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Implications of Sequence Stratigraphic Technique to Petroleum Exploration and Production: A Case Study of XP Field, Onshore Niger Delta, Nigeria

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ABSTRACT

This work builds on the detailed sequence stratigraphic analysis that has been carried out on the XP Field. It highlights the implications of the technique to exploration and production potentials in the XP field. Well logs and biostratigraphic data integrated revealed key Maximum Flooding Surfaces (MFS1, MFS2, and MFS3) and sequence boundaries designated SB1, SB2 and SB3, between the intervals of 3140 and 4232m. Maximum Flooding Surfaces are intervals showing high abundance and diversity of foraminifera which represent three regional marker shales identified, and act as seals to the hydrocarbon-bearing sands. The erosional surfaces coincide with intervals that are barren in faunal activity and are interpreted as sequence boundaries. The delineated sequences show three depositional patterns (progradation, retrogradation and aggradation) resulting from fluctuation in sea level (regression and transgression).Three systems tracts recognized include lowstand systems tracts (LST), transgressive systems tracts(TST) and highstand systems tracts (HST). The LST has excellent reservoir quality compared to TST (heterolithic reservoirs), and forms an exploration target during subsurface mapping. The stratigraphic positions of sequences with highest prospect falls within 4232m to 3140m (productive interval) and can be penetrated at approximately the same depth range across the field, except for fault interception. The youngest sequence has more water-bearing reservoirs, which provides a potential for water injection at the depleting stage of the reservoirs when natural drive mechanism can no longer be effective.

Keywords: *Sequence, Progradation, Aggradation, Prospect, Exploration, Production*

1. INTRODUCTION

Sequence stratigraphy is the study of sedimentary rock relationships within a chronostratigraphic framework (Wheeler, 1958; Fairbridge, 1961; Sloss, 1963; Van Wagoner et al., 1990; Neal and Vail, 1993). Predicting the lateral and vertical distribution of depositional sequences and their component systems tracts and facies plays an important role in exploration for and development of sandstone reservoirs (Slatt, 2006).

The Niger Delta sedimentary basin situated in the Gulf of Guinea comprises of traditionally three stratigraphic units of variable geologic characteristics. These can be classified as topset beds, foresets and bottomset as revealed from seismic stratigraphy. The topset portion is a regressive continental unit called the Benin Formation; the foreset unit forms the prograding Agbada Formation, whereas the marine clay/shale of the Akata Formation is the bottomset portion of the delta depositional system. Several works carried out by researchers have revealed the stratigraphy, Sedimentology, structural styles and the petroleum potential of the basin (Adesida eta al; 1977; Avbovbo, 1978; Reijers, 2011).

The Niger Delta (Fig. 1) has been the focus of hydrocarbon exploration since 1937. Now it is Africa's leading oil province. The delta has been penetrated by more than 5,000 wells. Recently, there is a paradigm shift in exploration activity towards the offshore part of the basin in a bid to increase oil and gas reserves. The evolution of the delta is controlled by pre- and synsedimentary tectonics as described by Evamy et al. (1978), Ejedawe (1981), Knox & Omatsola (1987) and Stacher (1995). The shape of the Cretaceous coast line (Reijers et al., 1997) gradually changed with the growth of the Niger Delta. A bulge developed due to delta growth. This changing coastline interacted with the palaeo-circulation pattern and controlled the extent of incursions of the sea (Reijers et al., 1997). Other factors that controlled the growth of the delta are change in climate, the proximity and nature of sediment source areas. Due to slow thermal cooling of the underlying lithosphere, the delta subsides gradually. During the Middle-Late Eocene, sediments were deposited west of the inverted Cretaceous Abakaliki High and south of the Anambra Basin in what became the northern depobelt of the Niger Delta. The first coarse clastic deposits have been dated on the basis of microfloral units (Evamy et al., 1978) as Early Eocene. Studies by Weber & Daukuro (1975), Ejedawe (1981) and Ejedawe et al. (1984) clarified that the embryonic delta subsided during the Late Eocene to Middle Oligocene <700 m/Ma and prograded approx. 2 km/Ma along three depositional axes that fed irregular, early delta lobes that eventually coalesced. Thick sandy sediment accumulations thus formed in the active Greater Ughelli depobelt. Stratigraphically, the delta-top Benin Group (Reijers, 2011) overlies the delta-front Agbada Group and the pro-delta Akata Group. The composition of the subsurface Benin Group reflects the present-day Quaternary land and swamp outcrops; the Agbada Group reflects the beach ridges and the Akata Group the offshore sands, silts and clays.

Previous sedimentological, biostratigraphical and sequence-stratigraphic studies (Ladipo, 1992; Stacher, 1995; Reijers et al., 1997) revealed the combined influence of eustatic cyclicity and local tectonics. Depositional sequences consist of strata bounded by unconformities and their lateral equivalents are only recognized in specific sectors of the delta, and in contrast, delta - wide genetic sequences as defined by Galloway (1989) are more readily identifiable in the Niger Delta (Reijers, 2011).

