Sequence stratigraphy study within a chronostratigraphic framework of 'Ningning field', Niger Delta

Sekvenčnostratigrafske raziskave "Področja Ninging" delte Nigra v kronostratigrafskem okviru

Oluwatosin John Rotimi[1, *]

[1]Petroleum Engineering Department, College of Science and Technology, Covenant University, Canaan Land, Km10 Idiroko road, P. M. B. 1023, Ota, Ogun State, Nigeria

*Corresponding author. E-mail: orotimi@covenantuniversity.com

Received: July 22, 2010 **Accepted:** November 5, 2010

Abstract: Sequence stratigraphy model developed for the Ningning field is based on the interpretation carried out on the different wells that penetrated the various subsurface lithologies. Basically three depositional sequences were delineated from the five wells studied. The Vail model used made out a third and forth order stratigraphic surfaces that all fall within the central swamp depobelt of the Basin. The five wells used show the presentation of the interpretation and the models. All the sequence tracts were appropriately represented starting from the Lowstand Transgressive and Highstand system tracts, except in well 005 where the Lowstand of the second sequence was missing. This is achieved by incorporating signature motifs from wireline logs coupled with biostratigraphy data and inferred paleobathymetry. This has revealed the field-wide reconstruction of a chronostratigraphically constrained biostratigraphy of subsurface lithological sequences with limited information.

Povzetek: Sekvenčno stratigrafski model polja Ningning temelji na interpretaciji različnih vrtin, ki sekajo različne kamnine pod površjem. Preiskava petih vrtin je omogočila prepoznati tri sedimentacijska zaporedja. Uporaba modela Vail je pokazala stratigrafske površine tretjega in četrtega reda, ki vse spadajo v osrednji močvirski sedimentacijski pas bazena. Interpretacijo in modele predstavljamo na podlagi petih uporabljenih vrtin. Ugotovili smo vsa sekvenčna zapo-

Original scientific paper

redja od začetnih plitvo transgresivnih do zaporedij z visoko vodo, razen v vrtini 005, kjer manjka plitvo stanje druge sekvence. Interpretacijo je omogočila povezava karotažnih zapisov z biostratigrafskimi podatki in s sklepanjem o nekdanjih globinah. Z maloštevilnimi podatki smo lahko podali širšo rekonstrukcijo kronostratigrafsko omejene biostratigrafije litoloških zaporedij pod površjem.

Key words: sequence, stratigraphy, depobelt, biostratigraphy, wireline-logs, lithologies

Ključne besede: sekvence (zaporedja), stratigrafija, pas sedimentov, biostratigrafija, karotaža, litologija

INTRODUCTION

A greater portion of the world's energy mix will come from hydrocarbon sources and its derivatives coming from the deeper portion of the various hydrocarbon habitats. It has therefore become imperative to apply newly emerging exploration and production tools and skills to adequately harness these resources. The petroliferous Niger Delta is one of the highest producing basins with more promising reserves yet to be discovered as exploration proceeds to the deeper water. Sequence stratigraphy is one of the twenty first century exploration and production tools that are used to unravel series of lithological and basinal intricacies bordering on sand packets, depositional sequences and paleoenvironmental analysis. Biostratigraphy is indispensable in the adequate delineation of chronostratigraphically significant surfaces in the subsurface formations encountered in hydrocarbon exploration. The study is aimed at subdividing the stratigraphic section within the study area into packages of sediments bounded by chronostratigraphically significant surfaces (condensed sections, their associated maximum flooding surfaces and sequence boundaries).

STUDY AREA AND REGIONAL GEOLOGY SETTING

The study area is a producing field located in the Niger Delta. The Niger Delta is situated in the Gulf of Guinea (Figure 1) and extends throughout the Niger Delta Province (KLETT et al., 1997). The Niger Delta is a large arcuate delta situated on the West Coast of Central Africa, between Lat 3^0 and 6^0 N and Long 5^0 and 8^0 E (REIJERS et al., 1997). The province contains known resources (cumulative production plus proved reserves) of 34.5 BBO and 93.8 TCFG (PETROCONSULT-

Ants, 1996b). Currently, most of this petroleum is in fields that are onshore or on the continental shelf in waters less than 200 m deep. Exploration focus is presently shifting to the deeper waters in the Niger Delta with huge discoveries like Bonga and Agbami fields (with about 1BBO reserve) increasing the prospectivity of oil search in the riskier deeper waters despite the high cost of exploration and development at these water depths.

From the Eocene to the present, the delta has prograded southwestward, forming depobelts that represent the most active portion of the delta at each stage of its development (Doust & Omatsola, 1990).

These depobelts form one of the largest regressive deltas in the world with an area of some 300 000 km^2 (Kulke, 1995), sediment volume of 500 000 km^3 (Hospers, 1965), and a sediment thickness of over 10 km in the basin depocenter. The Niger Delta Province has been identified to be a prolific hydrocarbon habitat and is known to contain one identified petroleum system (Ekweozor & Daukoru, 1984; Kulke, 1995) referred to as the Tertiary Niger Delta (Akata – Agbada) petroleum System. The sandstones and unconsolidated sands from which petroleum is produced in the Niger Delta have a geometry that has been grossly affected and controlled by the dominant growth fault configuration. The sand units are

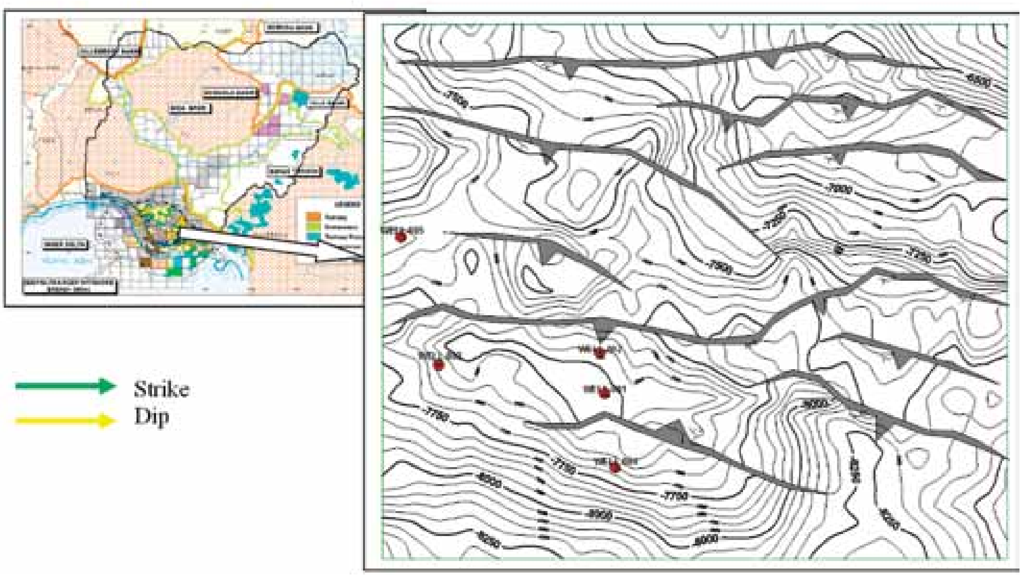

Figure 1. Niger Delta study location. Inset is field basemap with well posiions and correlation directions.

seen to thicken in the downthrown portion towards the fault dip direction (ROTIMI et al., 2010, WEBER & DAUKORU, 1975).

MATERIALS AND METHODS

Wireline logs were used for the purpose of this study in conjunction with biostratigraphy data. The method employed in this study is that of lithofacies identifications coupled with sequence stratigraphic concepts. Parasequences were identified based on the principle described by (VAN WAGONER et al. 1990). Their boundaries were identified and separated from others by flooding surfaces which are often characterized by a cycle of sediment that either coarsens or fines upward. These changes in grain sizes are abrupt and very conspicuous and allow for correlation of the parasequence boundaries across the field thus being a valid tool for chronostratigraphy although care must be taken in choosing these surfaces.

Stacking pattern for parasequences sets were evaluated as fundamental building blocks of a sequence. The identified stacking patterns include progradational, retrogradational and aggradational stacking patterns (VAN WAGONER et al., 1990*)*. These patterns are dependent on the ratio of the rate of deposition to that of accommodation. A progradational stacking pattern of parasequences refers to the pattern in which facies at the top of each parasequence becomes progressively more distal i.e. basinward (POSAMANTIER & VAIL, 1988; WILGUS et al., 1998). A retrogradational parasequence set has successively younger parasequences deposited farther landward in a backstepping pattern. Overall, the rate of deposition is less than the rate of accommodation.

An aggradational parasequence set is one in which successively younger parasequences are deposited above one another with no significant lateral shifts. The rate of accommodation approximates the rate of deposition (i.e. $R_{accm} = R_d$).

Some other differentiating factors include lithological ratio interplay of material deposited (i.e. sandstone or mudstone), the environment of deposition (i.e. coastal/shallow marine to deep marine) and the ratio of the thicknesses of the different parasequences and parasequence sets. All the aforementioned points were used for the purpose of this study.

