FACIES MODELLING AND RESERVOIR GEOLOGY OF THE OFFSHORE SEDIMENTS, SOUTH-EASTERN, NIGER DELTA, NIGERIA

Matthew O. Akpan[1], M.N.Oti[2] and Monday U. Udoh[3]

[1,2] Department of Geology, University of Port Harcourt, Port Harcourt, Nigeria.

[3]Pioneer Alfa Petroleum Services Ltd, Benin City, Nigeria.

ABSTRACT

The subsurface facies model, stratigraphic sequences, reservoir rock geometry and continuity in the Offshore reservoirs, E-Field, Southeastern Niger Delta, were studied by integrating stratal geometries from seismic data and well-log stacking patterns in conjunction with biostratigraphy. Facies model serves as an interpretative device employed to identify the depositional systems and explain facies assemblage. The objectives of this study were to highlight and delineate the lithology, depositional environments and reservoir stratigraphy in order to establish the chronostratigraphic framework of the sedimentary fill [deposits] and reconstruct the paleo-geography of the field. The resulting analyses and interpretation of wells in this field showed that sandstone reservoirs have different characteristics and quality which are controlled by the environments of deposition. A total of twenty four (24) reservoir sandbodies with variable net thicknesses ranging from 25-150m in places had been inferred. These sands are Late Miocene to Early Pliocene in age and were deposited in a deepwater setting on the slope of the E-Field by a range of depositional processes that include slumps, debris flows and turbidity currents. Most of these sands could be interpreted to relate to periods of base level fall, if not Global Eustatic Lowstands.. Out of nine (9) wells provided for this study, one (1) is mostly gas-bearing. The average net thickness (h), porosity, effective porosity, volume of clay and water saturation of 135m (approximately 473ft), 0.26, 0.22, 0.16 and 0.0252, respectively, were estimated. Working within a sequence stratigraphic framework, eight (8) sequences have been delineated on the basis of reflection termination patterns. The major sequences were related to a sea level fall during which the shelf was exposed to erosion. The presence of type-1 and type-2 sequence boundaries is indicative of stratigraphic signature of major drops in relative sea level during the Paleocene and Eocene.

INTRODUCTION

A depositional sequence is a genetic stratigraphic unit which depends upon the recognition of its boundaries for delineation rather than upon specific lithologies as was done for lithofacies (formational) units (van Wagoner et al, 1990). The importance of this distinction is that maps of depositional systems tracts within each sequence represent the distribution of environments within a time-slice. Out of twenty-four (24) wells drilled in this field, nine (9) wells were assigned for this work. The overall regressive sequence of clastic sediments in this field was deposited in a series of offlap cycles that were intermittently interrupted by periods of sea level change. These periods, according to Reijers, 1996, resulted in minor, although sometime widespread episodes of marine transgression. Changes in sediment accommodation in this field, as globally suggested by Posamentier and Vail (1998) and others, were caused by changes in relative sea level (RSL). These changes in RSL resulted from the interaction of tectonics and eustacy and they form a key factor in controlling the stratigraphic patterns of this field.

When a RSL fall occurs, the sequence boundary always consists of stratigraphic unconformity in its landward extremity and merges seaward into a surface of stratigraphic continuity. Both the Mfs's and SBs form recognizable surfaces in well logs and seismic sections. More recent studies have focused on modifications of basic sequence "model" (Pitman, 1986; Galloway, 1989; Miall, 1991; Posamentier and Allen, 1993), alternate methods of defining sequences and systems tracts (Galloway, 1989; Hunt and Tucker, 1992), or detailed descriptions of specific aspects of depositional sequences (Plint, 1988; Van Wagoner et al, 1990; Nummedal et al, 1992; Schuum, 1993).

A significant result of sequence stratigraphic interpretation in this study has been to focus attention on new types of sedimentary systems such as incised fluvial valleys, lowstand coastal sand deposits and submarine fans. Most of these deposits frequently occur in distal areas of the E-Field which had not been previously considered as sand prone.