Sequence stratigraphic technique applied in several sedimentary basins in the world has led to the discovery and recovery of more hydrocarbon reserves. In the north Central Gulf of Mexico this technique has improved reservoir development and management strategies, provided insights into basin fill history, and contributing to the ongoing exploration successes in the basins (Meckel, 2003). In the outer continental shelf Gulf of Mexico, 61% of proved reserves, 40% of produced hydrocarbon and 40% of remaining reserves were identified using high frequency sequence stratigraphic technique (Rassi, 2002; Rassi and Hentz, 2003; Hentz et al, 2002**).** The highest permeability reservoirs in the East Sakhalin Shelf, Russia, were identified by mapping 3rd order shoreface deposits (Mathew et al, 2003). The application of sequence stratigraphic concept in studying the various oil fields in the Niger Delta sedimentary basin is relevant to improved exploration techniques and the discovery of unidentified resources. The technique serves as a tool for both local and regional mapping and correlation of stratal units. The division of depositional packages into genetic units is well understood through the concept of sequence stratigraphy. The main objectives of this study involve applying the sequence stratigraphic technique in the prediction of depositional facies to identify potential source sediments, reservoirs and sealing potentials, and to identify exploration and production potentials and capabilities within the field.

2. GEOLOGICAL SETTING OF TERTIARY NIGER DELTA

The Niger Delta sedimentary basin evolved following the Early Cretaceous break up between the South American and the African plates. The tectonic framework, stratigraphy and sedimentation pattern of the Niger Delta sedimentary basin is well reported in several literatures (Weber and Daukoru, 1975; Short and Stauble, 1967; Whiteman, 1982, Doust and Omatsola, 1990, Reijers, 2011). Several episodes of transgressions and regressions accounted for the sedimentary units in both the Cretaceous and Tertiary Southern Nigerian sedimentary basins (Odigi, 2007). The delta covers an area extent of about 100,000 km^2 and represents the regressive phase of the third cycle of deposition in the southern Nigeria sedimentary basins, which began during the Paleocene and has continued to the present day.

3. STUDY LOCATION

The field is located in the onshore portion of the Tertiary Niger Delta sedimentary basin (Figure 1), and falls within the Greater Ughelli Depobelt. The three wells (A,B and C) studied in the area are separated at a distance of about 8km between A and B, and B and C, and about 15.2km between A and C covering an area extent of about 18.9 Sq.km.

Fig.1: Map of Niger Delta showing the Study Area

4. MATERIALS AND METHOD

The datasets issued for the three wells (A, B and C) include; a suit of well logs comprising of Gamma Ray, Resistivity, Sonic, Neutron and Density logs; biostratigraphic data contains information on foraminifera abundance and diversity, F-zonation and paleobathymetric data. Niger delta chronostratigraphic chart, an adaptation of the global chronostratigraphic chart of Haq et al., (1988) was used with the biostratigraphic data to assign ages to the bounding surfaces.

The top and base of major shale units that have significant paleontological record were correlated. The reservoirs fall within the shales. The stacking patterns of the systems tracts and their relationship with key chronosurfaces coupled with biostratigraphic information help in the subdivision of the entire stratigraphic section in the field into several depositional sequences using the Vail et al., 1977 approach.
The biofacies plots involving foraminiferal diversity versus depth, foraminifera abundance with depth, and environment versus depth were performed using Microsoft Excel and integrated into the log for detail interpretation.

4. RESULTS AND DISCUSSION

Integration of both well logs and biostratigraphic data has revealed hydrocarbon exploration and production potentials in the XP field. Two depositional sequences with its internal geometric elements have been reconstructed from three key dated unconformities and major flooding surfaces (Momta and Odigi, 2014).

LITHOLOGIC DESCRIPTION FROM WELL LOGS

Two major lithologic types are inferred from the gamma ray log motif as seen in Fig.3a and 3b. The key chronostratigraphic surfaces correlated below are based on time but also revealed

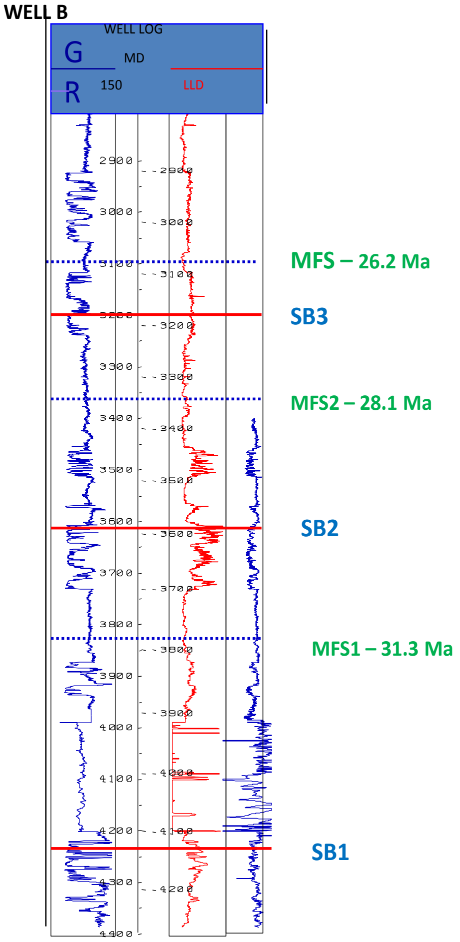

Fig.3a: Log of Well B Showing key Chronosurfaces

The two main lithologies present in the field. The interval having very high gamma ray log signal to the right (approaching 150^0 API) represents shale units. Three of these shales have been identified as regional. The shale occurred in both significant amounts in an environment that is wholly marine depositional setting, and in variable proportion for a paralic depositional setting. The high gamma ray log signal is interpreted to be very fine grained pelitic sediments (clay/shale).

