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Well log sequence stratigraphic analyses for reservoir delineation and hydrocarbon distribution in the eastern part of the central swamp depobelt, Niger Delta

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Abstract

Sequence stratigraphic analysis was conducted employing Gamma Ray and Resistivity logs from five wells in the eastern part of central swamp depobelt, Niger Delta. Interpretation by Kingdom Suite software shows that lithologies are defined by Sequences I, II and III comprising two marine transgressive shale markers and correspond to MFS. Sequences I and III are incomplete comprising one SB while Sequence II is complete. Types 1 and 2 sequence boundaries are contained within the sequences. Key stratigraphic surfaces subdivide strata into LST, TST and HST. LST consisting of SF and PC. Sequence I comprises LST and HST while sequence III comprises SMST bounded by type 2 unconformity. The TST of sequence II comprises a retrogradational set of parasequences while the HST of sequences I and II comprise a progradational set of parasequences. The LST shows high reservoir potential and may act as a stratigraphic trap for hydrocarbon because the shales overlying the LSF act as a seal and within the SF complex. To assign ages and depositional cycles to the identified surfaces, an integrated sequence stratigraphic analysis should be conducted to accurately model the lithostratigraphic and chronostratigraphic settings of the depositional sequence of the study area.

Keywords: Maximum Flooding Surface (MFS), Lowstand System Tract (LST), Transgressive System Tract (TST), Highstand System Tract (HST), Slope Fan (SF), Prograding Complex (PC), Shelf Margin System Tract (SMST), Lowstand Fan (LSF).

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1. Introduction

The application of well log sequence stratigraphic approach to reservoir basin analysis is an important phase in transforming lithologic information of the basin-fill from raw well log data into genetic packages useful in evaluating subtle stratigraphic reservoirs. It provides a technique for lithostratigraphic correlation of wells.

The essential stratigraphic parameters for evaluating reservoirs are Surfaces and Systems Tracts. Surfaces include: Sequence boundaries [SB 1 – Type 1 and SB 2 – Type 2], Downlap surfaces [Maximum Flooding Surface (MFS), Top Fan Surface (TFS), Top Leveed Channel Surface] and Transgressive Surface (TS) [First Flooding Surface above maximum regression] while the System Tracts include: Highstand Systems Tract (HST); Transgressive Systems Tract (TST), Lowstand Wedge Systems Tract (LSW); Lowstand Fan Systems Tract (LSF) and Shelf Margin Wedge Systems Tract (SMW) [1].

Appraisals based on these stratigraphic parameters serve as useful input for: both dynamic and static modeling of hydrocarbon reservoirs; delineation and characterization of potential reservoir sands; predicting the geometry, continuity and distribution of the reservoir sands and reduction in exploration risks in the Niger Delta as shown by several researchers [2], [3], [4], [5], [6] and [7] among others.

This research highlights the effective and optimal application of well logs characteristics of lithology in sequence stratigraphic analyses, subdividing the varied properties of reservoirs in the Niger Delta to identify specific genetic depositional settings necessary to accurately interpret the depositional histories and hydrocarbon distribution of the sedimentary fill of eastern part of the Central Swamp Depobelt.

2. Location and geology of the study area

2.1 Location

The study area is located within OML 11 in the eastern part of the Central Swamp Depobelt of the Tertiary Niger Delta (Figure 1).