MATERIALS AND METHODS OF STUDY

The available materials used in this study are:

Seismic sections (Dip- and Strike-oriented lines, NW-SE) covering nine (9) wells in the field; and is scaled 1:50,000 or 10cm/1 second; biostratigraphic/palaobathymetric reports of wells, well logs (scaled 1/10000), base map (seismic/well situation map) covering the offshore area (scaled
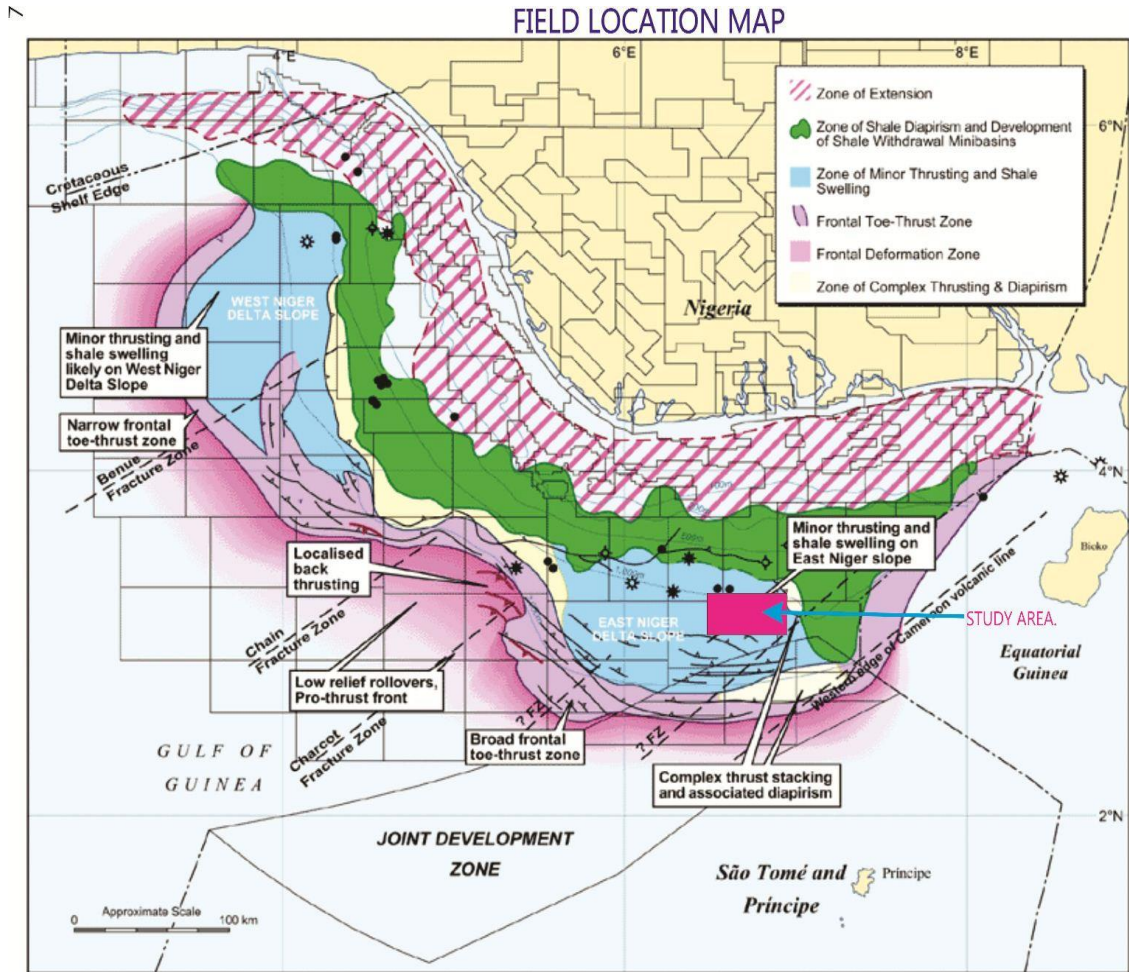
Figure 1: Field Location Map, with an area of about 990km², in the Deep Offshore Depobelt, Niger Delta.