A coarsening upward or fining upward unit within a forestepping or backstepping successions of the log pattern defines stacking patterns of genetic units. This aided well correlation, reservoir identification, and delineation of depositional environment. The environments inferred from the gamma ray log motif include channel sand, shoreface and deep marine clay/shale.

CHANNEL SAND

Channel sandstone is characterized by unidirectional, cross-bedded, moderate to poorly sorted, fine-coarse grained sandstone. The coarse grained and poorly sorted sandstone reflects a fluvial dominated environment in which sand deposition was as a result of the migration of sinuous to straight crested dunes under high energy fluvial currents. The Gamma Ray has a blocky profile with weak fining upward. This can be interpreted as tidally influenced fluvial dominated channel formed in marginal marine incised valley settings. It is characterized by good to very good reservoir quality.

UPPER SHOREFACE

This facies is characterized by shale-free sandstone successions. The basal unit is characterized by very well sorted, fine grained sand. The sedimentary structures and absence of shale deposits indicate deposition between fair weather wave base and beach.

LOWER SHOREFACE

This facie shows a coarsening upward from intensely bioturbated sandy and muddy heterolithics to hummocky cross-stratified and rippled sandy heterolithics. Vertically it displays a progressive increase in sand/shale ratio. Shoreface sands are interpreted to be wave-dominated with ripples and hummocky cross stratification. The intensely of bioturbation often indicates reduced sedimentation rates on a low energy, or more slowly prograding shoreface. The hummocky cross stratification units reflect sedimentation under conditions of alternating storm and quiet water conditions between storm and fair weather base. The lower shoreface is characterized by poor reservoir quality at the heavily bioturbated units. It represents a thin-bedded shoreface reservoir. The deep marine environment is composed of majorly shale displaying very high gamma ray values.

BIOSTRATIGRAPHIC DATA INTERPRETATION

Biostratigraphy uses the chronostratigraphic range of fossil species to correlate stratigraphic sections (Emery and Myers, 1997), and their paleo-environmental preference to provide information on depositional settings. It is an important tool in the identification of sequences and systems tracts, dating of sequence boundaries and maximum flooding surfaces (MFS). The biofacies data provided for this study shows abundance and diversity of foraminifera microfossils of which three were recognized as index fossils used in dating and identifying marker shales. Table 1 shows the depth interval where the foraminifera zones occur. The youngest (between 2790 and 2910m) marker shale is not dated here (Table 1), and may fall within Late Oligocene to Early Miocene. The Uvigerinella 5 zone, which is the oldest major flooding surface, occurs between 3870-3740m and the F-zone is F7600/F7800. The age of the sediments in the field dates between 26.2 – 31.3Ma **(**Early- Late Oligocene**)** and falls within the Greater Ughelli depobelt (Table 2).

Table 1: Microfaunal zonation of XP-Field

Top depth(m)	Bottom Depth (m)	F.Zone	Remarks
2790	2910	F7800	No data
3050	3110	F7800	Alabamina 1
3230	3450	F7800	Bolivina 27
3740	3870	F7600/F7800	Uvigerinella 8

Table 2: Biostratigraphic Data Table

Well name	Chronosurface	Depth (m)	Marker Shale	Age (Ma)	F Zones	P Zone	Epoch	Remark
B	MFS 3	3080	Alabamina 1	26.2	7800	580	Oligocene	Greater Ughelli depobelt
B	MFS 2	3420	Bolivina 27	28.1	7800	550	Oligocene	Greater Ughelli depobelt
B	MFS 1	3840	Uvigerinella 5	31.3	7600/ 7800	560	Oligocene	Greater Ughelli depobelt

DEPOSITIONAL SEQUENCES AND RECOGNITION OF KEY SURFACES

Two major depositional sequences have been reconstructed from three regional unconformities and three major maximum flooding surfaces (Fig.3b). Three sequence boundaries form the two major depositional cycles. The third sequence has an undated boundary and may be dated Early Miocene. Each sequence is recognized using the top and basal chronostratigraphic surface (SB) and the position of the systems tracts that stack to form the sequence.

