Application of Sequence Stratigraphy to Characterization of Thin Reservoirs in “AFUN” Field Deep Offshore Niger Delta

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Abstract: **The complex facies architecture in turbidite systems has necessitated the use of sequence stratigraphic methods in characterising thin reservoirs of the “AFUN” Field, offshore Niger Delta, Nigeria. 3D post-stack time migrated seismic, biostratigraphic data, core data as well as a suite of composite well log data from six wells drilled within the study area were the dataset used for this study. Sequence stratigraphic analysis of the study area involved the interpretation of biostratigraphic data of AF-SW1 well. Time significant surfaces and their respective ages were identified on this well using the chronostratigraphic correlation of all the well logs across the study area. The stacking trends were used to delineate sequence stratigraphic surfaces and the stacking patterns used to delineate systems tracts, and define stratigraphic sequences. The analysis yielded seven depositional sequences based on dated Sequence Boundaries and Maximum Flooding Surfaces. Six Lowstand Systems Tracts (LST) were delineated and includes the Lowstand Slope Fan (LSF) and Lowstand Prograding Wedge (LPW) varieties. LSF and LPW are predicted to be submarine fan deposits which were vertically smeared by pro-deltaic mud. Seventeen reservoirs exist were identified within the field of study with eleven in the Lowstand System Tracts and six of the reservoirs belonging to the Highstand System Tracts. Most of the reservoirs in “AFUN” Field were deposited during LST while the TST (comprising mainly shales) serve as seals that capped the reservoirs. Reservoir quality of “AFUN” field was interpreted based on depositional features which control reservoir characteristics in different facies of the reservoirs. This study has therefore, revealed that the stratigraphic traps with different reservoir sands can be characterized based on their associated system tracts for field development.**

Keywords: **sequence stratigraphy, chronostratigraphic correlation, reservoirs, depositional sequences, submarine fan.**

I. INTRODUCTION

Data acquired from the deep water systems are usually characterized by extreme complexity and variability due to the inherent heterogeneity of the available data. Hence, the data need to be analysed and interpreted by techniques that will bring out the most geologically reasonable interpretation of the sediments within a time- stratigraphic framework. Therefore, the exploration and exploitation of the deep water reservoirs can be greatly enhanced by applying sequence stratigraphy principles. This technique provides the accurate evaluation of hydrocarbon reservoirs and thus reduction of geologic uncertainties [1]. Sequence stratigraphy can be used to evaluate the spatial distribution of stratigraphic traps with complex reservoirs and seals components as can be found in case of deep water settings more systematically than lithostratigraphic approaches [2][3]. The use of sequence stratigraphy for reservoir characterization in deep water systems can be of help for accurate field management and production optimization of such deposits [4] [5]. Several case studies have shown successful use of sequence stratigraphic pinciples to better understand the stratigraphic distribution and prediction of reservoirs in turbidite systems and exploration potential of their reservoirs [6] [2] [7].

This study focuses on the application of sequence stratigraphy in the determination of reservoir depositional facies and environment of deposition of the “AFUN” Field. The study area lies within the deep offshore Niger Delta of water depth of about 990-1117 m (Fig. 1). and entrenched within the Gulf of Guinea at the Western Inner Fold Thrust Belt of the delta toe divided into lobes by the Charcot fracture zone. The lobes are characterised by numerous fracture zones [8]. “AFUN” Field covers an area extent of approximately 812 km^2 and has six oil wells drilled. The sediments have been deposited during Early to Late Miocene [9]. The main reservoirs in the study area lie in the paralic sequence of the Agbada Formation. High degree of reservoir heterogeneity is usually associated with the paralic successions of the Niger Delta Basin [10]. This field has been characterized using lithostratigraphic correlation that could not accurately define depositional environment and facies association due to the complex facies architecture in turbidite system. This has been the major challenge for explorationists to adequately model the reservoirs and estimate hydrocarbon reserves [11]. Consequently, there is the need for application of sequence stratigraphy for better understanding of the depositional environment so as to reduce uncertainties. In this study, a sequence stratigraphic approach using integration of biostratigraphic data, core data and well logs were used for establishing the chronostratigraphic framework of the study area in order to accurately define the environment of deposition of sand bodies within the “AFUN” field for optimal production and calibrating the subsurface risk for field development.

