Stratigraphy and Petroleum Plays of the late to middle Oligocene Sediments in the "XY" Field, Onshore Niger Delta Basin, Nigeria

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Abstract— Nigeria's search for increased oil and gas reserves requires the discovery of additional petroleum plays using more accurate exploration techniques like sequence stratigraphy. Sequence stratigraphic technique was applied to sediments in the "XY" Field, onshore Niger Delta by integrating six well logs and biostratigraphic data to subdivide the field's stratigraphic column into sequences, systems tracts and profitable plays. The analysis delineated seven complete (SEQs 1 to 7) and two incomplete 3rd order sequences. The key surfaces used for correlation across the sequences in Wells 002, 003, 005 and 001 were the 11.5Ma, 12.8Ma and 15.0Ma MFSs, while the link between these four wells and Wells 007 and 006 was the 15.9Ma MFS. The other constrained surfaces between Wells 007 and 006 were the 17.4Ma, 19.4Ma and 20.7Ma MFSs. These surfaces were delineated at varying depths in the wells, suggesting the existence of faults in the well field. The most laterally continuous sandstone unit, however, is the faulted prograding wedge complex (PGC) sands of SEQ 4 which represented the main petroleum plays in the field. Cyclic alternation of Transgressive Systems Tracts (TST), High-stand Systems Tracts (HST) and Lowstand Systems Tracts (LST) in the well field is suggestive of a union of the elements of a petroleum system which constitute favourable conditions for the generation, migration and structural and stratigraphic entrapment of hydrocarbons.

Index Terms— *Petroleum, Plays, Sequence, Straigraphy, Faults, Compartmentalization, Hydrocarbon, Reserves.*

1 Introduction

Exploration and exploitation activities in Nigeria had been concentrated in the Tertiary Niger Delta sequences of Eocene to Pliocene age, until recently when exploration efforts are gradually being shifted to the offshore (Pliocene–Pleistocene) sections. These areas have accounted for the country's current oil reserves estimated at about 35 billion barrels and an average annual reserve addition of about 800 million barrels in the last ten years [1]. These reserves that were mainly derived from the onshore, offshore and recently the deep offshore parts of the Niger Delta are presently intensely developed.

The Nigerian oil and gas industry is presently faced with the challenge of achieving the national crude oil reserves target of 40 billion barrels and production of increased volumes of Liquefied Natural Gas (LNG) in order to meet export and domestic needs. The domestic need is bolstered by the current government policy thrust for additional gas turbines for power generation and industrial projects [2]. Therefore, the future reserve/production ratio for oil/gas in Nigeria will be a cause for serious concern based on the present available reserves data, if additional reserves are not discovered.

The search for additional oil and gas reservoirs in the region will, therefore, require more accurate techniques of stratigraphic analysis [3]. These techniques will assist in the discovery of hithertho hidden, deep and tight reservoirs which will give the required boost to the existing reserves. Sequence stratigraphy has become an indispensable tool in hydrocarbon exploration because of its ability to provide a chronostratigraphic framework for the analysis and correlation of lithic fills in basins that are deposited in response to sea level changes, tectonism and sediment supply. The search for additional reserves in the Niger Delta Baasin can be enhanced by the use of this integrated approach for stratigraphic analysis and prediction [4], [5], [6], [7]. It will also give a better understanding of the linkage between sedimentation patterns in different parts of the basin and location of reservoirs, their continuity and seal prone zones (traps) and perfectly predicts bypassed pay zones and step-out potentials in a basin [8].

Therefore, to realize optimal hydrocarbon exploration, recovery and production, the understanding of the depositional setting and location of play elements within the depositional setting is required for a realistic or near realistic representation of the subsurface and paleoenvironmental conditions within the basin.

The aim of the present study in the onshore, Niger Delta is to subdivide the stratigraphic column of the "XY" well field into sequences and systems tracts based on the integration of well logs and high resolution biostratigraphic data for the delineation of reservoirs, their continuity and other elements of the petroleum system (source, traps, e.t.c) for the sustainable development of the resource in the region.

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2 LOCATION OF STUDY

The "XY" Field (a designation used for propriety purposes) is located at the fringe of the Greater Ughelli Depobelt in the Niger Delta Basin (Fig. 1). The Niger Delta is situated in the Gulf of Guinea on the west coast of central Africa (Fig. 1). It lies on Latitudes $4^0 00^1$N and $6^0 03^1$N and Longitudes $4^0 30^1$E and $8^0 30^1$E. During the Tertiary, the delta built out into the Atlantic Ocean at the mouth of the Niger-

Benue system on an area of catchment more than a million square kilometers of predominantly savanna-covered lowlands. From the Eocene to the present, the delta has prograded southwestward, forming depobelts that represent the most active portions of the delta at each stage of its development [9]. These depobelts form one of the largest regressive deltas in the world with an area of some 300,000 km^2 [10], a volume of 500,000 km^3 [11] and a sediment thickness of over 10 km in the basin depocenter [12]. The Greater Ughelli Depobelt, however, overlies a relatively shallow basement with increased steepness seawards [9].

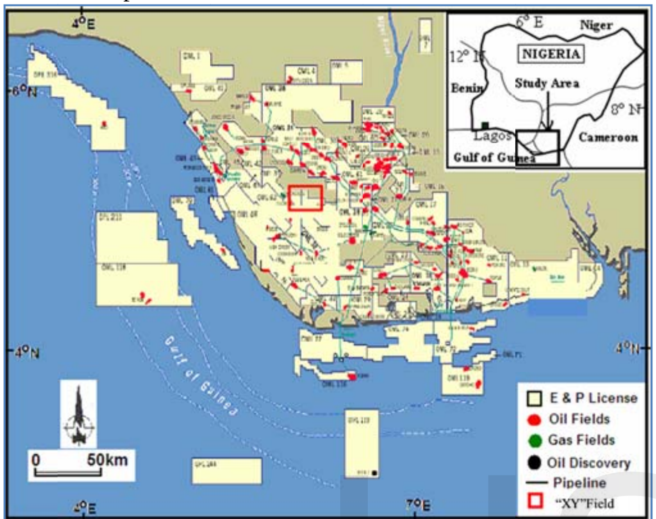

Figure 1. Map of Niger Delta Showing the Location of "XY" Field

3 PROVINCE GEOLOGY

The onshore portion of the Niger Delta Province is delineated by the geology of southern Nigeria and southwestern Cameroon (Fig. 2). The northern boundary is the Benin flank- an east-northeast trending hinge line south of the West African Basement Massif. The northeastern boundary is defined by outcrops of Cretaceous sediments on the Abakaliki High and further east-south-east by the Calabar flank-a hinge line bordering the adjacent Precambrian rocks. The offshore boundary of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey basin (the easternmost West African transform-fault passive margin) to the west, and the two-kilometer sediment thickness contour or the 4000-meter bathymetric contour in areas where sediment thickness is greater than two kilometers to the south and southwest (Fig. 2).