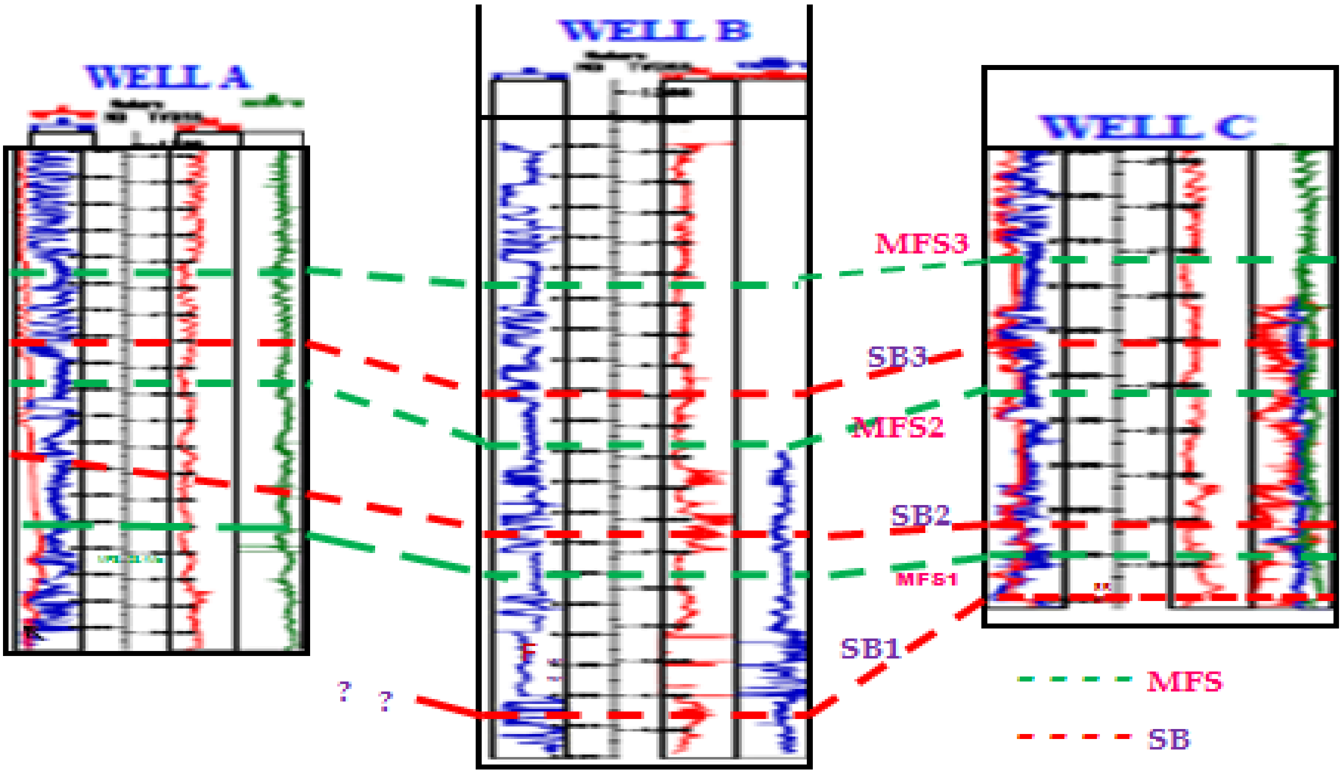

Fig.3b: Well Log Showing Three Wells Studied and Key Chronosurfaces

SEQUENCE BOUNDARIES

Sequence boundaries mark the transition from a reservoir to shale, or change in facies of different ages. They are significant surfaces that represent a time in which sediments were not deposited, or were deposited but have been eroded.
The three regional unconformities designated SB1, SB2 and SB3 subdivide the stratigraphic section into two depositional sequences with the third sequence not dated. The sequence boundaries fall within the sand-bearing intervals (Fig.3b) and correspond to the horizon that is barren in foraminiferal abundance and diversity (Fig.7). These surfaces were also recognized on well logs using log motifs and their consequent stacking patterns (Fig.4, 5). In the stratigraphic section, SB1 occurred at 4232m, SB2 at 3638m and the youngest dated boundary, SB3 occurs at 3140m (Fig. 3b).