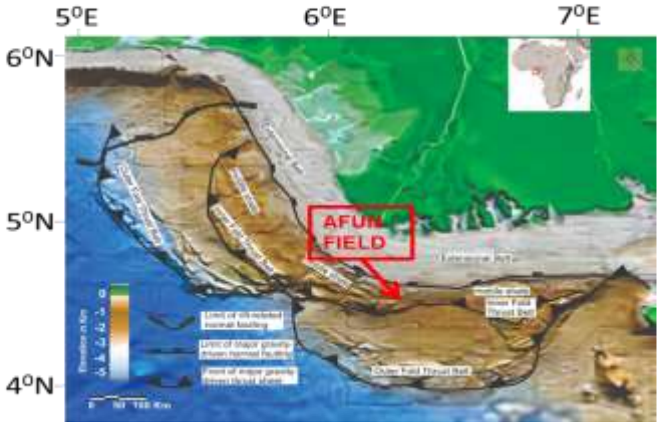


Figure 1: Map of Niger Delta showing the location of the study area [8]

II. GEOLOGY OF THE STUDY AREA

The Niger Delta is a large, arcuate delta of destructive, wave dominated type. It covers an area of about 75,000 sq km [12]. The delta proper began developing in the Eocene and composed of an overall regressive clastic sequence accumulating sediments of maximum thickness of about 9,000 to 12,000m. From the Eocene to the present, the delta has prograded southwestward forming depobelts that represent the most active portion of the delta at each stage of its development [13]. It is situated on the Gulf of Guinea on the West coast of Central Africa and on the southern end of Nigeria (Fig. 2). It is bordering the Atlantic Ocean between Latitude 4^0N and 6^0N and Longitude 3^0E and 9^0E [14]. It is bounded in the North by the older Cretaceous tectonic elements of the Benin flank, an east-northeast trending hinge line south of the West Africa basement massif, the Anambra Basin, Abakaliki uplift and Afikpo syncline. It is bounded in the west by the Benin flank and in the east by the Calabar flank which is a subsurface expression of the Oban massif (Fig. 2). The north-eastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south-east by the Calabar flank, a hinge line bordering the adjacent Precambrian.

The offshore boundary of the province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey basin (the eastern-most West African transform-fault passive margin) to the west, and the two kilometre sediment thickness contour or the 4000-meter bathymetric contour in areas where sediment thickness is greater than two kilometres to the south and southwest [15]. The lithostratigraphy of the Niger Delta Basin consists of three main rock stratigraphic units of Cretaceous to Holocene origin [16] [17] [18]. These are the Akata, Agbada and Benin Formations. The Niger Delta is a regressive sequence of clastic sediment developed in a series of offlap cycles. This is demonstrated in all the deep wells in the basin alongside with a tripartite lithostratigraphic succession [13]. It is believed that the shales of Akata Formation are the source rock for hydrocarbon in the Niger delta.

The base of the sequence consists of massive and monotonous marine shales. This grades upward into interbedded shallow – marine and fluvial sands, silts and clays representing a typical paralic facies. The uppermost part of the sequence is a massive non marine section [13]. These sequences represent the sediments of the marine, transitional and continental environments as would be expected of an advancing delta such as that of River Niger [16]. The overall sequence is strongly diachronous as in all deltas [13]. Three main formation names have been assigned to correspond to the tripartite sequence of the Niger Delta. These are the Akata, Agbada and Benin Formations in an ascending order [16] [17].

