International Journal of Science Academic Research
Vol. 01, Issue 04, pp.121-132, July, 2020
Available online at http://www.scienceijsar.com

Research Article

STRATIGRAPHIC INTERPRETATION OF SEISMIC SECTIONS FROM WELLS -‘B’ AND ‘C’, CENTRAL DEPOBELT, NIGER DELTA, NIGERIA

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Received 24th May 2020; **Accepted 17**th June 2020; **Published online 15**th July 2020

Abstract

Seismic and sequence stratigraphic approach was applied to sedimentary study of ‘X’ and ‘Y’ fields in the Central Depobelt of the Niger Delta using 2D seismic section, wire line logs (gamma ray and resistivity) and a high resolution biostratigraphic datasets of well-‘B’ and well-C’. The study observed succession of sediments being deposited progressively basin wards and overlain by thick marine shales and clay deposits. These thick, sand rich wedges are separated from each other by up-dip extending thinner sediments of fossiliferous marine shales. The extracted seismic horizons showed a more conspicuous and varied seismic pattern which has on one hand, predominantly a smooth texture; high amplitude; with a discontinuous rugged texture; whereas the chaotic seismic pattern was observed to possess a low coherence attribute. On the other hand, the low amplitude and variable frequency has a less predictable texture than the high-amplitude, continuous, coherent reflection pattern. Four regional transgressive shales, dated by characteristic foraminifera events, which correspond to the downlap surfaces were recognized in the wells analysed. These include; *Chiloguembelina cubensis* and/or *Globorotalia opima opima*, *Uvigerinellasparsicostata*, *Spiroplectammina wrightii* and *Hopkinsina bononiensis*. The delineated Maximum Flooding Surfaces (MFSs) in this study are dated 28.1/Ch*1Ma, 31.3/Ru*2Ma, 33.0/Ru*1Maand 34.0/Ru*1Ma for the candidate surfaces. However, the encountered depositional sequences are bounded with sequence boundaries dated 27.3Ma, 29.3Ma, 32.4Ma, 33.3Ma and 35.4Ma respectively. The delineated system tracts within the two wells are Lowstand, Highstand and Transgressive systems tracts with their associated aggradation, progradation and retrogradation stacking patterns. However, the identified Maximum Flooding Surfaces (MFS) were extrapolated on the seismic sections. It was observed that on the analysed seismic section, the Maximum Flooding Surface within these wells commonly appear as thick amplitude events that form the upper bounding surfaces of sandy, bright-amplitude intervals. In all stage boundaries, it coincides with flooding surfaces which occur at the tops of major upward-fining successions in the shelf deposits and ranges conspicuously between 1.9 – 3.0secs within the sections.

Keywords: Seismic/sequence stratigraphy, Seismic pattern, Reflection termination/configuration, Depositional sequence, Shale maker and Central Depobelt.

INTRODUCTION

Sequence stratigraphic interpreted inputs from two wells (‘B’ and ‘C’) were integrated with seismic stratigraphic analysis of five In-lines and one X-line seismic lines carried out in this study. The effective maximization and exploitation of hydrocarbon accumulation requires the full understanding of the reservoir beds and the pore space they contain, therefore, fundamental study of this nature on clastic sediments however produces a wealth of published information on the sediments distribution and continuity of the sandstones deposited in a particular environment. In this study, criteria for recognizing the various types of sediments and the proper prediction of their reservoir properties requires the utilization of the following subsurface data, such as ditch cuttings, well logs and seismic profile datasets. Models for predicting sand-body development, distribution and its continuity are also highlighted utilizing seismic sections, biostratigraphic and sedimentologic information coupled with the in-depth analysis utilizing the application concepts of sequence and/or seismic stratigraphic analysis. From seismic stratigraphic perspective, the continuity, distribution and of course, the internal characteristics of sediments are controlled primarily by its original environments of deposition. Therefore the determination of the continuity of sediments will substantially develop thorough understandings of the reservoir horizons within the available deltaic sub-environments encountered in the studied area. The application of the sequence stratigraphy in this study, being a recent methodology for stratigraphic understanding and interpretation is observed as a process-oriented approach for the interpretation of sedimentary packages. It is therefore an insight in the understanding of depositional processes within a sedimentary basin and the factors that directly influence them. This also describes the linkage between sedimentation patterns in different parts of basins and predicts the locations and extent of reservoir, seal-prone intervals, pay zones, occurrences and geometries of sedimentary facies within the basin. Recent studies on integrated reservoir studies have focused largely on modifications of the basic sequence stratigraphic model, in which their depositional cycles occur as large scale within an upward fining and upward coarsening succession (Udoh, 2004, and Zecchin *et al.,* 2006). Identification and delineation of horizons in sequence stratigraphic interpretations involve multiple disciplines where seismic profiles, well logs, and biostratigraphic data sets are used. Seismic data provide the large scale frame work of stratal geometries both locally and regionally. The subsurface ditch cutting samples after due process normally yield biostratigraphic information which provides highly useful facts on identifying the condensed

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sections and their ages in million years (Maximum Flooding Surfaces), sequence boundaries, chronostratigraphic surfaces, paleobathymetry and climatic conditions.

Field location and geological setting Niger delta

The two wells and all the datasets used in this study were obtained from Nigerian Agip Oil Company Limited in Port Harcourt. The study area of 'X' fields occupies about 616.79 acres in the onshore Niger Delta. The Fields location and the respective well distances between the two study wells are shown in Figs. 1 and 2 while Fig.3 shows the seismic base map of the wells. This field is pseudo-named 'X', for the purpose of confidentiality and they are located within Latitude: 5^0 20'N, Longitude: $6^0$40'E. The fields are situated in the eastern part of Central Niger depobelt and in north eastern part of Bayelsa State of Nigeria. A total number of two wells ('B' and 'C') are used in this research work. The oil wells on the fields are located on elongated rollover anticline bounded to the north against a large east- west trending growth fault and to the east by north west-south trending fault.