Sedimentary deposits in the basin have been divided into three large-scale lithostratigraphic units (Fig. 3): the basal Paleocene to Recent pro-delta facies of the Akata Formation, Eocene to Recent, paralic facies of the Agbada Formation, and Oligocene-Recent, fluvial facies of the Benin Formation [13], [14], [15]. These formations become progressively younger farther into the basin, recording the long-term progradation of depositional environments of the Niger Delta onto the Atlantic Ocean passive margin.

The stratigraphy of the study area is complicated by syndepositional collapse of clastic wedges as shales of the Akata Formation are mobilized under the load of prograding deltaic Agbada and fluvial Benin Formation deposits. A series of large-scale, basinward-dipping listric normal faults were formed as underlying shales diapired upward (Fig. 4). Blocks down-dropped across these faults and filled with growth strata, changed local depositional slopes and complicated sediment transport paths into the basin. For any given depobelt in the Niger Delta province, gravity tectonics was completed before deposition of the Benin Formation, which are expressed in complex structures, including shale diapirs, roll-over anticlines, collapsed growth fault crests, back-to-back features and steeply dipping, closely spaced flank faults [13], [16]. These faults mostly offset different parts of the Agbada Formation and flatten into detachment planes near the top of the Akata Formation.

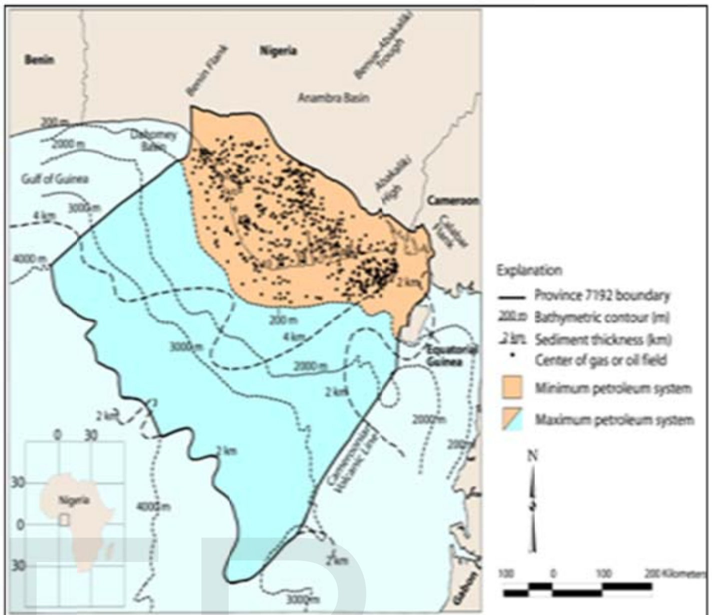

Fig. 2. Province Geology of the Niger Delta, southern Nigeria and southwestern Cameroon [17]

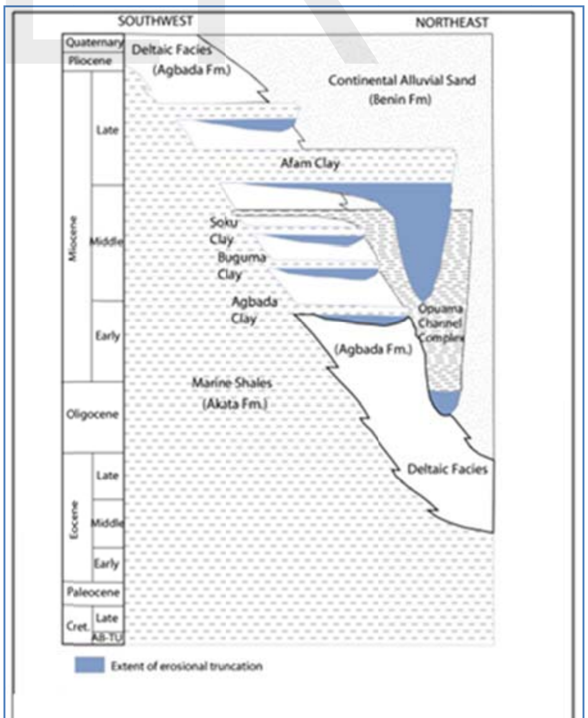

Fig. 3. Schematic Diagram of the Niger Delta Regional Stratigraphic and Variable Seismic Display of the main Stratigraphic Units with Corresponding Reflections [18]

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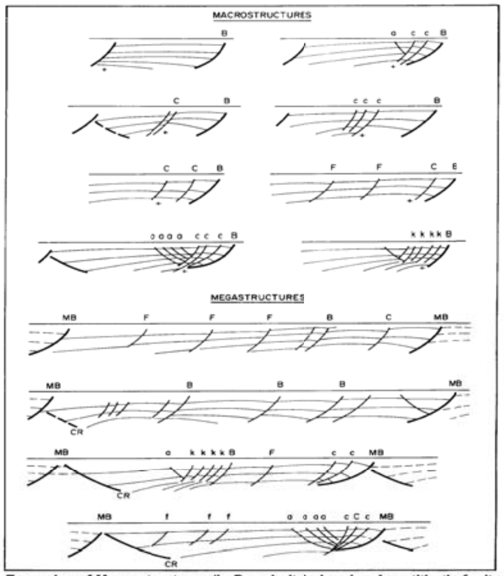


Fig. 4. Examples of Macrostructures (in Depobelts) showing A: antithetic faults; B: structure-building boundary faults, MB if major; C: crested faults; CR: counter-regional faults; F: flank faults; K:k-type faults [13].

5 Data Sets and Methodology

The data sets used for this study included 6 well log suites from the ‘XY” Field, Greater Ughelli depobelt, logged with gamma ray (GR) and resistivity logs (Fig. 5), biostratigraphic data (faunal zones and events) including palynological and foraminiferal information (Table 1) and the Niger Delta Chronostratigraphic Chart [19]. The data were acquired from Shell Producing and Development Company (SPDC), Port Harcourt, through the Directorate of Petroleum Resources (DPR), Nigeria. The non-availability of GR and SP logs at some sections of the studied intervals, however, affected interpretations at those depths.

5.1 Sequence Stratigraphic Application in “XY” Field

Athough sequence stratigraphy was originally designed for seismic sections, its principles can readily be applied to outcrops, cores and well logs [3]. Sequence stratigraphic analysis of each of the six (6) well log suites from the “XY” Field in the Greater Ughelli depobelt, Niger Delta Basin was achieved by the integration of biostratigraphic information (stratigraphic markers) and lithological data distilled out from the wireline log suites using the approach of [5].

