Seismic Sequence Stratigraphy and Structural Trends of the Clastic Deposits in Parts of Niger Delta, Nigeria

Selemo, A. O. I., Atunima, E. J., Akaolisa, C. Z., Onyekuru, S.O., Okereke, C. N., Ibeneme, S. I., Ezekiel, J.C. and Njoku, I. O.

Department of Geology, Federal University of Technology, P.M.B. 1526, Owerri, Nigeria.
Correspondence Email: samuel.onyekuru@futo.edu.ng

Abstract— Despite several exploration and exploitation activities in the Niger Delta basin of Nigeria, a clearer understanding of depositional styles and reservoir characteristics of some of its deposits are still elusive. A three–dimensional (3D) seismic data and well log suites from two oil fields (Onshore Field A, and Offshore Field B) were therefore obtained and analyzed with Petrel software in order to examine depositional styles, dominant structures and stratigraphy of the deposits. A total of five faults and two horizons that indicated faulted anticlinal closures were closely observed in the Onshore Field A, while about twenty five faults were observed in the Offshore Field B. The inferred depositional environments of sediments in the basin consist of shelf, slope and deep basin settings. The deep basin settings are mainly dominated by submarine canyons and channel-levee systems whose deposits appear on seismic records as layered and chaotic facies. The channel-levee systems are interpreted as turbidites, distributary channel complexes, crevasse splays, hemi pelagic deposits as well as chaotic slump and debris flow deposits. The generated based on the 3D seismic data revealed that the stratigraphic architecture of deposits in the basin was controlled by variable subsidence.

Index Terms— Depositional Styles, Reservoir, Seismic, Seismostratigraphic Models, Stratigraphy, Structures and Subsidence,.

◆

1 INTRODUCTION

THE Niger Delta of Nigeria is a passive continental margin (Fig. 1). It is one of the foremost oil producing regions in the world, where hydrocarbon is being exploited from both the onshore and offshore parts of the delta. Knowledge of the structure and stratigraphy of sediments in the basin is very essential to exploration and production activities. A variety of facies have been delineated in the Niger Delta basin, most of which contain productive hydrocarbon reservoirs [1]. Several submarine canyons (e.g Calabar, Qua Iboe, Niger, Avon and Mahin Canyons; Figure 2) characterize the offshore Niger Delta [2][3]. These features have been interpreted on seismic sections as layered seismic facies and acoustically chaotic, hummocky, transparent seismic reflection packages [4]. Studies of submarine channels have shown that channel profiles adjust to base level changes in a manner analogous to graded fluvial system [5]. Also channel behavior has been reported to vary along the length of the system [6]. Hence the concept of graded channel profile systems can be used to explain channel architecture and fan accumulation. Sinuous channel systems, however, have been reported as the commonly observed depositional elements in the slope settings of passive margins.

Reservoir quality is largely controlled by depositional setting[7]. Hence, knowledge of the depositional environment, structural setting, stratigraphy and the distribution of facies in the Niger Delta Basin would be critical for development and optimal exploitation strategies. Insights gained from this type of study would permit the development of predictive analogue models for application in other reservoir systems at deeper prospect intervals in the Niger Delta.

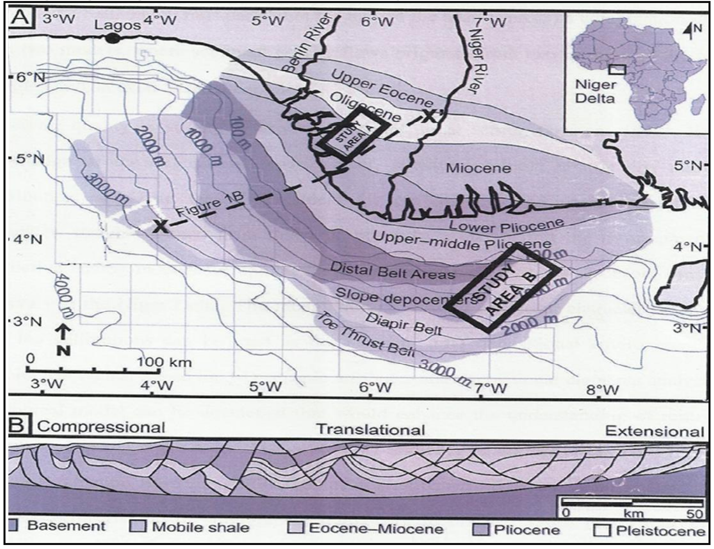

Figure 1: Location Map of the Study Area (Adapted from Armentrout et al., 2000; Hooper et al., 2002).

Location and Geological Setting of the Niger Delta

The Niger Delta is located in the Gulf of Guinea, central West Africa, at the southern culmination of the Benne Trough [8]. The Tertiary Niger Delta covers an area of about 75,000 sq km[9]. It is one of the largest regressive deltas in the world [10]. It is considered a classical shale tectonic province [11]. The

Niger Delta is bounded by the Cameroon Volcanic line to the east and the Dahomey Basin to the West (Figure 2). The shape and the internal structure of the delta are also controlled by fracture zones along the oceanic crust, such as the Charcot fracture zones. These fracture zones are expressed as trenches and ridges that formed during the opening of the south Atlantic in the Early Jurassic – Cretaceous. The Niger Delta sits at the southern end of the Benne Trough which corresponds to the failed arm of a triple rift junction. The rifting ceased in the late Cretaceous [12].