Chronostratigraphically Significant Surfaces

Sequence boundaries were identified based on the methodology described by VAN WAGONER et al., (1990). Sequence boundaries were identified by the most basinward shift in facies, within a coarsening upward sequence (Emery & Myers, 1996). These are usually located between two maximum flooding surfaces. Typical lg pattern in neritic environment is an aggradational (massive) lg pattern that overlies an interbedded lg pattern. This boundary corresponds to the position of highest resistivity and lowest lithology lgs.

Below the sequence boundary is a trend of decreasing flooding surface as indicated by increasing flooding surface shale resistivity, while above the boundary is a trend of increasing flooding surface and decreasing flooding surface shale resistivity. Maximum flooding surface caps the transgressive system tracts which represents the most landward transgression of the shoreline.

In recognizing the various systems tract (lowstand, transgressive and highstand), procedure that involves first, locating the maximum flooding surfaces within major condensed sections on the well-lgs, followed by the location of the sequence boundary between the two maximum surfaces was adopted.

The Lowstand System Tract: This comprise of the basin floor fan, the slope fan and the prograding wedge complex all have their boundaries marked by maximum flooding surfaces (MFS) recognized as an extensive blanket of shale minor or major with fauna and floral diversities (Vail & Wornardt, 1992).

The Transgressive System Tracts**:** This is characterized by an overall upward fining and thinning (backstepping parasequence set) on lgs, although the individual parasequence tends to prograde. It is bounded below by a transgressive surface and above by a maximum flooding surface. The portion of the lg with lowest shale resistivity and which corresponds with the maximum deflection on the GR and/or the SP lg were selected as the maximum flooding surfaces. A condensed section is associated with the maximum flooding surface that marks the upper boundary of the transgressive system tracts as the parasequences backsteps landwards (Loutit et al., 1988). It is characterized by the greatest abundance and diversity of fauna within the sequence and starved of terrigenous materials.

The Highstand System Tracts**:** This is bounded below by a downlap surface of maximum flooding and above by a sequence boundary. The early highstand is characterized by aggradational parasequence set, while the late highstand is characterized by a set of prograding, coarsening upward and shallowing upward parasequences that terminate at the sequence boundary. Lg correlations in the highstand is difficult and lg patterns, commonly indicate interbedded sand and shale lithofacies, while the reservoir continuity is fair (VAIL & WORNARDT, 1990).

Eustatic sea level charts derived from eustatic cycles of the Niger Delta and the coastal onlap have been correlated to derive the regional chronostratigraphy of the Niger Delta. This has aided the prediction, location and dating of sequences, their correlatable boundaries, and other chronostratigraphically important surfaces in the Niger Delta. The Niger Delta Cenozoic chronostratigraphic chart Figure 2, is a geological data table containing up to date information on the chronostratigraphy of the Niger Delta, its marker shales and maximum flooding surfaces, the Pollen (P-zone data) and Foraminifera zonation (F-zone data), the Niger Delta depobelts and its sequence stratigraphy (HAQ et al., 1988). The chart was used variously in the course of this study to determine amongst others, the ages of the maximum flooding surfaces and the sequence boundaries.

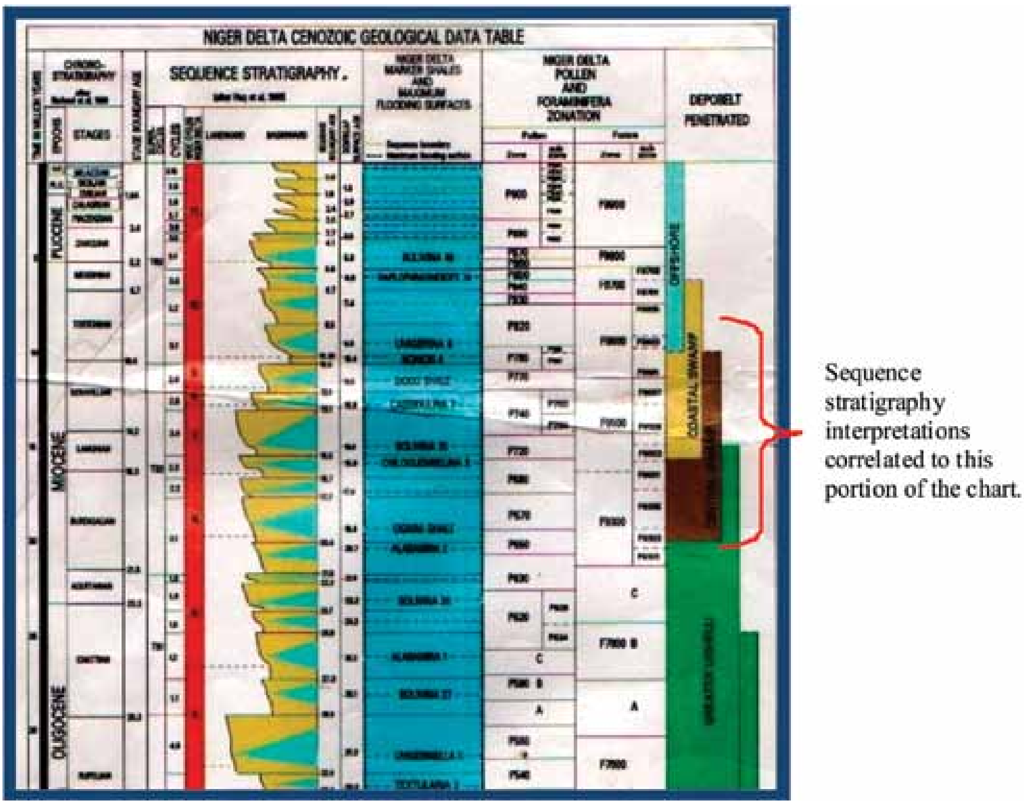

Figure 2. The Niger Delta Cenozoic Chronostratigraphic Chat (HAQ et al. 1988)

Well Correlation

Correlation of wells along strike and dip lines was made towards the development of a chronostratigraphic framework for the study area. The correlations made over the entire field starting from the control well 001. This was done to build a holistic sequence stratigraphic framework. The correlations were carried out along one strike and one dip line. This is limited based on the location and position of the wells as displayed on the base map and well positions relative to each other as seen on the basemap (Figure 1). Due to the localization of the wells, there is dire need to start correlation within this area and also in the vicinity of the identified chronostratigraphic surfaces e.g. the correlatable marker shales.

Results and interpretation

Sequence boundaries in the field were identified based on the interpretation of unconformity surface seen on the lgs assisted by the interpretation of stacking patterns, lg shapes and motifs. This is discovered to be the effect of basinal drift in the sediment/ horizon sets on and facies arrangement on the wells which was a major focus. The major Sequence Boundary recognized included 17.7 Ma, 14.8 Ma, 12.1 Ma, and 10.38 Ma. Unconformity surfaces marks the sequence boundaries while on the well lg the highest value on the Resistivity lg which corresponds to the lowest value on the SP lg indicates the sequence boundaries mapped. The formations mapped are predominantly of the prolific hydrocarbon bearing Agbada formation of the Niger Delta which is thick sequences of early to middle Miocene age. The discussion is presented below.

Discussion

SEQUENCE BOUNDARIES (SB)

17.7 Ma SB

This is the oldest sequence boundary identified in the study area. It was penetrated by Wells 001, 002 and 003 at depths of 2 951 m, 2 836 m, and 2 860 m respectively. This surface was not recognized on Well 005 due to the depth to which it was drilled and a projection was done to include Well 004 from the other array of wells, as it was situated at some distance basinward. The lg motif shows abrupt change from an upward deepening facies succession to an upward shallowing one. Paleobathymetric deduction and lg signatures shows that such horizons are devoid of pollens as there are indications of forams present (F-zone data). The depositional environment deduced from the lgs depicts a shelf environment (Figure 3).

14.8 Ma SB

This Sequence Boundary is well marked on all the lg signatures and was penetrated by all the wells in the field. The depth of occurrence varies with respect to the position of the wells on the block and relative to each other. The lg signature associated with this boundary is slightly featureless and in some part blocky. It is associated with a boundary of graded sandy shale sequence. This interpreted the pre-channel facies of the field as it resembles a basin floor fan complex but it can be said to be of the slope fan complex. Due to the non-uniform lg shape it could be inferred that the lithology must have been deposited in a high to moderate energy regime with limited time for sediment sorting and hence the intercalation of the beds and consequent aggradations (Figure 3).