1:200,000-Figure 1) with closely spaced lines. Out of nine (9) wells provided for this study, one was designated as producing only gas while the remaining were producing oil and gas. In this field, dip and strike-oriented lines: 4384/1942, 4408/2194 and 4412/2558 pass through deep wells W_D, W_E, and W_F, respectively (Refer to interpreted seismic section -Figure 2).
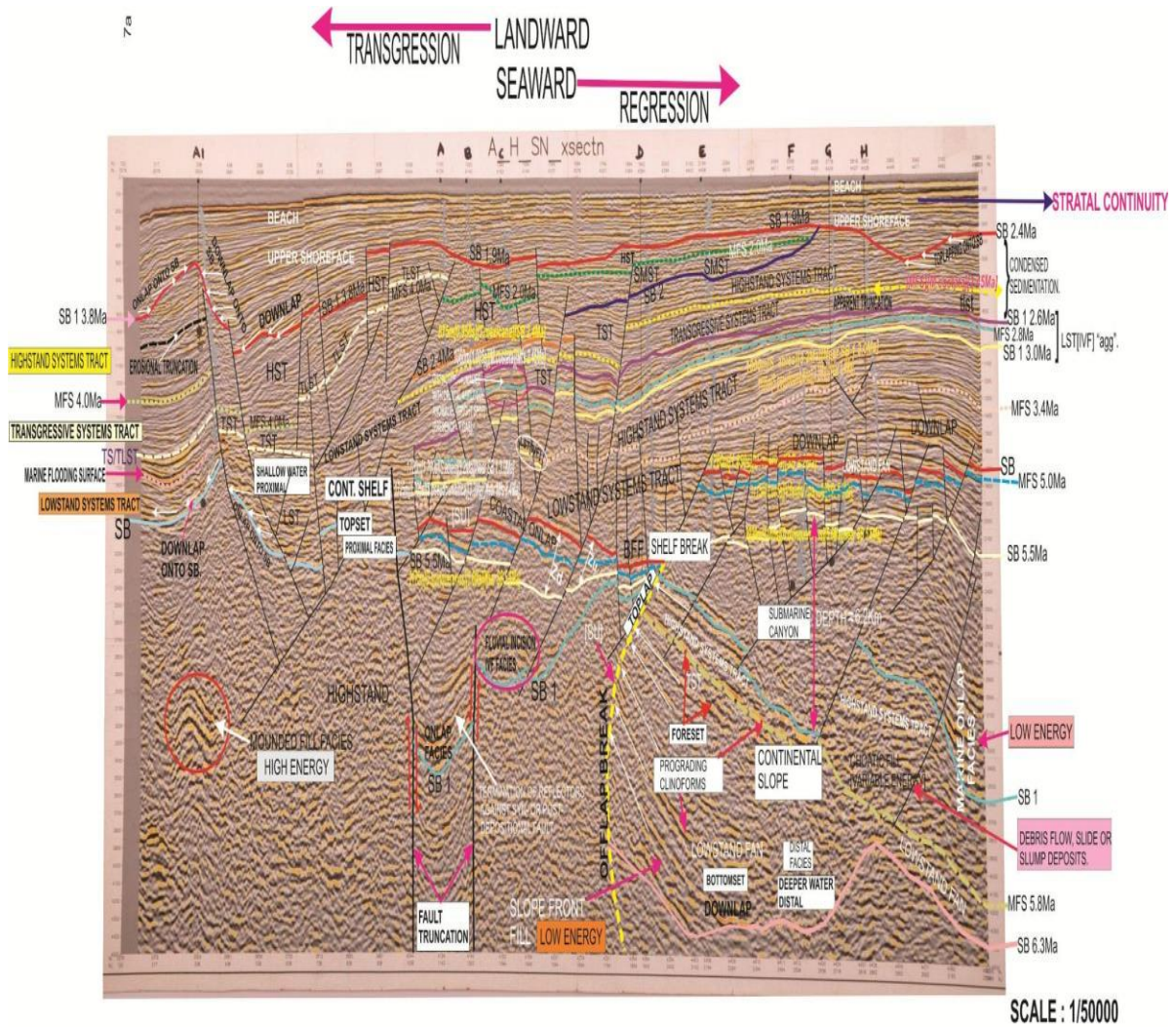
Figure2: Seismic Facies Analysis of E-Field