The Niger Delta and other major deltaic regions, such as the Texas and Louisiana elements of the Gulf of Mexico, showed structural evolutions controlled by large prograding deltaic depocenters. They have been deposited on over-pressured prodelta shales and/or salt [13][14]. A comparison of the Niger Delta with the Gulf of Mexico by Morley and Guerin [15]; Wu and Bally [11] revealed that the basins have been characterized by extensive gravity-driven decollement fold belts. These were of a distinct non-orogenic character.

Stratigraphy and Depositional Environment

The sedimentary fills in the Niger Delta basin is a series of offlap cycles: fluviomarine systems that have succeeded one another in a stepwise fashion reflecting the basinward, i.e. net southward progradation, extending over the continental edge into the oceanic basement. A study by Oomkens [16] reveals that tidal channel sands dominate the uppermost 30 m of the deltaic complex; fluaviatile sands become predominant below 30 m. The development of the delta of the River Niger started in the Cenozoic and has continued to the present day: Initially, a major transgression referred to as the Sokoto Transgression [3] initiated the deposition of Imo Shale in the Anambra Basin and the Akata Shale in the Niger Delta. The deposition of paralic sediments later began in the Eocene when sedimentation in the Niger Delta basin became predominantly wave dominated and as sediments prograded into the sea, the coastline became progressively more convex seaward [2,10] .

The Tertiary section of the Niger Delta is comprised of three Formations; representing prograding depositional environments [17][18][9] . According to Doust and Omatsola[10], these tripartite regressive sequences that were deposited in the Niger Delta are referred to as Akata, Agbada and Benin Formations.

The Akata Formation is composed of clays, shales and silts which occur at the base of the delta sequence. They were generally believed to contain source rocks – and might also contain some turbidite sands. The formation has a thickness range of about 2000 m (6,600 ft.) to 7000 m (23,000 ft.). In deep-water; it is up to 5000 m (16,400 ft.) thick [10]. The Agbada Formation is the major petroleum-bearing unit in the Niger Delta. This paralic clastic sequence known as the Agbada Formation is present in all the depobelts and ranged in age from Eocene to Pleistocene. It is more than 3500 m (11,500 ft.) thick and represents the actual deltaic sequence that accumulated in the delta-front, delta – topset and fluvio-deltaic environments[10]. Channel and basin floor fan deposits in the Agbada Formation formed the primary reservoirs in the Niger Delta. The Benin Formation is the uppermost unit in the Niger Delta and is composed of Late Eocene to Holocene continental deposits. These include alluvial and coastal – plain sands that are about 2000 m (6,600 ft.) in thickness [18].Onshore in some coastal regions, the Benin Formation overlies the Agbada Formation [19]. Offshore the continental sands of the Benin Formation becomes thinner and disappears near the shelf edge [20].A representation of the lithostratigraphic equivalences of Recent sediments and Tertiary Formations in the Niger Delta basin is shown in Table 1.

Table 1: Comparing Recent sediments with those of the Tertiary Formations in the Niger Delta – lithostratigraphic equivalencies.

Present Niger Delta	Outcrops of Tertiary Strata	Subsurface Units
Continental Sands	Benin Formation	Benin Formation
Interlayered continental, brackish water and marine sands and shale	Ogwashi-Asaba, Ameki and Nanka Formations	Agbada Formation
Marine clays and sands	Imo Formation	Akata Formation

2 PROCEDURE OF RESEARCH INVESTIGATION

2.1 General Summary

The study basically involved the integration of 3-D seismic reflection, checkshot velocity, biostratigraphic and well log data to identify sequences, accompanying systems tracts and constrained key stratigraphic surfaces of deposits in the study area. Field A was interpreted with the aid of Petrel software while Field B was interpreted manually. The sequence of evaluation followed an interpretive workflow chart (Fig. 3) which starts with the identification of sequences and accompanying systems tracts and constrained surfaces on wireline logs. The second stage involved the definition of sequence stratigraphic framework and structural interpretation/mapping of horizons and faults from vertical seismic sections especially the inline sections. The third and last stage involved the identification of surfaces and sequences using available biostratigraphic data which were used as controls on the surfaces and sequences interpreted using the wireline log and seismic. The closures identified in depth structural maps were subsequently used to identify the plays in the fields.

2.2 Well Data

Data from wire line log suites which included gamma ray, resistivity, sonic, combined neutron and density logs from four wells (Q, U, V and W) were analyzed (Fig. 4). The gamma ray log was used to discriminate reservoir rocks and other lithological units. It was also used to infer depositional facies and environments, as well as for well – to – well correlation. The combined density – neutron logs were used to discriminate reservoir fluids and lithology. The resistivity log measures formation's resistance to the flow of electric current. According to Rider [21] most rock materials are insulators with only the pores fluids accounting for electrical conductivity (low resistivity fluids). Hydrocarbon–bearing rocks give high resistivity readings.