12.1 Ma SB

The 12.1 Ma sequence boundary overlies the succession of lithologies penetrated by all the wells 001, 002, 003 and 005. A careful projection was also made to well 004 so as to gain proper chronostratigraphic correlation coverage of the field. This sequence boundary is well marked on all the wells as it occurs at different depth range, but as delineated in the field the boundary falls within the depth range of 1 762 m in Well 001 and 2 083 m in Well 005. The aggradational lg shape of the sand body sequence is typical of channel levee complex and at the proximal portion of the basin a prograding wedge complex (Figure 3). This near cylindrical lg shape shows slight left side deflection and a corresponding right side Resistivity lg signature. This is characteristic of a channel complex environment serving as a suitable clear demarcation for the overlying Lowstand system tract.

10.35 Ma SB

This marks the youngest sequence boundary penetrated in the study area as it marks the base of the Benin sand formation. It occurred in all the wells and also a projection done to incorporate the more proximal well 004. This marks the channel sequence of the distal pre Benin sequence deposited. This sequence has a blocky lg shape as much as depicted on the log motif and indicates a channel sand deposit marked abruptly by complex of slope wedge deposits. This is well correlated to the Niger Delta chronostratigraphic chart and accurately mapped (Figure 2).

Maximum Flooding Surfaces

Maximum flooding surface were delineated as points of occurrence of an extensive blanket of shale and starved of terrigenous material with biofacies diversity. The surfaces were picked on the well lgs as the top of a retrogradational complex. The lowest value on the Resistivity curve which corresponds to the highest value on the lithology curve depicts the point where the surface occurs.

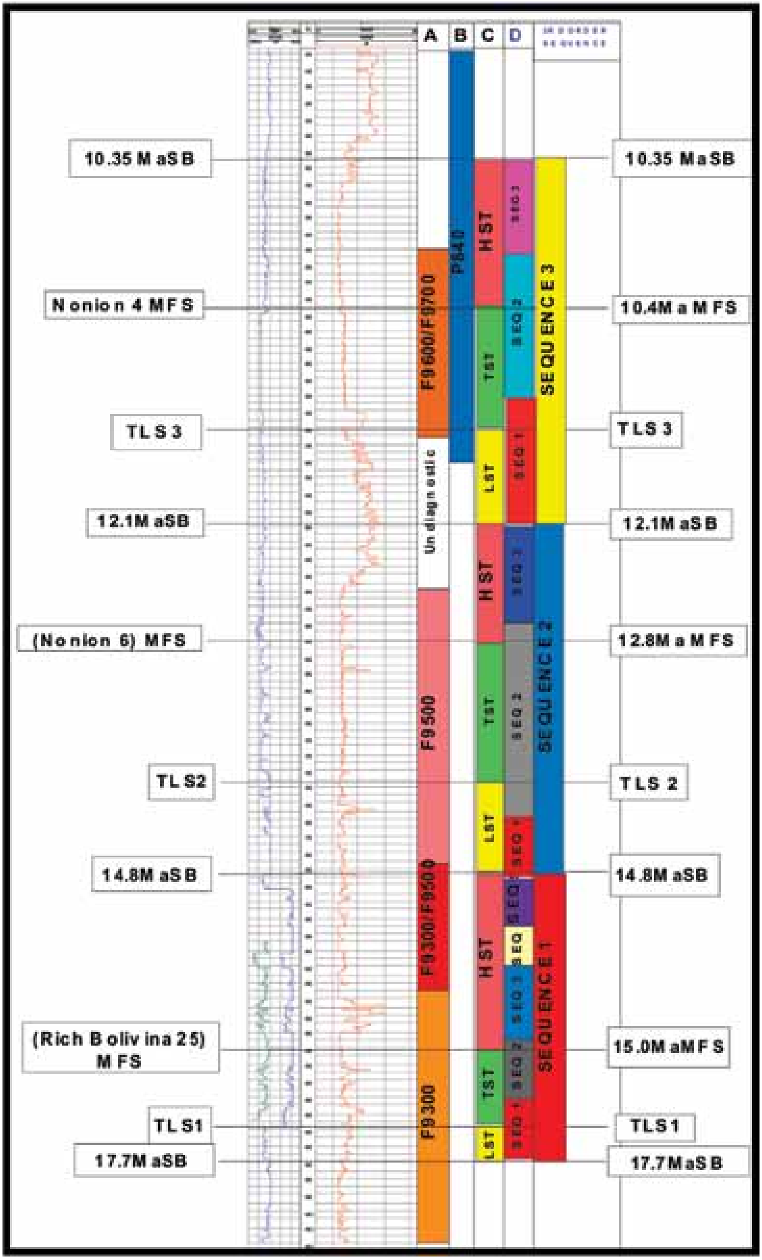

Figure 3. Well 1 showing sequences and stratigraphically significant surfaces

Identification of higher frequencies depositional sequences

In addition to the various 3rd order depositional sequences, system tracts and flooding surfaces identified, a number of higher order frequencies depositional sequences of the Forth order, were adequately identified and delineated in the wells studied (GOLDHAMMER et. al., 2000). Although most of the wells in the study area exhibited mainly 3rd order depositional sequences, these sequences were subsequently subdivided into higher order sequences denoted with numbers 1–3 and 1–6 as the case may be. This subdivision is done as a branching out of the major depositional cycle depicted by the major sequence boundaries of the depositional sequence and their associated flooding surfaces. This identified higher order sequences is interpreted as indications of the minor position at different times of the shoreline within the mega cycle which are therefore eustatic and represents the major depositional sequences.

THIRD (3RD) ORDER DEPOSITIONAL SEQUENCE STRATIGRAPHIC INTERPRETATION OF WELLS

Well 001

Sequence 1

This sequence starts at depth 2 951 m and ends at 2 743 m. The lowstand system tract begins this sequence bounded below by the 17.7 Ma sequence boundary. The sand package above the boundary is described as a prograding complex showing a fining upward pattern capped by a minor condensed section associated with abundance and diversity peak that terminates at the maximum shale point (i.e. top of lowstand - TLS 1). This is overlain by the transgressive system tract (TST) that covers a depth of 144m above the TLS 1 and consists of an overall retrograding parasequence stacking pattern capped by the 15.0 Ma *Rich Bolivina 25* maximum flooding surface (Figure 3).

The highstand system tract rest on the TST and covers the depth range of 2 743 m to 2 416 m. It starts with an aggradation parasequence stacking pattern and subsequently starts to prograde upward. It is truncated at the top by the 14.8 Ma sequence boundary.

Sequence 2

This sequence starts with an almost uniform shape, non graded sand body of about 160 m that forms the base unit of the lowstand system tract (Figure 3). The near blocky signature signifies a sandy lithology showing a slightly fining upward trend indicating a well developed channel sand body of a slope fan complex and terminates at the to of lowstand (TLS) 2.

The transgressive system tract extends from a depth of 2 256 m to 1 984 m.

This portion of the subsurface is found to exhibit individual Parasequence pattern prograding and showing a motif similar to that of an incised valley fill. The TST is capped by the 12.8 Ma – *Nonion 6* MFS associated with a major condensed section.

This sequence is terminated by the highstand system tract which starts at depth 1984 m showing some initial aggradational stacking pattern and later progrades to be terminated at the distal portion by the 12.1 Ma sequence boundary (Figure 3).

Sequence 3

Resting upon the 12.1 Ma sequence boundary is the uppermost sequence encountered in this well. It is characterized by back stepping signature o the lithology lg although it shows spurious effect on the saturation. Such can be interpreted to be a channel facies deposited under turbulent energy this with no time for consolidation or sorting. The Nonion4 MFS appears at 1364 m to caps the top of the transgressive system tract appearing in the middle of the LST and HST. The pattern that starts this sequence grades into a more uniform and characteristically blocky unit of rock typical of a time of recession in energy of the medium. At 1 070 m the 10.35 Ma sequence boundary caps this section to terminate the observed third order sequences for this well.

Well 002

Sequence 1

The Lowstand system tract begins this sequence at depth 2 836 m and ends at 2 735 m. The whole sequence covers a total depth of 466.6 m (1531 ft) and bounded at the base by the 17.7 Ma sequence boundary (Figure 4). The sediment package constituting this system tract shows a rounded lg signature typical of an aggradational Prograding complex. The Transgressive system tract overlies the LST and covers a depth of 231 m above it. The laterally extensive shale blanket which distinguishes it from the major condensed section is of the shelf environment, it consists of a series of fining upward retrograding parasequence pattern capped by the 15.0 Ma *Bolivia 25* maximum flooding surface (Figure 4). The highstand systems tract caps sequence 1 as it sits on the TST at depth of 2 504 m to 2 370 m just below sequence 2. This system tract shows bulky aggradational parasequence pattern as it progrades upward to be capped by the 14.8 Ma sequence boundary.

Sequence 2

Sequence 2 starts with a crescent shaped lg pattern which grades into a Prograding complex and body with no grading pattern observed. This basal unit of the Lowstand system tract starts from depth of 2 370 m to 1 923 m. It is bounded below by the channel sand body which marks the base of this sequence boundary of 17.7 Ma. Parasequence set motifs exemplified by some minor abundance and diversity peaks mark the top of this system tract (Figure 4). The Transgressive system tract covers a total depth of 166m as it exhibits a slightly aggradational parasequence set typical of a shelf environment terminated at the top by the major condensed section embedded in the 12.8 Ma maximum flooding surface.