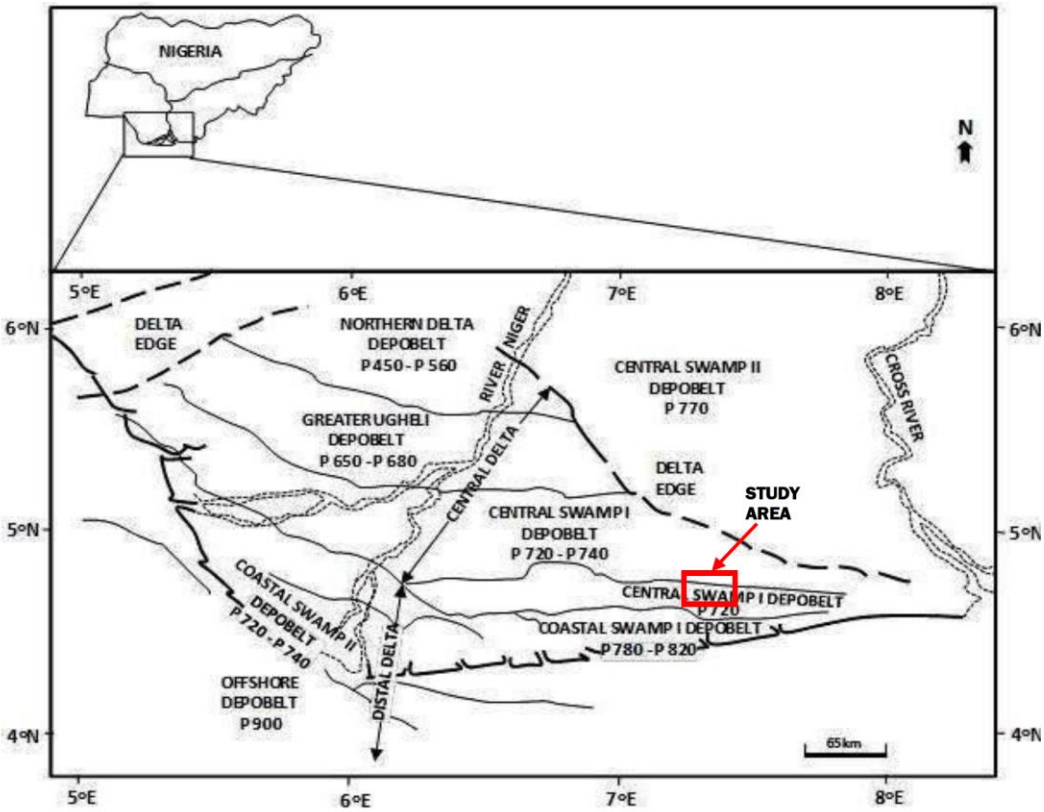

Figure 1: Map of Niger Delta showing depobelts and location of the study area - eastern part of central swamp depobelt (Modified after [11]).

2.2 Geology

The Central Swamp Depobelt is one of the most prolific oil provinces in the whole of the Niger Delta as revealed by the sheer number of fields, sizes, reserves and production levels [8]. In the conventional sections, collapsed crests grading into the K-type and faulted rollover structures characterize this area. At depth, this trend is also characterized by mainly deep footwall closures with some hanging wall components in a limited sense [8].

Sedimentation within the Central Swamp Depobelt was mainly wave-dominated and the activity of the Opuama Canyon has been initiated on the north-western flank of the Delta [9]. The oldest sediments in the Central Swamp Depobelt are dated around the Latest Oligocene. Sedimentation in this area was mainly starved at this time as only shales of the Akata Formation were deposited [10]. Deposition of the paralic facies (Agbada Formation) probably took place from the earliest Miocene times onwards.

3. Methodology

3.1 Well locations

Sequence stratigraphic parameters in the study area were evaluated by digitizing and correlating a suite of logs comprising: Gamma Ray and Resistivity from Wells Afam 15 and 16, Korokoro 003 and 006 and Obeakpu 005 (Figure 2) using the Seismic Micro Technology (SMT, Kingdom Suite) software.