The depositional sequence was mapped and interpreted based on the regressive-transgressive cycle formed between successive episodes of RSL fall. Transgressive sands were identified by their high Gamma ray (GR) peak and high resistivity opposite negative SP log response.
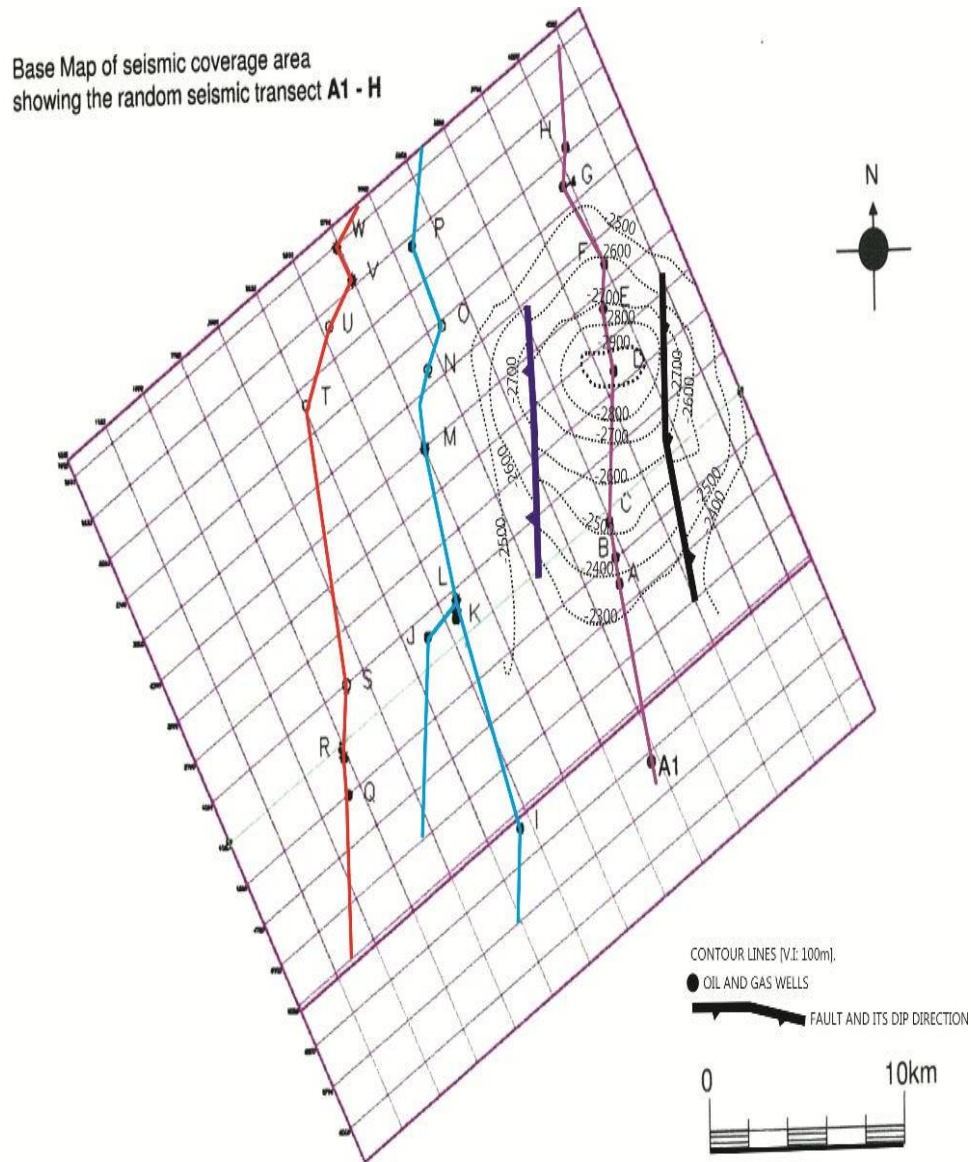
Figure 3: Base Map of Seismic coverage area

On the seismic profile, sequences were identified between two parallel and continuous marker horizons, otherwise termed unconformities. The sequence boundary on log – motifs was marked by the sharp-based bottom of basin-floor thicks and incise-valley fill, and in updip areas by the sharp-top of uppermost prograding parasequence or the sharp-based blocky sand on an incised-valley fill (Armentrout el at, 1993).

A model published by Allen, (1997) was applied for sequence boundary delineation and recognition. Sequence boundaries (SBs) were generally recognized biostratigraphically by the marked absence of known

bioevents. The used of faunal abundances and diversity curves alongside well logs enhanced the recognition of maximum flooding Surfaces (MFS's). This step consisted of subdividing the sediment column into obvious regressive-transgressive cycles and identifying maximum flooding surfaces (MFS's). MFS's correspond to the maximum shale peaks visible on the GR, resistivity and neutron logs. By using several wells, MFS's were generally correlated regionally.

In this study, each systems tract forms a characteristic facies succession and bounds by key stratigraphic surfaces. Other methods of log interpretation applied in this study include: Checking correlatable time-constant horizons using log markers (which could be a distinctive lithology, a distinctive peak or a distinctive shape). This involves well-to-well correlation, identifying stratigraphic breaks (faults) on well logs, recognizing and delineating shear-zones, faults on dip logs and establishing their trapping capabilities.

RESULT AND DISCUSSION

In the E-Offshore variations in the rate of change of relative sea-level probably give the characteristic patterns in the Topset – Clinoform System . A well-developed topset-clinoform package can be interpreted as representing a systems tract of paralic to shelfal unis (the topsets) and slope sediments (clinoform). The interpreted seismic section illustrates- seismic reflections passing continuously from a Top-; Fore- to a Bottom-set configuration. In a geological sense, it means going from a sand-prone shelf (proximal = closer to source area of sediments), into a shale-prone (further from the source and thus fine grained); and finally ending up in a distal shale-prone deeper basinal environment (distal = far from sediment source) (Catuneanu, D; 2006).