The Offshore Niger Delta is characterized by an extension of onshore succession in shallow water region with a continuation of the extensional growth fault structural regime. It consists of continental shelf with slope morphology of about 2-4^0 and continental rise located under continental slope which is a plain that goes all the way to deep sea to form a marine fan. Deep marine or deep offshore of Niger Delta is made up of sediments transported under gravity flow processes and deposited at water depth greater than 500 m [19]. It is characterized by the depositional systems of variation in size and geometry of sand bodies due to the nature of the transportation system of the deposits (Fig. 3) [20].

Figure 2: Geologic Map of Nigeria showing the Location of the Niger Delta Region Indicating Major Structural Elements (Modified from [21]).

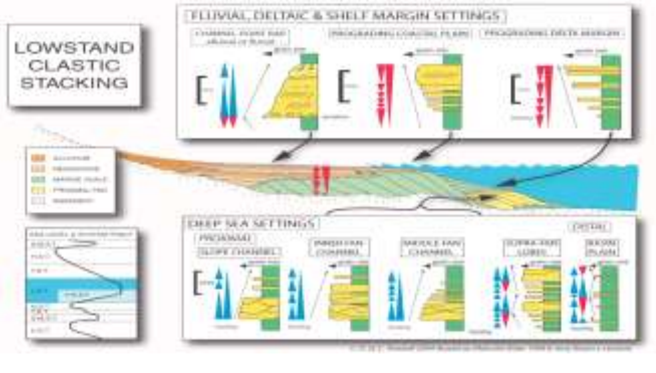


Figure 3: Clastic LST stack as demonstrated by Hunt and Tucker (1992) the up dip erosion that builds most fan complexes is associated with the base level fall that drives forced regressions of the Shoreline [22]

III. METHODOLOGY

The available sets of data for this study are six (6) well logs (including gamma ray, density, neutron, sonic, and resistivity logs), biostratigraphic data, core data and detailed report for two (2) wells. The data analyses were done using the Petrel software. LAS file of logs was imported into the Petrel 2013 software (powered by Schlumberger) as well as seismic data. The integrated asset evaluation was carried out using basically two major geophysical datasets, which include: well logs and seismic data. The logs include lithologic log (gamma ray), resistivity log (deep induction log), and porosity logs (bulk density, sonic and neutron). The well logs were carefully studied. Biostratigraphic data were available for only one well (AF-SW1) and were sourced from the well completion reports. Sequence stratigraphic analysis was carried out based on biostratigraphic data (pollen pores and foraminifera), depositional environments and well logs (gamma ray, resistivity, neutron and density) in the AF-SW1 well [23]. Plots of pollen and foraminiferal abundance and diversity in well completion report helped to identify the maximum flooding surfaces in the well. The MFSs corresponded at depths with a relative high abundance and diversity of pollen and forams.

These depths were confirmed by wide separation of neutron and density logs (high density and high neutron count), low resistivity reading, and high gamma ray count. MFSs are horizons of maximum transgression within a sequence [5]. Consequently, other time significant surfaces (Sequence Boundary and Trangressive Surfaces) and their respective ages were identified from AF-SW1 well log following the procedure recommended by [24]. SB were recognized as areas with low abundance and diversity of pollens and forams which corresponds to low gamma ray and high resisitivity. TS were identified as prominent flooding surfaces forms the base of the retrogradation parasequence stacking patterns of the TST. These surfaces were used to carry out the chronostratigraphic correlation on all the well logs across the study area. The stacking trends were used to delineate sequence stratigraphic surfaces and the stacking patterns used to delineate systems tracts, and define stratigraphic sequences. The log signatures aided in determining the environment of deposition by analysing their stacking patterns. Depositional (II) model of [25] was employed for the subsurface facies within the depositional profile.