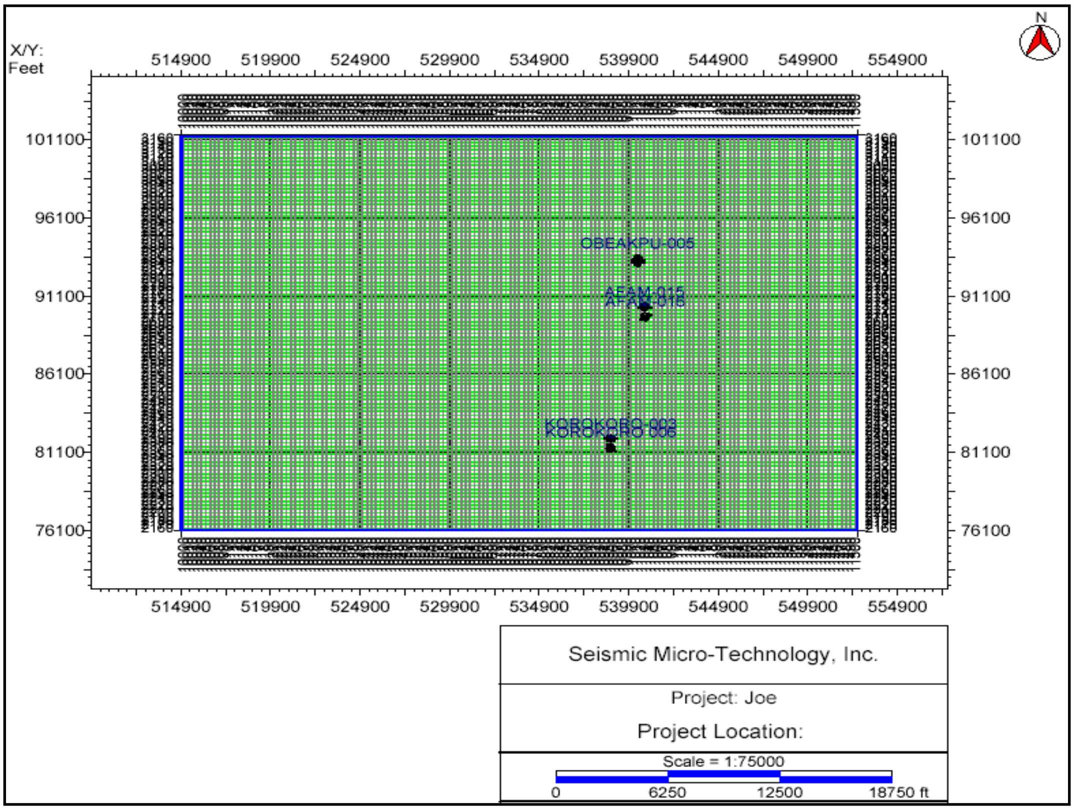

Figure 2: Base map of the study area showing the wells locations

3.2 Sequence stratigraphic interpretation

In conducting the sequence stratigraphic interpretation, the basin-fill was subdivided into genetic packages bounded by unconformities or their correlative conformities. The interpretation scheme employed is adopted from [12].

3.3 Sequences and system tracts boundaries identification from well logs

Well logs trends were observed and correlated with trends in depositional settings and thus with patterns of sedimentary fill. A number of distinctive trends were recognized and described from the gamma or SP log and resistivity logs expression to depict the various depositional settings. Key stratigraphic surfaces were recognized from the log characters followed by parasequences and parasequence stacking patterns.

Sequence and systems tract boundaries were delineated from the log characters and the parasequence stacking patterns. Sequence boundaries were identified mainly on the basis of inflection from overall progradation to overall retrogradation of the parasequences. Parasequences subdivide the sequence and systems tract into the smallest genetic units for detailed prediction, correlation and mapping of depositional environments [12]. The sequence boundaries were also identified by abrupt changes in lithology.

4. Results and discussion

The tops and bases of sequence boundaries (SB of sequence III and SB of sequence II) respectively correspond to depths of 1078.4m and 1808.8m in Afam 15, 1059.8m and 1839.9m in Afam 16, 991.5m and 1854m in Korokoro 006, 975m and 1871.6m in Korokoro 003 and 880.2m and 1854.6m in Obeakpu 005.

Transgressive surface was identified from the log section by the first major landward flooding surface above the sequence boundary and below the maximum flooding surface (Figure 3). This transgressive surface corresponds to depth of 1590.2m in Afam 15, 1695.4m in Afam 16, 1408.2m in Korokoro 006, 1399.7m in Korokoro 003 and 1544.2m in Obeakpu 005.

The key stratigraphic surfaces have been defined (Table 1) and these belong to one or more of the eleven well-defined third-order sequence stratigraphic building blocks or depositional "cycles" which have been recognized in the Niger Delta [13], [14]. A depositional sequence represents a complete cycle of relative sea level rise and fall. The sequence is divided into systems tracts thus forming a sequence model.

4.1 Sequence I

This is an incomplete sequence comprising a lowstand systems tract capped by MFS-I shale which is overlain by a fairly thick highstand systems tract (1809-1983m in Afam 15; 1840-1977m in Afam 16; 1854-1998m in Korokoro 006; 1872-2019m in Korokoro 003 and 1855-2072m in Obeakpu 005). The stacking pattern of the lowstand systems tract shows thick shale and thin sand retrogrational units in Afam 15 and Afam 16 wells and thin shale and thick sand units in Korokoro 003 and Korokoro 006 wells. The separation of the highstand systems tract from the transgreesive systems tract is based on the cyclic pattern of the resistivity log readings within the highstand systems tract showing an overall progradational pattern.

4.2 Sequence II

This is the only complete sequence observed in this study. It is bounded at the base by a type I sequence boundary and at the top by a type II sequence boundary. This sequence is divisible into lowstand systems tract (LST), transgressive systems tract (TST) and the highstand systems tract (HST). The lowstand systems tract has a thickness of approximately 457m in Korokoro 003 and Korokoro 006 wells whereas in Afam 15, Afam 16 and Obeaku 005 wells, it has a thickness of approximately 213m. This is due to the fact that some parasequences appear to be missing in Afam 15, Afam 16 and Obeakpu 005 wells. A fairly thick transgressive systems tract separated by a transgressive surface overlies the lowstand. The transgressive systems tract comprises a retrogradational parasequence mainly consisting of transgressive shale. It has an estimated maximum thickness of 196m in Afam 16 well. The highstand systems tract is made up of an interbedded sequence of sands and shales where the sand units are prograding. The highstand systems tract has a maximum thickness of 416m in Obeakpu 005 well.