2.3 Well – To – Well Chronostratigraphic Correlation

This is the determination of structural or stratigraphic units that may be equivalent in time, age or stratigraphic position. It involved the recognition of patterns on well logs and the matching of such pattern of curves from one well to another. Accurate correlation of well logs is very important for reliable geological interpretations, which provides subsurface information such as lithology, reservoir thickness, formation tops and bases, porosity and permeability of production zone [22].

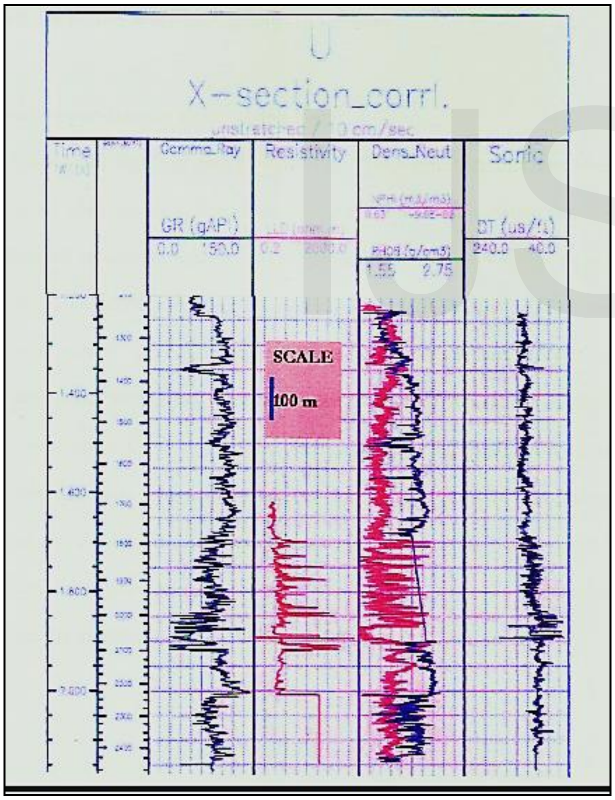

Figure 4: Representative Wireline Logs of one of the Wells

3 RESULTS AND DISCUSSION

Analysis of 3-D seismic and well log data provided the basis for seismostratigraphic interpretation, structural interpretation, sequence stratigraphy and depositional environment. Seismostructural and seismic facies interpretation was done using the criteria defined by Brown and Beaubouet and Friedmann [1], Adeogba et al.[23] and Heinio and Davies [4] . Sequence stratigraphy was interpreted following Vail and Wornart procedures [24]. Log – motif patterns for depositional environment were recognized using criteria by Rider [21].

3.1 Fault Interpretation

Four faults (FIA, F2A, F3A and F4A) were interpreted from the inline sections of Field A (Fig. 5). Twenty faults (FO1 - F25) were identified on CC' (Fig. 6) of Field B. Nine of the faults: F03, F04, F06, F08, F09, F10, F15, F18 and F19 are synthetic faults dipping in a north-south direction. Faults F01, F02, F05,

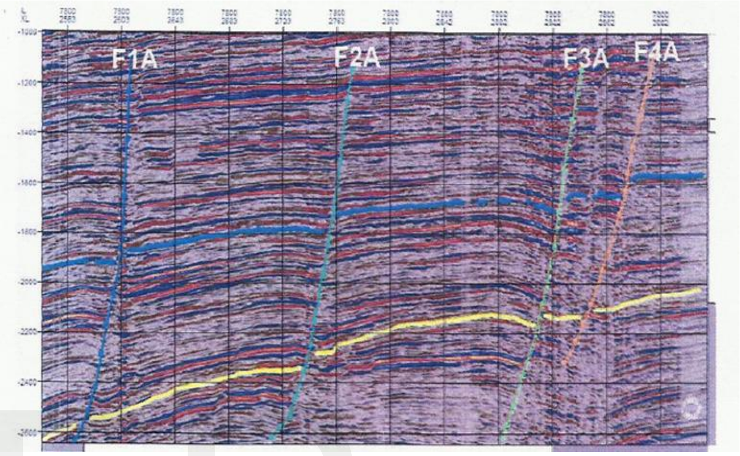

Figure 5: Structural Interpretation of Inline 7800 of Field A

Table 2: Estimated Throws of some of the Major Faults (meters) interpreted

Fault	Point on Hanging Wall	Point on Foot-wall	Throw
F02	1175	1110	65
F05	1230	1175	55
F06	1500	1320	180
F07	1420	1325	95
F10	1290	1100	190
F12	1125	1070	55
F13	825	725	100

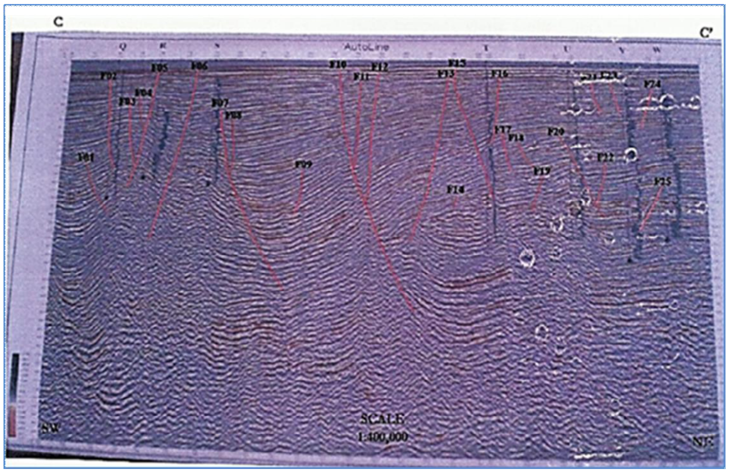

Figure 6: Fault interpretation of Line CC¹ of Field B

3.2 Fault Geometry

The major faults show a listric geometry. The throw decreases at great depth until it dies out. The fault pattern suggests extensional tectonism. Most of the major faults dip in the north – west direction.

