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Facies Architecture and Depositional Environments of Reservoir Sands in 'X' Field, Eastern Niger Delta, Nigeria

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ABSTRACT

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Keywords

Facies Architecture, Depositional Environment, Reservoir, Wireline Log, Electrosequence, Correlation, Systems Tract. The facies architecture and depositional environments of the 'X' Field reservoirs have been studied in Wells NDI-A10, A12, A11, A7, A2P2 and A2, using wireline log data. The logs were examined and analyzed for reservoir identification, thickness distribution, continuity, and connectivity. The depositional environments were determined by closely comparing the log shapes of interest with the standard log motifs of Schlumberger (1985) and Emery (1999). Three deltaic sub-environments of deposition were recognized: beach-barrier, river mouth bar and shoreface. The sequence stratigraphic concept has been applied to these subenvironments. Six reservoirs: I, J, K, L, M and N, and five stratigraphic sequences: SEQ.I, SEQ.II, SEQ.IV and SEQ.V, were identified. The reservoirs were deposited as progradational parasequences during a high-frequency highstand systems tract, while the shale units underlying and overlying the reservoirs were deposited as retrogradational parasequences. The consistent alternation of progradational sand units and retrogradational shale units have been interpreted as a tripartite union of source rock, reservoir and seal, essential for hydrocarbon generation, accumulation, and trapping in the 'X' Field. Well-towell correlation across the entire field allowed a reconstruction of the depositional history of the reservoirs and delineation of the reservoir geometry. There was more development of the reservoirs in the northeastern part of the field which has been interpreted as the direction of sediment supply, but the overall depositional trend is similar to that of the present-day Niger Delta.

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Introduction

A reservoir rock is a subsurface body of rock which has significant porosity and permeability to store and transmit fluids (oil, gas or water). Porosity is a measure of the amount of pore space in a given rock volume; while permeability is the ability of rock or sediment to transmit fluids. The two main types of reservoir rocks are: carbonate reservoir rocks and siliciclastic reservoir rocks (sandstones and conglomerates). According to Weber and Daukoru (1975), the reservoir rocks in Niger Delta are mainly sandstones.

A rock facies is defined as a body of rock with specified set of features that characterize it. These features include geometry (bed thickness and shape), colour, mineral composition, texture (grain size, shape and sorting), sedimentary structures and fossil content. In other words, a rock facies is a distinctive rock that formed under certain conditions of sedimentation, reflecting a particular process, set of conditions, or environment. Sandstones occur in different sedimentary environments and such variations in sedimentary environments are attributed to variations in energy levels, flow velocity, and climate which ultimately result in differences in qualities of reservoir sandstones as well as their production performance.

Determination of facies architecture and depositional environments are of great importance in exploration for and development of clastic reservoir systems. The depositional processes associated with clastic sedimentary environments impart variation and heterogeneity which strongly influence reservoir distribution, continuity and connectivity as well as the vertical and horizontal arrangement of reservoir and nonreservoirs facies and lithotypes, which control fluid flow and production performance. Wireline logs provide a strong

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mechanism for interpretation and determination of depositional environments, reservoir facies architecture and identification of reservoir units (Galloway and Hobday, 1983). This is essential for subsequent drilling and field development.

Facies architecture refers here to the stacking pattern of a vertical succession of rock sequences, which can be progradational, retrogradational or aggradational stacking patterns.

A depositional sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities (Mitchum et al., 1991). It is the product of a cycle of rise and fall of relative sea level. On wireline logs, they are referred to as 'electrosequences' - an interval defined on wireline logs, through which there are consistent or consistently changing log responses and characteristics, sufficiently distinctive to separate it from other electrosequences.

Objectives

i) To identify the reservoir sand facies.

ii) Attempt a correlation of the reservoir sand facies and determine their thicknesses, continuity and connectivity.

iii) Identify the stratigraphic sequences and stacking patterns of the reservoir sand bodies across the field.

iv) Determine the depositional environments of the reservoir sand units.

v) Develop a depositional model for the 'X' Field reservoirs.