The highstand systems tract found directly overlying sequence 2 starts from the top of the TST at depth 1 923 m to 1 818 m showing some initial crescent-shaped retrogradational stacking pattern fining upward indicating that of a channel complex. This system tract terminates at the 12.1 Ma sequence boundary.

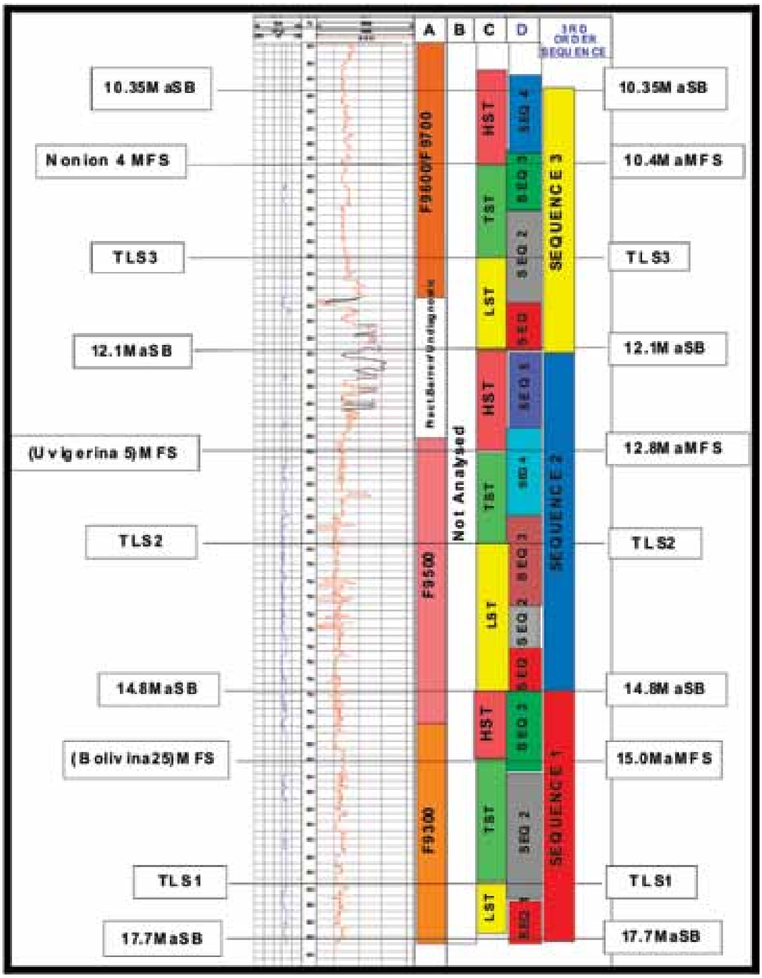

Figure 4. Well 2 showing sequences and stratigraphically significant surfaces

Sequence 3

Sequence 3 episode of deposition extends from 1 736 m (lower sequence boundary) to 1 242 m (upper sequence boundary). The lowstand system tract starts this sequence with the slope fan complex covering about 494 m and overlain by the transgressive systems tract deposit. A laterally extensive marine shale which serves as the maximum flooding surface at 1 382 m is observed to cap this deposit as it is marked by the 10.4 *Nonion 4* MFS at 1382 m. The highstand system tract terminates this sequence at 1 242 m and covers 140 m (Figure 4).

Well 003

Sequence 1

This sequence starts with the lowstand sequence tract at the depth of 2 859 m to 2 329 m. The whole sequence is about 530 m and has a combination of Prograding and slightly aggrading parasequence stacking pattern. The lowstand systems tract has a sand package which shows a fining upward sequence and then interfingering of some minor shale lithology which marks the top of the lowstand systems tract (Figure 5). The transgressive system track overlies this and covers the depth of about 164 m showing a series of upward aggradational pattern typical of the shelf environment. A blanket of extensive marine shale is seen to be truncating the TST with the embedded condensed section. highstand system tract caps this deposit at 2 329 m and marked by the 14.8 Ma sequence boundary.

Sequence 2

The upper and lower sequence boundary occurs at depth 1 709 m and 2 329 m respectively, enveloping the whole system tracts of this depositional episode. The prograding complex and the slope fan deposits mark the lowstand system tract which covers a depth of 184 m within the interval of 2 329 m and 2 145 m. The transgressive system tract with its characteristic fining upward pattern rests on the transgressive surface (i.e. top of the lowstand system tract TLS 2), and truncated by the shale blanket of the maximum flooding surface at 1 909 m marked by the 12.8 Ma *Cassidulina7* MFS (Figure 5). This depositional sequence has the highstand system tract deposit as the cap which starts from 1 909 m to terminate at 1 709 m which is the topmost sequence boundary.

Sequence 3

Sequence 3 episode of deposition started with the lowstand system tract having a slope fan complex as a typical signature at 1 709 m to 1 574 m, and was immediately followed by the transgressive system tract deposits of about 140 m. The maximum flooding surface marked by the 10.4 Ma *Nonion 4* MFS truncates it at 1 434 m as it is subsequently overlain by the highstand system tract. This system tract represented by the aggrading to prograding lg pattern terminates the studied depositional episode of this well. The lower and upper sequence boundaries of the highstand systems tract occur at 1 434 m to 122 m respectively.

Well 004

Sequence 1

Sequence 1 episode of deposition commenced with the lowstand system tract

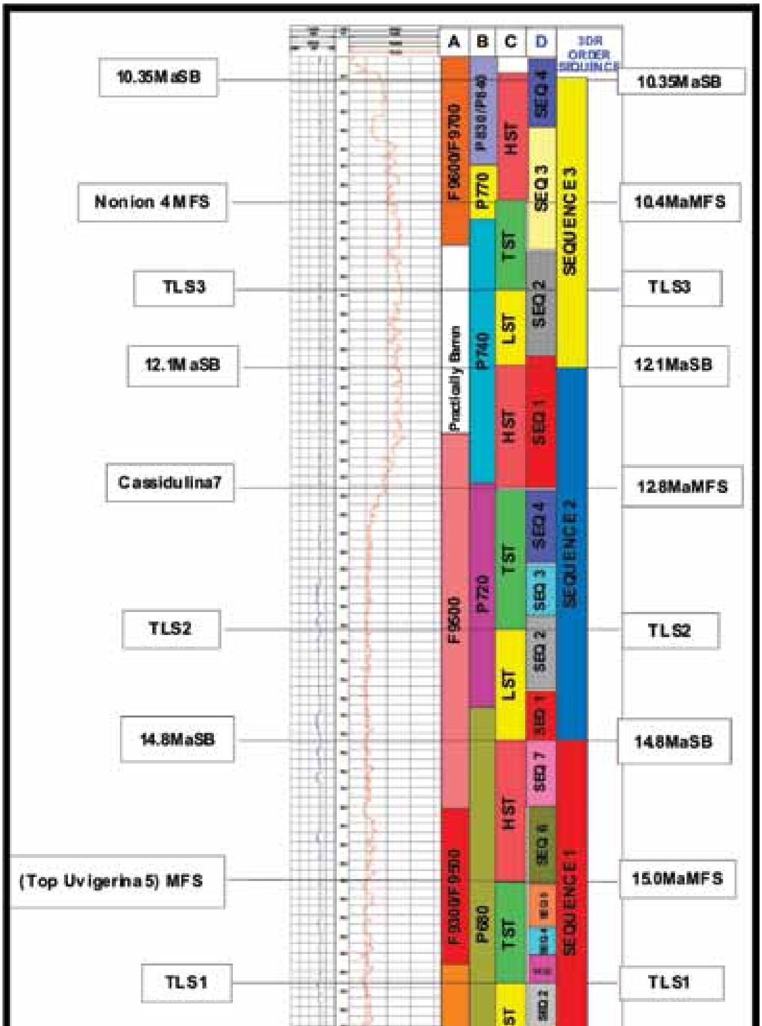

Figure 5. Well 3 with sequences and stratigraphically significant surfaces

which range from 3 459 m to 3 133 m. A short interval of transgressive system tract overlies this prograding slope fan deposit of the lowstand systems tract deposit. Maximum flooding surface marked by 15.0 Ma *Rich Bolivina 25* MFS occurs at 2 940 m to cap the retrogradational pattern of the transgressive systems tract that terminates at the same point. Overlying it unconform-