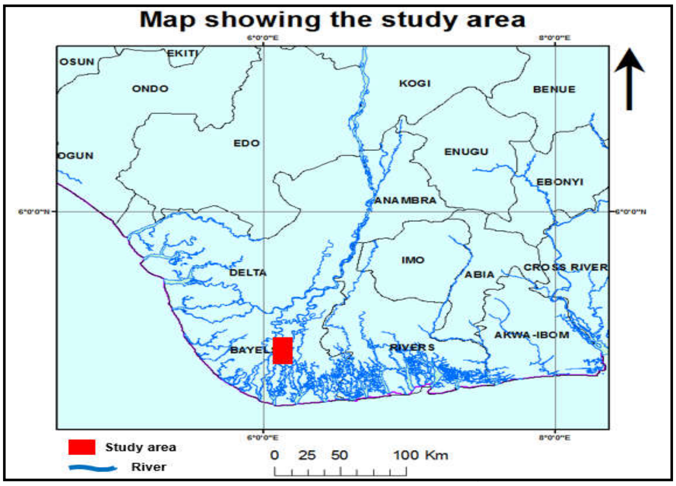

Fig.1. Location map of the study area

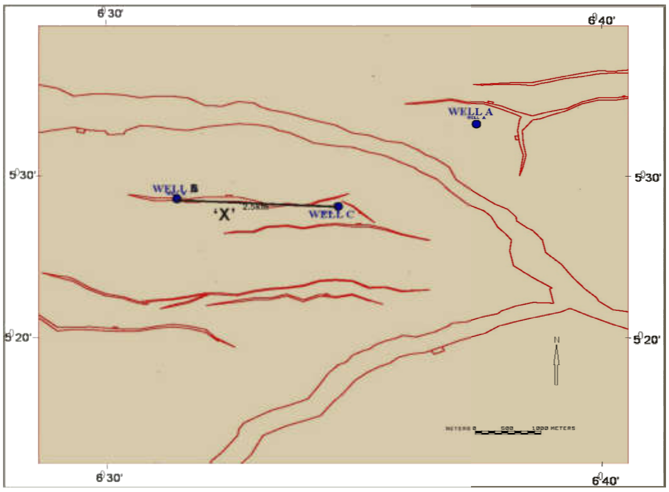

Fig. 2. Wells location and their distances within the Fields

The Niger delta basin is located within the Gulf of Guinea and covers an area of about 75,000km^2 and has an average sediment thickness of about 12,000m (Reijers *et al.,* 1997). The geologic evolution of the Niger Delta basin transcends and predates the Paleocene regressive clastic wedge that is conventionally ascribed to the delta (Frankl and Cordry, 1967; Short and Stauble 1967; Weber and Daukoru, 1975). It is connected to the tectonic setting of the southern Benue Trough, which is the mega-structure whose coastal and oceanward part lies the Niger Delta (Avbovbo, 1978), however, the Benue Trough is a NE - SW folded rift basin that runs diagonally across Nigeria. It represents a failed arm of a triple junction associated with the opening of the Gulf of Guinea and the equatorial Atlantic in Aptian-Albian times when the equatorial part of Africa and South America began to separate (Benkhelil, 1987). The formation of the Niger delta basin began after second depositional cycle (Campanian-Maastrichtian) of Benue Trough that formed the proto-Niger Delta. The third and last depositional cycle of the southern Nigerian basin formed the Niger delta formations.

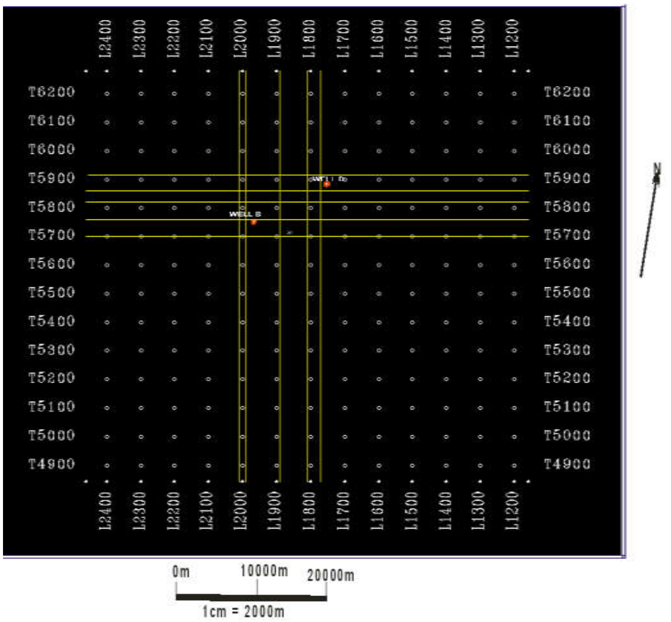

Fig. 3 Base map showing wells location on the T – L Horizons

According to Short and Stauble (1967), the stratigraphy of the Niger Delta can be divided into three major units ranging in age from Eocene to Holocene. However observation from the base showed that the Akata Formation, which includes at least 6500m (21,400ft) of marine clays with silty and sandy interbeds (Whiteman, 1982). The Agbada Formation, which is characterized by paralic to marine coastal and fluvial-marine deposits mainly composed of sandstones and shale organized into coarsening-upward off-lap cycles (Weber, 1971). The Benin Formation, which consists of continental and fluvial sands, gravel, and back swamp deposits of about 2,500m (8,250ft) thick (Reijers, 2011). Notable authors such as Ejedawe, 2012, Doust and Omatsola, 1990, Stacher, 1995and Frankly and Cordry, 1967 showed that this three diachronous formations occur within the growth fault bounded sedimentary units called depobelts or depocentres that succeed each other in a southward direction (Fig. 4). The sedimentation in each depobelts was a function of rates of deposition and subsidence with syn-sedimentary growth fault upsetting the balance (Evamy *et al.,* 1978). The growth faults are generated by rapid sedimentation and gravitational instability during the accumulation of Agbada deposits and continental Benin sands over mobile and under-compacted Akata prodelta shales. Lateral flowage and extrusion are also responsible for the diapiric structures on the continental slope of Niger delta (Reijers et al. 1997).

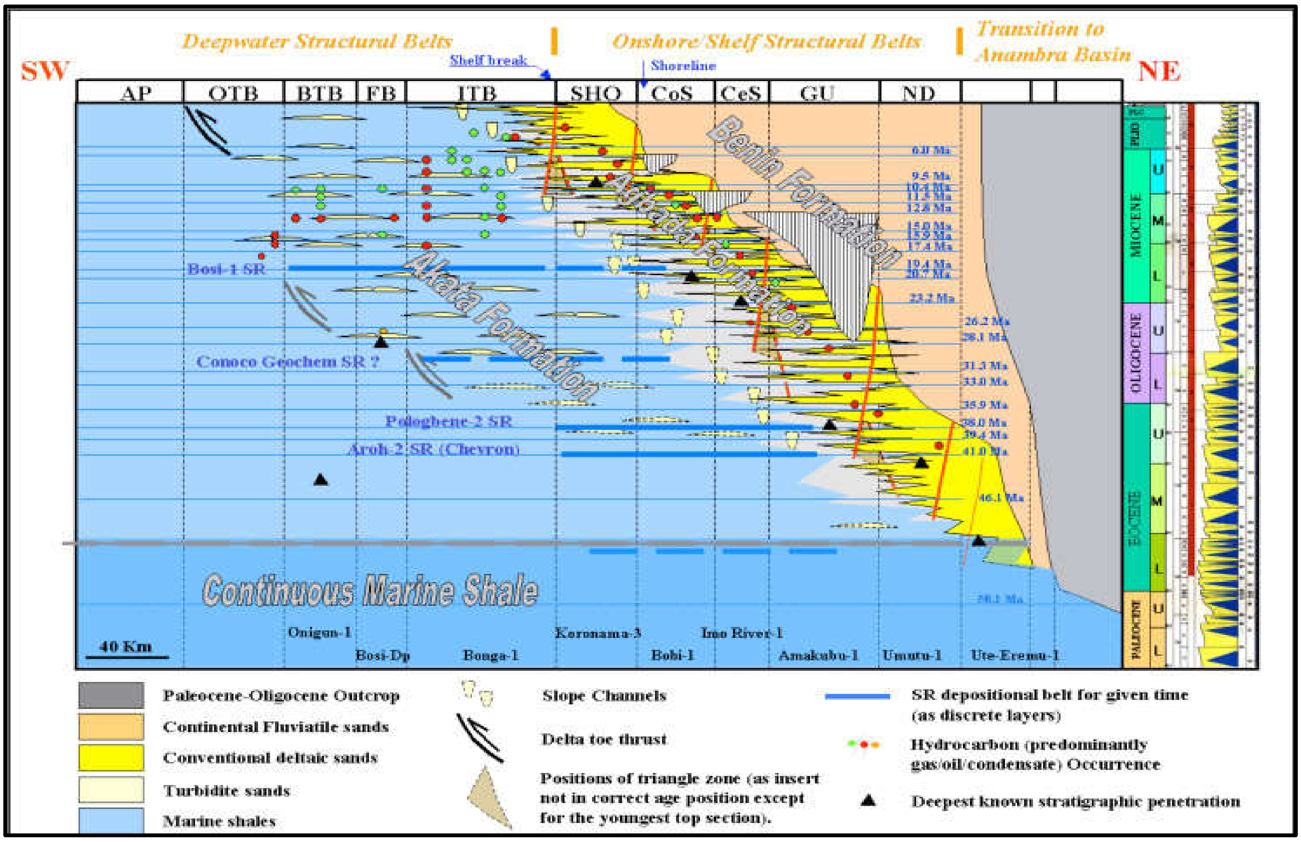

Fig.4. Stratigraphic column showing formations of the Niger Delta (After Ejedawe, 2012)