Significance of the Study

The exploration and development of a reservoir requires reasonable understanding of its occurrence and morphology. This study provides knowledge of the nature of the depositional environments and stacking patterns of hydrocarbon reservoirs in



the 'X' Field, so as to enable predictions to be made concerning the likely geometry and connectedness of the reservoir units and thus, their production behavior. Initially, the wells were producing at maximum capacity, but the productivity declined with down-hole water cut after sometime. This necessitated this research.

Study Location

The 'X' Field under study is located within the shallow offshore depobelt of the south-eastern Niger Delta Basin, where thick Late Cenozoic Clastic sequence of the Agbada Formation were deposited in a deltaic fluvio-marine environment (Figure 1a). Geographically, the Field lies between latitude 6°24'00'' and 6°40'00''N and longitude 65°80'00'' and 66°30'00''E within the Niger Delta basin. Wells NDI-A10, NDI-A11, NDI-A12, NDI-A2P2, NDI-A7 and NDI-A2 are located within the 'X' Field as indicated on the base map (Figure 1b).



Figure 1. (A) Geological Map of Niger Delta and (B) Base Map of Study Area Showing Distribution of 'Wells' Sedimentology and Stratigraphy Of Niger Delta

The lithostratigraphic build-up of the Niger Delta basin was accompanied by syn-sedimentary tectonics normal to the progradation, resulting in a series of parallel, fault-bounded depobelts, which become progressively younger from north to south as the delta progrades southward (Stacher, 1995). Integrated geological studies have shown that about six depobelts are present in the Niger Delta Basin. These depobelts are: Northern Depobelt, Greater Ughelli, Central Swamp, Coastal Swamp, Shallow Offshore (Continental Shelf) and Deep Offshore (Figure 2). According to Short and Stauble (1967), Frankl and Cordry (1967), and Avbovbo (1978), the Lithostrigraphy of Niger Delta basin is represented by three (3) major diachronous formations ranging in age from Paleocene to Recent and comprising from base to top - the Akata, Agbada and Benin Formations; and were laid down under marine, transitional (paralic) and continental environments respectively (Figure 3).



Figure 2. Niger Delta Depobelts (Reijers, 1997)



Figure 3. Stratigraphic column showing the three Formations of the Niger Delta:the Marine Akata Shale, the Paralic Agbada Formation and the Continental Benin Sandstone (From Doust and Omatsola, 1990)

Akata Formation

Akata Formation (the lowermost lithological unit of the Niger Delta complex) consists of marine shales (potential source rock), turbidites (potential reservoir in deep water), and clay and silt intercalations in places (Short and Stauble, 1967). This lithostratigraphic unit is thought of as the Prodelta megafacies of the Niger Delta complex, formed during lowstand when terrestrial organic matters and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency (Stacher, 1995).

The Akata Formation ranges in thickness from 2000 m (6600 ft) at the most distal part of the delta to 7000 m (23,000 ft.) thick beneath the continental shelf (Doust and Omatsola, 1990). The Akata Shale is under-compacted and over-pressured (Merki, 1972) and according to Beka and Oti (1995), turbidite currents likely deposited the turbidite sands within the upper Akata Formation of the Niger Delta. Petroleum Geologists in the area believe the Formation is the main source rock in Niger Delta and it is a lateral equivalent of the Imo Shale. The age of the Akata Formation ranges from Paleocene – Recent and grades imperceptibly upwards into the Agbada Formation.

Agbada FORMATION

The Agbada Formation (Short and Stauble, 1967; Frankl and Cordry, 1967) overlies the Akata Formation and underlies the Benin formation and forms the second of the three strongly diachronous Niger Delta complex formations. It consists of alternating sandstones and shales, representing deposits of the delta front megafacies, in which hydrocarbons are trapped in rollover anticlines against growth faults. The interbeded shales are thought of as source rocks for some of the petroleum pools and fields in these areas (Evamy et al, 1978).