The depositional environments of the study area were interpreted using the characteristic patterns and curves of the gamma ray logs in line with the published charts of Kendall, 2004 (Fig. 4). Apart from wireline logs that come close to revealing the actual subsurface geology displayed by seismic lines, cores describe the nature of subsurface to a much greater detail. The cores studied thus far were from two wells, AF-4 and AF-4ST1, available out of the six wells in the study area. Also, the abundance and diversity of palynofacies derived from well completion reports reveal the depositional environment. The depositional environment of AFUN Field, Niger Delta was therefore predicted using integration of results from gamma ray log, biostratigraphic and core data.

Lithostratigraphic correlation within the delineated stratigraphic sequences were carried out using gamma ray and resistivity logs. Hydrocarbon bearing sands were identified within the established system tracts from the log signatures. Sand units of interest were carefully picked and correlated across the wells to give an idea of the continuity of the reservoirs at different depths across the study area. The fluid type (oil, gas or water) in the reservoirs was determined using the Neutron-Density crossplot and pressure-depth plot generated from the data provided. The reservoirs mapped were interpreted as oil reservoirs when there are little or no separations between neutron and density curves in the reservoirs. Gas usually shows high neutron-density separation, mostly referred to as gas effect [26].

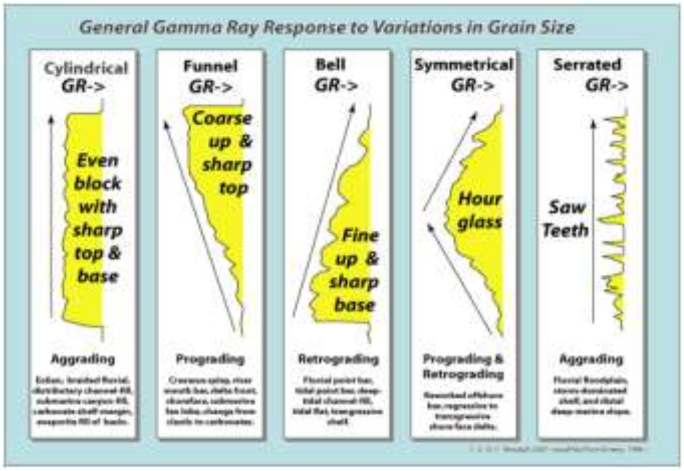


Figure 4: General gamma ray response to variations in grain size [21]

IV. RESULTS AND DISCUSSION

AF-SW1 (distal) is the southernmost well while well AF-1 (proximal) is the northernmost well in the study area. From the biostratigraphic data of AF-1SW well (Fig. 5), it can be deduced that the high proportion of shale (90%) over the well section is indicative of dominance of low energy depositional conditions. The ubiquitous presence of pyrite and fairly regular occurrences of Carbonaceous detritus within the unit lends credence to this interpretation. The few and thin sands within the unit may represent short-lived periods of energy burst in the otherwise quiet environment (Fig. 5). The lower part of the AF-1SW well section (13650 – 9860 ft) is dominated by rich and diverse deep water arenaceous benthics. However, within 9860 – 8540 ft interval, calacareous benthics dominated the microfaunal assemblage. Deep water calcareous benthics recorded include Hanzawaia mantaensis, Globocassidulina subglobosa, Uvigerina hispida, Anomalinoides alazanensis, Oridosalis umbonatus, Hoeglundina elegans and Sphaeroidina bulloides. Associated deep water arenaceous benthic present include Karreriella siphonella, Karreriella bradyi, Eggerella bradyi, Glomospira charoides, Valvulina flexilis, Ammodiscus glabratus and

Cyclammina cancellata. The above foraminiferal association is indicative of sediment deposition in an upper to lower Bathyal environments. The palynofacies assemblage of the well section over interval 13650 - 10700 ft is characterized by lower abundance of microfloral species such as the grass pollen and mangrove plant pollen as well as dinoflagellate cysts relative to the upper section (10700 – 8540 ft) where high abundance and diversity of marine dinoflagellate cysts were recorded. In addition, abundant small-sized black and brown woody elements and black coal or charcoal with common amorphous organic matter dominate the palynodebris assemblage of the well. This assemblage is suggestive of a marine depositional environment. Integration of the pyrite occurrence, foraminifera assemblages and the lithology suggested that the study area is composed essentially of deep sea (Upper Bathyal – Lower Bathyal) facies of hemipelagic shales and gravity flow sands. The sands are interpreted as being essentially turbidites (submarine fans). It was also believed that the well penetrated early to late Miocene succession of sediments.