3.3 Time Structural Maps

Two horizons were interpreted and mapped. Both horizons show faulted anticlinal closures in time (Figs. 7 and 8).

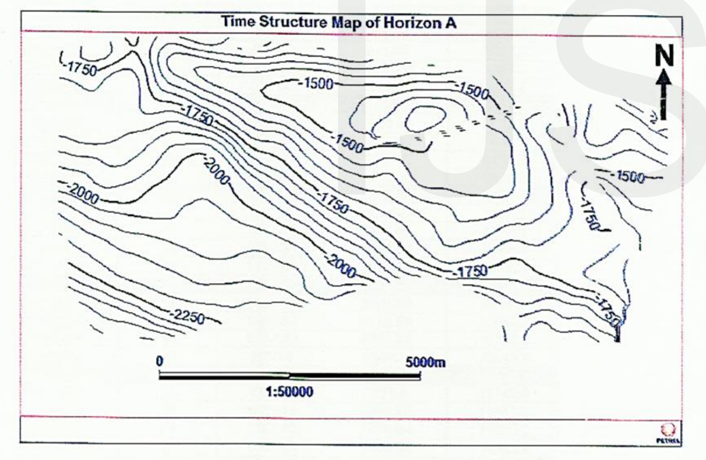

Figure 7: Time Structural Map for Horizon A

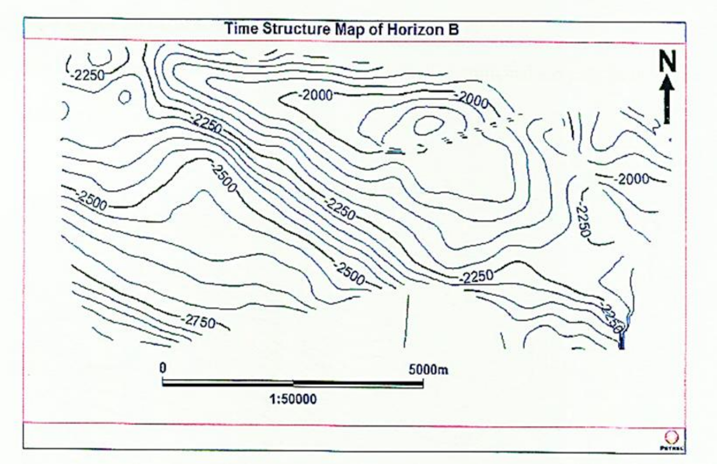

Figure 8: Time Structural Map of Horizon B

3.3 Time - Depth Conversion

The time maps were depth converted using the checkshot data shown in Table 3.

3.4Depth Structural Maps

The depths of Horizons A and B also show faulted anticlinal closures in the same trend as the time structural maps (Figures 9a, 9b, 10a, and 10b).

Survey Type	Shot No.	One-way time	Two-way time	Depth (Feet)
Checkshot	1	386.68	773.36	2537.2
Checkshot	2	456.83	913.66	3037.2
Checkshot	3	518.93	1037.86	3487.2
Checkshot	4	589.03	1178.06	4027.2
Checkshot	5	678.11	1356.22	4737.2
Checkshot	6	762.18	1524.36	5437.2
Checkshot	7	806.21	1612.42	5837.2
Checkshot	8	870.25	1740.5	6457.2
Checkshot	9	890.26	1780.52	6657.2
Checkshot	10	924.28	1848.56	7007.2
Checkshot	11	957.3	1914.6	7327.2
Checkshot	12	1017.32	2034.64	7957.2
Checkshot	13	1066.34	2132.68	8492.2
Checkshot	14	1119.36	2238.72	9092.2
Checkshot	15	1168.37	2336.74	9641.2
Checkshot	16	1185.38	2370.76	9808.2
Checkshot	17	1209.38	2418.76	10087.2
Checkshot	18	1232.39	2464.78	10337.2
Checkshot	19	1259.4	2518.8	10648.2
Checkshot	20	1297.4	2594.8	11037.2
Checkshot	21	1307.4	2614.8	11142.2
Checkshot	22	1352.41	2704.82	11611.2
Checkshot	23	1379.42	2758.84	11885.2
Checkshot	24	1400.42	2800.84	12133.2
Checkshot	25	1419.42	2838.84	12316.2
Checkshot	26	1438.42	2876.84	12517.2

Table 3: Checkshot velocity data for Time-Depth Conversion.