The Agbada Formation is more than 3500 m (11,500 ft.) thi ck and represents the actual deltaic portion of the sequence. This clastic sequence was accumulated in delta-front, delta-topset, an d fluvio-deltaic environments (Corredor et al, 2005). About 99% of the sandstone reservoirs in the Niger Delta occur within this succession. The Agbada Formation varies in thickness from 9.600–14,000 ft in the central part of the delta, thinning seaward and towards the delta margin (Weber and Daukoru 1975). The Agbada Formation ranges in age from Eocene to Recent and grades upwards into the Benin Formation. Surface outcrops of equivalent strata along the delta margin are assigned to the

Ogwashi-Asaba and Ameki Formations (Short and Stauble, 1967).

Benin Formation

The Benin Formation is the uppermost unit in the Niger Delta and comprises a succession of massive poorly indurated sandstones, thin shales, coal beds and conglomerates of continental to upper delta plain origin. The Benin Formation is up to 2000 m thick in the central onshore part of the delta and thins towards the delta margins. The deposition is thought to have taken place on the Delta Plain mega environment. However, Allen (1965) and Oemkens (1974) demonstrated that the Late Quaternary post-glacial transgressive deposits occur locally within the upper 0-30m of the Benin Formation in lower delta plains of the study area.

According to Omatsola and Cordry (1976), an unpublished report, a relatively thick clay unit informally referred to as the 'Afam Clay Member' and thought of as a submarine canyon fill; occur within the basal portion of the Benin Formation in places. Thus, the Benin formation is essentially fluvial in origin and comprises unconsolidated, massive, and porous freshwaterbearing sands with localized shale interbeds. All the Aquifers in the Niger Delta region are located within this lithounit, which ranges in age from Miocene to Recent.

These three lithostratigraphic units have been established in both the Onshore and Continental Shelf terrains as the main Petroliferous Units in Niger Delta of Nigeria.

Unlike the Onshore, Niger Delta Continental Shelf is characterized with shale diapirs and growth faults. The shale diapirs have not been found in the Onshore Niger Delta to date. Growth Faults and associated Rollover Anticlines are the main structural trapping mechanism for petroleum in the Niger Delta. The geological age of the Niger Delta ranges from Paleocene to Recent.

Structural Features

The Cenozoic Niger Delta complex is little disturbed at the surface, but the subsurface is affected by large scale synsedimentary features such as growth faults, rollover anticlines, collapsed crest structures and diapirs (Evamy et al, 1978; Etu-Efeotor, 1997).

Growth triggered penecontemporaneous fault by deformation of deltaic sediments are the common structures in the Niger Delta, (Merki, 1972; Evamy et al, 1978). They are generated by rapid sedimentation and gravitational instability during the accumulation of the Agbada deposits and continental Benin sands over the mobile under-compacted Akata prodelta shale. Lateral flowage and extrusion of the Akata prodelta shale during growth faulting also account for the diapiric structure on the continental slope of the Niger Delta in front of the advancing depocentre of paralic sediments (Selley, 1997). Weber and Daukoru (1975) recognized four main types of oil field structures in the Niger Delta: (a) simple rollover structure (b) structure with multiple growth fault (c) structure with antithetic fault (d) collapsed crest structure. These structural features are shown in Figure 4.

Materials and Method

The various materials used in this research include: wireline logs (gamma ray, resistivity, neutron, sonic, density and spontaneous potential logs), base map showing Well location (Figure 1) and the Well header information. These materials were provided by Moni Pulo Nigeria Limited, Port Harcourt, for the purpose of this research; to have a general understanding of the reservoir sand bodies in the 'X' Field.