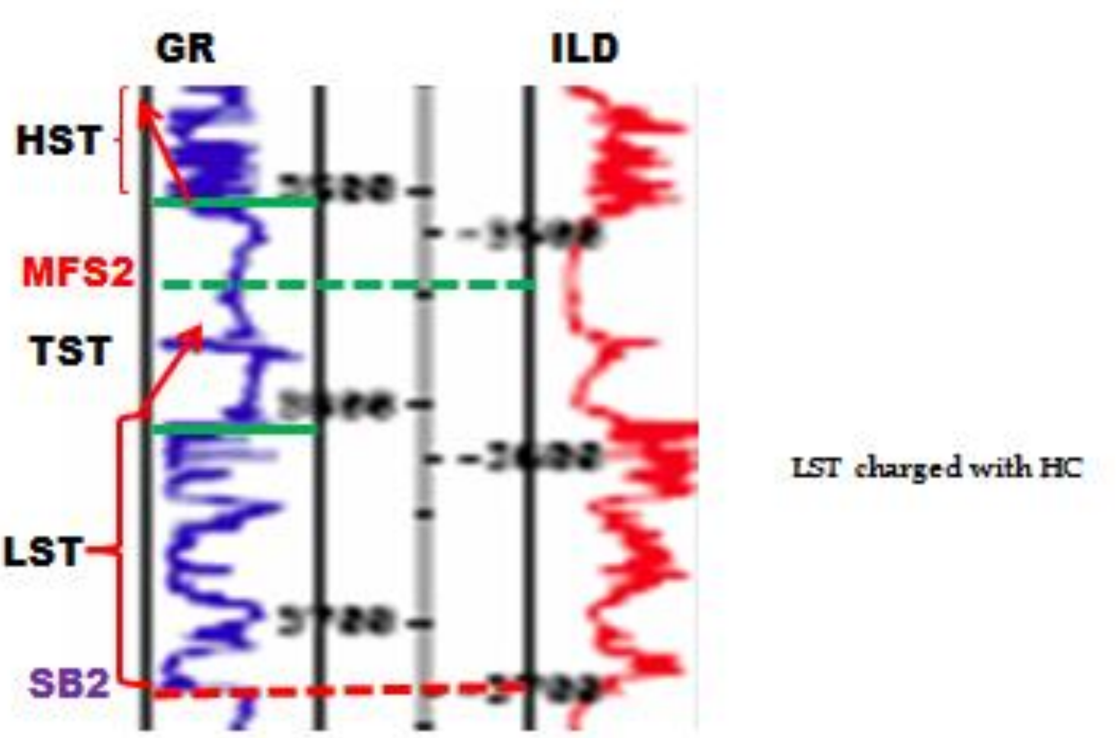

Fig. 4: A portion of Well B showing SB2, LST, TST, MFS2 and HST. LST and HST are charged with hydrocarbons.

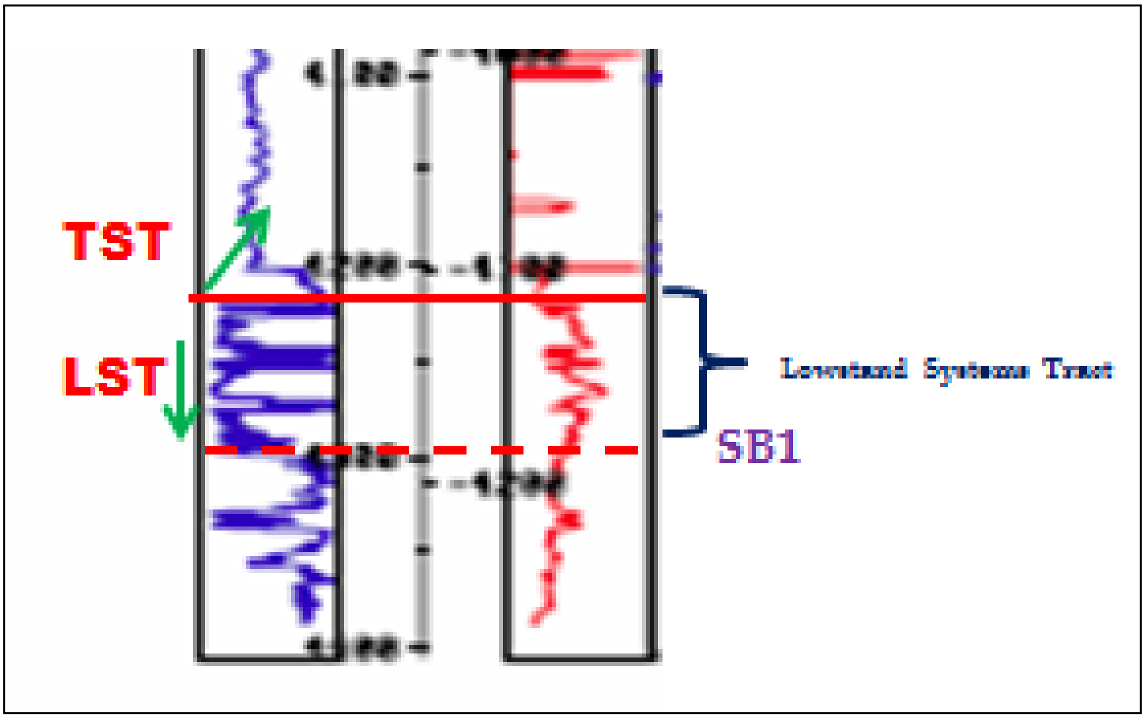

Fig. 5: Sequence Boundary 1 and associated Systems Tracts

Sequence 1 (SB1) is dated 32.4Ma (4232m).The base of this sequence designated SB1 occurred at 4232m depth and overlain an agradationally stacked sand unit (the Lowstand Systems Tract) and a transgressive unit at the top (Fig. 4). The thickness of the sand-body at the base of this sequence is about 70m (4230-4300m) in well B. Overlying this unit is a thick shale that represents a deep marine deposit. This sequence is not represented in other wells but the top of it forms the base of sequence 2.