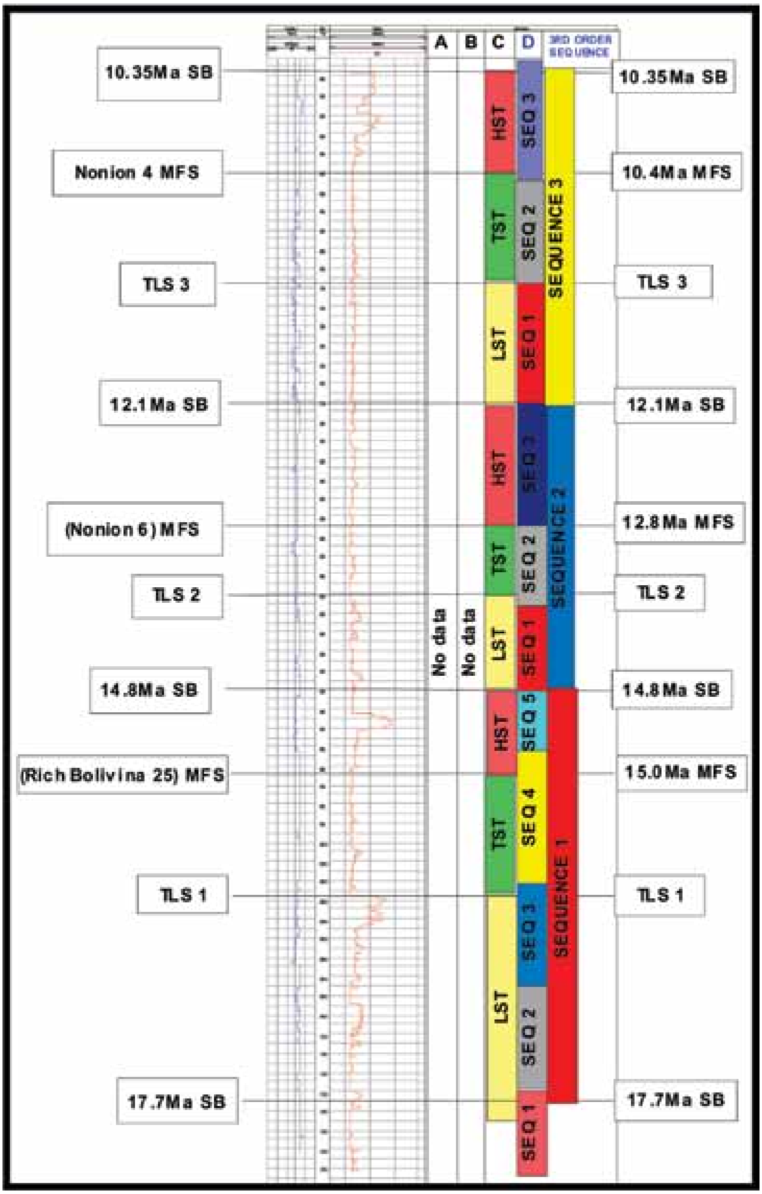

Figure 6. Well 4 with sequences and stratigraphically significant surfaces

ably is the highstand systems tract deposit covering about 133 m and bounded at the upper part at 2 807 m by the 14.8 Ma sequence boundary (Figure 6).

Sequence 2

Sequence 2 observed in well 004 in the study area is bounded at the base and top by sequence boundaries at depths 2 807 m and 2 352 m respectively covering 153 m. it starts with a lowstand systems tract covering 152 m, overlain by a Transgressive Systems Tract that is truncated by a maximum flooding surface marked by the 12.8 Ma *Nonion 6* MFS at 2 540 m. Capping this sequence is the Highstand Systems Tract extending from the top of the maximum flooding surface to a depth of 2 352 m marking the top of the sequence.

Sequence 3

Sequence 3 of Well 004 in this field of study has a thickness ranging from 2 352 m at the lower boundary to 1 821 m at the apex of the sequence. The Lowstand Systems Tract lies on the lower sequence boundary covering 196 m as it terminates at the occurrence of an extensive shaly bed initiating the start of the transgressive systems tract seen to overlay the lowstand system tract. The 10.4 Ma *Nonion 4* maximum flooding surface caps this transgressive system tract at 1 981 m. The Highstand Systems Tract covers the top of this sequence and terminates at 1 821 m, a total of 160 m has been observed for it (Figure 6).

Well 005

Sequence1

The lower sequence boundary of this Sequence 1 occurs at 3 030 m. The top of the lowstand systems tract occurs at 2 841 m with prograding complex pattern as it is overlain by the transgressive systems tract. The maximum flooding surface with lowest shale resistivity value and high value on the SP lg occurs at depth of 2 769 m (Figure 7).

This is in turn overlain by the blocky sand of the highstand systems tract initiated by the slightly coarsening upward pattern immediately above the marker surface. The upper sequence boundary occurs at 2 498 m.

Sequence 2

This sequence lies on the lower sequence boundary at 2 498 m, and the depositional episode commenced with the deposition of transgressive systems tract unconformably on the lower boundary, culminating in the transgressive peak at the maximum flooding surface at a depth of 2 324 m. The highstand systems tract extends from the top of the maximum flooding surface to terminate at 2 083 m, at the position which marks the top of the sequence boundary (Figure 7).

Sequence 3

This depositional sequence covers a total depth of 672 m as it commenced with a lower sequence boundary at 2 083 m. This sequence is initiated by the lowstand system tract as it is marked by a characteristic lg motif typical of coarsening upward backstepping aggradational stacking pattern. This system tract is overlain by the shaly formation of the transgressive system tract. This transgressive system tract initiated at 1 896 m was caped by the maximum flooding surface depicted by the *Nonion 4* marker at 1 699 m. The highstand system tract tops the set of sequences interpreted in this well as it covers a total depth of 287 m and terminates at 1412 m which marks the upper boundary.