5.2. Determination of Lithology, Stacking Patterns and Depositional Settings

The wireline logs were used to delineate lithofacies based on the physical criteria extracted from the electric logs’ responses. The gamma ray log records radioactivity of formations, hence shales (or clay-minerals) commonly have relatively high gamma radioactive responses and consequently taken as good measures of grain size. The log is thus used to infer depositional energy. Coarse-grained sand, which contains little mud, will have low gamma ray value, than mud with high gamma ray signal. Gamma ray values are measured in API (American Petroleum Institute) units and range from very few units (in anhydrite) to over 200 API units in shales.

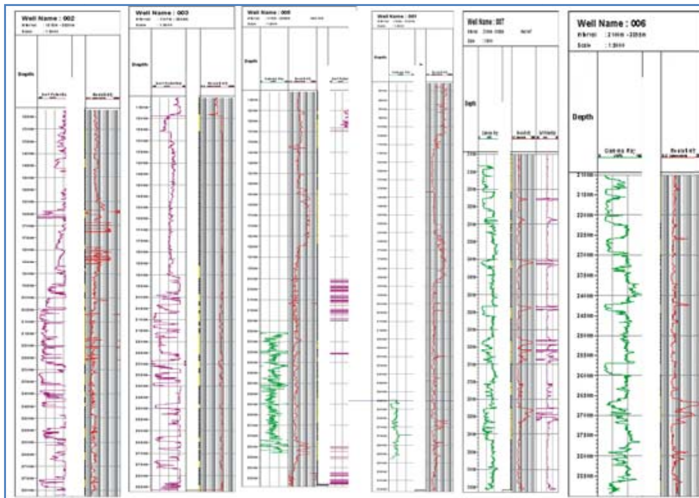


Fig. 5. Showing Well Log Suites provided for the Study

Table 1. Representative Stratigraphic Markers of Well 001 Greater Ughelli Depobelt

Form Code	Depth (AH), Ft
D1000 base	6390
D1000 top	6350
D1100 base	6487
D1100 top	6403
D2000 base	6656
D2000 top	6542
D3000 base	6960
D3000 top	6677
D3000_HWC_contact	6689
D4000 base	6998
D4000 top	6972
D5000 base	7340
D5000 top	7004
E1000 base	7465
E1000 top	7402
E2000 base	7610
E2000 top	7518
E2000_DHO_contact	7532
E2000_HWC_contact	7574
E3000 base	7690
E3000 top	7647
E3100 base	7792
E3100 top	7782
E4000 base	8026
E4000 top	7933
E4000_HWC_contact	7952

Form Code	Depth (AH), Ft
E5000 base	8095
E5000 top	8075
E6000 base	8253
E6000 top	8179
E8000 base	8515
E8000 top	8407
E9000 base	8617
E9000 top	8593
F1000 base	8760
F1000 top	8703
F1400 base	8917
F1400 top	8768
F2000 base	9178
F2000 top	9123
F2000_DLG_contact	9155
F2100 base	9229
F2100 top	9202
F2100_DHO_contact	9203
F2200 base	9260
F2200 top	9250
F2300 base	9350
F2300 top	9328
F3000 base	9688
F3000 top	9360
F3000_DHO_contact	9362
F3000_HWC_contact	9404
F3100 base	9782
F3100 top	9720
F4000 top	10172
ZZC	7464

The intervals of progradation, retrogradation and aggradation were delineated from the succession patterns of strata expressed in the logs, which depict various parasequences and/or parasequence sets. These patterns which display vertical occurrences of repeated cycles of coarsening upwards (CU) or fining upwards (FU) sequences were inferred from the gamma ray log signatures.

The environment of deposition for the respective units was inferred from the gamma log expression of grain size [5] and depositional systems determination distilled from stacking patterns [3].

Progradation or Cleaning-up Trend (funnel shape) means a coarsening upward sequence (Fig. 6). It also means a gradual upward decrease in gamma ray response. In shallow marine settings, this trend reflects a change from shale-rich into sand-rich lithology and an upward increase in depositional energy with shallowing-upward and coarsening. In deep marine settings, this trend reflects an increase in the sand content of turbidite bodies [20].

Retrogradation or Dirtying-up Trend (bell shape) means a fining upward sequence or a gradual upward increase in gamma response (Fig. 6). This trend may reflect upward fining (example, a lithologic change from sand to shale) or upward fining of sand beds in a thinly interbedded sand-shale unit. This trend usually implies a decrease in depositional energy. In non-marine settings, fining upward is predominant within meandering or tidal channel deposits with an upward decrease in fluid velocity within a channel (coarser sediments are usually at the base of channels). In shallow-marine settings, this trend usually reflects an upward deepening and a decrease in depositional energy (net landward shoreline movement). In deep-marine settings, this trend reflects waning of submarine fans resulting in the reduction of sand contents [20].

Aggradation or Boxcar Trend (cylindrical or blocky shape) means piling up of sediments on top of each other, hence the gamma ray shows neither increase nor decrease (Fig 6.). Sometimes the gamma ray response has low gamma and sharp boundaries and no internal change. This trend is predominant in fluvial channel sands, turbidites (typically with greater range of thickness) and aeolian sands. Evaporites also can have a cylindrical gamma trend.

5.3 Definition of Key Stratigraphic Sequences from Logs

The definition of key stratigraphic surfaces from well logs, which includes for example, Sequence Boundary (SB) and Maximum Flooding Surface (MFS) and their relative ages was done by identifying candidates and events of the surfaces in the following ways:

Candidate SBs on log-motifs were marked by the sharp-based bottom of the basin floor thicks and incised-valley fills and in updip areas by the sharp-top of the uppermost prograding transgressive parasequence, low gamma, high resistivity and the use of the provided stratigraphic markers [21]. Candidate SB was also identified from facies discontinuities in the logs. From the logs, a change from forward stepping to back stepping parasequence stacking pattern was looked out for in the gamma ray log. The trend of shale resistivity shows increased resistivity towards SB and a decrease away from SB. From the biofacies data, candidate SB was inferred using the provided stratigraphic markers. Facies expression of the SB depends on the paleogeographic location of the section in the basin and the Systems Tract.

MFS and condensed sections were identified from log trend boundaries and/or log character and the provided biostratigraphic data. Gamma ray logs have high values at MFS and condensed sections. Shale resistivity values decrease towards MFS and increase away from MFS [21]. Faunal/floral density trends display increased density towards flooding surface and decreased density away from the flooding surface.

5.4 Delineation of Systems Tracts

Delineation of systems tracts was done after the surfaces were identified. Parasequence stacking patterns were used to identify the Lowstand Systems Tracts (LST), Transgressive Systems Tracts (TST) and Highstand Systems Tracts (HST), enveloped by the constrained surfaces (MFS, TS and SB).