Figure 4. Niger Delta Oil Field Structures and associated Trap types. From Doust and Omatsola (1990) and Stacher (1995)

Gamma ray log is best used for facies delineation because its curve gives greater variety of shapes, show greater definition and has more 'character' than other logs (Serra and Sulpice, 1975). Gamma ray logs are often complemented by resistivity logs. Thus, only gamma ray and resistivity logs were used in this research.

The wireline logs were first subjected to qualitative analysis and later followed by quantitative analysis.

The qualitative interpretation involved visual analysis of the log shapes and trends for the interpretation of lithology, identification reservoir tops and bases, correlation of the reservoir facies, delineation of reservoir facies architecture and geometry, and inferring environments of deposition from the log shapes using standard log motifs of Schlumberger (1985) and Emery (1996).

Quantitative analysis on the other hand, involved only the estimation of reservoir thickness for the production of isopach map (thickness map) for each reservoir sand body.

Log Shapes

Shapes of gamma ray logs can be interpreted as grain-size trends and by sedimentological association as cycles. A decrease in gamma ray value will indicate an increase in grain size (Figures 5a&b). Small grain size will correspond to higher gamma ray values. The sedimentological implication of this relationship, leads to a direct correlation between facies and log shapes (Rider, 1990; Serra, 1989).

A Bell Shaped Curve with gamma ray value increasing regularly upwards shows an increase in clay content (dirtying upward). This corresponds to a decrease in sand content and grain size. This trend usually implies a decrease in depositional energy. In a non-marine setting, fining upward is predominant within meandering or tidal channel deposits with an upward decrease in fluid velocity within the channel (coarser sediments at the base of channel); and also occur in transgressive shelf sands. In a shallow- marine setting, this trend usually reflects an upward deepening and a decrease in depositional energy (shoreline retreat). In deep-marine settings, the trend reflects waning of submarine fans (i.e reduction of sand contents).

A Funnel Shaped Curve with an abrupt upper and gradational lower contact indicates a coarsening upward trend. This is typical if beach sands, barrier bar sands, and stream mouth bars, which characterizes shoreline deposits and deltaic environments. In shallow-marine settings, this trend reflects a change from shale-rich into sand-rich lithology and upward increase in depositional energy. In deep-marine settings, the

trend reflects an increase in the sand contents of turbidite sand bodies. This trend also may indicate gradual change from clastic to carbonate deposition.



Figure 5a. The basic geometrical shapes and description used to analyze Gamma Ray Response to Variation in grain size (modified from Emery & Meyers, 1996)

A Blocky or Cylindrical Shaped Curve (having both abrupt upper and lower contacts) indicates massive or thickly bedded sandstone which is lithologically uniform or with very thin intercalations of shale. These types of sands are characteristics of tidal channel, barrier bars and fluvial channel sands in the delta plain. The smooth cylindrical curve is commonly indicative of more uniform massive bedding and consistent depositional energy within the bed. When the log curves are serrated, it indicates short term fluctuations in depositional energy and is usually representative of thin interbedded shale laminae.

The interpretation of the environments of deposition presented here was based on log shapes. This was done by comparing the identified log shape with the standard log motifs of Schlumberger (1985) and Emery (1996)



Figure 5b. Electrofacies classification for deltaic environment from Gamma Ray logs (Adapted from Schlumberger, 1985)

Depositional Facies Architecture

Depositional sequences are stratigraphic units composed of relatively conformable strata deposited during one cycle of rise and fall of relative sea level. Within a depositional sequence, progradational, retrogradational and aggradational stacking patterns can be defined (Figure 6).



Figure 6. Depositional Sequence Stacking Patterns (After Van Wagoner et al, 1990)

Progradational stacking pattern occurs when the rate of sediment supply exceeds the rate of creation of accommodation volume. It is marked by seaward movement of the shoreline (regression), coarsening upward (CU) facies reflecting increasing depositional energy and upward shallowing.