MATERIALS AND METHODS

The methodological approach spelt out in this study involves recent adoption of both sequence and seismic stratigraphic principles and this includes:

Sequence Stratigraphic Analysis

The sequence stratigraphic analysis was carried out independently as a first step from biofacies and log datasets, and results were subsequently compared and integrated. Well logs interpretation involved detailed subdivision of the successions into the constituent parasequences types and parasequences sets, from which lateral facies changes and the creation of accommodation space with changes in relative sea level were interpreted. These models therefore explain the types and distribution of reservoir sand body found within the individual systems tracts, which have been applied reliably in this interpretation. The following approach was employed in the sequence stratigraphic analysis and interpretation. However, the integration of biostratigraphic/biofacies, sedimentologic attributes and wireline log datasets allowed for:

(a) The identification and chronostratigraphic dating of all the key stratigraphic surfaces amongst; transgressive surface (TS), sequence boundary (SB) and maximum flooding surface (MFS). The ability to recognize these key surfaces helps to unravel the stacking pattern thereby giving a clue in the understanding and interpretation of the sequence stratigraphic framework of the environment.
(b) With the observed wireline logs and biofacies, respective systems tracts were correctly delineated.
(c) Depositional environments were defined using logs signatures and biostratigraphic datasets.

Seismic Stratigraphic Analysis

The seismo-structural and facies interpretations in this study was done using defined criteria adopted by Gorneyet al., (2007) and Adeogba *et al.,* (2005). On the other hand, facies analysis of all the seismic sections in this study followed standardized method specified by Gorney *et al.,* (2007). In this investigation, Highstand systems tract (HST), Transgressive systems tract (TST) and Low stand systems tracts (LST) were recognized based on the reflection configurations and termination patterns as well as their position relative to the Maximum Flooding Surfaces (MFS) and Sequence boundaries (SB). Absolute ages for these isochronous surfaces were derived from the chronostratigraphic chart for the Niger delta which was correlated with sea level curves of Haqet al., (1987). Sequence Boundaries (SB) and Maximum Flooding Surfaces (MFS) were correlated between the wells in the study area by relating their respective well log patterns to specific reflections and vertical changes in the seismic facies and were traced between the wells thus, matching similar well log patterns with adjacent well.

Following the successful identification and delineation of all surfaces for all the two wells and the accurate conversion of the time at which they occurred to depth, these surfaces were therefore conspicuously identified, traced and equally represented on the seismic sections. Conversely on the log motifs, the Maximum Flooding Surfaces were marked by the highest Gamma ray peak (finning upward trend) and low deep induction resistivity; on the seismic sections it is coincident with the downlap surfaces (MFS) to a set of prograding clinoforms. However, the Sequence boundaries are coincident with the coastal onlap surfaces. Interpretations of all the given seismic sections (inlines and crosslines) adopt the following methods as shown below:

(i) Delineation of all the existing faults within the seismic sections was done by using pencil and their identifications was carried out by recognizing the following features;

  a) Configuration and termination of events and offset of reflections
  b) Abrupt change in the geologically dip configuration.

(ii) Horizons were picked, which represent top and bottom of the reservoir units identified and picked from well logs provided. The selected reflectors are marked and traced; the discontinuities along the reflectors were observed and marked as faults structures.
(iii) Picking and posting of the maximum flooding surfaces, sequence boundaries and the respective systems tracts within the seismic sections were also swiftly delineated.
(iv) Reflections and configurations pattern were then picked accordingly.

RESULTS AND DISCUSSION

Interpretation of Seismic line (1990) denoted as B - B':

This seismic section is denoted by inline 1990 and has shown four seismic facies units with their corresponding depositional settings as shown in Fig. 5 below. Well 'B' is located on this section at T5760 shot point.

The seismic facies encountered between T5350 and T6250 shot points is designated as unit 'A' and lie within 100 – 600m interval depth. The reflection configuration is regarded as being free with a relatively low frequency, amplitude, continuity and intensity. These characteristics depict sediments deposited within the Back shoreface environments. It forms an onlap boundary at the base of the underlying horizon of the sediments. Underlying the 'A' facies unit is another type of facies unit denoted by 'B'. This facies unit falls within 600 – 2150m depth interval and displayed a way to parallel type of internal reflection configuration. However, Unit 'B' seismic facies is characterized by low to moderate amplitude and continuity with absolutely low intensity. Deposition within this horizon took place in the Fore – Upper shoreface environments. Seismic facies unit 'C' lies within the 2150 – 3600m interval depth. Observation from this seismic package shows that it has continuous beddings with high reflector amplitude anomalies, high continuity and intensity respectively.

This section exhibits contorted geometries as these structures are indicated close to the faults (FB_1 and FB_2) structures and within this level is a thick wedge of shallow water deltaic deposits prograded- basin ward. However, this unit is downlap at the base and its depositional settings has been interpreted as being minor channel deposits found within the Lower – Proximal shoreface environments. At the lower setting of the section is facies Unit 'D' and extends from 3600 – 4500m interval depth and downward with variable high energy environment. The upper horizon of this seismic facies consists of irregular, discontinuous and sometimes sub-parallel segments which show random to hummocky internal reflection pattern and is marked by non-systematic reflection termination while the lower section shows chaotic reflection type.