The enveloping Sequence Boundary (SB) of a sequence, or its down dip correlative conformity, lies between the Highstand Systems Tract (HST) and the Lowstand Systems Tract (LST) according to the sequence stratigraphic depositional model propounded by [3], (Fig. 7). Transgressive Surface (TS) lies between the Lowstand Systems Tract (LST) and the Transgressive Systems Tract (TST). The Maximum Flooding Surface (MFS) caps the TST (Fig. 8).

TST is characterized generally by an overall retrogradational/fining upward stacking pattern of a sequence (Fig. 6). The stacking pattern can also be aggradational.

The HST is usually delineated by progradational/coarsening upward stacking patterns of parasequences (Fig. 6). The HST is also sometimes associated with blocky/serrated log motifs. However, the sediment/particle size of HST sediments remains relatively coarser in a shallow or shoaling paleobathymetric setting. The HST is bounded below by the MFS and above by the SB [3], (Fig. 7).

LST (PGC) is characterized by progradational/coarsening upward parasequences. It can also be blocky (BFF/PGC) (Fig. 6). The LST is bounded below by an SB and above by a Tansgressive Surface (TS) (Fig. 8).

5.5 Dating of identified Surfaces

Dating of identified key stratigraphic surfaces (where possible) was achieved by correlation to the third order cycles chart of [19], (Fig. 9) in association with chronostratigraphically significant bio-events (Table 1), wherever they were recorded. The marker shales *Bolivina sp, and Chiloguembelina sp*, etc., identified from biostratigraphic data were used to assign geologic age to the inferred surfaces.

Correlation of sequences, systems tracts, parasequence and/or parasequence sets of the wells was done using Petrel and Strata bug softwares.

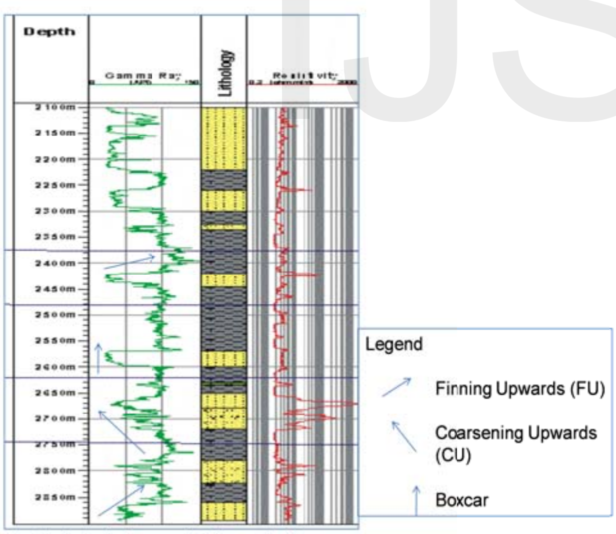


Fig. 6. Showing Stacking Patterns used in the interpretation of Parasequences

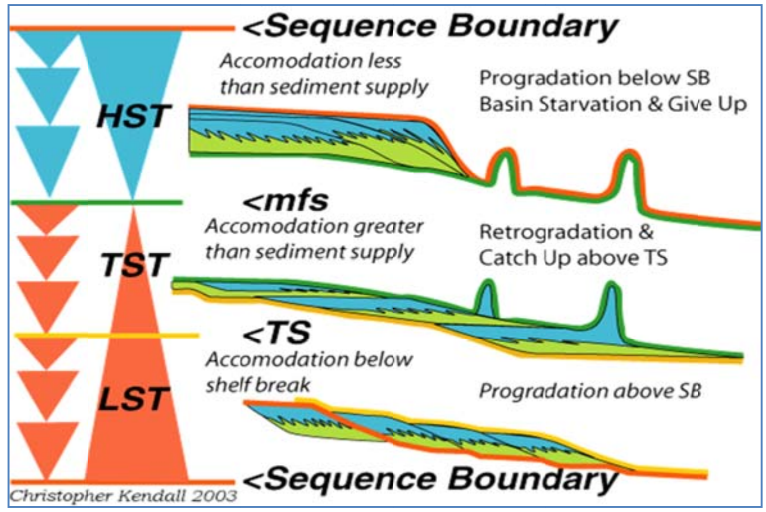


Fig. 7. Sequence Stratigraphic Model for the Interpretation of Systems Tracts and accompanying key Stratigraphic Surfaces [3].

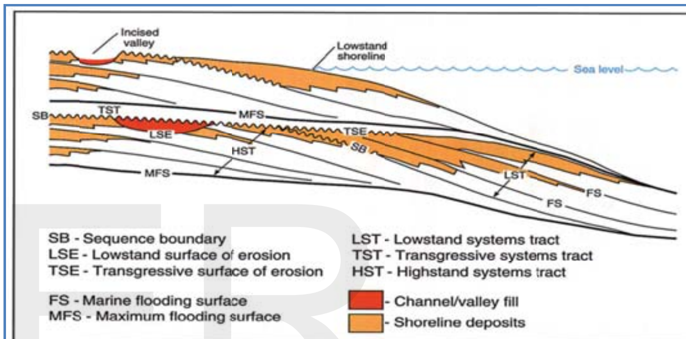


Fig. 8. Definition diagram showing sequences, Key surfaces and systems tracts [22].

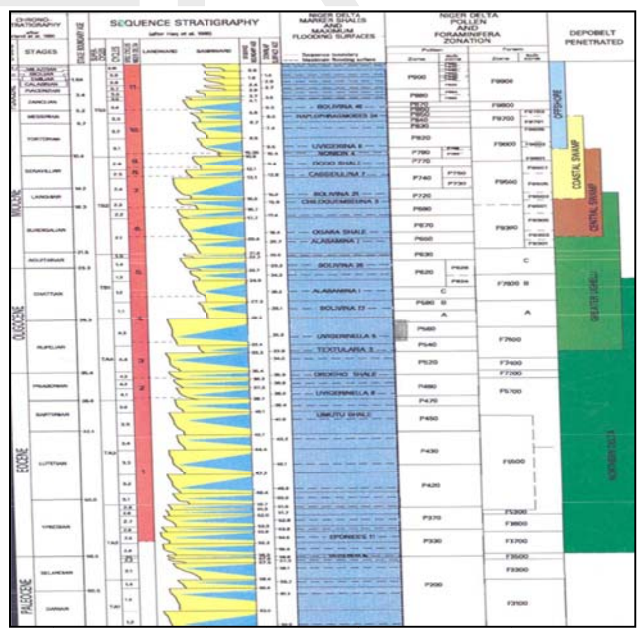


FIG. 9. NIGER DELTA CHRONOSTRATIGRAPHIC CHART [19]

6 RESULTS

The wells in "XY" field were arranged and interpreted according to spatial distributions in the well field which arranged the wells according to affinity and not with respect to well numbers (Fig. 5). The wells were numbered (001, 002, 003, 005, 006 and 007) based on time of drilling and completion.