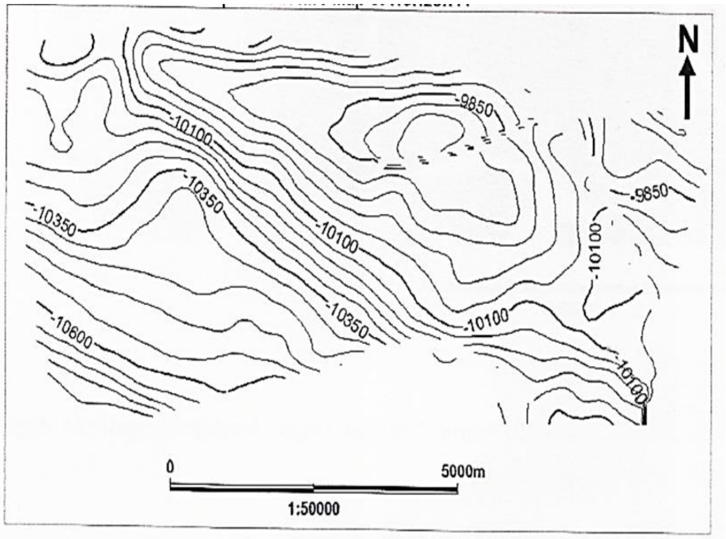

Figure 9a: Depth Structural Map of Horizon A

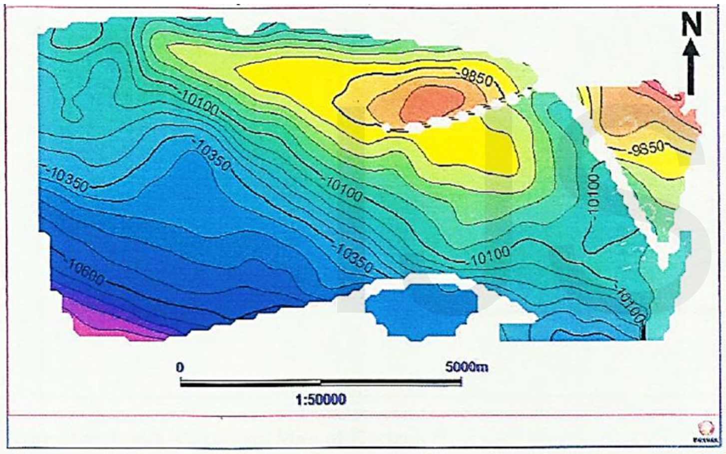

Figure 9b: Shaded Depth Structural Map of Horizon A

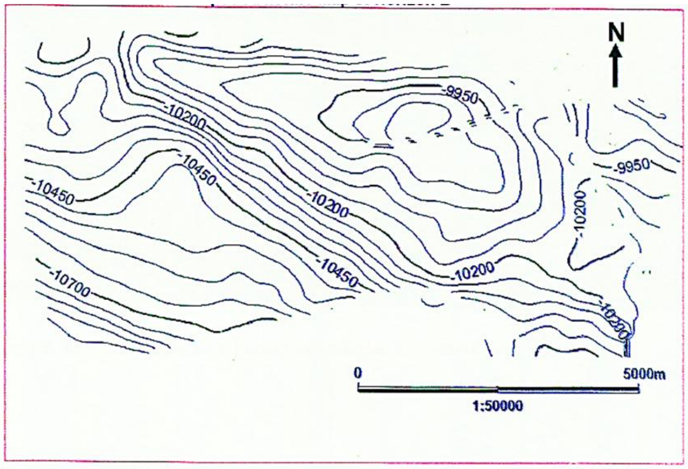

Figure 10a: Depth Structural Map of Horizon B

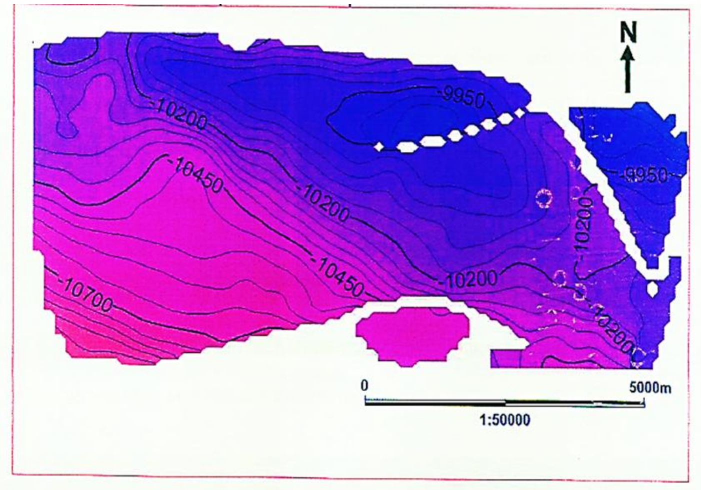

Figure 10b: Shaded Depth Structural Map of Horizon B

3.6 Seismic Facies Analysis

Seismic facies analysis of a typical line CC' was based on the following seismic attributes: reflection continuity, configuration, amplitude, frequency and geometry. Representative samples are shown in Figure 11.