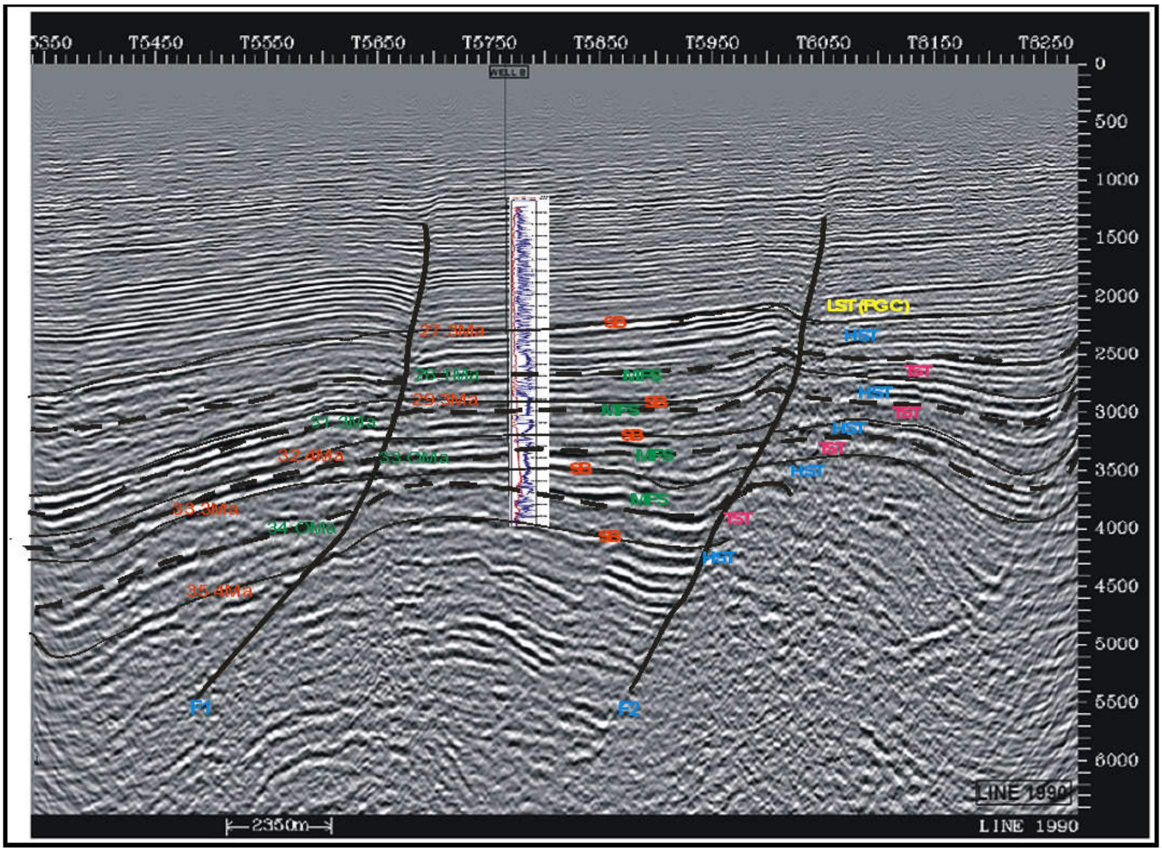

Fig. 5 Interpretation of Seismic line 1990 denoted as B - B'

Table 1. Conversion of depth (m) to time (millsecs.) for all the Key candidate surfaces (MFS and SB) in wells - 'B' and 'C'.

	Wells	'B'		'C'	
Age	Key Dated Surfaces (Ma)	Depth (m)	Time (millsecs)	Depth (m)	Time (millsecs)
	SB_6 (24.9)	-	-	-	-
Late Oligocene	MFS (26.2)	-	-	-	-
	SB_5 (27.3)	2180	1862	-	-
	MFS (28.1)	2558	2092	2500	2062
	SB_4 (29.3)	2685	2194	2645	2164
Middle Oligocene	MFS (31.3)	2940	2352	2930	2338
	SB_3(32.4)	3240	2524	3050	2424
Early Oligocene	MFS (33.0)	3390	2626	3330	2410
	SB_2(33.3)	3630	2768	3520	2704
	MFS (34.0)	3740	2830	3700	2806
Late Eocene/E. Oligocene	SB_1(35.4)	3870	2852	3980	2948

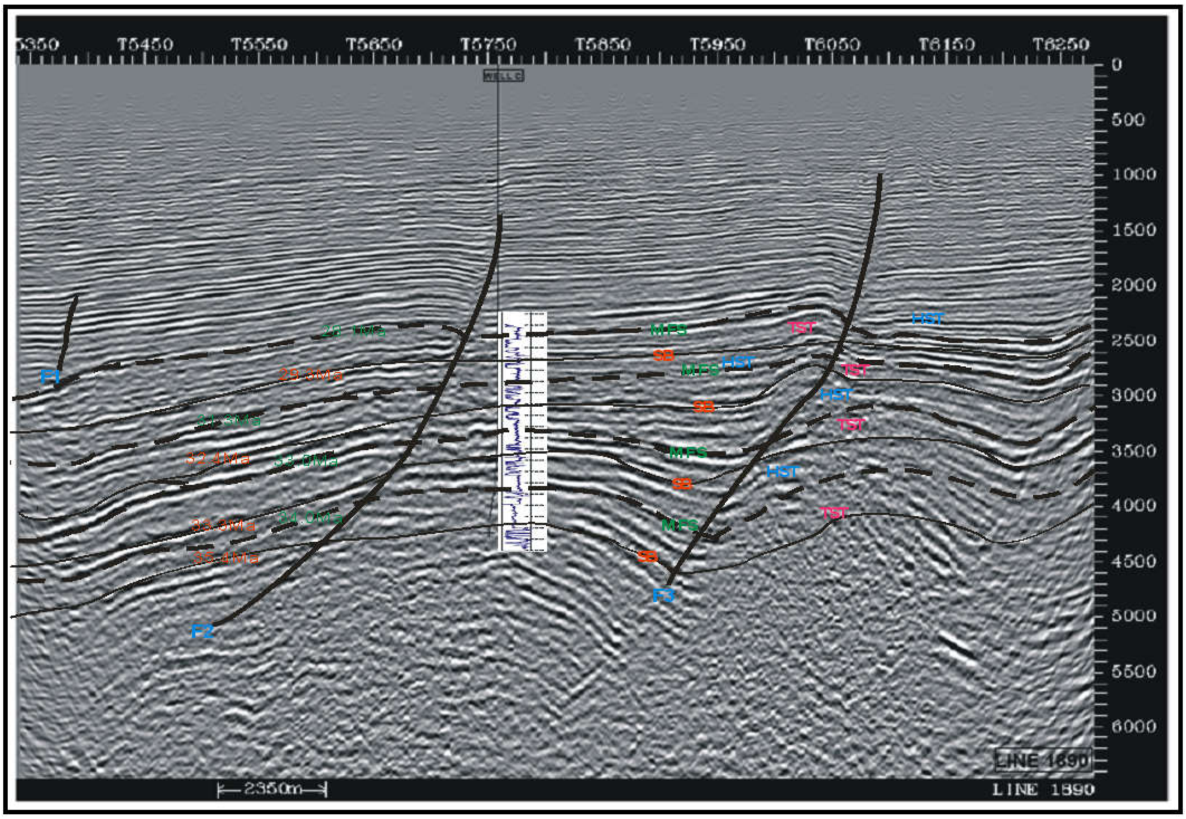

Fig. 6. Interpretation of Seismic line 1890 denoted as C –C

The fault structure (FB_2) observed within this seismic section has set the horizon between T6050 and T6250 shot points to be grossly uplifted (up-thrown) relative to the fault FB_1 thereby dipping the observed beds between T5350 and T5950 shot points respectively. It has been observed that the time equivalent on the seismic horizon derived from the depth time conversion ranges between 2.1 – 2.8secs respectively (Table 1).

Interpretation of seismic line (1890) denoted as C - C'

This seismic section is denoted by inline 1980 and has shown three seismic facies units with their characteristic features which depict their corresponding depositional settings as shown in Fig. 6. Well -'C' is located on this section at T5760 shot point. The seismic horizon facies unit of line 1890(C - C') contains facies that is not quite different from the one occurring within seismic line B - **B**'. However, the interval of 100 – 600m is characterized by free reflection pattern which are unstratified rock or sediments in nature, with homogeneous lithology.

Immediately underlying the 'A' unit is another facies unit denoted as 'B' unit. This seismic facies unit lies within 600 – 2510m interval depth and spread from T5350 – T6250 shot points. Unit B therefore showed a characteristic wavy, parallel to sub-parallel reflection configurations. Reflection continuity was generally continuous as observed form the seismic section. Amplitude was high basinward (i.e. eastward). The frequency was uniformly narrow at the upper part but somehow broad at the lower part of this seismic horizon. This facies unit displayed wedged shape geometry and forms concordant relation at the top and onlap at the base boundary of the facies package. This seismic facies unit is interpreted to be associated with shale and sand deposits probably depicting channel sand which typified a prograding shelf setting within the Lower shoreface. Facies unit 'C' extends downward from 2510 – 3595m interval depth. This horizon is characterized by chaotic reflection configuration. Again, the frequency of the reflection within this package is highly variable with respect to its internal heterogeneity; its continuity pattern is also highly discontinuous. The amplitude anomalies is low and the reflection geometry is described as being contorted and discordant, therefore, interpretation of this facies unit is associated with high energy environments which depicts foreshore – Upper shoreface depositional setting. The time equivalent on the seismic horizon ranges between 2.1 – 2.8secs.