Retrogradational stacking pattern develops when the rate of sediment supply is less than the rate of creation of accommodation volume. It is marked by landward movement of the shoreline (transgression), fining upward sequences (FU), reflecting decreasing depositional energy and upward deepening.

Aggradational stacking pattern occurs when the rate of sediment supply balances the rate of creation of accommodation volume. Here, there is no landward or seaward movement of the shoreline; facies are uniform, reflecting consistent depositional energy.

The log shapes were used to define possible coarsening upward or fining upward units within progradational, retrogradational or aggradational stacking patterns across the field.

Results and Interpretation

Lithology Interpretation and Correlation

The lithology in the study area – the 'X' Field, is mainly sands and shales with some intermediate nomenclature such as sandy shale or shaly sand depending on the unit that predominates within the layer. The combination of gamma ray and resistivity logs was used in the interpretation of lithology and picking of the reservoir units of interest.

Gamma ray log is frequently an indicator of shale content because natural radioactive elements are often concentrated in shales. The gamma ray logs used in this study have a shale reference line (cut-off line) of 75°API chosen from the usual potential range of 0-150°API. Sands show gamma ray log signatures deflecting to the left of the reference line, while shales show log signatures deflecting to the right of the reference line. Resistivity logs record the resistance of the rock formation to the flow of electric current. Porous and permeable rocks (e.g. sandstones) show high resistivity values, while shales show low resistivity values.

In this study, six (6) reservoir sand bodies (informally designated as 'I', 'J', 'K', 'L', 'M' and 'N' from top to bottom) were identified in all the wells, with reservoir 'I' the youngest and thinnest; and reservoir 'N' the oldest and thickest. A Lithostratigraphic correlation of the wells was carried out along the southwest - northeast direction of the field (Figure 7). This was done using persistent and prominent gamma ray signature as

a datum, to map the development of the reservoir sand bodies across the field. In order to reveal the lithologic variations in the field, the sections were chosen along depositional strike and dip of the reservoir sand bodies.

From the correlation, it was observed that the reservoirs: 'I', 'J', 'K', 'L', 'M', and 'N' are correlatable across the field. Generally, the reservoir sand bodies in all the wells are more developed in the north-eastern part of the field, which has been interpreted to be the direction of sediment influx and gradually become shaly towards the south-west (Figure 7).



Figure 7. Lithostratigraphic Correlation of the reservoirs across the 'X' Field

Delineation of Reservoir Geometry

The thickness of the reservoir sand bodies, were estimated from the gamma-ray logs by the difference between the tops and bases of each reservoir sand body across the wells (Tables 1).

The thickness of the reservoirs increases from top to bottom, with reservoir sand body 'N' showing the maximum thickness and reservoir 'I' showing the minimum thickness across the field. Generally, the shape of the reservoir sand bodies suggests that they are incised valley fills.

 Table 1. Thickness Distribution of Reservoir Sand

 Bodies across the Wells in the 'X' Field

	WELLS							
RESERVOIR	NDI-	NDI-	NDI-	NDI-	NDI-	NDI-		
	A10	A11	A12	A2	A2P2	A7		
Ι	36.78	41.86	39.46	67.38	65.53	71.07		
J	28.81	31.15	27.91	88.45	92.91	92.90		
K	86.06	87.54	88.29	58.61	70.00	65.29		
L	71.22	69.73	76.41	84.57	90.51	95.70		
М	130.16	138.77	122.48	245.08	276.31	247.08		
N	225.91	250.40	240.83	456.16	437.02	443.44		

The reservoir thickness estimated for each well from the cross-sections was plotted back into the base map according to well locations. Points of equal thickness were joined together to obtain a thickness (isopach) map for each reservoir (Figures 8), which revealed the geometry of the reservoir sand bodies in the 'X' Field.