Seven maximum flooding surfaces were identified as peaks of gamma ray within the stacked packages of the logs. The MFSs marked the transition of surface from underlying fining upward (prograding) units to an overlying coarsening (aggrading) units. These surfaces correspond to condensed sections of age 17.4, 15.9,15.0, 12.8, 10.4, 9.5, and 7.4 Ma respectively which were identified based on microfossil abundance and diversity maxima in AF-SW1 well (Fig. 5). Six sequence boundaries were also identified based on sharp gamma ray transition from shale to sand i.e. coincide with erosional base of sand bodies. The surfaces were dated 16.7, 15.5, 13.1, 12.1, 10.35 and 8.5 Ma respectively. Fig. 6 shows the correlation panel that display dated surfaces, Sequence Boundary (SB) and Maximum Flooding Surface (MFS). Transgressive surfaces were identified as surfaces lie above the SBs in the study area. These surfaces which were seven in number mark abrupt changes from progradational units to retrogradational units. Transgressive surfaces indicate a decrease in sand thickness of sand deposited during sea level fall. The chronostratigraphic correlation assisted in subdividing the subsurface sequences penetrated by the wells into depositional sequences and systems tract (Fig. 7). Seven (7) depositional sequences were delineated. Three systems tracts namely Lowstand Systems Tract (LST), Transgressive Systems Tract (TST) and Highstand Systems Tract (HST) were identified in each of the sequences (Fig. 7). The bounding surfaces of these sequences correspond to seismic reflections that represent uncomformities. (Fig. 8). Systems tracts LST, TST and HST are arranged through one depositional sequence based on stacking patterns of log motifs (Fig. 7). LST were stratigraphically position directly above sequence boundaries and overlain by transgressive surfaces. LST are characterized with fining upward and coarsening upward profiles which comprise of progradational and aggradational stacking patterns at the levels they occur within the wells. TST were stratigraphic positioned directly overlying maximum flooding surfaces and above transgressive surfaces. They enclosed fininng upward profiles (retrogradational stacking patterns). HST were made up of prograding shales and aggrading sands units which overlain the MFSs and terminated at the base of the SB. The lowstand aggrading sequences crescentic (or bow), serrated and a funnel shape of Gamma ray log signatures were observed in three of the wells (AF-3ST1, AF-4 and AF-1). Even block of well sorted sand was observed at depth of between 9465 ft to 9490 ft in well AF-3ST1. This type of GR log signature is characteristic of basin floor fans (Fig. 9). It depicts an episode and event of sand deposition into the deep sea intermittent to the quiescence that generally characterises pelagic environments. A bell shape log signature was observed in well AF-4 between 8100 ft and 8400 ft. It indicates a finning up sequence of more than 300 ft thick of sand and depicts deep tidal channel fill (Fig. 10). Also, a serrated shape log signature