Interpretation of seismic line (5760) denoted as B - C'

The X-line 5760 seismic section denoted by B – C' contained an assemblage of four seismic facies units as shown in Fig. 7. However, this section has wells - 'B' and 'C' located on it at L1990 and L1890 lines respectively. In section **B - C'**, the facies units and the reflection characteristics encountered within this section are almost the same as those sections described for seismic lines B - **B'**. This section shows its faults (F1, F2 and F3) orientation in the North to South direction as in fig. 7, therefore this section B - **C'**, is more or less correlatable structurally in this respect as their close description showed the existence of the faults throw (that is, well 'B' is at the up throw side relative to well - 'C') and its displacement between the wells ('B' and 'C').

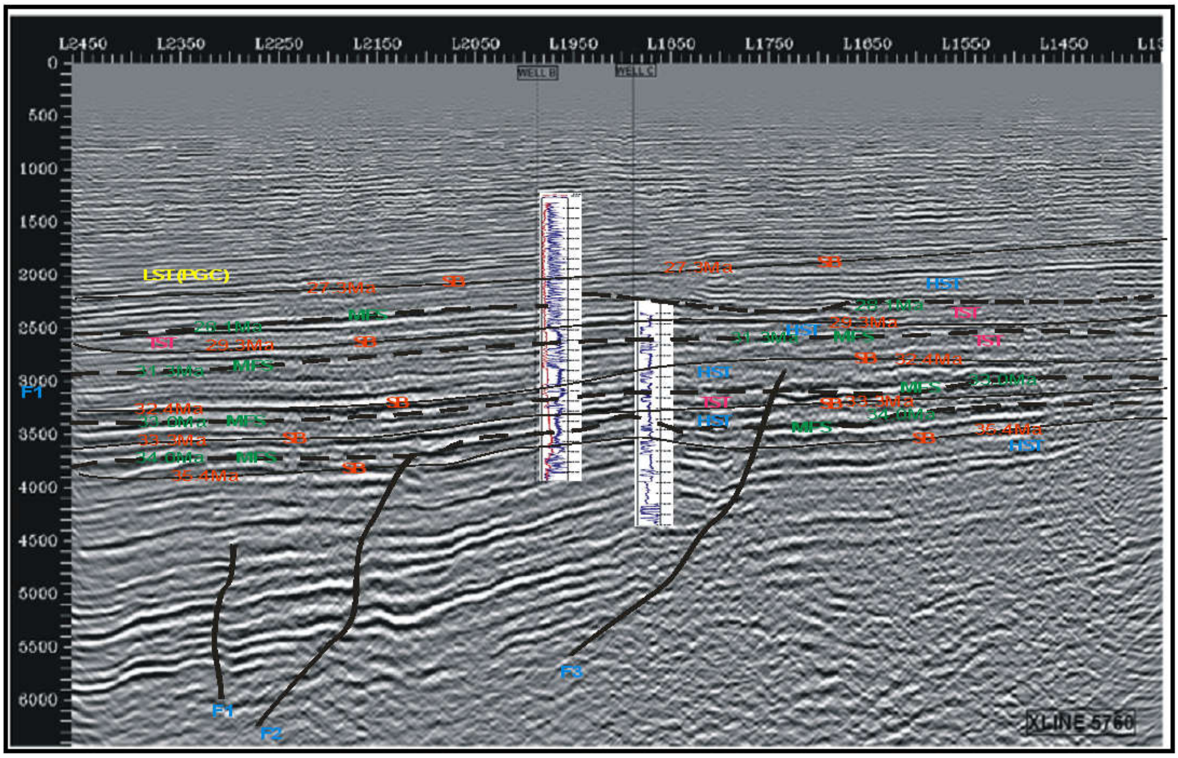

Fig. 7 Interpretation of Seismic line 5760 denoted as B – C'

Sequence Stratigraphic Interpretation of well - 'B'

Sequence stratigraphic analysis of well 'B' was undertaken and the results are presented in Fig. 8 while the Table 2 shows the summary of the interpretation. The onset of the highstand systems tract with interval depth of 3974 – 3870m (104m) as shown on the distribution chart of well – 'B' was probably not tested in this study at the Total Depth (TD) of the well. This predominantly sand interval (with shale intercalations) was deposited in Inner Neritic paleo-water depth; and is characterized by progradational to blocky (coarsening upward) log signatures typical of a low sea level regime. The peak of regression was delineated at 3870m, where a relatively low Gamma ray and a high Deep Induction Resistivity log values are associated with the faunal minima. The sequence boundary (SB) encountered at the top this system tract is dated 35.4Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). Underlying the highstand systems tract is the transgressive phase of deposition within the depth range of 3870 - 3740m (130m). These sediments were observed to show aggradational/retrogradational log motifs and are associated with predominantly shaly lithofacies deposited in Inner to Middle Neritic paleo-water depths. This phase of transgression culminated at the MFS delineated at 3730m based on the high Gamma ray log value (low Deep Induction Resistivity log within the interval) associated with relatively high abundance and diversity of foraminifera at this depth. The MFS is dated 34.0/Ru*1Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). The Last Downhole Occurrence (LDO) of *Hopkinsina bononiensis* at 3370m supports this interpretation. This bioevent is dated 34.0/Ru*1 Main the Niger Delta. A renewed phase of highstand systems tract merged within the interval of 3740 – 3630m (110m) below the transgressive systems tract. The shales (hemi-pelagic – pelagic) and sands encountered in this interval were predominantly deposited in Inner to Middle Neritic paleo-water depths. This shallowing upward sequence is associated with stacks of progradational log motifs; typical of regressive phase. The peak of this regressive phase (SB) was delineated at 3630m based on the low Gamma ray log value (high Deep Induction Resistivity log) associated with faunal minima at this depth. The Sequence boundary is dated 33.3Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). This predominantly shale interval (with minor sand intercalations) was observed to be associated with overall retogradational log pattern sediments deposited within the next phase of the transgressive systems tract with interval depth of 3630 – 3390m (240m). This lithofacies were deposited in Outer Neritic – Upper bathyal water regime. This overall deepening upward sequence defines this transgressive phase,

Table 2. Sequence Stratigraphic summary of Well - 'B':

Depth Interval (m)	Systems Tract/ Key Surfaces
1766 – 2180	LST (PGC)
2180	SB (27.3Ma)
2180-2558	HST
2558	MFS (28.1Ma)
2558 – 2685	TST
2685	SB (29.3Ma)
2685 -2940	HST
2940	MFS (31.3Ma)
2940-3240	TST
3240	SB (32.4Ma)
3240 – 3390	HST
3390	MFS (33.0Ma)
3390 – 3630	TST
3630	SB (33.3Ma)
3630 – 3740	HST
3740	MFS (34.0Ma)
3740– 3870	TST
3870	SB (35.4Ma)
3870 – 3974	HST