Figure 8. Isopach Map of Reservoir Sand body 'J'

The reservoir sand bodies in the 'X' Field under study display similar isopach maps as well as similar geometry. The sandstone reservoir geometry is interpreted as a thick blanket that is continuously present in all the six wells. The isopach maps depict elongate geometry (bar- finger) characteristic of a deltaic environment. It trends in the SW-NE margin of the Field and generally suggests regional tilting of the reservoirs towards the NE. The maximum thickness of the reservoir sand bodies is assumed to correspond to the direction of greatest sand development (Figures 8).

Reservoir Facies Architecture

The stratigraphic sequences and stacking patterns of the reservoir sand bodies in 'X' Field were delineated and correlated across the six wells under study. This generally revealed a predictable arrangement of progradational and retrogradational stacking patterns across the field.

The progradational stacking patterns correspond to the reservoir sand bodies, while the retrogradational stacking patterns correspond to the non-reservoir shale units (Figure 9). Below and above each reservoir sand unit, is a shale unit which occupies this stratigraphic position throughout the wells studied in the 'X' Field.

This alternation of sands and shales was interpreted as a union of reservoir, source rock, and seal essential for hydrocarbon generation, accumulation, and trapping in the 'X' Field. The impermeable shales overlying the reservoirs can provide excellent seals, while those underlying the reservoirs can provide good source rocks.

Five depositional stratigraphic sequences were also delineated across the field using progradational and retrogradational stacking patterns, while six candidate sequence boundaries were identified at depths 4723.21m, 3958.05 m, 3548.69 m, 3374.17 m, 3181.80 m, and 3024.19 m from base to top. Each sequence is composed of progradational sand facies and retrogradational shale facies.



Figure 9. One-Dimensional Stacking Pattern Showing the Delineated Depositional Sequences Depositional Environment

The interpretation of environments of deposition of the reservoir sand units was based on log shapes. The Log shapes

were compared with standard log motifs of Schlumberger (1985) and Emery (1996) (Figures 5a&b).

Barrier-Beach Bar

The GR log shape of this unit displays a general coarsening-upward sequence with gradational upper and lower contacts and large-scale serrations from base to top. By comparing the log shape with those of Emery (1996) and Schlumberger (1985) electrofacies classification model for deltaic environments (Figures 5a&b), beach/barrier bar depositional environment was inferred (Figure 10a).



Figure 10a. Log Shape of Barrier-Beach Bar Deposit displayed by Reservoirs 'I'

Since the gamma-ray log shape of barrier/beach reservoir unit 'I' is similar to those of sand units 'J', 'K' and 'L', they have all been interpreted as barrier-beach deposits. According to Allen (1965), barrier-beach deposits are composed of mainly evenly laminated, clean fine to medium sands, with primary current lineation, very rare small ripples and no mottling).

River Mouth Bar

The GR log shape of reservoir 'M' (Figure 10b) is a serrated funnel shape, characterized by sharp upper contact and gradational lower contact, indicating a coarsening upward sequence which was interpreted as river mouth bar, based on the similarity between this log shape and standard log shape classification models of Schlumberger (1985) and those adopted from Emery (1996).



Figure 10b. Log Shape of River Mouth Bar Deposit of Reservoir 'M'

Allen (1965) and Coleman (1982), described deposit of river mouth bar to compose primarily of clean, very fine to medium sands with even lamination and cross stratification. They form a coarsening upward facies sequence and are included within the Agbada Facies of Short and Stauble (1967) and Weber (1971). They also form reservoirs within the Agbada Formation. Apart from the similarities of log shapes with that of Schlumberger (1985) and Emery (1996) for river mouth bars, the log shape of river mouth bar encountered in this study are similar to that described by Adedokun (1981). They display funnel-shaped log profile characterized by abrupt upper contact and gradational lower contact with a coarsening upward facies sequence.