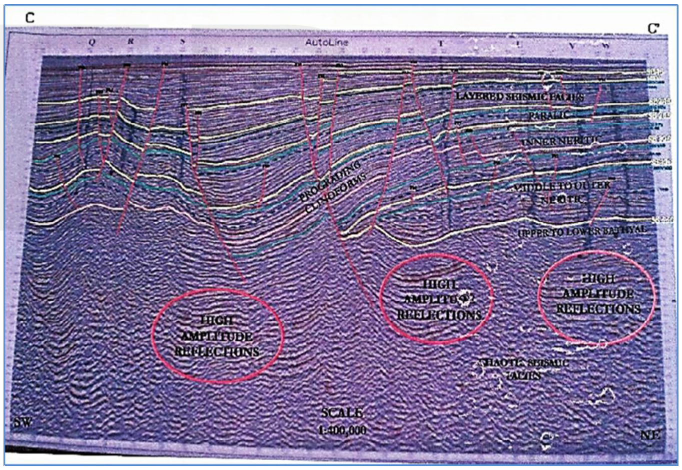

Figure 11: Seismic Line Cc' showing Sequence Boundaries, Seismic Facies and High Amplitude Reflections

3.7 Sequence Stratigraphic Interpretation

Results of sequence stratigraphic analysis are presented in Figures 12-14. Gamma ray log patterns, paleobathymetry data and total facies abundance (TFA) patterns were used to interpret condensed section/maximum flooding surfaces (mfs), sequence boundaries and the various sequences and accompanying systems tracts (Highstand systems tract, transgressive and low stand systems tract). They are represented on the wireline log as a change from a fining upward gamma ray log pattern to coarsening upward patterns. The coarsening upward, fining upward and aggrading (uniform) log patterns were defined as prograding, retrograding and aggradational stacking patterns respectively.

The highstand systems tract is bound by sequence boundaries on top and maximum flooding surfaces at the base; with funnel shaped log motif. The transgressive systems tract, TST are bounded on top by maximum flooding surfaces and below by transgressive surface. They display bell shaped log motif.

The low stand systems tracts, LST are bounded on top by transgressive surface (TS) and below by sequence boundaries (SB). They are not recognized by distinct stacking patterns. They represented the innermost systems tract and include the basin floor fan and prograding complex.

Well Q: The sequence stratigraphic interpretation of well Q based on gamma ray log patterns and total fauna abundance plot revealed three depositional sequences as shown in Fig. 12. Fining upward retrogradational log patterns represent condensed sections as well as hemipelagic shale.

Well U: The sequence stratigraphic interpretation of well U identified four depositional sequences Fig. 13. The sequences consist of a well-defined low stand systems tract beneath a sequence boundary at the 1350m depth as well as transgressive and high stand systems tracts. Above the maximum flooding surface at the 1600m depth is a prograding complex. Below this depth is a basin floor fan and slope fan.

Well W: Like well U, four genetic sequences were identified in well W (Fig. 14). These sequences consist of a low stand system tract, high stand and transgressive systems tracts. The low stand systems tract is characterized by sharp lower contact and low gamma readings.