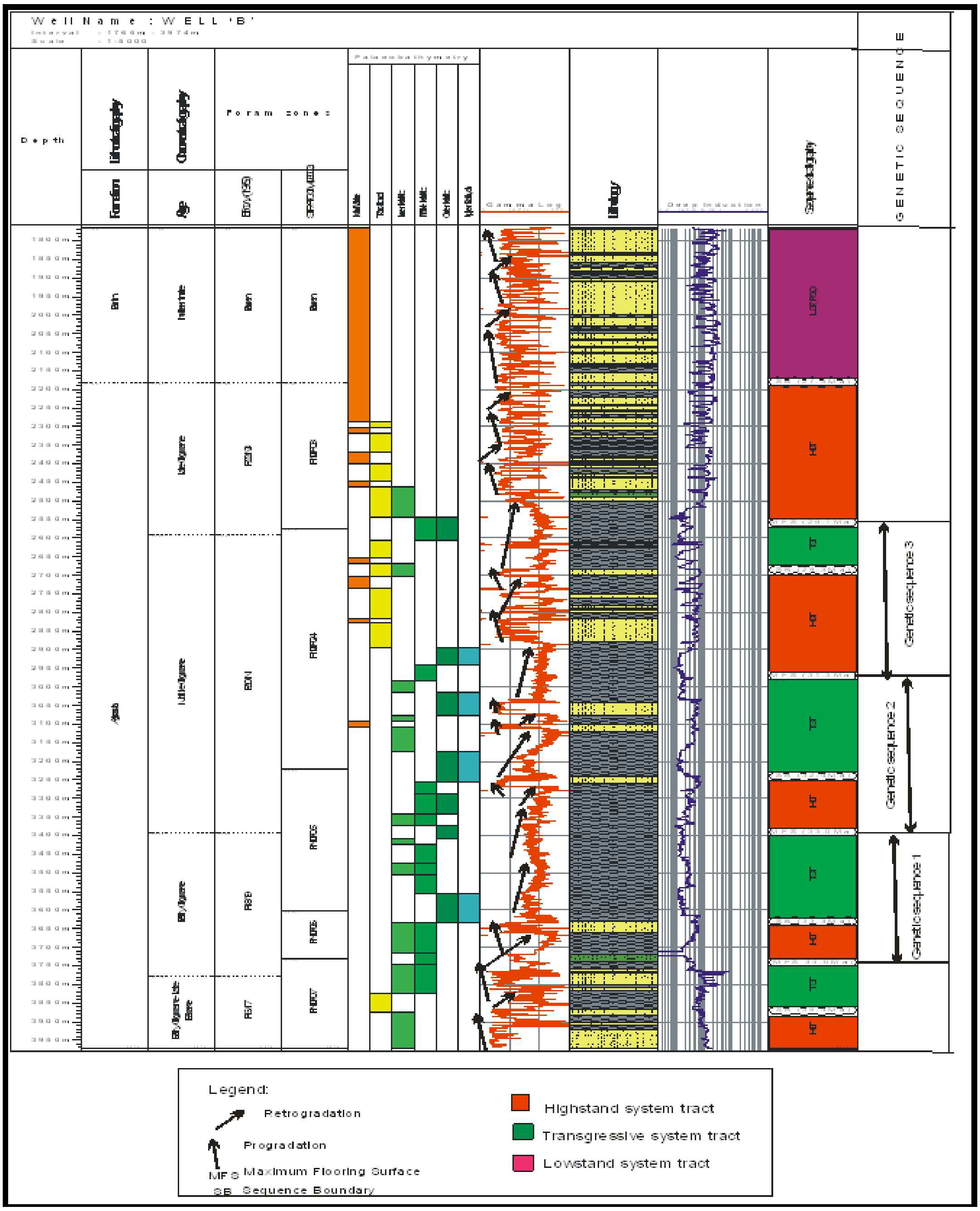

Fig. 8. Sequence stratigraphic interpretation showing vertical pattern and genetic sequence in well-'B'

with its peak (MFS) delineated at 3390m, based on the relatively high Gamma ray and low Deep Induction Resistivity log values associated with a high abundance and diversity of microfauna at this depth. This is probably the equivalent of the *Spiroplectammina wrightii* MFS which is dated 33.0/Ru*1Maby correlation to the third order cycles chart of Haq *et al.,* (1988). Within the interval depth of 3390 - 3240m (150m) the sediments observed within this well were deposited in a predominantly regressive phase depicting a Highstand setting. The shales and sands encountered in this interval were deposited in an overall shallowing upward depth of deposition within Outer through Middle to Inner Neritic paleo-water depths. Stacks of progradational log motifs as seen more clearly from the Gamma ray and Resistivity logs characterize the regressive phase which reached its peak (SB) at 3240m. The Sequence boundary was delineated based on the relatively low gamma ray and high Deep Induction log values associated with faunal minima at this depth. It is dated 32.4Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). However, stacks of retrogradational (backstepping) log motifs associated with predominantly shaly lithofacies with minor sand packages within the depth 3240 – 2970m (270m) were deposited in the paleo-water depths that fluctuated between Non marine, Inner to Middle Neritic through Outer to Upper bathyal bathymetric realms and was observed to occur in a transgressive phase. This overall deepening upward sequence defines this transgressive phase; the peak (MFS) of this phase was delineated at 2970m (log adjusted) based on the relatively high Gamma ray and low Deep Induction Resistivity log values at this depth. The high foraminiferal abundance and diversity associated with this surface is recorded at 2910m; this is attributed to the nature of the samples (ditch cuttings) used. This is the equivalent of the *Uvigerinellasparsicostata* MFS and it is dated 31.3/Ru*2Maby correlation to the third order cycles chart of Haq *et al.,* (1988).

The coarsening upward log motifs was observed to underlie the transgressive phase of the overlying section and was interpreted as the highstand phaseinitiated with an interval depth of 2970 – 2685m (285m). Stacks of retrogradational/ progradational parasequences characterize the lithofacies encountered in this interval. The lithofacies were deposited in the Middle to Inner Neritic through Non-marine paleo-water depths. The peak of progradation (SB) was delineated at 2685m and is characterized by low Gamma ray and high Deep Induction Resistivity log values associated with faunal minima at this depth. It is dated 29.3Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). The overall retrogradational log signatures depicting the transgressive phase within the well at 2685 – 2558m (127m) characterized the shale and sand lithofacies of this interval. The lithofacies were deposited in paleo-water depths that fluctuated between Non-marine, Shallow-Inner, Inner through Middle to Outer Neritic bathymetric realms. The overall deepening upward sequence defines this transgressive phase, with its peak (MFS) delineated at 2558m, based on the relatively high Gamma ray and low Deep Induction Resistivity log values associated with high abundance and diversity of microfauna at this depth. This MFS is dated 28.1/Ch*1Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). The First Downhole Occurrence (FDO) of *Chiloguembelina cubensis* at 2446m supports this interpretation and this bioevent is dated 28.1/Ch*1Main the Niger Delta. Sequence stratigraphic analysis within the interval depth of 2558 - 2180m (378m) unveiled stacks of progradational to blocky parasequences characterize the lithofacies (sand and shale) encountered in this interval believed to have been deposited within the Highstand systems tract. The lithofacies were deposited in Non-Marine to Inner Neritic paleo-water depths. The peak of progradation (SB) was delineated at 2180m and is characterized by low Gamma ray and high Deep Induction Resistivity log values associated with faunal minima at this depth. It is dated 27.3Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). Lowstand systems tract (Prograding Wedge Complex) was analysed for the sediments deposited towards the topmost part of this well from 2180– 1766m (414m). The sands and shale encountered in this interval were deposited in predominantly Non-marine paleo-water depths. These lithofacies are associated with stacks of progradational and aggaradational log motifs (as observed on the corresponding high Gamma ray with Deep Induction Resistivity log signatures) probably depicting a Lowstand Prograding Complex (PGC). The peak of this regressive phase was probably not penetrated at the top depth; as a transgressive surface; usually depicted by an abrupt shift of the Gamma ray log to the right was not observed in the interval.