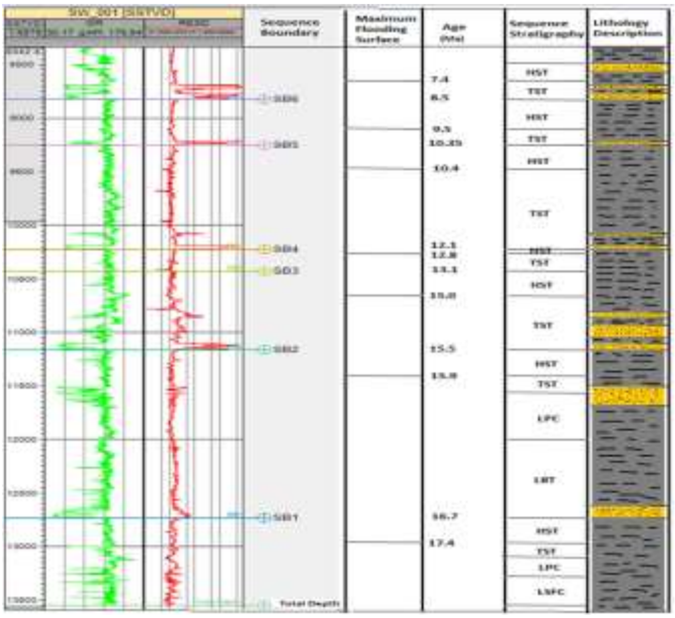
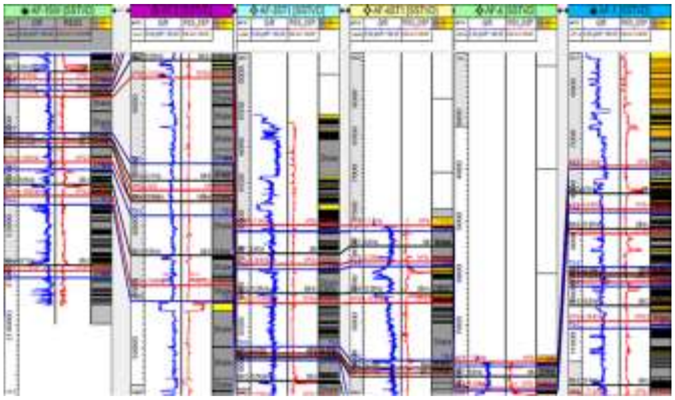


Figure 5: Palaeontology summary of well AF-SW1 showimf the facies proportion with their respective system tracts

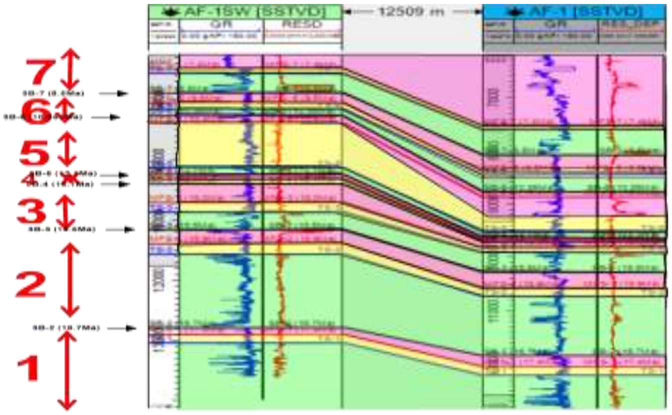


SB: Sequence Boundary, MFS: Maximum Flooding Surface, TS: Transgressive Surface

Figure 6: Chronostratigraphic correlation of AFUN Field showing the dated surfaces (SB and MFS)

was observed in well AF-1 at the depth between 8000 ft and 8080 ft. It indicates aggrading sequence of about 80ft thick and depicts deep marine lobe (Fig. 11).

Lithostratigraphic correlation was also carried out on the subsurface facies of “AFUN" Field, Niger Delta. For the lithostratigraphic correlation, seventeen (17) reservoir sands namely B1, B2, C1, C2, C3, C4, C5, C6, D1, D2, E1, E2, F1, G1, G2, G3 and G4 (Fig.12) were correlated for the study. From the lithostratigraphic panel, it can be deduced that there is reservoir discontinuity and lateral facies change, that is, thickening and thinning of reservoir (some reservoir pinch out from sand to shaly sand). It can also be deduced from the well correlation that the reservoir series



HST : Highstand Systems Tract

TST : Transgressive Systems Tract

LST : Lowstand Systems Tract

SB: Sequence Boundary, MFS: Maximum Flooding Surface, 1 – 7: Depositional Sequences