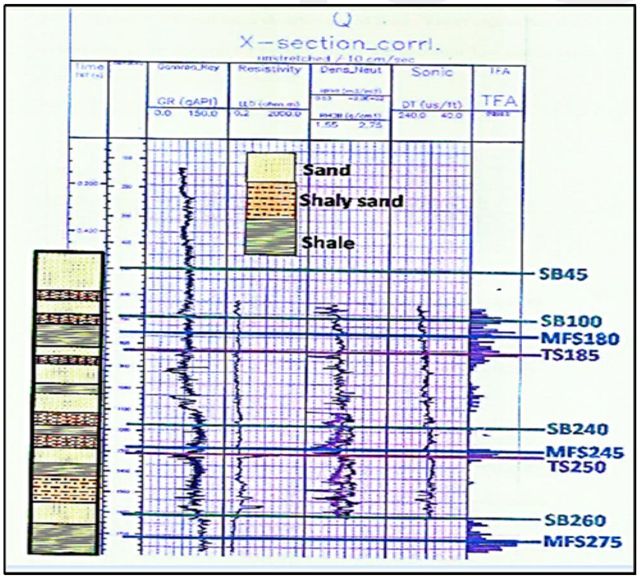

Figure 12: Sequence Stratigraphic Interpretation of Well Q

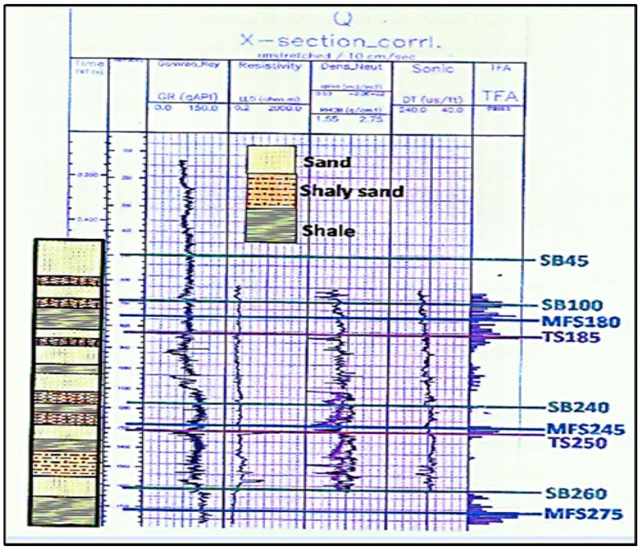

Figure 13: Sequence Stratigraphic Interpretation of Well U

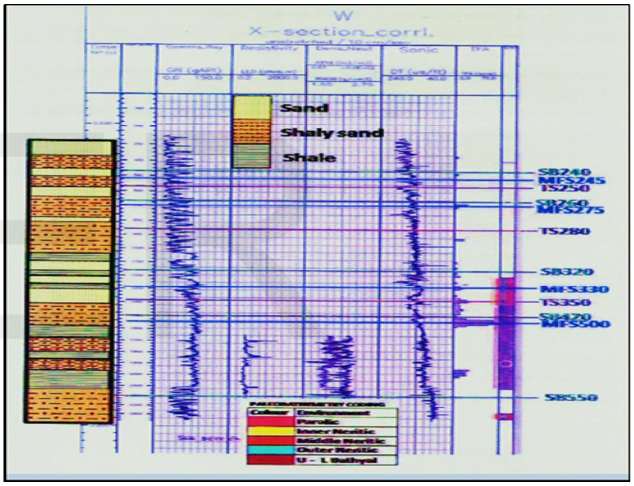

Figure 14: Sequence Stratigraphic Interpretation of Well W

3.8 Depositional Model:

By integrating the results from the gamma ray facies analysis, sequence stratigraphy, seismo-structural and seismo-stratigraphic analysis, a conceptualized depositional model has been designed for the study area (Fig. 15). The model which was calibrated using a composite of geophysical, geological as well as paleographical observations show the depositional transect down the axis of a fluvial–deltaic depositional system transporting sediment through submarine canyons – into a base slope and basin as fans. Variable sediments supply and sea level changes filled the incised channels and submarine canyons with a range of sands, heteroliths and mudstones.

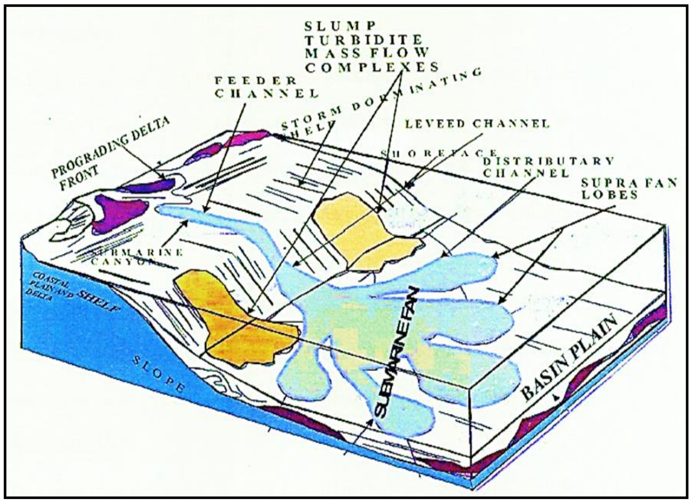

Figure 15: Conceptualized Depositional Model of Clastic Deposits in the Eastern Part of Deep Offshore, Niger Delta.

4 CONCLUSION

3D seismic data and well logs have been used to interpret the structure and stratigraphy of an onshore field (Field A) and an offshore field (Field B) in the Niger Delta of Nigeria. Four faults and two horizons have been interpreted and mapped in Field A. The depth structural maps for the two interpreted horizons indicated faulted anticlinal closures.

In Field B, seven field –wide unconformities or sequence boundaries were identified. All the faults are listric in geometry. The normal fault pattern indicates that Field B is located within the extensional part of the Niger Delta basin. Based on seismic and well log interpretations, it is evident that different styles of depositional patterns occurred along structures in the Niger Delta. The stratigraphic architecture of the studied area is controlled by variable tectonic (shale) subsidence rate and variable degrees of sediment supply due to channel switching during the late Miocene to Pliocene time. Clastic deposits of the offshore, eastern Niger Delta occurred on seismic records as layered seismic facies and chaotic seismic configuration packages.

The complex fault pattern as well as the discontinuous nature of sand bodies favor combined structural and stratigraphic entrapment for reservoirs which are heterogeneous and possibly compartmentalized.

REFERENCES

[1] R.T Beaubouef And S.J. Friedmann; "High Resolution Seismic/Sequence Strategraphic Framework For The Evolution Of Pleistocene Intraslope Basins, Western Gulf Of Mexico Depositional Model And Reservoir Analogs, In: P. Weimer; R.M. Slatt; J. Coleman; N.C. Rosen; H. Nelson. A. H. Bouma; M. J. Styzeen and D. T. Lawrenc (Eds)", *Deep – Water Reservoirs of the World*: Gulf Coast Section SEPM Foundation 20th Annual Research Conference, pp. 40 – 60, 2000.

[2] K. Burke, "Longshore Drift, Submarine Canyons and Submarine Fans In Development Of Niger Delta*," American Association Of Petroleum Geologists Bulletin,* 56, 1975 – 1983, 1972.

[3] T.J.A. Reijiers, S.W. Peters and C.S. Nwajide, "The Niger Delta Basin In African Basins"*Sedimentary Basins Of The World, pp. 3, (151 – 172),* 1997.