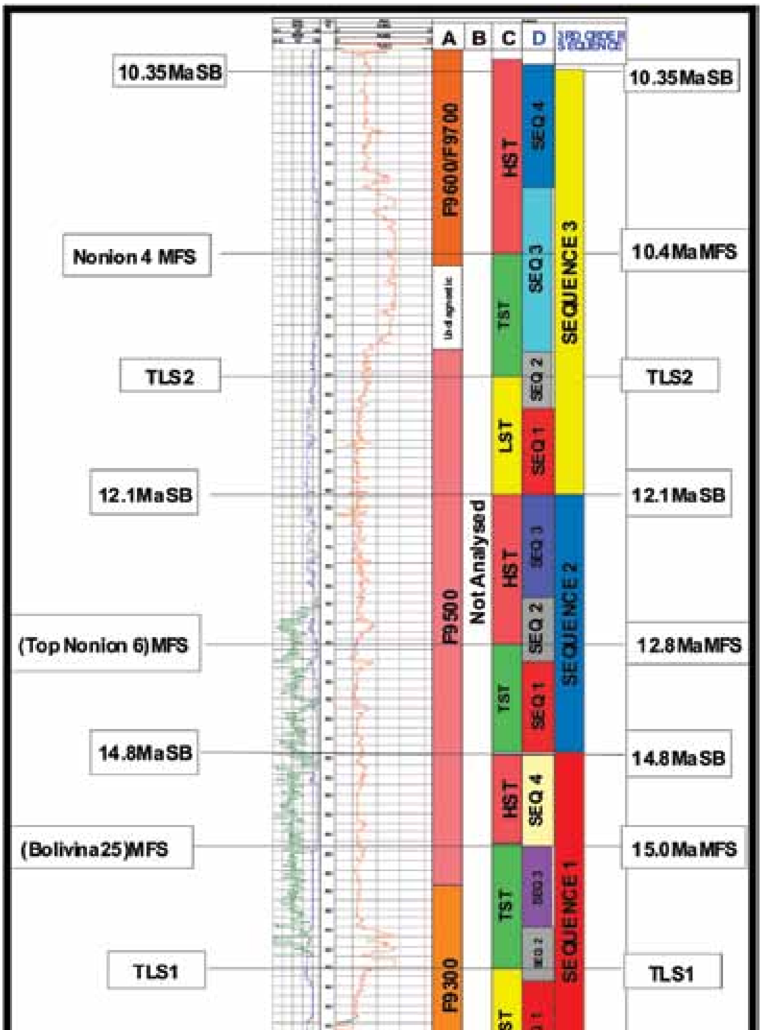

Figure 7. Well 5 with sequences and stratigraphically significant surfaces

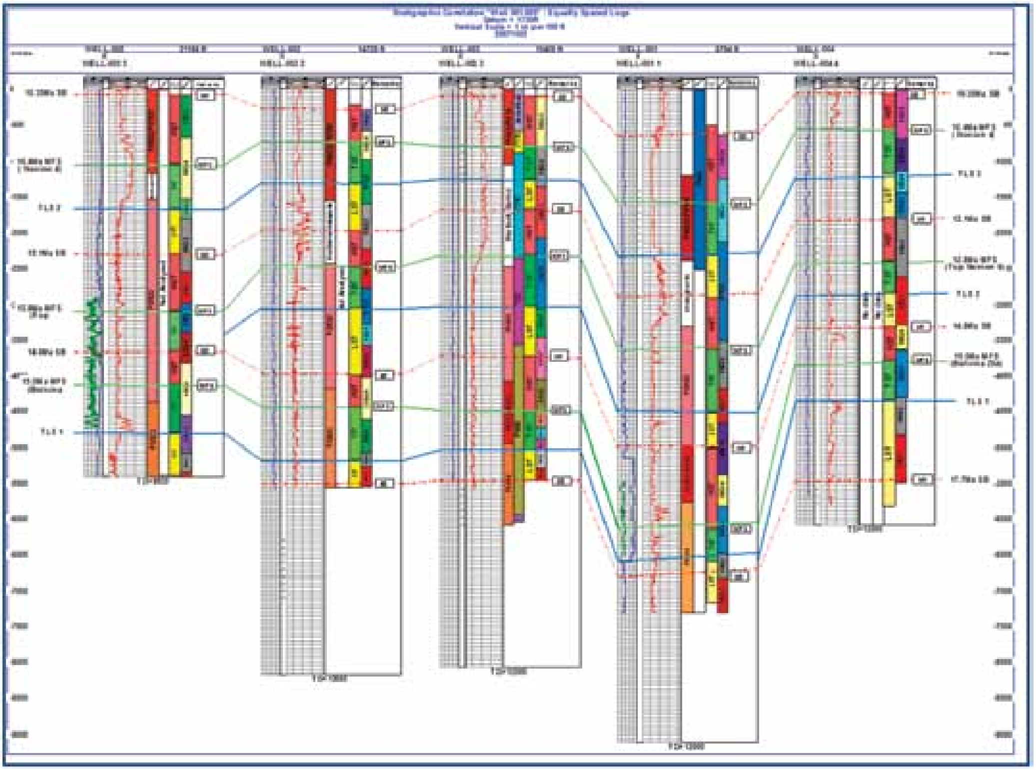

Figure 8. Stratigraphic correlation showing all 5 wells in the field of study

WELL CORRELATION

Strike line Correlation

This is carried out along the fault blocks in a bid to understand the relationships between well tops and stratigraphic surfaces in the studied wells, and in building a depositional model to know what the basin architecture looks like. This assisted in the determination of the lateral extent, continuity and homogeneity of the reservoir units and some marker shales, and also for accurate age dating of the subsurface strata of interest penetrated in the field. Figure 8 shows the lithofacies correlation and the crosscutting effect of fault on it at the subsurface. Figures 8 and 9 show the strike line and dip line correlation respectively carried out along fault blocks in the site of the wells as shown on the map (Figure1). This strike section cuts across wells 002 and 003, and the correlation shows normal delta progradation, continuity of lithofacies with thickening and thinning effect of some sequences. It is inferred in agreement with OZUMBA (2005), the late Miocene sequences are thicker than the middle Miocene sequences. Furthermore, sandy lithologies with shale interfingering identified are of middle Miocene which is comparable with other facies of the same age in the Agbada Formation. The sequence stratigraphic correlation shows that the sequences and surfaces identified were present and then confirms the continuity of the lithologies and horizons mapped (Figure 8)