4.3 Sequence III

This is an incomplete sequence bounded by a type II sequence boundary at its base. Shelf margin systems tract was the only systems tract observed in this sequence, which extends to the top of the log section.

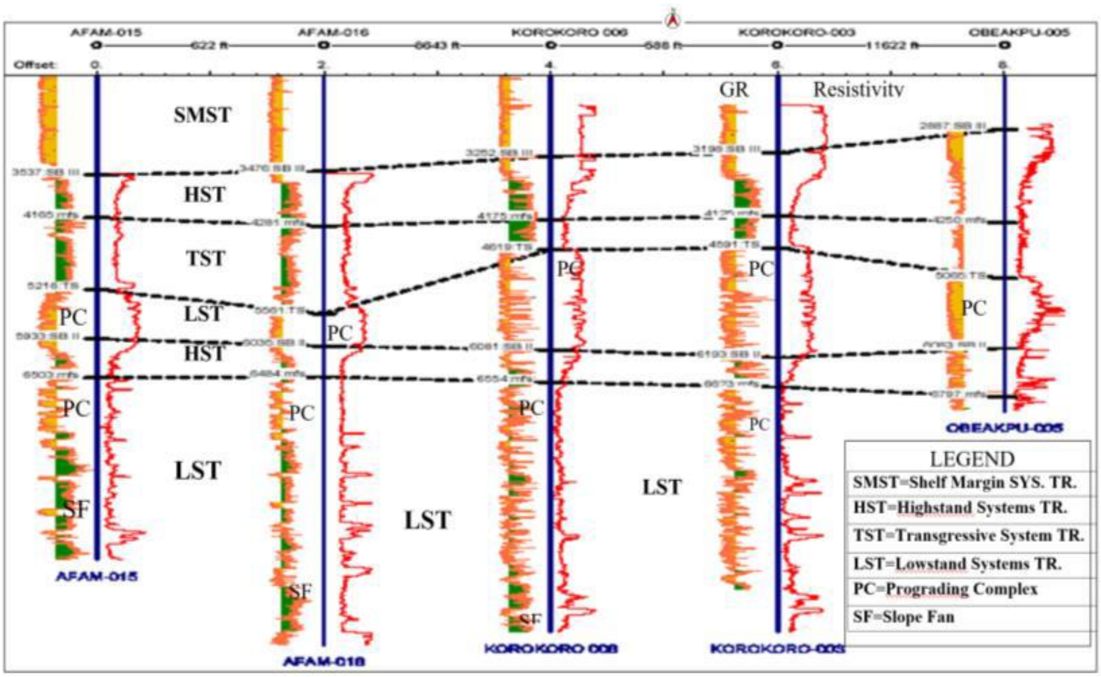

Figure 3: Key Stratigraphic Surfaces and their associated Systems tracts.

Table 1: Key stratigraphic surfaces recognized from well logs

Key Stratigraphic Surfaces	Wells with Depths to the Top of Recognized Surfaces				
	Afam 15 (m)	Afam 16 (m)	Korokoro 006 (m)	Korokoro 003 (m)	Obeakpu 005 (m)
SB of Sequence I	**Absent due to erosion and truncation**				
MFS-I	1983	1977	1998	2019	2072
SB of Sequence II	1809	1840	1854	1872	1855
MFS-II	1270	1305	1273	1258	1296
TS of Sequence II	1590	1695	1469	1400	1544
SB of Sequence III	1078	1060	991	975	880

4.4 Parasequence and parasequence stacking pattern

More than 30 parasequences exist within the log section of the wells. Marine flooding surfaces bound each parasequence which are useful for parasequence correlation. Parasequences stack to form parasequence sets which make up the systems tract and thus the depositional sequence. However, these parasequence sets are controlled by rate of creation of accommodation and flux of sediment supply. More than one parasequence set can make up a systems tract. About eight parasequence sets are composed within the strata of the study area as seen from the log sections (Figure 4).

Starting from the base, Afam 15, Afam 16 and Korokoro 006 wells show a retrogradational parasequence composed of massive 705m, 1005m and 305m thick of marine shale respectively. This is followed by a progradational parasequence sets mainly composed of 309m thick shoreface prograding sands and 116m thick marine shales in Korokoro 006 and 406m thick shoreface prograding sands and 107m thick marine shales in Korokoro 003 wells but missing in Afam 15 and Afam 16 wells (Figure 5). Above this is an aggradational parasequence set composed of aggrading sand and shale units of about 214m in Afam 15 and Afam 16 wells and 363m in Korokoro 006 and Korokoro 003 wells (Figure 6). This implies that accommodation was filled at the same rate it was created.