The second sequence boundary (SB2) occurred at (3640m) and is dated 29.3Ma**.** This sequence begins at the base with a blocky/crescentic shape sand-body (3640m – 3610m). It has sharp lower and upper contacts and represents an aggradational stacking unit typical of LST (see fig. 4). The LST forms as the rate of eustatic fall slows. It eventually equals the rate of subsidence and is then exceeded by the rate of subsidence, leading to a slow relative rise in sea-level. The entire sequence is found between the intervals of 3640m-3140m.

Sequence boundary 3 (SB3) is the top boundary in sequence 2, and occurred at 3140m. The interval above this sequence boundary forms the third sequence and categorized as an undated sequence because it has no top boundary. It occurs between the intervals of 3140m-2400m and the chronosurface is at 3140m in well B. MFS 26.2Ma occurs within this cycle, and comprises of three regional thick shale units that are traceable in all the wells with some minor sand-shale intercalations. Likely environments deduced from this sequence based on their stacking patterns include channel sands, point bars, overbanks and deltaic front facies. A possible sequence boundary is noted at depth 2930m in well B. The sand-body here shows gradational base and sharp upper contact (fig.4). This contact occurs at depth 3040m in well A, and 2860m in well C. Thick shale overlies this sequence, and above the shale is a massive sand unit with minor shale intercalations that does not seem to be disturbed by the growth fault system. This is the Benin Formation. This sequence is the youngest and may represent the Late Oligocene to Miocene deposit.

REGIONAL MARKER SHALES (MAXIMUM FLOODING SURFACES (MFS)

The biofacies data shows abundance and diversity of foraminifera microfossils with three recognized as index fossils used in identifying and dating the marker shales. Three maximum flooding surfaces designated MFS1, MFS2 and MFS3 are recognized. They show an interval with high peaks of faunal abundance and diversities (Fig.3a, 6, 7), which also correspond to intervals with high Gamma Ray log values (Fig. 3a). Maximum Flooding Surfaces represent the period of maximum transgression which separates the transgressive and highstand system tracts. It shows the peak of marine events characterized by abundance and diversities of fauna and flora. These three significant surfaces fall within the 3rd order sequence and aged between Early to Late Oligocene.

These shales (marker shales), appear to have been deposited over a large area. Widespread deposition of these marker shales suggests deep water setting. In the XP Field, these shales serve as regional stratigraphic marker horizons for correlation and interpretation of ages and environments of deposition. In analog subsurface reservoir mapping, the shale might act as vertical barriers to communication between sandstone reservoirs in addition to being excellent correlation marker beds. MFS1 occurred at the depth of 3840m, above the first sequence boundary (Fig. 3a, 4). It forms the top seal for reservoirs in sequence 1.The second flooding surface occurred at 3420m. Thickness of this shale is about 200m (3250 – 3450m) (Fig. 3a, 3b). It forms a regional seal that enhances hydrocarbon entrapment in the field. The reservoir unit capped by this shale shows evidence of petroleum accumulation as seen in the high resistivity value (ILD) (Fig. 3a, 4).This is the youngest marine shale that occurred above the last sequence boundary. The top sequence boundary in this sequence is absent, and no biozonation data available for it.