[4] P. Heinio and R.J. Davies, "Degradation of compressive fold belts, Deepwater Niger Delta", *American Association of Petroleum Geologist Bulletin,* 90, 753 – 770, 2006.

[5] C. Pirmez, R.T. Beaubouef, S.J. Friedmann And D.C Mohrig, "Equilibrium Profile And Base Level In Submarine Channels,Examples From Late Pleistocene Systems And Implications For The Architecture Of Deep – Water Reservoirs," In: WEIMER P., SLATT R. M., COLEMAN J., ROSEN N.C., NELSON, A. H., STYZEN M. J. And LAWRENCE D. T. (Eds*), Deep – Water Reservoirs of the World. Gulf Coast Section SEPM 20th Annual Research Conference* (761 – 805), 2000

[6] S.M. Hubbard, B.W. Romans, S.A. Graham and D.R. Lowe, "Downstream Variability In Deep – Water Channel Deposit Character And Associated Sedimentary Processes, Cretaceous Cerro Toro Formation Outcrop Belt, Magallanes Basins, Chile (Abs)". *Geological Society of America Annual Meeting Official Program, Denver,* 36, pp. 73, 2004.

[7] A. Brown, "Interpretation of Three-Dimensional Seismic Data," *American Association of Petroleum Geologists Memoir,* 42, pp. 514, 1999.

[8] F. Corredor , J.H. Shaw And F. Bilotti , "Structural Styles In The Deep –Water Fold And Thrust Belts Of The Niger Delta," *American Association Of Petroleum Geologist Bulletin*, pp. 89, 753 –780,2005.

[9] B.D. Evamy, J. Haremboure, P. Kamerling , W.A. Knapp, F.A. Molloy and P.H. Rowlands, "Hydrocarbon Habitat Of Tertiary Niger Delta," *American Association Of Petroleum Geologist Bulletin*, 62, (1 – 39), 1978.

[10] H. Doust and E. Omatsola, Niger Delta. In: J.I. Edwares & P.A. Santogross (Eds) "Divergent / Passive margin basin" *American Association of Petroleum Geologists Memoirs* (48, 201 – 238), 1990.

[11] S. Wu and A.W .Bally, "Slope Tectonics – Comparisons and Contrasts of Structural Styles of Salt And Shale Tectonics Of Offshore Nigeria," In: W. Mohriak & M. Talwani (Eds), *Gulf of Mexico With Shale Tectonics of Offshore Nigeria In Gulf Of Guinea, Atlantic Rifts And Continental Margins,* American Geophysical Union (151 – 172), 2000.

[12] P. Lehner and P. A. C De Ruiter., "Structural History of the Atlantic Margin of Africa," *American Association of Petroleum Geologist Bulletin* (61, 961 – 981), 1977.

[13] D.M. Worral And S. Snelson, "Evolution Of The Northern Gulf Of Mexico, With Emphasis On Cenozoic Growth Faulting And The Role Of Salt," In A.W. Bally & A.R.A. Palmer (Eds), *The Geology Of North America*: An Overview. Geological Society of America, (7 – 138), 1989.

[14] P. Weimer, "Sequence Stratigraphy, Facies Geometry and Depositional History of the Mississippi Fan, Gulf of Mexico,"

American Association of Petroleum Geologist Bulletin, (74,425 – 453), 1990.

[15] C.K. Morley and G. Guerine, "Comparison Of Gravity – Driven Deformation Style Sand Behavior Associated With Mobile Shale And Salt," *Tectonics*, pp. 15, 1154 – 1170, 1996.

[16] E. Oomkens, "Lithofacies Relations In Late Quaternary Niger Delta Complex*, Sedimentology*," pp.21 195 – 222, 1974

[17] K.C. Short and A.J. Stauble, "Outline of Geology of Niger Delta," *American Association of Petroleum Geologist Bulletin (51, 761 – 779),* 196*7.*

[18] A.A. Avbovbo, "Tertiary Lithostratigraphy of Niger Delta", *American Association of Petroleum Geologist Bulletin 62, 295 – 300*, 1978.

[19] H. Kulke, Nigeria, In KULKE H. (Ed), "Regional Petroleum Geology of the World Part II," *Africa America, Australia and Antarctica,* Berlin, Gebruder Borntraeger, (143 – 172), 1995.

[20] H. A. Cohen and K. Mc Clay, "Sedimentology and shale tectonics of the northwest Niger Delta,"*Marine and petroleum Geology* 82, pp.1903, 1996

[21] M. Rider, "The Geological Interpretation of Well Logs," Gulf Publishing Company Houston, pp.280, 1996

[22] D. Tearpock and R.E. Bischke, "Applied Subsurface Geological Mapping," New York, Printice Hall, pp. 780, 1991.

[23] A. Adeogba, A.T.R Mchargue and A Graham, "Transient Fan Architecture And Depositional Control From Near – Surface 3 – D Seismic Data, Niger Delta Continental Slope", *American Association of Petroleum Geologist Bulletin*(89, 627 – 643), 2005.

[24] P.R. Vail and W.W. Wornardt, "Well Log Seismic Stratigraphy: A New Tool for Exploration In the 90's. Gulf-Coast Section". *SEPM Eleventh Annual Research Conference Programs and Abstracts* (379 – 388), 1990.