Sequence Stratigraphic analysis of Well - ‘C’

Sequence stratigraphic analysis of well - ’C’ was achieved with the integration of derived sedimentological suites, wireline (Gamma ray and Deep induction Resistivity) log datasets and foraminiferal inferences and events drawn from wells - ‘B’. These allowed the interpretation/analysis of the sequence stratigraphic development within the analysed interval of the well within the interval depth of 2400 – 4400m. However, the non-availability of wireline log from the top of this well (interval 1200 – 2400m) precludes detailed Sequence stratigraphic interpretation of this interval. The stratigraphic summary of well – ‘C’ is shown in Table 3. The approach of Vail and Wornadt (1991) was followed in attempting this interpretation, while also taking into consideration the pitfalls associated with log facies analysis. The interpretation of the sequence stratigraphic development of well - ‘C’ (interval 2400 – 4400m) was relied on the sedimentologic suites and wireline logs data sets. This was as a result of the non-availability of foraminiferal information within the interval. The associated four Maximum Flooding Surfaces (MFS’s) have been delineated at 2500m, 2930m, 3330m, and 3700m and dated 28.1/Ch*1Ma, 31.3/Ru*2Ma, 33.0/Ru*1Maand 34.0/Ru*1Ma respectively. These dated surfaces were based on the stratigraphic position as extrapolation from the correlation events of the other wells (‘B’, ‘D’ and ‘E’) within the stratigraphic framework. However, these MFSs were dated against the third order cycles chart of Haq *et al.,* (1988). The Maximum Flooding Surfaces (MFS) in this well were delineated on the basis of high Gamma ray and low Resistivity log readings while Sequence boundaries (SB) on the other hand, were recognized from abrupt kick of the Resistivity log to the left. However, dating of the key candidate surfaces (MFS and SB), where possible, was achieved by correlation to the third order cycles chart of Haq *et al.,* (1988). The stacking pattern of this well which shows three distinctive genetic sequences and a sequence stratigraphic summary chart of the analyzed interval of the well are presented in Fig. 9 and Table 3.

Table 3. Sequence stratigraphic summary of well - 'C':

Depth Interval (m)	Systems Tract/ Key Surfaces
2370 – 2470	HST
2500	MFS (28.1Ma)
2500 – 2645	TST
2645	SB (29.3Ma)
2645 -29300	HST
2930	MFS (31.3Ma)
2930-3050	TST
3050	SB (32.4Ma)
3050 – 3330	HST
3330	MFS (33.0Ma)
3330 – 3520	TST
3520	SB (33.3Ma)
3520 – 3700	HST
3700	MFS (34.0Ma)
3700– 3980	TST
3980	SB (35.4Ma)
3980– 4400	HST

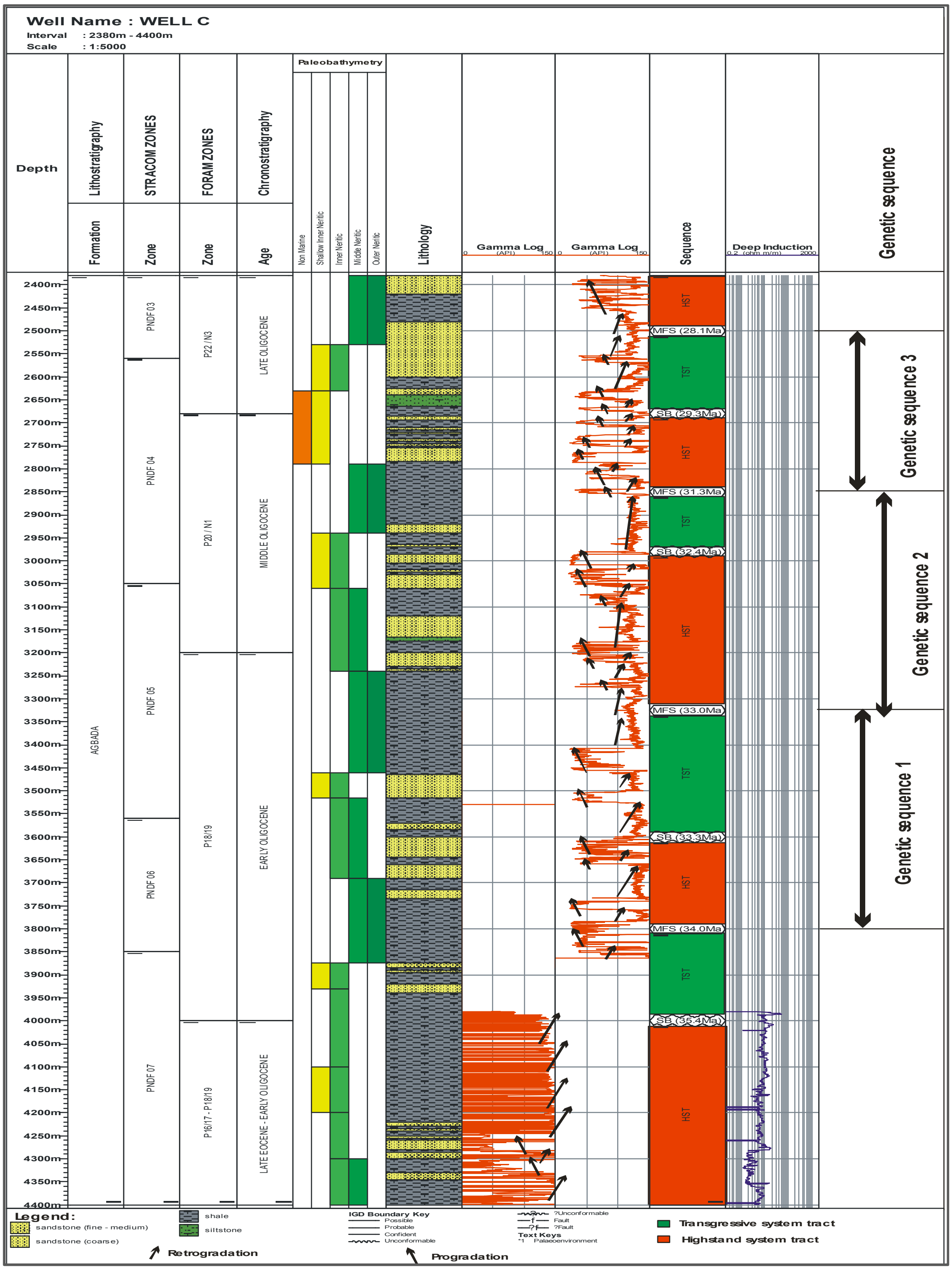

Fig. 9. Sequence stratigraphic interpretation showing vertical stacking pattern and genetic sequence

The sequence stratigraphic interpretation of well – 'C' was undertaken and the results are presented below:

The interval depth of 4400 – 3980m (420m) experienced the occurrence of regressive sediments with this well. However, the onset of this systems tract was not tested in this study well. The stacks of sand within this interval constitute this systems tract. The overall coarsening upward parasequence sets characterize this interval with fine - medium sand grained at the top of this interval while the base exhibits intercalations of shale deposits with minor medium to coarse sand grained. The sequence boundary (SB) delineated at 3980m terminated this systems tract as observed from the low Gamma ray and high Resistivity log readings at this depth and dated 35.4Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). Underlying the highstand systems tract is the predominantly occurring shale with minor occurrence of sand zone typified by the interplay of parasequence sets within the transgressive phase. This transgressive systems tract showed a thickness of about 280m (3700 – 3980m). The backstepping log patterns observed in this interval are associated with pelagic shales, sands and silts intercalations. This phase of transgression terminated at the MFS delineated at 3700m based on the high Gamma ray log value (low Deep Induction Resistivity log motifs). The maximum flooding surface (MFS) is dated 34.0/Ru*1Ma by correlation to the third order cycles chart of Haq *et al.,* (1988).The transgressive phase was succeeded by the emergence of the highstand system tract at the top with an overall thickness of 180m (3700 - 3520m).The delineated MFS at 3800m marks the onset of this regressive phase which is predominantly characterized by an overall coarsening upward (forestepping) log pattern. This interval is characterized by medium to coarse grained sediments with minor shale interbeddings. The SB delineated at 3520m which terminates this systems tract showed a low Gamma ray and high Resistivity log motifs and is dated 33.3Ma by correlation to the third order cycles chart of Haq *et al.,* (1988).