6.1 Sequence Stratigraphy

The representative sequence stratigraphic interpretations in the "XY" field for Wells 006 and 007 are shown Figs. 10 and 11, respectively, while the comprehensive interpretations for the six wells are presented in tables 2, 3, 4, 5, 6, and 7 for Wells 002, 003, 005, 001, 007 and 006, respectively.

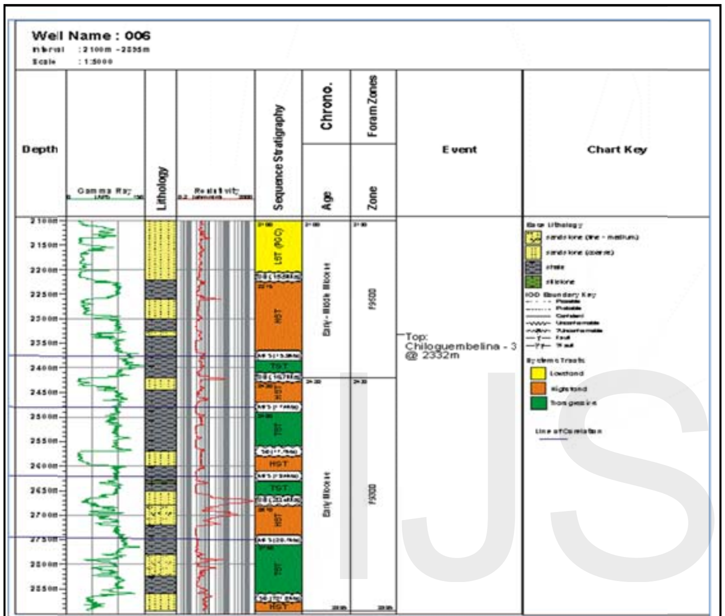


Fig. 10. Showing Representative Sequence Stratigraphic Interpretation of 006 Well, "XY" Field, Northern Niger Depobelt

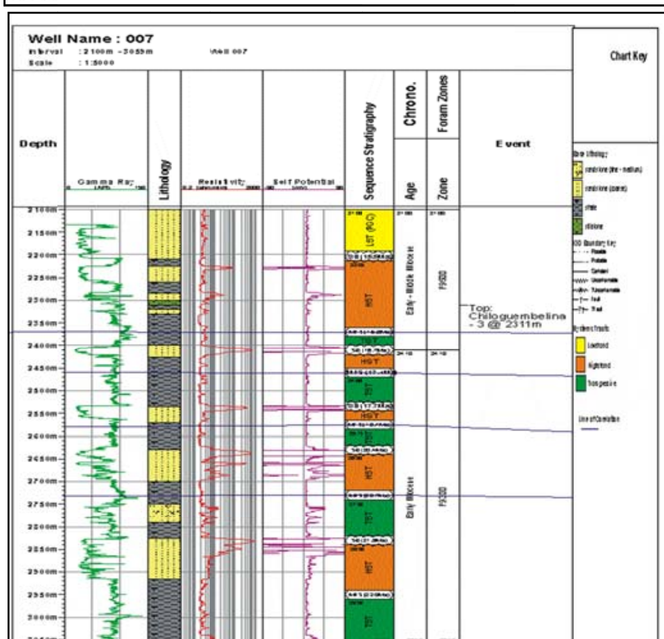


Fig. 11. Showing Representative Sequence Stratigraphic Interpretation of 007 Well, "XY" Field, Northern Niger Depobelt

Table 2. The summary of the sequence stratigraphic interpretation of Well 002 (2820-1218 m)

Interval (m)	Lithology	Stacking Pattern/Log Motif	Systems Tract	Depth/type of Chrono- Surface	Date of Chrono- Surface (Ma; after Haq et al., 1988)/Remarks
2820-2755	Sand/shale	Progradational (CU) – Blocky log motif	HST	2755 -SB	15.5 (Low SP and high Resistivity Values)
2755-2700	Sand/Shale	Retrogradational (FU)	TST	2700 - MFS	15.0 (High SP & low Resistivity logs values)
2700-2460	Shale/Sand	Progradational (CU)	HST	2460 -SB	13.1 (High resistivity & low Sp @ 2460 m)
2460-1960	Stacks of Sand/ Shale + Silt iontercalations	Progradation (CU): Blocky SP log Motif	LST (PGC)	1960 -TS	Sudden deflection of SP log to the left (High SP) = renewed transgression
1960-1915	Sand/Shale	Retrogradation (FU)	TST (Short-lived)	1915 -MFS	12.8 (High SP, low resistivity and top ooccurrence of *Uvigerina sp* at the depth of 1866m)
1915-1640	Shale/Sand i.e. (Bar Deposits)	Generally Progradational (CU)	HST	1640 -SB	12.1 (Low SP & high resistivity)
1640-1510	Sand/Silt/Shale	Retrogradation (FU)	TST	1510 -MFS	11.5 (High SP and Low Resistivity value)
1510-1460	Sand (+ Shale Laminae)	Aggradational	HST	1460 -SB	10.6 (Low SP and high resistivity log values at that depth
1460-1218	Sand/Silt/Shale	Retrogradation (FU)	TST	Peak not seen	-

Table 3. The summary of the sequence stratigraphic interpretation of Well 003 (2865-1107 m)

Interval (m)	Lithology	Stacking Pattern/Log Motif	Systems Tract	Depth/type of Chrono- Surface	Date of Chrono- Surface (Ma; after Haq et al., 1988)/Remarks
2865-2800	SandSilt//Shale	Retrogradational (FU)	TST	2800 - MFS	15.0 (retrogradational SP log motif and rich occurrence of Bolivina sp @ 2700m)
2800-2400	Sand/shale intercalations	Progradational (CU) – Blocky log motif	HST	2400 -SB	13.1 (Low SP Values)
2400-1990	Sand/Shale laminae	Blocky- Serrated	LST (PGC)	1990 - TS	SP log showed a sudden deflection to the right (i.e. high SP) initiating another transgression
1990-1960	Sand/Shale	Retrogradation (FU)	TST (Short interval)	1960 -MFS	12.8 (High SP and top ooccurrence of *Uvigerinassp* at the depth 1920m)
1960-1900	Shale/Sand	Progradational (CU)	HST	1900 -SB	12.1 (High resistivity @ 1900m)
1900-1550	Sand/Silt/Shale	Retrogradation (FU)	TST	1550 -MFS	11.5 (High SP)
1550-1260	Shale + Sand)	Progradational (CU)	HST	1260 -SB	10.6 (Low SP & high resistivity)
1260-1160	Sand/Shale	Retrogradation (FU)	TST	1160 -MFS	11.5 (High SP and Low Resistivity value)
1160-1107	Shale/Silt	Aggradational (Toe section of HST)	HST	Peak not seen	(Late rise of sea level)

6.2 Correlation of wells in the "XY" Field

The stratigraphic correlation of the six wells (002, 003, 005, 001, 007 and 006) was carried out using the interpreted Maximum Flooding Surfaces (MFSs). The wireline signatures of the genetic wells (002 and 003; 005 and 001 and 007and 006) also aided interpretations between well pairs.

