1980). Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits- A preliminary note. *Geology* **8** 543-546.

Walker RG and James NP (1992). Facies Model: response to sea-level change: Geoscience Canada.

Weber KJ and Daukoru E (1975). Petroleum geology of the Niger Delta: *9th World Petroleum Congress Proceedings* **2** 209-221.

Weimer P and Posamentier HW (1993). Recent developments and applications in siliciclastic sequence Stratigraphy. In: *Siliciclastic Sequence Stratigraphy - Recent Developments and Applications*, Memoir 58, edited by Weimer P and Posamentier HW (American Association of Petroleum Geologists) 3-12.

Williams H, Berge C, Hartung M, de Rurter R and Ugueto CA (1997). Prediction of Nigerian reservoir sands through integration of seismic imaging and sequence stratigraphy *EPNL Special Issue*.

Zaitlin BA, Dalrymple RW and Boyd R (1994). The stratigraphic organization of incised valley systems associated with relative sea-level change. In: *Incised-valley systems: origin and sedimentary sequences*, Vol 51, edited by Dalrymple RW and Zaitlin BA (SEPM special Publication) 45-60.