A 109m retrogradational parasequence set of marine shale follows this aggrading package in wells Afam 15, Afam 16, Korokoro 006 and Korokoro 003. This set indicates that accommodation was created at a faster rate than it was filled. This in turn is followed by a progradational parasequence set composed of prograding sands of 281m thick in Afam 15 and Afam 16 wells, 520m thick in Korokoro 006 and Korokoro 003 wells and 516m thick in Obeaku 005 well. Above this is a retrogradational parasequence composed of massive marine shale of 573m thick in Afam 15 and Afam 16 wells, 330m thick in Korokoro 006 and Korokoro 005 wells and 404m in Obeaku 005 well (Figure 7).

The last parasequence set observed in the log section spans estimated thickness of about 1103m to the top of the log section (Figure 4). This progradational parasequence contains about 15 parasequences with coarsening upward (funnel) of prograding sands of high depositional energy. The sand units increase progressively up the section. This is indicative that accommodation was created at a slower rate than it was filled, thus, the deposition of shoreface and coastal sediments.

4.5 System tracts and depositional settings

From logs interpretation data, three sequences with their associated systems tracts have been identified in the five wells studied (Figure 3). The systems tracts identified are lowstand, transgressive and highstand systems tracts. The log pattern displayed by the lowstand system tract is an overall coarsening upward pattern, the transgressive systems tract is fining upward (back-stepping funnel) and highstand systems tracts is coarsening upward pattern on the log. The log motif is described as fore-stepping funnel.

The relative thicknesses of the systems tracts reveal changes in sediment accumulation rate as a result of varying conditions such as availability of accommodation space, effects of gravity tectonics as well as regional and eustatic changes in sea level [12].

4.6 Lowstand system tract (LST)

In the study area, it was observed in sequence I that a slope fan underlies a lowstand prograding complex which in turn underlies a highstand systems tract capped by MFS-I (Figure 3) while in sequence II a lowstand prograding complex overlies the highstand systems tract of sequence I and underlies the transgressive systems tract of sequence II. The lowstand systems tract in sequence I consists of massive turbidite sands fining upward with sharp base in the slope fan section and aggradational stacking patterns of sand units in the prograding complex section while in sequence II, it consists of progradational stacking patterns of sand units in the prograding complex section.

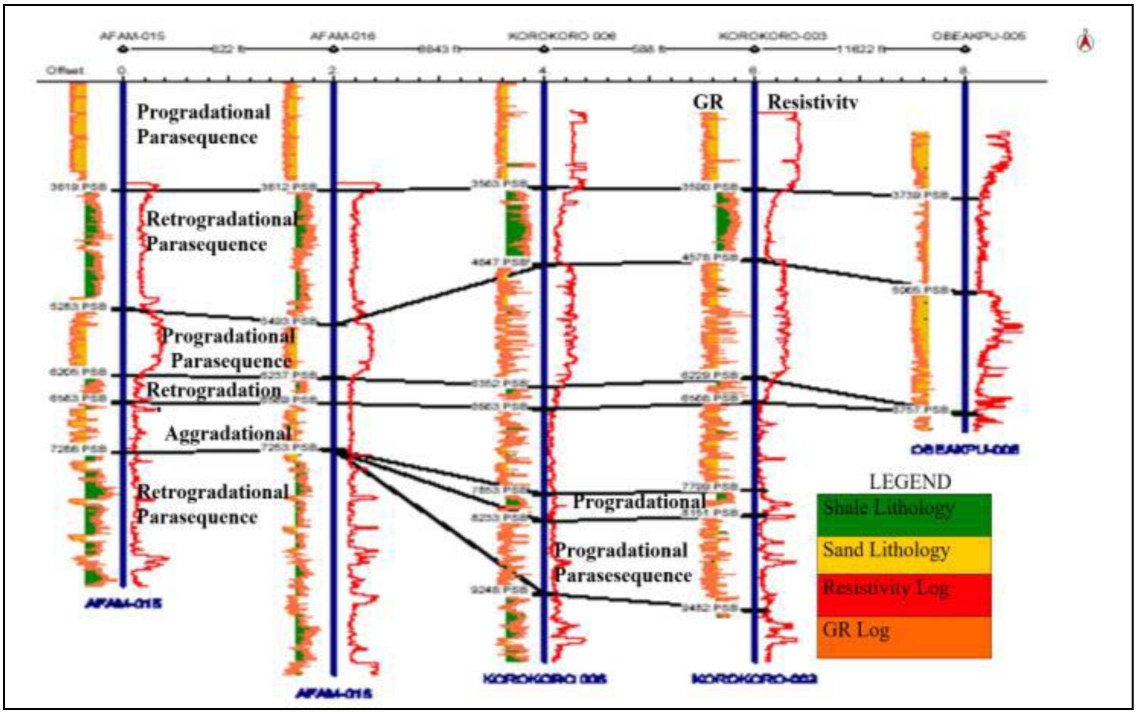

Figure 4: Parasequence Stacking Patterns within the Wells.