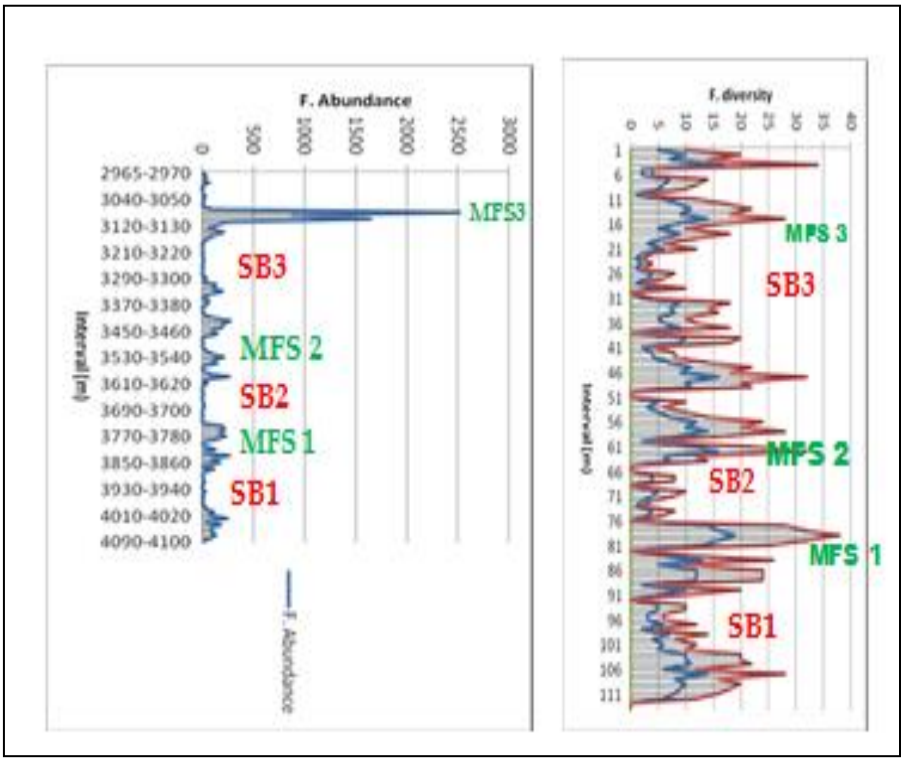

Figure 6: Biofacies Plots Showing Faunal Abundance and Diversities

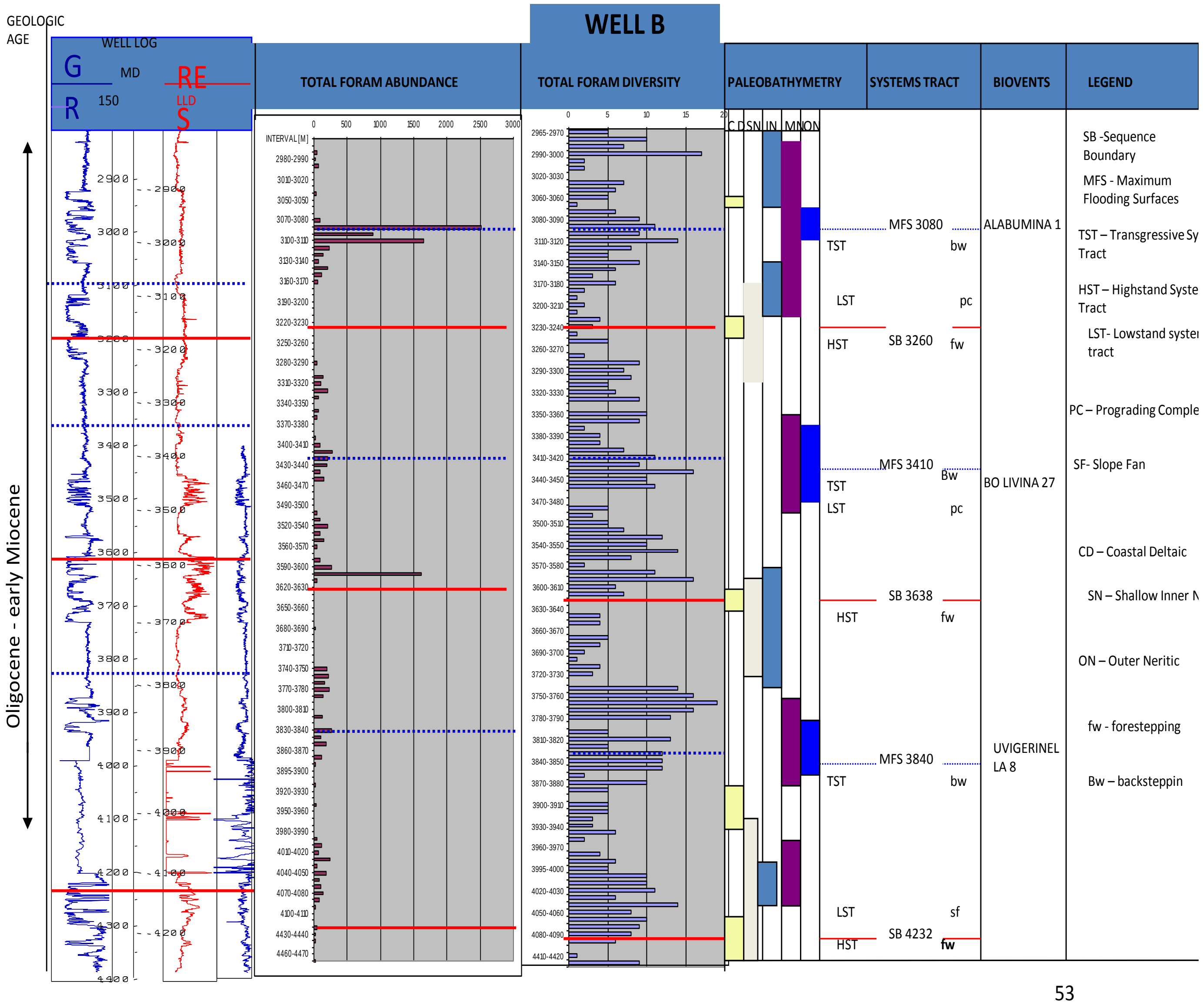

Fig. 7: Biostratigraphic Interpretation and Well Log Integration

SYSTEMS TRACTS

Three systems tracts common in the XP - Field include; Highstand Systems Tract (HST), Transgressive Systems Tract (TST) and Lowstand Systems Tract (LST) (Fig.5). Systems tracts are genetically associated stratigraphic units that were deposited during specific phases of the relative sea-level cycle and represented in the rock record as three-dimensional facies assemblages. They are defined on the basis of bounding surfaces, position within a sequence, and parasequence stacking pattern.

The Highstand Systems Tract (HST) displays a coarsening upward (Fig.5) trend and it downlaps the maximum flooding surface. Four of this unit occurs in Well B, and forms the dominant stacking pattern in the field typical of a deltaic progradational depositional setting.