(a) Facies Analysis and Modelling Characteristics: In this study, a facies model serves an interpretive device employed to explain a facies assemblage (e.g; a block-diagram paleo-geographic/depositional model). Sedimentary facies models were useful to explain spatial relationships of co-eval facies in the modern and to identify a genetic succession correctly. A facies model was constructed, so that proximal to distal facies relationships could be assigned. This was done by carefully studying the sedimentology of succession; identifying the processes that were taking place during the deposition of the sediments, and interpreting environments of deposition. In a vertical succession, using the facies model, shallowing-upward successions [parasequences] were defined.

Sequences were divided into distinct systems tracts that were deposited during a specific stage of a transgressive-regressive cycle. The recognition of a sequence depended mainly upon the delineation of significant breaks, markers and/or facies changes in the stratal record that document a bounding unconformity.

In this study, the concept of depositional sequences was particularly applied for siliciclastic sediments in the continental margin settings that comprise   a shelf-break, slope, and a deeper basin.The E-Field depositional configuration was strongly influenced by tectonic activities of the Miocene-Pliocene

Epochs.

In the E-Field, the important morphological elements are the offshore depozone, the shoreface depozone (which was divided into the lower, middle and upper zone) and the foreshore depozone. The lower shoreface is transitional between the middle shoreface and the offshore zone. The offshore zone is characterized by fine clastic sedimentation under low-energetic hydrodynamic conditions below the fair-weather-wave-base [FWWB]. The shale lithofacies is representative for this depozone and effected by high-energetic conditions only during storms.

In genetic stratigraphic sequence, the fundamental unit of genetic stratigraphy is bounded by intervals of sediment starvation. In this study, it was discovered that intervals of sediment starvation are laterally persistent and paleontologically useful. Boundaries of depositional sequences are associated in places with subaerial hiatuses, and they are the primary stratigraphic discontinuities in a succession. Boundaries of genetic stratigraphic sequences are located within intervals of sediment starvation, and they tend to onlap depositional sequence boundaries toward the basin margin.

In the basinward position of the E-Field, sequences are bounded by transgressive surfaces. The transgressive surface marks the change from regression to transgression. For a basinwide sequence stratigraphic concept, the integrated transgressive-regressive sequence model of Embry, 1993 was chosen in this study because:

➢ The transgressive – regressive sequence model is an appropriate concept for progressively evolving tectonic settings. The concept implies exclusively tectonic control on the generation of sequences.

➢ Transgressive surfaces and deposits can be identified in siliciclastic successions in the E-Field. The alternative models are applicable only where lithologic and facies contrasts are pronounced.

According to Embry, 1993; the T-R sequence is judged to be the best type of sequence for regional basin analysis because sub-aerial unconformities form its boundaries and do not occur within it and the designated correlative conformity, the transgressive surface, can be recognized in most cases. The differences in the definition of bounding surfaces between the discussed depositional, genetic and transgressive-regressive stratigraphic sequences are shown in the Chronostratigraphic and Correlation Charts of the study area. Sequence boundaries in the genetic sequence model are related to maximum flooding surfaces.

Further, Systems tracts for the transgressive-regressive sequence model of two systems tracts were defined:

➢ Transgressive systems tract (TST) that includes the stratal record between the basal bounding unconformity and the maximum flooding surface.

➢ Regressive systems tract (RST), which comprises strata between the maximum flooding surface and the upper bounding unconformity (e.g.; Embry, 1993).

The regressive systems tract (RST) was mapped and interpreted. It includes : Highstand Systems Tracts and Lowstand Systems Tracts or Shelf-margin Systems Tracts of the succeeding depositional sequence model.

In the E-field, large-scale [second-order] Miocene - Pliocene eustatic cycle forms distinct patterns within third-order sequences, reinforcing the transgressive systems tracts during the 'mid' Miocene and the lowstand and late highstand systems tracts during the late Miocene and early Pliocene. These large-scale cycles resulted in alternating cyclic episodes of rapid shelf progradation and transgression or aggradation (Allen, 1997).