Stacked Regressive Shoreface Bar

The log shape of this sand body shows a serrated, multistorey and generally coarsening upward sequence with sharp upper and lower contacts (Figure 10c). The log shape is characterized by progradation and transgression which was interpreted to be a stacked regressive shoreface bar due to its similarity to the standard electrofacies classification models of Emery and Meyers (1996) and Schlumberger (1985), (Figures 5a&b) for such environments.



Figure 10c. Log Shape of Stacked Regressive Shoreface Deposits of Reservoir 'N'

The shoreface is the area where sediment-laden fluvial currents enter the basin and interact with the basinal processes. The shoreface facies displays a coarsening upward trend and commonly show an upward gradation from mudstone to sandstone. They show serrated funnel log shape with abrupt upper and lower contacts and generally coarsening upward. **Depositional History**

Wireline log data for the NDI wells in the 'X' Field were used to reconstruct the depositional history of the reservoirs. There is a good correlation between the gamma ray logs and lithological variations across the Field. During the middle Miocene, there was a relative rise in global sea level (Vail et al, 1977; Haq et al., 1988), but very rapid deposition sustained the southward progradation of the Niger Delta Shoreline. However, sea- level fluctuations led to cyclical deposition in the delta (Weber, 1971), and it is suggested that the 'X' Field reservoirs were deposited as one parasequence of shallow-marine and delta plain deposits during a high-frequency highstand systems tract. The identified sub-environments appear to be conformable and can be correlated across the entire wells (Figure 7).

Deposition commenced in the delta front with the deposition of a progradational, stacked regressive bars within the shoreface, possibly just above the storm wave base. This unit occurred as stacked coarsening-upward sequence and stacking possibly could have resulted from channel abandonment. With continued progradation during the highstand, this unit was succeeded by coarsening-upward sands of the river mouth bar. The lower part of the unit was probably deposited in the shoreface and it is characterized by gradational lower contact (Figure 10c). The upper part of the unit was possibly deposited in high-energy foreshore beach environment. According to Oboh (1992a), the unit represents minor incised valley fills formed during very brief periods of falling sea level.

In the 'X' Field, river mouth bar deposition was terminated by the deposition of barrier-beach sands in the lower delta plain. Oomkens (1974) also noted the dominance of tidal channel-fills in Late Quaternary sediments in the Niger Delta and thus queried the preservation potential of barrier-beach bars in subsurface Tertiary sequences. This is because lateral migration of tidal inlets reworks the coarsening-upward sand bodies, resulting in their preservation as tidal channel-fills. The preservation of barrier-beach bars in the 'X' Field may be due to the following reasons: firstly, the middle Miocene probably had fewer tidal inlets in the lower delta plain in comparison with the Late Quaternary, when the recent rise in sea level resulted in the development of several tidal inlets. Secondly, the energy regimes of the tidal inlets were generally lower and this minimized their ability to rework the barrier-beach sediments. Thus, a slow rise in sea level as experienced in the middle Miocene, enhances the existence of beach ridges and barrier

islands with lagoons behind them (Hoyt, 1967). The beach barrier bar deposition was terminated by deposition in the lower delta-plain sub-environments which include the distributary channel, the lagoon/tidal flat, the lagoonal delta and the flood tidal delta; where deposition was controlled chiefly by fluctuations in sediment supply, channel abandonment, tidal and wave currents, differential subsidence and minor sea level fluctuations.

A depositional model for the 'X' Field reservoirs (Figure 11) which shows a progradational sequence has been proposed.



Figure 11. A Schematic Depositional Model for the 'X' Field Reservoir Sand Bodies. Note: The Model is based on vertical distribution of depositional facies in log signatures Summary, Conclusion and Recommendation

This research was carried out using wireline log data to study the facies architecture and depositional environments of 'X' field reservoirs in Eastern Niger Delta. Prominent gammaray log signatures have been used as a datum for field-wide correlation of the wells and for reconstructing the depositional history of the 'X' Field reservoirs.