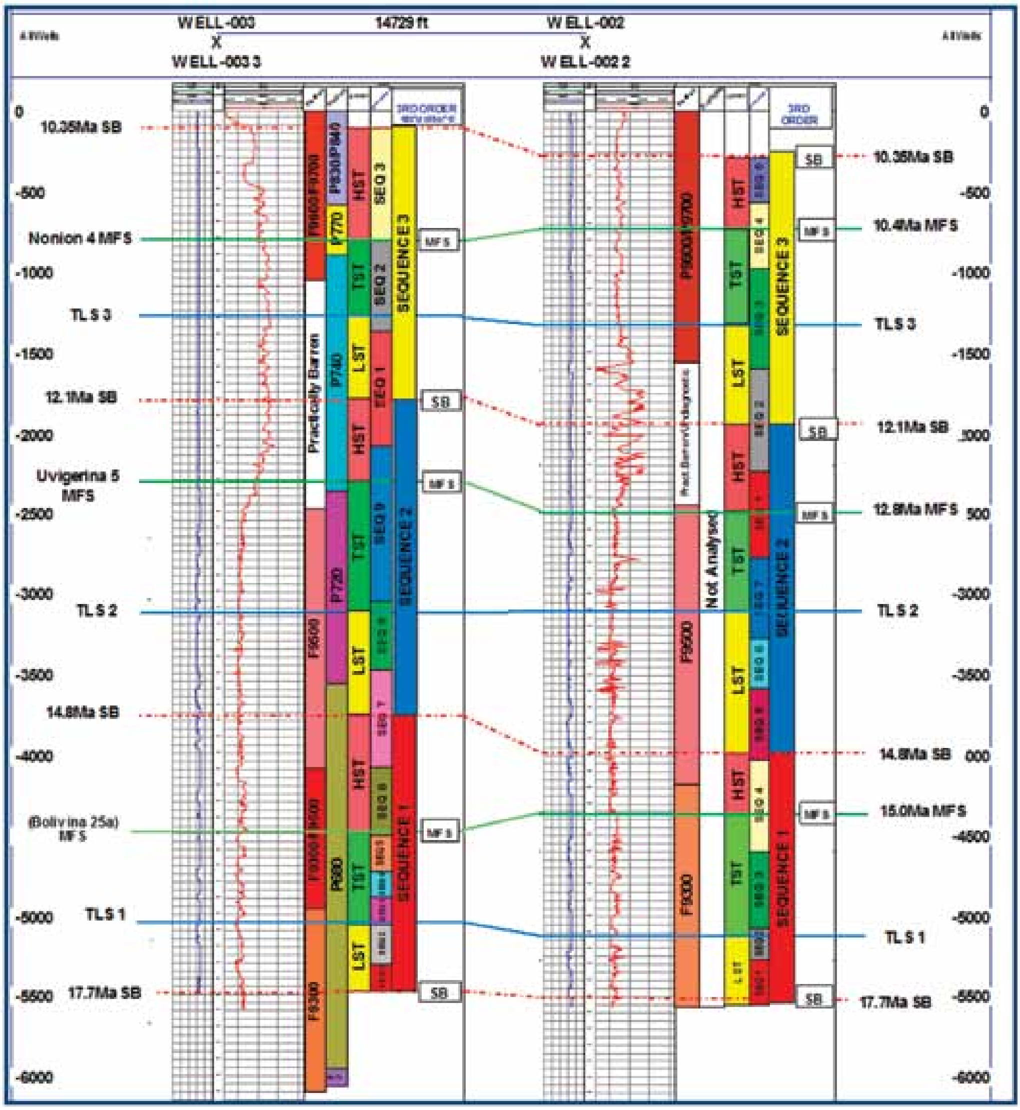

Figure 9. Strike line stratigraphic correlation of wells 002 and 003

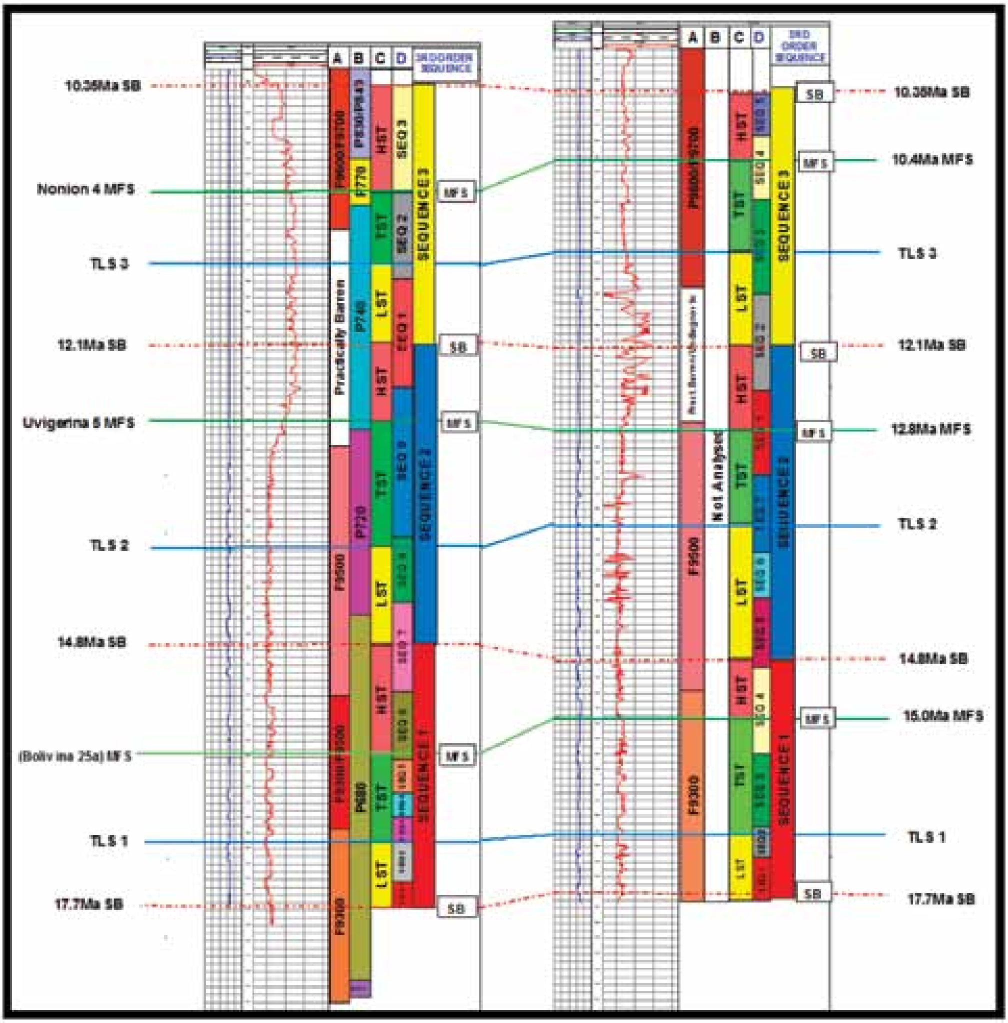

Figure 10. Structural cross-section showing features of wells 002 and 003

Dip line correlation

Dip line correlation was made across different fault blocks from the northern end to the southern end in the distal portion of the field of study. This was necessary in a way to determine the effects of structural elements like faults, and anticlinal closures on the connectivity and continuity of the reservoir sand bodies as they cut across different fault blocks. Essentially the dominant migration pathway of hydrocarbon which was along fault planes and also the trapping mechanism of hydrocarbon in the field were appreciated as much insight was gained into this. Basinal progradation was seen more clearly here as the thickening and thinning of the litholo-

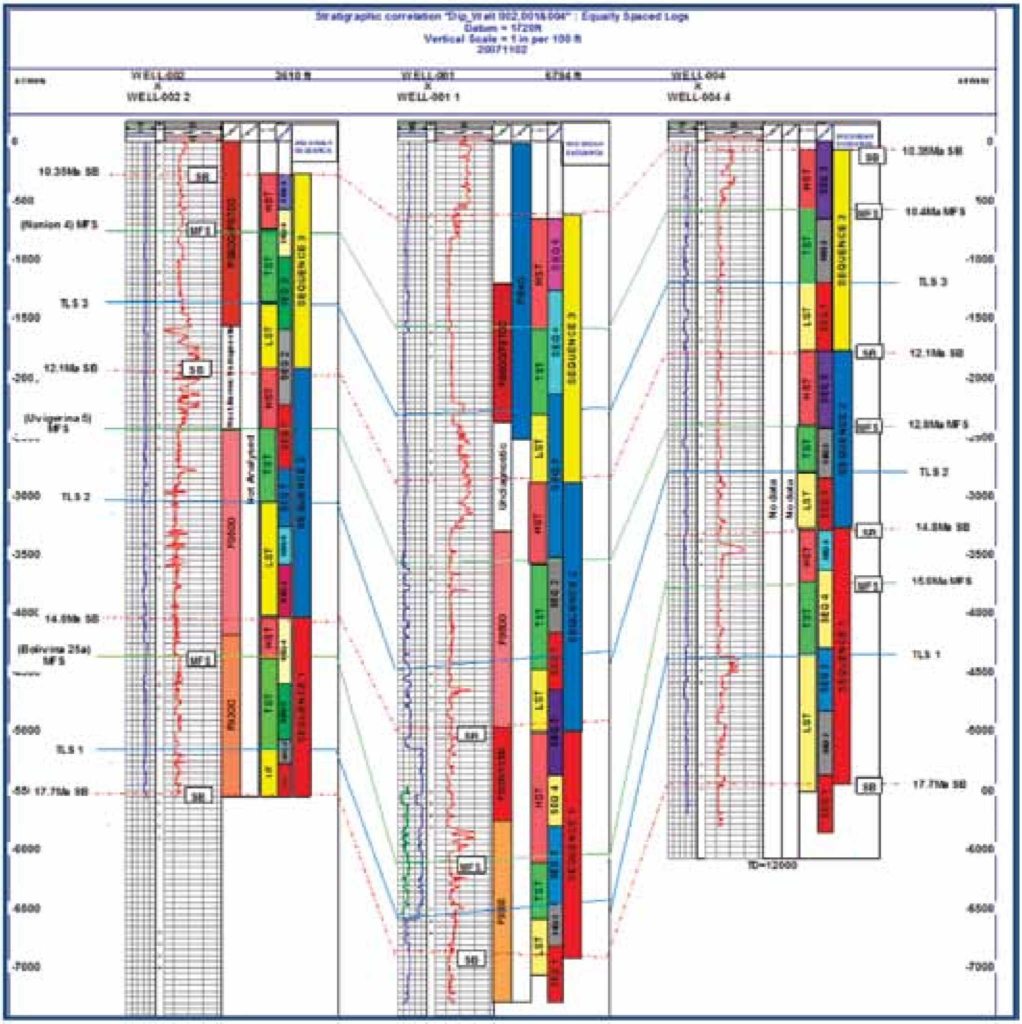

Figure 11. Dip line stratigraphic correlation of wells 002, 001 and 004.

gies was obvious (Figures 11 and 12). The wells 002, 001 and 004 used exhibited the effect of structural instability. The up and down pattern signifies the presence of this lithological units on separate portions of a growth fault structure with some sort of roll-over anticline typical of the Basin. The reservoir horizon mapped which shows some alternation of lithologies is that of the Agbada Formation.

The horizon shows continuity and connectivity, though the shaliness of the beds is slightly high. It could be inferred from the sequence stratigraphic correlation of the chronostratigraphic significant surface that the LST and the

TST hosts the reservoir units mapped in the Agbada Formation on the downthrown side in the hanging wall of the synsedimentary faults (Ainsworth, 2005). They are seen to increase and show maturity in thickness downslope as the basin progrades in the proximal direction and hence the high probability of having enormous accumulation of commercially exploitable hydrocarbon in the deeper portion and offshore depobelt of the basin beyond the field of study (Figure 13).

Conclusions

In the light of the various approaches of investigations and detailed analyses discussed earlier in the methodology, a series of 3rd and 4th order stratigraphic surfaces were identified. The study area has a sequence stratigraphy within a chronostratigraphic framework that is composed of four sequence boundaries varying from 17.7 Ma to 10.35 Ma and three intervening maximum flooding surfaces between 15.0 Ma and

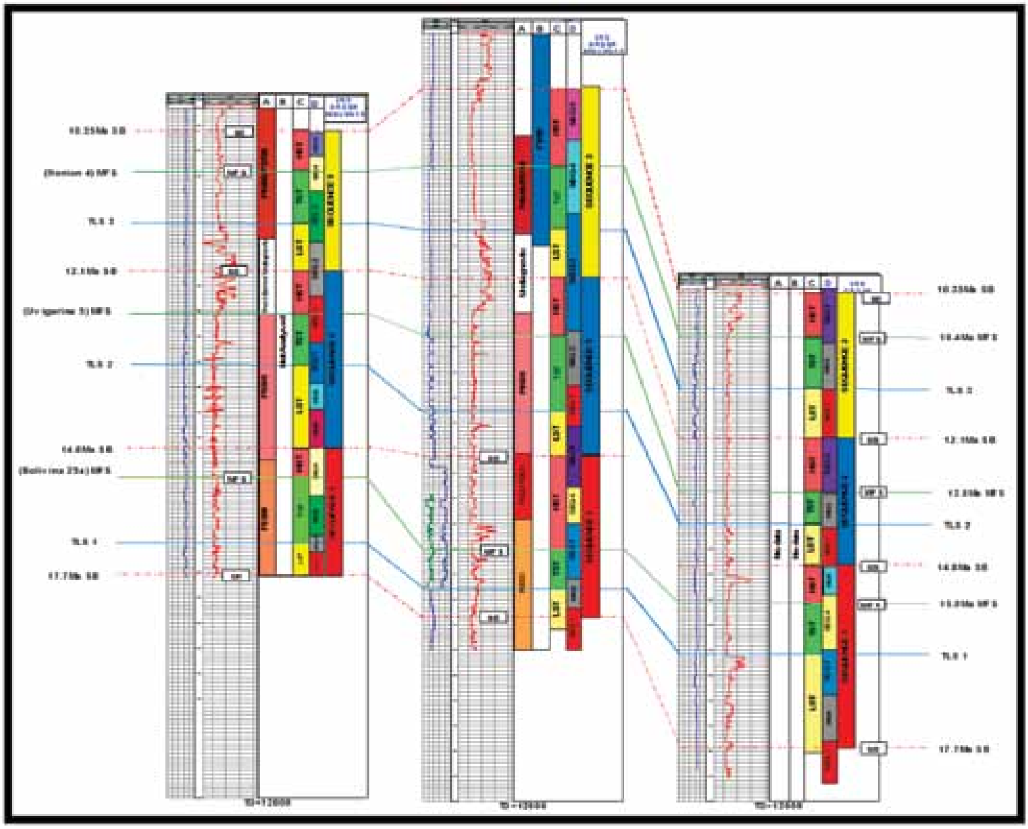

Figure 12. Dip line structural cross-section correlation of wells 002, 001 and 004