(b) Reflection Coefficients and Amplitude Response Analysis from seismic data: Quantitative approach involves interpreting lithology from seismic data. This is seismic modeling based on the synthetic seismogram. The synthetic seismogram is the first seismic model derived from a well log which gives a close relation of the seismic trace with the stratigraphy. For the E-field reservoir, the following averaged [and rounded] parameters have been determined using Dix Formula, 1956:

V_{sm}, velocity of E-field sandstone matrix   = 923m/s

ρ_{sm}, density of E-field sandstone matrix   = 2.65g/cc

V_w, velocity of reservoir water   = 1625 m/s

$\emptyset$, Average porosity of the reservoir   = 0.315 or 31.5%

V_{OSH}, velocity of overlying shales   = 1000 m/s

ρ_{osh}, Density of overlying shales   = 2.217g/cc

S_w, Average water saturation of reservoir = 0.0252

V_{ush}, velocity of underlying oil shales   = 1071.4m/s

ρ_{osh}, Density of underlying oil shales   = 2.35g/cc

V_g,   Velocity of reservoir gas   = 1100m/s

ρ_g,   Density of reservoir gas   = 2.13g/cc

V_{log},   Velocity log [sonic log] of gas   = 190μs/ft

V_{oil},   Velocity of reservoir oil   = 1283 m/s

ρ_{aveg}, Average density of reservoir oil   = 2.176 mg/cc

Average log density of some wells in the E-Field was 2.13 g/cc. This is considerably below the computed value probably because of mud invasion. In well F , at 2150-2800 m intervals, Neutron and Density curves with sandstone compatible scales practically overlay in the water-bearing zone. This is referred to as the cleanest water-bearing zone.

- Thickness of the cleanest water-bearing Zone   = 1625m/s
- Velocity of E-field sandstone, water saturated, V_{EW} = 1068.5m/s
- For ρ_{EW}: reservoir density, water saturated   = 2.13 g/cc
- Reflection coefficient for the top of the Gas column, RC_{Eg} = 0.5481
- Reflection coefficient for the gas/water interface, Well C   = 0.5389.
- For $V_{E[OIL]}$, the velocity of the oil saturated E-field sandstone   = 1012.6m/s

- For $\rho_{E\,[OIL]}$: Reservoir density, oil-saturated   = 2.49 g/cc
- Reflection coefficient, RC for the bottom of the E-field oil reservoir $= -0.05117$
- Reflection coefficient for the oil/water interface   = 0.0071
- Reflection coefficient for the off-structure top of E- field, wet,   = 0.01291

TWT [S]	Medium [m]	Density, ρ[g/cc]	Velocity, V [m/sec]	Acoustic Impedance, Z [gm/sec cm2 x 10^{-4}]
0.475	Beach | Upper Shoreface 475	2.65 1.95 – 2.08	923.08 1000.00	2446.15 2080
0.916	Middle SF | Lower SF 860	2.08 – 2.35	873.02	1815.9 – 2051.6
1.575	Beach Barrier Island 1575	2.217 – 2.448	10.84. 98	2405.4 – 2690.8
1.7375	[Prodelta] 'Oil' Shale 1775	2.217 – 2.48	1242.24	2754.05 – 3080.76
1.867	Prodelta | Channel Bar 1925	2.08 – 2.48	1158.30	2409.3 – 2872.58

2.275	Shallow Deep Channel Deposits	2450	2.15 – 2.48	1286.8	2766.6 – 3191.26

Table 1: Progagation Velocities of Compressional Waves, Densities and Acoustic Impedances for Selected Media in Well C, E-Field.