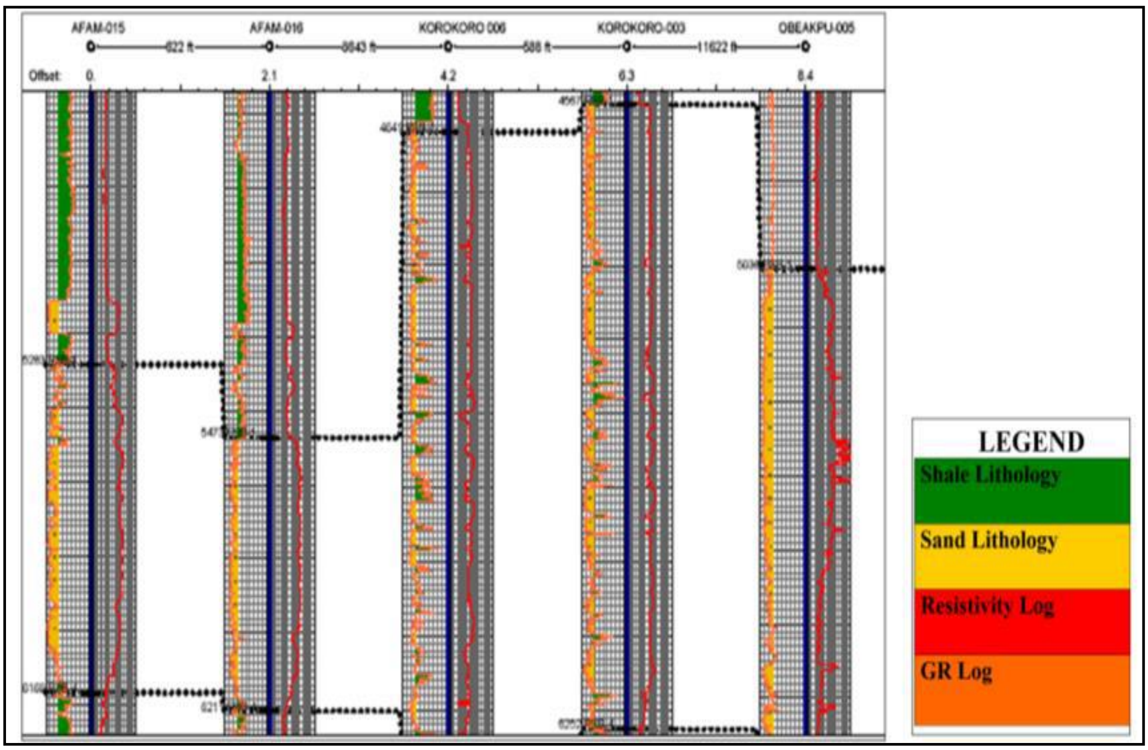

Figure 5: Progradational Parasequence Set within the Wells

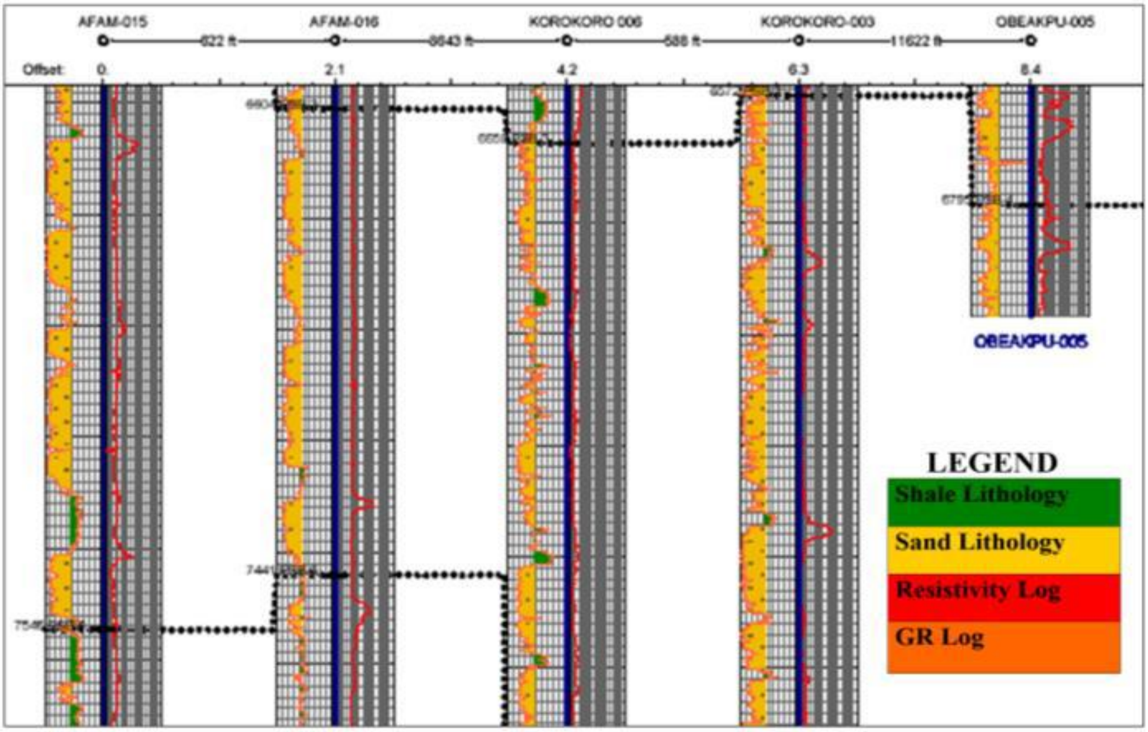

Figure 6: Agradational Parasequence Set within the Wells

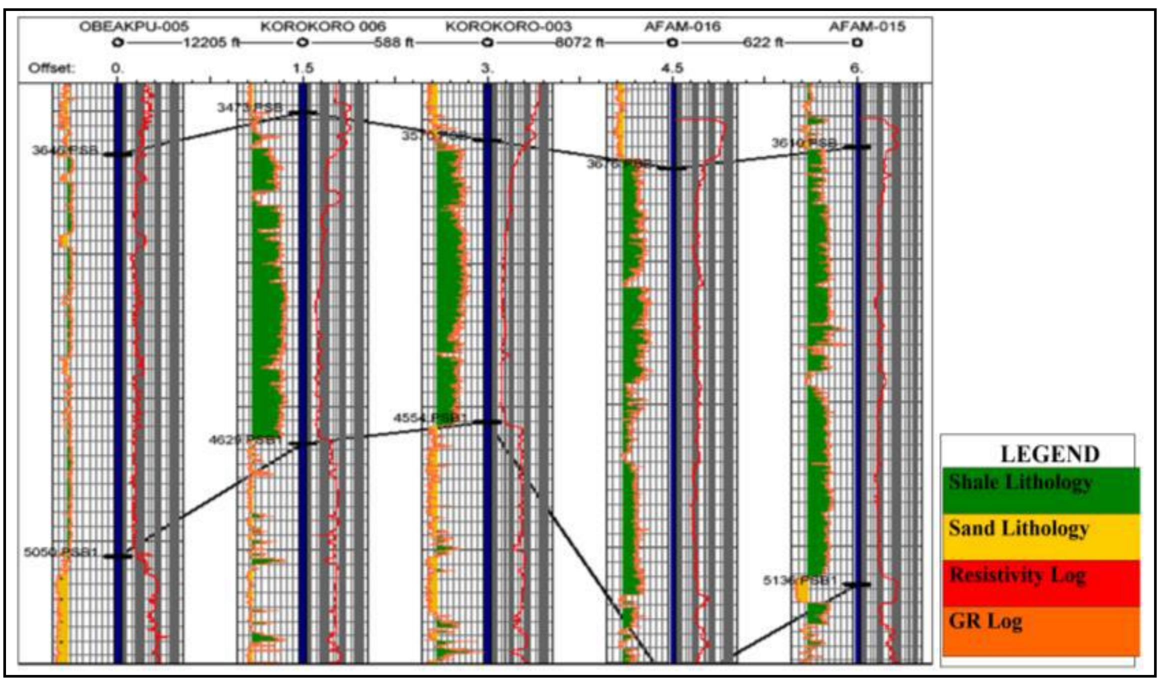

Figure 7: Retrogradational Parasequence Set within the wells

4.7 Slope fan (SF)

In sequence I, slope fan was identified in Afam 15 from 2221.3m, Afam 16 from 2211.3m, Korokoro 006 from 2510.1m and Korokoro 003 from 2485.1m to the end of these wells. This is formed as the rate of eustatic sea level fall becomes less than the rate of rise associated with subsidence and characterized by crescent shapes of individual levee channel units, thickening and thinning of individual overbank sands and fining upwards of individual channel sands from a sharp base.