The key surfaces used for correlation between Wells 002, 003, 005 and 001 are the 11.5Ma, 12.8Ma and 15.0Ma MFSs; while the link between these wells and wells 007 and 006 is the 15.9Ma MFS. The other correlation surfaces between Wells 007 and 006 are the 17.4Ma, 19.4Ma and 20.7Ma MFSs (Fig. 12).

Table 4. The Summary of the sequence stratigraphic interpretation of Well 005 (2890-1113 m)

Interval (m)	Lithology	Stacking Pattern/Log Motif	Systems Tract	Depth/type of Chrono- Surface	Date of Chrono- Surface (Ma; after Haq et al., 1988)/Remarks
2890-2885	Silt/Shale	Retrogradational (FU)	TST	2890 - MFS	15.0 (very Low resistivity)
2885-2770	Shale/Silt/Sand	Progradational (CU)	HST	2770 -SB	13.1 (Low GR & High resistivity)
2770-2500	Shale/Silt/Sand	Retrogradational (FU)	TST	2500 - MFS	12.8 (very Low resistivity & high GR)
2500-2300	Shale/Silt/Sand	Progradational (CU)	HST	2300 -SB	12.1 (High Resistivity)
2300-1950	Sand/Shale	Retrogradation (FU)	TST	1950 -MFS	11.5 (Top occurrence of Nonion sp at 1824m)
1950-1610	Shale/Sand	Progradational (Blocky Motif)	HST	1610 -SB	10.6 (High resistivity)
1610-1400	Sand/Shale	Retrogradation (FU)	TST	1400 -MFS	10.4
1400-1200	Shale/Silt/Sand	Progradational (Blocky Motif)	HST	1200 -SB	10.35 (High resistivity and low SP values esp. b/w 1285-1200)
1200-1113	Sand/Shale	Retrogradation (FU)	TST	Peak not seen	Abrupt shift of Resistivity log to the left and SP log to the left is suggestive of transgression

Table 5.The summary of the sequence stratigraphic interpretation of Well 001 (3057-756 m)

Interval (m)	Lithology	Stacking Pattern/Log Motif	Systems Tract	Depth/type of Chrono- Surface	Date of Chrono- Surface (Ma; after Haq et al., 1988)/Remarks
3057-2865	Sand/Shale	Progradational (CU)	HST	2865 -SB	16.7 (Low GR & High resistivity)
2865-2750	Sand/Silt/Shale	Retrogradational (FU)	TST	2750 - MFS	15.9 (very Low resistivity & high GR)
2750-2665	Shale/Sand	Progradational (CU)	HST	2665 -SB	15.5 (Low GR & High Resistivity)
2665-2550	Sand/Silt/Shale	Retrogradation (FU)	TST	2550 -MFS	15.0 (Low Resistivty; NO SP and GR logs at this depth; Rich occurrence of *Bolivina sp* at depth 2598 assisted interpretation)
2550-2300	Shale/Sand	Progradational (CU)	HST	2300 -SB	13.1 (High resistivity)
2300-2100	Silt/Shale	Retrogradation (FU)	TST	2100 -MFS	12.8 (Low Resistivity & high GR)
2100-2040	Shale/thin sand unit	Progradational (CU)	HST	2040 -SB	12.1 (High resistivity)
2040-1920	Sand/Shale	Retrogradation (FU)	TST	1920 -MFS	11.5 (Low Resistivity value; Top occurrence of *Nonion sp at 1854m)*
1920-1690	Sand	Blocky (Channels)	HST	1690 -SB	10.6 (High resistivity)
1690-1370	Sand/Silt/Shale	Retrogradation (FU)	TST	2370 -MFS	10.4 (Low Resistivty)
1370-1030	Shale/Sand	Progradational (CU)	HST	1030 -SB	10.35 (1035m is the base of sand body = incised valley fill)
1035-756	Silt/Sand	Blocky (Channels)	LST (PGC)		End of phase (TS) not seen at the top of the interval

Table 6. The summary of the sequence stratigraphic interpretation of Well 007 (3059-2100 m)

Interval (m)	Lithology	Stacking Pattern/Log Motif	Systems Tract	Depth/type of Chrono- Surface	Date of Chrono- Surface (Ma; after Haq et al., 1988)/Remarks
3059-2950	Shale	Retrogradational (FU)	TST	2950 - MFS	22.0 (High GR, high SP & low Resistivity logs values)
2950-2830	Shale/Sand	Progradational (CU)	HST	2830 -SB	21.8 (Low GR and High resistivity)
2830-2730	Stacks of Sand/ Shale	Retrogradational (FU)	TST	2730 -MFS	20.7 (High GR and SP with low Resistivity log values at 2730)
2730-2630	Shale/Sand i.e. (Distr. Mouth Bar Deposits)	Generally Progradational (CU)	HST	2630 -SB	20.4 (Low GR, low SP & high resistivity)
2630-2575	Sand/Shale	Retrogradation (FU)	TST	2575 -MFS	19.4 (High SP and Low Resistivity values)
2575-2535	Shale + Sand	Aggradational/ Progradational	HST	2535 -SB	17.7 (Low GR and high resistivity log values at that depth
2535-2460	Predominantly Shale	Retrogradation (FU)	TST	2460 -MFS	17.4 (High SP and Low Resistivity values)
2460-2410	Shale/Sand	Progradational (CU)	HST	2410 -SB	16.7 (Low GR and high resistivity log values at that depth
2410-2370	Predominantly Shale	Retrogradation (FU)	TST	2370 -MFS	15.9 (High SP and Low Resistivity values; Top occurrence of Chiloguembelina-3 at 2311)
2370-2230	Shale/Silt/Sand	Progradational (CU)	HST	2230 -SB	15.5 (Low GR and high resistivity log values at that depth
2230-2100	Predominantly Sand (Channel Fill Deposits)	Progradational (CU)	LST (PGC)	Peak of the interval was not Observed -	

Table 7. The summary of the sequence stratigraphic interpretation of Well 006 (2895-2100 m)