Sea-level change and structural movements during Miocene time triggered the development of a complex system of large-scale submarine canyon in this E- field. The sedimentary fill within these channels gives rise to the principal velocity problems experience in the E-Field. Reflection quality in the entire field is good and the picks are reliable over the main structure. In well C **(**figure 4**),** for example, the occurrence at 1.250s level [SP 4152/1394], of a flat, slightly dipping reflector. As suggested by Cumming and Wyndham, 1975; its contrast with anticlinal curvature of the structure and its flatness suggest it is a gas/water contact.
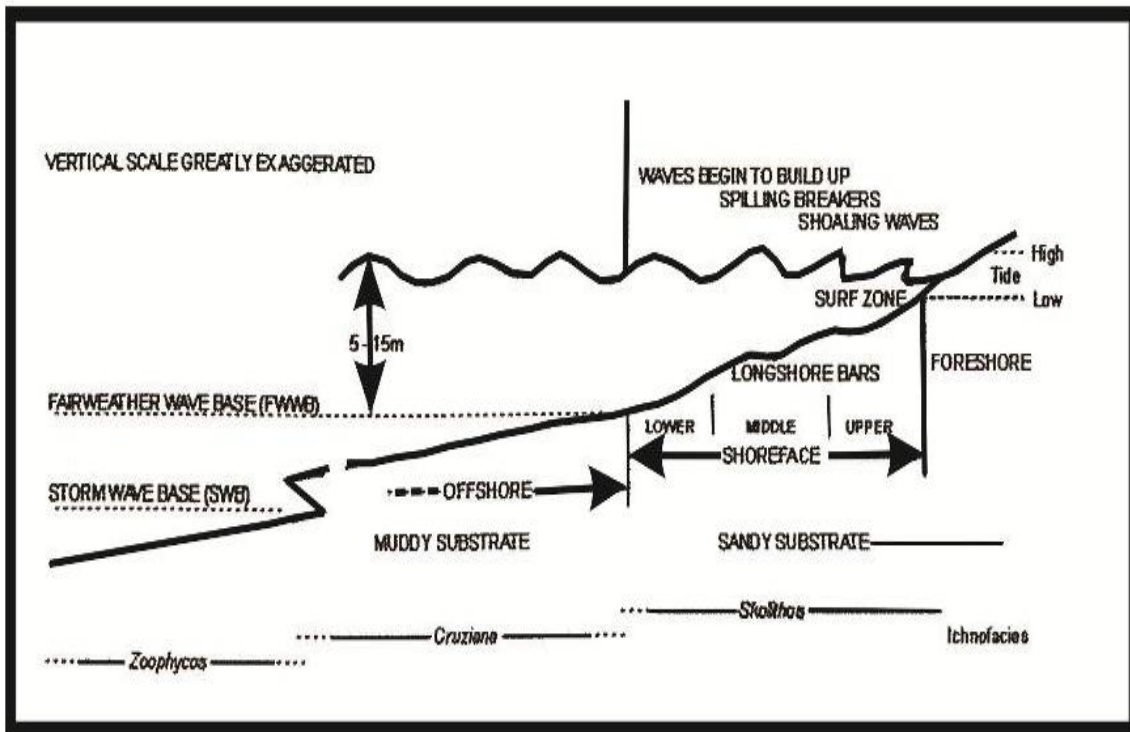

Figure 4: Spatial arrangement of foreshore,shoreface and offshore areas(modified from Walker& Plint, 1992).

Based on the calculated reflection coefficients, a convincing explanation can be made about the meaning of several seismic events in the study area. With equal and opposite coefficients the top pay zone

and gas/water reflections are ripe for exhibiting tuning or bright spots as the pay thickness tends towards the $\lambda/4$ [0ne way time] [Mcquillin et al., 1984].

➢ A gas-induced bright spot should show a negative polarity reflection at the top of the gas column.

➢ Where reservoirs are thick [for example, as observed in Wells C, and F]; and include a sharp gas-liquid contact a reflection may be from this horizontal reflector to show a "flat-spot". Lateral velocity variations may have caused apparent tilt or these may have been a genuinely filled contact induced by hydraulic forces. Further, acoustic contrasts along hydrocarbon/water interface may be enhanced when sedimentation has taken place in the water-bearing zone.

➢ The major effect of the changed velocity on seismic data is a changed reflection coefficient. The near-zero acoustic impedance calculation for oil is indicative of "dim spots" reflection events. As observed in this work, the acoustic impedance contrast decreases with an increase in hydrocarbon concentration in the reservoir.

➢ A bright spot has important indicators of high amplitude, low frequency content, and phase reversal. The bright spot is at 1.45 s, which is the most probable to accumulate gas. At 1.60 to 1.85s levels [Well C][Figure 3] the reflection of the positive polarity is the most probable to accumulate oil and water.

The basic idea is that bright spots having low frequency content are only true in a small section of a seismogram. The black portion of Well C – at 1.225s is probably the result of using envelope and instantaneous frequency with positive polarity and comes from the interference effect of thin-bed.

From the practical points of view, an important problem in this work was to describe how seismic velocity varies with porosity [$\emptyset$] and with the nature of the pore-fill [liquid or gas]. Here, a simple empirical equation proposed by Wyllie et al., 1956; was applied.

The change in seismic velocity, as observed in this study, may have caused a marked change in amplitude of the seismic reflection on passing laterally from gas-filled to oil-filled sandstones.
The decrease of bulk density with decreasing water saturation, S_w, leads to an increase in $S_{w[ave]}$ velocity.

The presence of gas within the pore space of a rock lowers the velocity compared with water in the pore spaces. In this field, the continuity of reflections and constancy of reflection character indicate marine deposition. Sediments formed in the deep sea by the raining of debris should have the same thickness and character regardless of pre-existing topography [Mcquilin et al., 1984]. Thus, units, which are laterally uniform and drape over topography with little change indicate fine-grained pelagic or hemipelagic sediments.