A renewed sequence within the interval depth of 3520 - 3330m (190m) with a deepening paleo-setting is observed from the retrogradational log motifs within this interval, which is a typical scenario of a transgressive phase. Lithologically, shale predominates over silt and fine grained sand counterparts. These shales and silts gradually increased from the base of this interval to the top. However, this overall deepening (fining upward trend) defines a transgressive phase; the peak (MFS) which was delineated at 3330m was based on the high Gamma ray and low Deep Induction Resistivity log values at this depth. This is probably the equivalent of the *Spiroplectammina wrightii* MFS, and it is dated 33.0/Ru*1Maby correlation to the third order cycles chart of Haq *et al.,* (1988).The shales and sand litho-units encountered within the interval depth of 3330 - 3050m (280m) were deposited in an overall shallowing upward depth of deposition. Stacks of progradational (coarsening/shallowing upward) log motifs which depicts a progressively deposition of sand bodies as seen from the Gamma ray and Deep Induction Resistivity logs characterize this regressive phase which reached its peak (SB) at 3020m. The sequence boundary (SB) was delineated at 3050m based on the relatively low Gamma and high Resistivity log values at this depth. This interval is dated 32.4Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). Underlying the regressive phase is the transgressive section found within the interval depth of 3050 - 2930m (120m). This retrogradational or fining upward log patterns observed in this interval are associated with shales and silts with medium to coarse grained sand intercalations. This transgressive phase which terminates at the maximum flooding surface (MFS) was delineated at 2930m based on the high Gamma ray and low Resistivity log values at this depth. This is probably the equivalent of the *Uvigerinellasparsicostata* MFS which is dated 31.3/Ru*2Ma by correlation to the third order cycles chart of Haq *et al.,* (1988). Within the interval depth of 2930 - 2645m (285m) is occurrence of the regressive sands found in this well. The MFS delineated at 2850m marks the onset of this highstand systems tract which is characterized by an overall coarsening upward (forestepping) log trend. The basal part of the interval characterized by the coarse grained sediments which progress gradually into sand. The sequence boundary (SB) delineated at 2645m which terminates this systems tract is also characterized by low Gamma ray and high Resistivity log values at this depth and is dated 29.3Ma by correlation to the third order cycles chart of Haq *et al.,* (1988).A gradual transgression is initiated at 2645m depth with an overall thickness of 145m and possesses medium grained sands with interfingering coarse sands, silts and shales at the top of the systems tract. This depositional trend depicts an overall fining upward (backstepping) log pattern. The peak of this transgression (MFS) which terminated the systems tract was delineated at 2500m. The log motifs which characterize this maximum flooding surface (MFS) within this interval were high Gamma ray and low Resistivity log readings at this depth. This is probably the equivalent of the *Chiloguembelina cubensis* MFS and it is dated 28.1/Ch*1Ma by correlation to the third order cycles chart of Haq *et al.,* (1988).This section of the systems tract (highstand) which falls within 2500 - 2400m (100m) was tested in this study and is characterized by silts and shales with minor sand. These lithofacies are associated with fining upward log motifs; which suggest that only the basal part of this systems tract (late rise of sea level) was tested in this study well while the SB was not reached.

Conclusion

The sequence stratigraphic analysis was carried out independently as a first step from biofacies and log datasets, and results were subsequently compared and integrated. Well logs interpretation involved detailed subdivision of the successions into the constituent parasequences types and parasequences sets, from which lateral facies changes and the creation of accommodation space with changes in relative sea level were interpreted. These models therefore explain the types and distribution of reservoir sand body within the individual systems tracts, which have been applied reliably in this interpretation. The sequence stratigraphic succession of the wells in this study unveiled the following system tracts, namely, Lowstand, Highstand and Transgressive systems tracts with their included candidate surfaces (Maximum Flooding Surfaces, Transgressive surfaces and Sequence boundaries) and genetic sequences. These wells in their vertical successions were composed of the following elements in the order of Lowstand systems tract (LST), Sequence Boundary (SB), Highstand systems tract (HST), Maximum Flooding Surface (MFS) and Transgressive systems tract (TST). The dating of these key surfaces was achieved by correlation to the third order cycles chart of Haqet al., (1988) as well as inferences from chronostratigraphically significant bioevents.

Seismic stratigraphic studies encompass horizons with homogenous, rugged or contrasting and random patterns. The time equivalent within the seismic horizon ranges between 1.9 – 3.0secs. The Maximum flooding surfaces and the Sequence boundaries were observed to exhibit thick amplitude intervals. However, the various Maximum Flooding Surfaces encountered within the wells 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. This will be useful in identifying the various pressure regimes during drilling exploratory, appraisal and production wells. Four dated regional transgressive shale markers have been delineated in the analyzed wells. These shale markers are *Chiloguembelina cubensis* and/or *Globorotalia opima opima* (28.1/Ch*1Ma), *Uvigerinellasparsicostata* (31.3/Ru*2Ma), *Spiroplectammina wrightii* (33.0/Ru*1Ma) and *Hopkinsina bononiensis* (34.0/Ru*1Ma) which also coincide with the above mentioned time equivalent.

However, these four identified shale markers are believed to mark the base of major regressive sedimentary cycles. Seismic stratigraphic analysis was adopted as a predictive tool arising from assumptions concerning the development of sequence bounding unconformity surfaces which separate the sequences in time permitting large scale chronostratigraphic correlation based on stratal contact of the geometries. It was further discovered that these seismic sections possess texture which is defined by internal stratigraphic configurations, terminations and amplitudes which are composite of seismic attributes and diverse stratigraphic properties such as lithology, thickness of the beds and its continuity. These sections consist of variable degrees in terms of its amplitude anomalies, these include, low amplitude, low seismic pattern (homogeneous) with smooth texture; high amplitude, high frequency, discontinuous seismic pattern with rugged (contrasting) texture and chaotic pattern with a low coherence, low amplitude and variable frequency which has less predictable (random) texture. It was observed that on the analysed seismic lines, the maximum flooding surfaces within these wells commonly appear as thick amplitude lines that form the upper bounding surfaces of sandy, bright-amplitude intervals. In all stage boundaries, it coincides with flooding surfaces which occur at the tops of major upward-fining successions in the shelf deposits and ranges conspicuously between 1.9 – 3.0secs within the sections. It has been presumed that the Early Oligocene sequence has higher hydrocarbon potential. Conversely, the 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, it is also noted that youngest sequences have 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.

Acknowledgement

The first author is very grateful to the Nigerian Agip Oil Company Limited (NAOC)for the provision of the datasets used in this work and also the Department of Geology, University of Port Harcourt, Rivers State for providing a good learning atmosphere to carry out this study.

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