Interval (m)	Lithology	Stacking Pattern/Log Motif	Systems Tract	Depth/type of Chrono- Surface	Date of Chrono- Surface (Ma; after Haq et al., 1988)/Remarks
2895-2870	Sand	Progradational (CU)	HST	2870 -SB	21.8 (Low GR and High Resistivity). Onset of this regressive phase was not observed at the TD.
2870-2750	Predominantly Shale units	Retrogradational (FU)	TST	2750 -MFS	20.7 (High GR and low Resistivity log values at 2750)
2750-2670	Shale/Sand	Progradational (CU)	HST	2670 -SB	20.4 (Low GR & high resistivity)
2670-2620	Sand/Silt/Shale	Retrogradation (FU)	TST	2620 -MFS	19.4 (High SP and Low Resistivity values)
2620-2570	Shale + Sand	Progradational /Blocky log motifs	HST	2570 -SB	17.7 (Low GR and high resistivity log values at that depth
2570-2480	Sand/Shale	Retrogradation (FU)	TST	2480 -MFS	17.4 (High GR and Low Resistivity values)
2480-2420	Shale/Sand	Progradational (CU)	HST	2420 -SB	16.7 (Low GR and high resistivity log values at that depth
2420-2375	Sand/ Shale	Retrogradation (FU)	TST	2375 -MFS	15.9 (High SP and Low Resistivity values; Top occurrence of Chiloguembelina-3 at 2332 m)
2375-2215	Shale/Sand	Progradational (CU)/Bloky log motifs	HST	2215 -SB	15.5 (Low GR and high resistivity log values at that depth)
2215-2100	Stacks of blocky log motifs (Sands of Channel Deposits)	Progradational (CU)/ Blocky	LST (PGC)	Peak of this interval was not Observed at the top depth of the analysed interval of the well -	

The result of the interpretations across the well field showed that Well 002 has three complete and one incomplete 3rd order sequence (SEQs 4 to 7), including a Low Stand Systems Tract (LST) of the prograding wedge or slope complex (PGC) in SEQ 4; Well 003 has two complete and two incomplete 3rd order sequences (SEQs 4 to 7), also with the LST (PGC) in SEQ 4; Well 005 has three complete 3rd order sequences (SEQs 5 to 7) and two incomplete sequences; Well 001 has five complete 3rd order sequences (SEQs 3 to 7) capped by a PGC unit in SEQ 7. Wells 007 and 006 both have four complete 3rd order sequences also capped by the PGC in SEQ 4 (Fig. 12). The LST in SEQ 4 delineated in four wells (002, 003, 007 and 006) was not observed in Wells 005 and 001. The unit may have been eroded before the deposition of the overlyng TST.

Another PGC (LST), delineated in SEQ 7 in Well 001 was not delineated in the other five wells (Fig. 12). Well 001 has the most extensively logged depth of 3057-756 m. The continuity of the predominantly sandy systems tract (LST) in SEQ 7 was not ascertained based on the available data as sections that represent the upper sections/sequences (less that 750 m) in the well field were not provided.

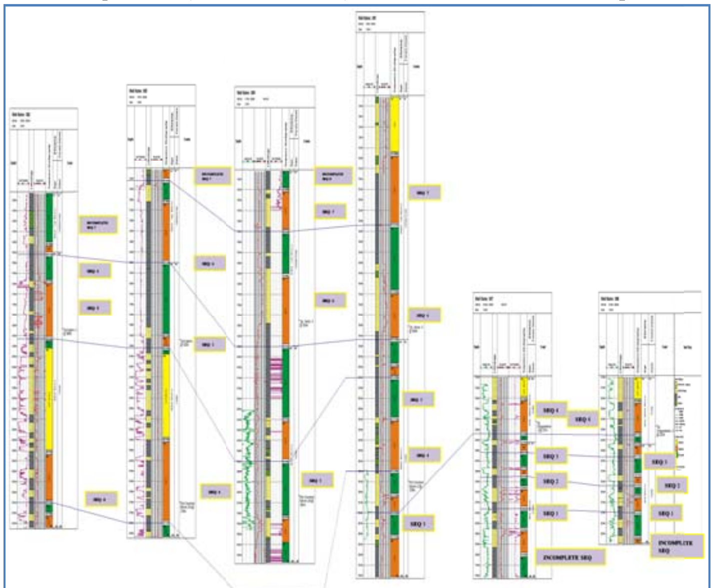


Fig. 12. Correlation panel of wells in the "XY" Field Greater Ughelli Depobelt Niger Delta

The key surfaces used for correlation between Wells 003, 002, 005 and 001 (i.e. 11.5Ma, 12.8Ma and 15.0Ma MFSs) were delineated at different depths in the four wells (Table 8).

From the foregoing (Table 8), it can be established that the "XY" Field is faulted and/or have its accompanying clinoforms dipping in one direction. Normal (growth) fault regime is prevalent in the Tertiary Niger Delta of Nigeria, hence, displacements resulting from normal faults is inferred for the sequences in the "XY" field. Well 003 is on the downthrown side of Well 002 while Well 005 is on the downthrown side of Well 001 (Table 8). Similarly, the variation in the depth of occurrence of the 15.9 Ma chrono-surface in Wells 005, 007 and 006 and that for other surfaces linking Wells 007 and 006 shown in table 9 also highlighted the down-dropping of Well 006 relative to Well 007. The throw is relatively small (about 5m) compared to that between Wells 005 and 006 (385m). This discontinuity and the down-dropping of strata in the well field fingerprint the degree of compartmentalization in the "XY" well field.

Table 8. Showing observed variations in depth of the key chronostratigraphic surfaces in "XY" Field

Well No.	Logged Depth (m)	Depth of 11.5Ma Chrono-surface (m)	Depth of 12.8Ma Chrono-surface (m)	Depth of 15.0Ma Chrono-surface (m)
003	2865-1107	1550	1960	2800
002	2820-1218	1510	1915	2700
005	2890-1113	1950	2500	2890
001	3057-756	1920	2100	2550

Table 9. Showing observed variations in depth of the key chronostratigraphic surfaces across Well 005, 006 and 007 in "XY" Field

Well No.	Logged Depth (m)	Depth of 15.9Ma Chrono-surface (m)	Depth of 17.4Ma Chrono-surface (m)	Depth of 19.4Ma Chrono-surface (m)	Depth of 20.7Ma Chrono-surface (m)
005	2890-1113	2750			
006	2895-2100	2375	2480	2620	2750
007	3059-2100	2370	2460	2575	2730

7 DISCUSSION

7.1 Depositional Sequences in the "XY" Field

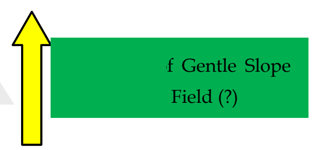
The studied stratigraphic column in the "XY" field is comprised of a total of nine genetic sequences made up of seven complete 3rd order sequences (SEQ 1-7) and two incomplete sequences. Sequence distribution in the field showed that Well 002 has three complete and one incomplete 3rd order sequences (SEQs 4 to 7), including a Low Stand Systems Tract (LST) of the prograding wedge or slope complex (PGC) in SEQ 4; Well 003 has two complete and two incomplete 3rd order sequences (SEQs 4 to 7), also with the LST (PGC) in SEQ 4; Well 005 has three complete 3rd order sequences (SEQs 5 to 7) and two incomplete sequences; Well 001 has five complete 3rd order sequences (SEQs 3 to 7) capped by a PGC unit in SEQ 7. Wells 007 and 006 both have four complete 3rd order sequences also capped by the PGC in SEQ 4 (Fig. 12).