Turbidites were delineated and interpreted as relatively reflector-free or having a chaotic reflection pattern. Tilting contemporaneous with deposition causes intervals to thin and some to become too thin to produce reflections. For example, in Wells D and E, reflection events characterized by these wells indicate convergence of reflection toward the margin.

The concept of sea level variations also control depositional systems as applied in seismic stratigraphic interpretation. A landward migration of coastal onlap, as observed in this study, indicates that sediment aggradation has occurred. With the seismic response determination, the sub-surface geology,

including structural, stratigraphic, or lithological features were resolved.

(c) Depositional Environments Model: The present day surface relief of this field can be traced in large part to a succession of episodes of deformation and other geologic processes that occurred over the past few tens of millions of years. The form of a mature continental margin inferred from this study is a constructional feature formed by the interplay between differential subsidence, rapid deposition and re-sedimentation, with lowstand submarine fan incision resulting multiple basin-margin faults caused initially wide tilt blocks to be fragmented into smaller blocks by new faults in the old hanging wall. Fan incision may have resulted from purely climatic or run-off changes. The faulted footwall margins in other areas of this field have led to the formation of alluvial fans, fan deltas and submarine fans.

CONCLUSION

In this paper, an attempt has been made to review state of the art basic approaches to sequence stratigraphic interpretation for accurate delineation and determination of the formation's lithology, seal and source rock of petroleum, the presence, nature and spatial vertically-stacked reservoirs and environmental re-construction.

E-Field appraisals have been carried out from petrophysical analysis, well log-seismic sequence stratigraphy and high-resolution biostratigraphy. Reservoir quality is strongly influenced by grain size. Porosity estimates in these E-Field reservoirs vary from 0.18-0.35 and the net thicknesses of the reservoir sand range from 37.5m (123.1ft) to 375m (1230ft).Porosity and permeability increased with increasing reservoir quality.

Depositional environments in this field have been delineated to characterize the distribution of reservoir facies. The depositional environments include: coastal deposits and prodelta sands, reworked sand units and shoreface sands, slope fan, basin floor fan and submarine fans. Detailed study of the seismic data provided for this work shows that the E-Field strata were deposited in the Southeastern Niger Delta; a broad region from the shelf – slope break extending to the Ultra Deep Waters (>1500m).

REFERENCES

1. Allen, G. P; 1997: Principles of Siliciclastic Sequence Stratigraphy and Applications to Fluvial and Shelf Deposits; p. 1 – 58.

2. Armentrout, J. M; Malecek, S. J; Fearn, L. B; 1993: Log motif Analysis of Paleogene Depositional Systems Tracts, Central and North Sea: Define by Sequence – Stratigraphic Analysis London Geological society, P. 1 – 41.

3. Berg, R. R; and A. H. Avery; 1995: Sealing Properties of Tertiary Growth Faults. Texas Gulf Coast. AAPG Bull; V. 79; No. 3, P. 375 – 393.

4. Emery, D. and Myers, K. J; 1996: Sequence Strtigraphy, Blackwell Science, Oxford.

5. Galloway, W. E; 1989; Genetic Stratigraphic Sequences in Basin Analysis 1: Architecture and Genesis of Flooding – surface   Bounded Depositional Units. AAPG Bulletin, V. 73, No. 2; P 125 – 142.

6. Leblanc, R. J; Sr; (1972): Geometry of Sandstone reservoir bodies. Amer. Assoc. Petroleum Geol; Memoir 18, P. 133 – 177.

7. McQuillin, R; Bacon, M; Barclay, W; 1984: An Introudtion to Seismic Interpretation 2nd ed; P. 175 – 261.

8. Nummedal, D; Riley, G. W; and Templet, P. L; 1992: High resolution Sequence architecture: A chronostratigraphic model based on equilibrium profile studies; In: H. W. Posamentier;

9. Posamentier, H. W; and Vail, P. R; 1998: Eustatic control on deposition 11 – Sequence and Systems tract models; In: Wilgus, C. K. Hastings, B. S. Kendall, C. G. St. C; Posamentier

10. Reijers, T. J. A; 1996: Selected Chapters on Geology and Three case studies and field guides: Sedimentary Geology and Sequence Stratigraphy in Nigeria. Shell Petroleum Dev. Co. (Nig.) Ltd. International Publication, P. 45 – 149.

11. Schlumberger, 1985: Well Evaluation Conference – Nigeria.