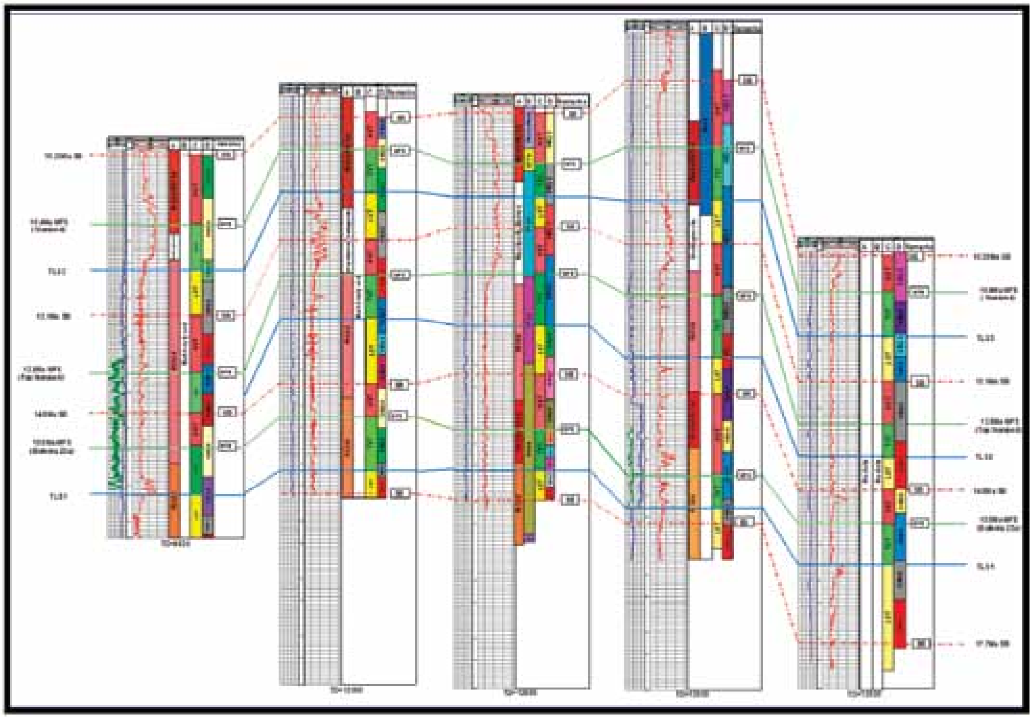

Figure 13. Structural cross-section correlation of all the wells in the field

10.4 Ma. These surfaces were all associated with the strata of early to middle Miocene age and corresponding to pollen zones P830-P670 and foram zones F9300- F9600 and foram sub zones F9301-F9605. The recognized maximum flooding surfaces were tied to the Niger delta chronostratigraphic chart and all was found to fall within the Central Swamp Depobelt.

Acknowledgements

The author is grateful to the Shell Petroleum Development Company (SPDC) for providing the data used for this study and the effort of Dr. Orodu O. D., is also appreciated for prove reading the manuscript.

References

Ainsworth, R. B. (2005): Sequence stratigraphic-based analysis of reservoir connectivity: influence of depositional architecture – a case study of a marginal marine depositional setting. *Petroleum Geoscience*; EAGE/ Geological Society, London; Vol. 11 2005, pp. 257–276.

Doust, H., Omatsola, M. E. (1990): Niger Delta, In: J. D. Edwards, P. A Santogrossi (eds.), Divergent/passive margin basins, *American Association of Petroleum Geologists*; pp. 239–248.

EKWEOZOR, C. M., DAUKORU, E. M. (1984): Petroleum source-bed evaluation of Tertiary Niger Delta; discussion and reply, *AAPG Bulletin*; Vol. 68, pp.387–394.

EMERY, D. & MYERS, K. (1996): *Sequence Stratigraphy*. Blackwell Science Ltd., London, UK. 297.

GOLDHAMMER, R. K., DEV WICKENS, H., BOURMA, A. H. & WACH, G. (2000): Sequence stratigraphic architecture of the late Permian Tanquan submarine fan complex, Karoo Basin South Africa, in A. H. Bourma and C. G. Stone, ed., fine grained Turbidite systems, *AAPG Memoir 72/SEPM special Publ.*; Vol. 68, p.165–172.

HOSPERS, J. (1965): Gravity field and structure of the Niger Delta, Nigeria, West Africa. *Geological Society of American Bulletin*; Vol. 76, p. 407–422.

HAQ, B. U., HARDENBOL, J. & VAIL, P. R. (1988): Mesozoic and Cenozoic chronostratigraphy and eustatic cycles. In: Sea-level –an integrated approach, Wilgus, C. K., Hasting, B. S., Kendall, C. G. St., Posamentia, H., Ross, C. A. and Van Wagoner (eds.). *Jour. Soc. Econs. Paleotol. Mineral. Spec. Pub.*; Vol. 42, p. 47–70.

KULKE, H. (1995): Nigeria, In: Kulke, H., ed., Regional Petroleum Geology of the World: Part II, Africa, America, Australia and Antarctica: Berlin, Gebruder, Bontraeger, p. 143–172.

KLETT, T. R., AHLBRANDT, T. S., SCHMOKER, J. W. & DOLTON, J. L. (1997): Ranking of the world's oil and gas provinces by known petroleum volumes: U.S. *Geological Survey*, Open-file Report, 97–463, CD-ROM.

LOUTIT, T. S., HARDENBOL, J., VAIL, P. R., BAUM, G. R. (1988): Condensed section: the key to age dating and correlation of continental margin sequences. In: Seal level changes: an integrated approach (Eds Wilgus, C. K., Hasting, B. S., Kendall, C. G. St., Posamentia, H., Ross, C. A. and Van Wagoner, J.), *Soc. Econs. Paleotol. Mineral. Spec. Publi.*; Vol. 42, pp. 3–17.

OZUMBA, M. B., OMENE, D. A. & OTOGBILE, C. (2005): The Opuma channel area 3D prospectivity review, impact of high-resolution sequence stratigraphy, *NAPE Bulletin*; Vol. 18, No. 1, p. 1–10.

PETROCONSULTANTS (1996): Petroleum exploration and production database: Houston, Texas, Petroconsultants, Inc.

POSAMENTIER, H. W & VAIL, P. R. (1988): Eustatic control on clastic deposition, conceptual framework. In: Seal level changes: an integrated approach (Eds., Wilgus, C. K., Hasting, B. S., Kendall, C. G. St., Posamentia, H., Ross, C. A. and Van Wagoner, J., *Soc. Econs. Paleotol. Mineral. Spec. Publi.*; Vol. 42, pp. 125–154.

REIJERS, T. J. A., PETTERS, S. W. & NWAJIDE, C. S. (1997): The Niger Delta basin. In: Selley, R. C. (Ed), African basins, Amsterdam, *Elsivier science, sedimentary basins of the world*; Vol. 3, p. 151–172.

Rotimi, O. J., Ameloko, A. A., Adeoye, O. T. (2010): Application of 3-D Structural Interpretation and Seismic attribute Analysis to Hydrocarbon Prospecting over X – Field, Niger – Delta. *International Journal of Basic & Applied Sciences*, IJBAS/IJENS, 10(4) 105104 – 8383, ISSN: 2077–1223.

Vail, P. R. & Wornardt, W. W. (1990): Well log seismic Sequence stratigraphy: An integrated tool for the 90's: gulf coast section of Society of Economic Paleontologist and Mining Foundation, Eleventh Annual Research program and extended abstract, pp. 379–388.

Vail, P. R. & Wornardt JR, W. W. (1992): Well log-seismic sequence stratigraphy, course notes presented on behalf of Global Geotechnical & Mosunmolu limited, November 26–28th 1992, Lagos, Nigeria, 490 pp.

Van Wagoner, J. C., Mitchum, R. M., Campion, K. M. & Rahmanian, V. D. (1990): Siliciclastic sequence stratigraphy in well logs, cores and outcrops: concept for high-resolution correlation of time and facies, AAPG methods in exploration series, No. 7, 55 pp.

Weber, K. J. & Daukoru, E. M. (1975): Petroleum geology of the Niger Delta: Proceedings of the 9th World Petroleum Congress, Vol. 2, Geology: London, Applied Science Publishers, Ltd., p. 210–221.

Wilgus, C. K., Hasting, B. S., Ross, C. A., Posamentier, H. W., Van Wagoner, J. & Kendall, C. G. ST. C. (1998). Sea level changes, an integrated approach, *SEPM special publication*; Vol. 42, 407 pp.