The other accompanying systems tracts in the sequences, however, formed distinct deltaic complexes consisting of a number of genetically linked retrogradational, progradational and aggradational systems comprising of TST, HST and LST. The major architectural facies elements of the systems include: shoreface deposits, channel fills, prodelta shales and prograding slope complexes.

The overall similarity recorded in the organization and distribution pattern of the sequences and systems tracts in the "XY" Field and the observed gradational migration and gentle sloping depositional systems in non-faulted blocks depict clinoforms that are laterally continuous and traceable in the subsurface. For example, the LST in SEQ 4 slopes gently from wells 006 to 002 (Table 10).

Table 10. Showing the trend of LST in SEQ 4 in the "XY" Field

Well	Depth (m)
002	2460 – 1960
003	2400 – 1990
007	2230 – 2100
006	2215 – 2100



It has been noted that the absence of this depositional system (i.e the LST in SEQ 4) in Wells 005 and 001 is probably due to subsidence and erosion, which corroborates the existence of episodic and asymmetrical subsidence in the Tertiary and Quaternary periods [23]. These structures are probably responsible for the displacements (faults) that have compartmentalized the "XY" Well field.

Hence, local tectonics affected the sedimentation pattern in the "XY" Well Field. Stratigraphic base level changes caused by eustacy also played a role in the development of the sequences since the delineated MFSs matched with major sea level rises recorded in the Chronostratigraphic Chart of [19].

A tectono-eustatic control is therefore, proposed for the development of stratigraphic sequences of the Tertiary strata in the Greater Ughelli Depobelt, Niger Delta.

7.2 Petroleum Plays of the "XY" Field

The "XY" Field is compartmentalized into three major blocks by synthetic faults which are suggested to have been formed as a result of subsidence. The weight of the ensuing sand accumulations in the sequences may have triggered faulting in the well field [24]. The resulting main compartments are: Block 1 comprising of Wells 002 and 003; 2 housing Wells 001 and 005 and Block 3 with Wells 007 and 006. The throw between Blocks 1 and 2 is relatively small comapared to that between Blocks 2 and 3. This trend is consistent with the growth fault pattern in the Niger Delta. The compartmentalization of the "XY" field as a result of rifted fault blocks would no doubt reduce the areal extent and continuity of the reservoirs in the "XY" Field for exploration and development.

The most laterally continuous sandstone unit in the well field, however, is the Prograding Wedge Complex (LST) sands of SEQ 4 obserevd in Blocks 1 and 3 (Fig. 12). Despite the obvious truncations observed in Wells 5 and 1 of Block 2, SEQ 4 was also observed to be laterally significant in Wells 7 and 6.

The sands of this Lowstand Systems Tracts (LST) of the earliest sequences (SEQ 4), within each of the two blocks, therefore hold great potentials for hydrocarbon accumulation and can be targeted as the major petroleum plays in the "XY" Field. Accumulation of hydrocarbons can occur in the structural traps provided by the deformed LST reservoirs of SEQ 4, if the other elements of a petroleum system (source rock, timing, seal rock) are present. It has been widely reported that growth fault-related structural traps form the dominant traps in the petroliferous Niger Delta [24].
However, part of the reasons why sequence stratigraphy was advanced in the study area was to discover subtle stratigraphic traps that result from rapid facies changes occurring between successive systems tracts. The cyclic pattern of the alternating Transgressive Systems Tract (TST) and the Highstand Systems Tract (HST) in the studied wells is indicative of a good environment for organic matter accumulation and generation. The pelagic shales of the TST could form good source rocks and cap rocks for the underlying and overlying HST and LST given the right conditions.

Reservoir quality sands within the HST could also serve as good reservoirs while faults, active in this area, could serve as traps and/or conduits for migration of hydrocarbons. The distal shale toes of the prograding wedge and transgressive shales would form seals for (potential) stratigraphic traps in the study area. In fact the alternation of HST and TST sands and shales respectively, provides a union of reservoir and seal rocks that are essential for hydrocarbon accumulation and stratigraphic trapping.

If the sands within the prograding wedge complex are endowed with and sealed by the overlying transgressive shales, potential stratigraphic traps would be formed.

8 CONCLUSION

The task of achieving Nigeria's crude oil reserves target of about 40 billion barrels and production of increased volumes of Liquefied Natural Gas (LNG) in order to meet increasesd export and domestic demands necitated the search for oil and gas with a more accurate technique in the Greater Ughelli Depobelt, Niger Delta.
Sequence stratigraphic technique was used to subdivide the stratigraphic column of the "XY" well field into sequences and systems tracts based on the integration of well logs and biostratigraphic data. The technique also delineated quality petroleum plays (reservoirs), their continuity and other elements of the petroleum system (source, traps, e.t.c) for the sustainable development of the resource in the Niger Delta Basin.
The summary of the sequence stratigraphic interpretation of Wells 002 (2820-1218m), 003 (2865-1107 m), 005 (2890-1113 m), 001 (3057-756 m), 007 (3059-2800 m) and Well 006 (2895-2800 m) revealed a total of nine sequences comprising of seven complete and two incomplete 3rd order sequences.

The accompanying systems tracts in the sequences that formed distinct deltaic complexes consisted of a number of genetically linked retrogradational, progradational and aggradational deltaic systems that recorded similar organization and spatial distribution that depict a number of clinoforms which would be traceable in the subsurface.

The stratigraphic correlation of the six wells carried out using the interpreted Maximum Flooding Surfaces (MFSs) revealed the existence of faults/discontinuities, which has compartmentalized the "XY" Field into three main blocks. The faults could form structural traps and conduits for migration of generated hydrocarbon if the other elements of a petroleum system (source rock, timing, seal rock) are present.

The absence LST of SEQ 4 in wells 005 and 001 is attributed to subsidence and erosion, which corroborated the existence of episodic and asymmetrical subsidence in the Tertiary and Quaternary periods. Local tectonics therefore, affected the sedimentation pattern in the "XY" Well Field, while stratigraphic base level changes caused by eustacy also played a role in the development of the sequences.

The sands of the Lowstand Systems Tracts (LST) in SEQ 4, within each of the mini-basins hold great potentials for hydrocarbon accumulation and can be targeted as the main petroleum plays in the "XY" Field.
The cyclic alternation of Transgressive Systems Tracts (TST) and the Highstand Systems Tracts (HST) in the studied wells is indicative of good environments for organic matter accumulation and generation. The pelagic shales of the TST could form good source rocks and cap rocks for the underlying and overlying reservoirs of the HST and LST given the right conditions.

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