TRANSGRESSIVE SYSTEMS TRACT (TST)

Transgressive System Tract can be recognized by its position in a sequence and stacking pattern. It occurs between the Maximum Flooding Surface the Transgressive Surface. On well log it shows a fining upward trend of increasing water depth, a retrogradational parasequence stacking. Net sandstone and sandstone reservoir quality of each parasequence within the retrogradational parasequence set (**TSTs**) will decrease upward (Fig. 4).

LOWSTAND SYSTEMS TRACT (LST)

The Lowstand Systems Tract is made up of three sub-depositional units; the prograding complex, slope fan and the basin floor fans. The unit forms a prograding to aggradational stacking pattern. Parasequences are not recognized in the lowstand basin floor and slope fans, possibly because facies in bathyal and deeper water depths are not sufficiently sensitive to minor changes in sea level which produce parasequences in shallow marine environments (Posamentier et al., 1988., Van Wagoner et al., 1988). Lowstand System Tracts are recognized in a type 1 sequence. In a type 2 setting, the equivalence of LST is the Shelf Margin System Tract (SMST). The LST lies directly on the lower sequence boundary and is overlain by the Transgressive System Tract. LST occurs in well B between 3040 to 3115m just above SB3, and between 2485 and 2500m in well C. Lowstand systems Tracts contain coarse grained sands/sandstone with good reservoir characteristics showing the presence of hydrocarbon saturation with its high resistivity values (Fig. 4,5). The LST has excellent reservoir quality compared to TST (heterolithic reservoirs). It is an exploration target within the field.

Transgressive systems tract (TST) helps to determine production mechanism. High-frequency parasequences – which are composed of laterally continuous shale, and of sandstones that have laterally and vertically variable reservoir quality and continuity – can have a major effect on reservoir performance. Thus, they should be identified as early as possible in the life of a field by sequence stratigraphic analysis (Slatt, 2006). This unit displays a fining upward gamma ray motif and occurred at the top of lowstand system tract.

IMPLICATIONS FOR HYDROCARBON EXPLORATION AND PRODUCTION

The study reveals excellent plans for drilling campaign in the field. Sequence 1 and 2 possess high prospect for hydrocarbon exploitation**.** The stratigraphic positions of sequences with highest prospects falls within 4232m to 3140m (productive interval) and can be penetrated at approximately the same depth across the field, except for fault interception. The sequence boundaries mark the transition from a reservoir to shale. This help to decide casing landing depth, well total drill depth, completion zones for drain hole, and the decision for gravel packing/sand control during production. They represent intervals with high porosity and permeability, and help in reservoir compartmentalization and flow units demarcation.

The various Maximum Flooding Surfaces serve as regional seals and source sediments. They act as vertical baffles or seals, and occur in association with faunal abundance and diversity peaks, and often correspond to abrupt change in incremental overpressure (Meckel, 2003). This will be useful in identifying the various pressure regimes during drilling exploratory, appraisal and production wells.

The various systems Tracts, LST, TST and HST serve as reservoirs with variable petrophysical characteristics. The HST and LST form good reservoirs with higher reservoir quality than the TST. They form exploration prospects and should be targeted during subsurface mapping. Identifying TST helps to determine production mechanism. High-frequency parasequences – which are composed of laterally continuous shale and sandstones that have laterally and vertically variable reservoir quality and continuity – can have a major effect on reservoir performance. Thus, they should be identified as early as possible in the life of a field by sequence stratigraphic analysis (Slatt, 2006).

The Early Oligocene interval (sequence) has higher hydrocarbon potential. Late Oligocene to Early Miocene is the youngest sequence with little hydrocarbon potential, probably due to low thermal regime and shallow depth or that hydrocarbon migration may not have been completed in this sequence. In the offshore locations, Miocene successions have high hydrocarbon prospect. Youngest sequence has more water-bearing reservoirs, which provides a potential for water injection at the depleting stage of the wells when natural drive mechanism can no longer be effective.

5. SUMMARY AND CONCLUSIONS

Well log and biostratigraphic data integrated to study XP Field onshore Niger Delta reveal three depositional cycles in the study area, with the last sequence boundary not dated. Three regional dated unconformities and flooding surfaces are recognized. The unconformities provide conduits for hydrocarbon entrapment and accumulation. The regional shales (MFS) provide excellent seal and source rock potentials in the field. The XP Field reservoirs consist of several 3rd order stacked regressive and transgressive units. The sedimentary fills in this field are majorly regressive deposits of two main depositional cycles that took place during the Oligocene time of delta development. The maximum flooding surfaces (shales) are laterally extensive and may form vertical barriers between parasequence sandstones. The highstand systems tract (HST), will prograde basin-ward with a decrease in reservoir quality (decrease in porosity and permeability) because of the basin-ward decrease in net sandstone and probable decrease in sandstone grain size within the field. Net sandstone and sandstone reservoir quality of each parasequence within the retrogradational parasequence set (TST) will decrease upward (Figs.4, 5). The Lowstand Systems Tracts show high hydrocarbon prospect and should be targeted within the field.

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