4.8 Prograding complex (PC)

In sequence I, prograding complex was identified in Afam 15 and Afam 16 from 2007m to 2221.3m, in Korokoro 006 and Korokoro 003 from 2002.4m to 2377.7m while in sequence II, PC was identified in Afam 15 and Afam 16 from 1674.7m to 1901.5m, in Korokoro 006 and Korokoro 003 from 1416.8m to 1899.1m and in Obeaku 005 from 1544.2m to 2060.1m. This develops by prograding the slope as relative sea level approaches the previous shelf edge. It consists of shallowing upward deltas or terraces which onlap the slope and downlap the basin floor fan. The top of the lowstand prograding complex consists of a marine flooding surface or transgressive surface.

4.9 Transgressive system tract (TST)

Transgressive systems tract of sequence II is well developed in all the wells in the study area (Figure 3). The TST is mainly composed of massive transgressive marine shales with retrogradational sand units. Thus, a fining upward sequence is associated with the TST on the well logs. Transgressive systems tract develops due to an increase in the rate of relative sea level rise. As the rate of relative sea level rise reaches its maximum, the amount of sediment available gets less than the amount of space created and retrogression occurs.

4.10 Highstand system tract (HST)

The HST in the wells has thick intervals as compared to other systems tract. This can be attributed to very high rates of subsidence, high sediment input and instability. The HST is identified in sequence I and sequence II (Figure 3). The HST develops during the decrease of relative sea level rise [1]. However, as the sea level rise slows and stabilizes, a new shelf builds out by progradation. This systems tract is characterized by intervals of coarsening and shallowing upwards trends, both with fluvial and deltaic sands near the top of the unit prograding into neritic shales.

4.11 Shelf margin system tract (SMST)

The shelf margin systems tract onlap onto the sequence boundary of sequence III prograding to the top of the log section in wells studied (Figure 3). It is characterized by one or more weakly progradational to aggradational parasequence sets, which onlap onto the sequence boundary in a basinward direction [15].

4.12 Hydrocarbon distribution within the system tracts

Potential reservoirs, hydrocarbon distribution and associated systems tracts are identified in the study area. Each systems tract has a predictable set of associated reservoirs which are the main exploration targets.

From the petrophysical evaluation conducted within this study area by [16], it can be observed that hydrocarbon mainly exists within the lithostratigraphic intervals of the TST of sequence II and the LST of sequence I and sequence II. The reservoir units of the TST within this sequence are deposited as fine sand bar within shallow marine environment. The organic-rich shales that are commonly associated with the transgressive marine shales may provide petroleum source rocks as well as regional seals.

Several reservoir sand units belonging to the LST may contain sufficient quantities of hydrocarbon. These reservoir sand units are the PC and SF within sequence I and sequence II (Figure 3). It was observed that the LST of sequence I was gas prone [16]. The gas proneness may probably be related to the early generation of oil in the early phase which was subsequently flushed updip towards the flank by the gas generated later within the deeper parts of the basin.

5. Conclusion

The results from this research show that the lithologies in the study area are defined by three sequences: Sequences I, II and III. These sequences are composed of two marine transgressive shale markers which correspond to maximum flooding surfaces. Types **1** and **2** sequence boundaries are contained within the sequences as recognized from the inflection patterns of the well logs.

The key stratigraphic surfaces (SB and MFS) subdivide strata into sequences and systems tracts: LST, TST and HST. The LST is made up of slope fan (SF) and prograding complex (PC). Sequences I and III are incomplete sequences composed only of one SB while Sequence II is the only complete sequence in the study area. Sequence I consist of the LST and HST while sequence III is associated with SMST bounded by type **2** unconformity. The TST of sequence II consists of a retrogradational set of parasequences while the HST in sequences I and II consists of a progradational set of parasequences.

6. Recommendation

This research reveals that LST shows high reservoir potential and may act as a stratigraphic trap for hydrocarbon. Hence, it is recommended that the LST be assigned high priority with potential for prospect and play generation because the shales overlying the lowstand fans act as a seal and within the SF complex and the best reservoirs could be located within the channel sands. The currently producing reservoirs in the study area by Multinational Companies are situated within the TST and HST of most of the depositional sequences.

More so, in order to assign ages and depositional cycles to the identified surfaces, an integrated sequence stratigraphic analysis of the field should be conducted employing a suite of well logs, 3D seismic data, high resolution biostratigraphic and biofacies data, and the well pollen and faunal zonation data to accurately model the lithostratigraphic and chronostratigraphic settings of the depositional sequence of the Central Swamp Depobelt in the Niger Delta

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