Well-to-well correlation revealed that the 'X' Field reservoirs are continuous and interconnected across the field; and are generally more developed in the northeastern part of the field which was interpreted to be the direction of sediment supply; and becomes shaly towards the southwest (i.e. basin ward). It also showed that beach-barrier deposits have been preserved in the 'X' Field, in contrast with the present-day Niger Delta, where tidal inlets and channels rework such sediments. It is possible that there were fewer tidal inlets during the period of deposition and/or that the tidal inlets had lower-energy regimes in comparison with the Late Quaternary delta.

Isopach maps of the 'X' Field reservoirs revealed elongate (bar-finger) geometry for the reservoir sand bodies, which is characteristic of a deltaic environment. It also showed that the reservoir sand bodies trend in the southwest-northeast margin of the field, suggesting SW-NE regional tilting.

Integrating log data with sequence stratigraphic concepts indicated that the reservoirs were deposited during a highfrequency highstand systems tract as progradational parasequences; while the shale units underlying and overlying the reservoirs were deposited as retrogradational parasequences. The consistent alternation of progradational and retrogradational stacking patterns was interpreted to have formed a tripartite union of reservoir, source rock, and seal that was essential for hydrocarbon generation, accumulation and trapping in the 'X' Field.

The determination of the environment of deposition of the reservoir sand bodies was achieved by comparing gamma ray log shapes with the standard log motifs of Schlumberger (1985) and Emery (1996). Three sub-environments of deposition were

recognized. These are the barrier-beach, the river mouth bar, and the regressive shoreface from top to base. Reservoirs I, J, K, and L display similar, spiky, highly serrated and coarsening-upward log shape with gradational upper and lower contacts characteristic of beach-barrier bar and therefore, they have been collectively interpreted as beach-barrier deposits. Reservoir 'M' shows a serrated funnel- shaped (coarsening upward) log shape with sharp upper contact and gradational lower contact typical of river mouth bar. While reservoir 'N' shows a multi-storey, serrated log signature and generally coarsening upward sequence interpreted to be regressive shoreface depositional environment.

Wireline logs (gamma ray and resistivity) have been used to carry-out this study in an attempt to determine the architecture (stacking pattern) and depositional environments of the reservoir sands in the 'X' Field. By careful analysis of the wireline logs, it has been possible to identify and interpret six reservoir sand bodies designated as reservoirs 'I', 'J', 'K', 'L', 'M', and 'N'; five stratigraphic sequences: SEQ I, SEQ II, SEQ III, SEQ IV and SEQ V, with their bounding candidate sequence boundaries; two predominant depositional stacking patterns: progradational and retrogradational stacking patterns; and three deltaic subenvironments: beach-barrier, river mouth bar and regressive shoreface in Wells NDI-A10, NDI-A12, NDI-A11, NDI-A7, NDI-A2P2 and NDI-A2 of the 'X' Field. The gamma-ray logs were invaluable in identifying the reservoir facies and interpreting depositional environments, because of their excellent correlation with lithological variation.

The geometry of the reservoir sand bodies has shown that they are incised valley fills, deposited during a high-frequency highstand systems tract as progradational parasequences. There was more development of the reservoirs in the northeastern part of the field which has been interpreted to be the direction of sediment supply, but however, the overall depositional trend is similar to that of the present-day Niger Delta.

Thus, this study has shown that substantial sequence stratigraphic and paleo-environmental information can be derived from wireline logs. Knowledge of the nature of the geometry, continuity, connectivity, stacking pattern and depositional environments of the 'X' Field hydrocarbon reservoirs has been provided; which is essential for field development and enhancement of reservoir production performance.

Based on the analysis and interpretation of the wireline log data used in this research, the following recommendations have been made:

1. An integrated study of the hydrocarbon reservoirs should be carried-out using core data, biofacies data, seismic sections and wireline logs.

2. More wells should be drilled along the northwest-southeast margin of the field.

3. The existing wells should be drilled to a higher depth.

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