Figure 7: Chronostratigraphic correlation of the study area showing the sequences and identified systems tract

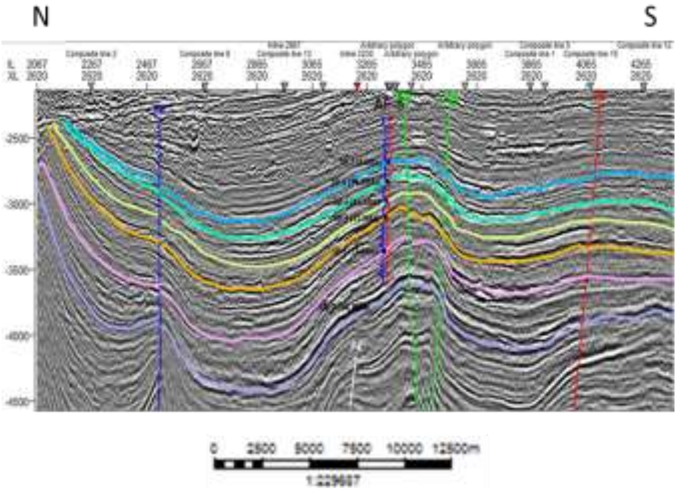


Figure 8: Seismic crossline 2620 showing mapped sequence boundaries

Almost crescentic shape gamma ray log signature at depths of between 465ft to 9490 ft. about 25ft thin of clean sand layer. Sharp termination at the base and top

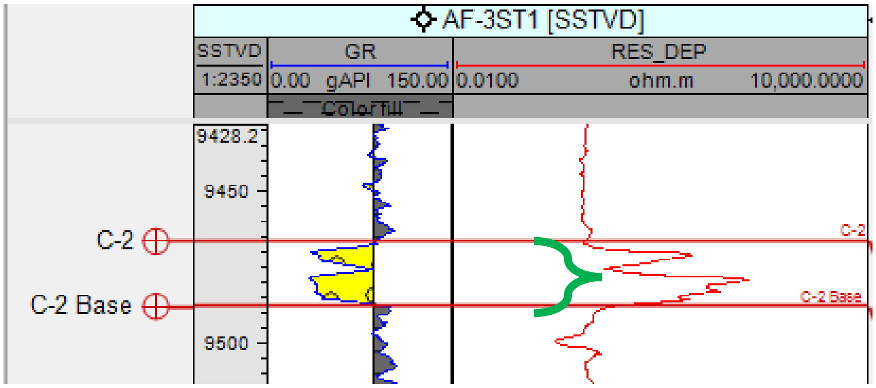


Figure 9: Crescentic shape Gamma Ray log signature in well AF-3ST1

Bell shape gamma ray log signature observed at depths between 8100 ft and 8400 ft approximately 300 ft. thick. This indicates a finning upward sequence as the submarine fan lobe.

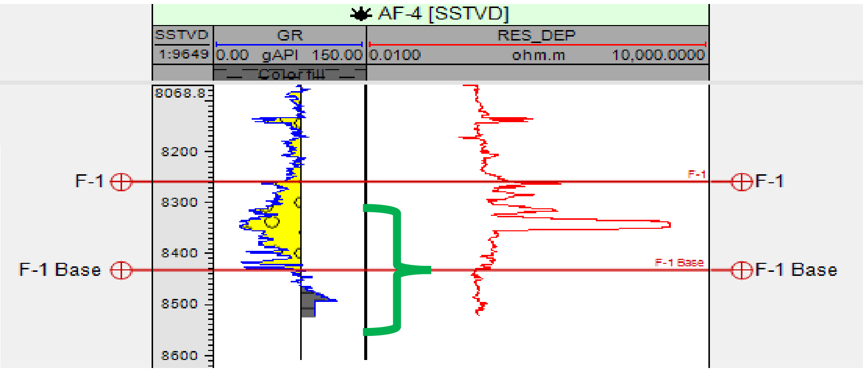
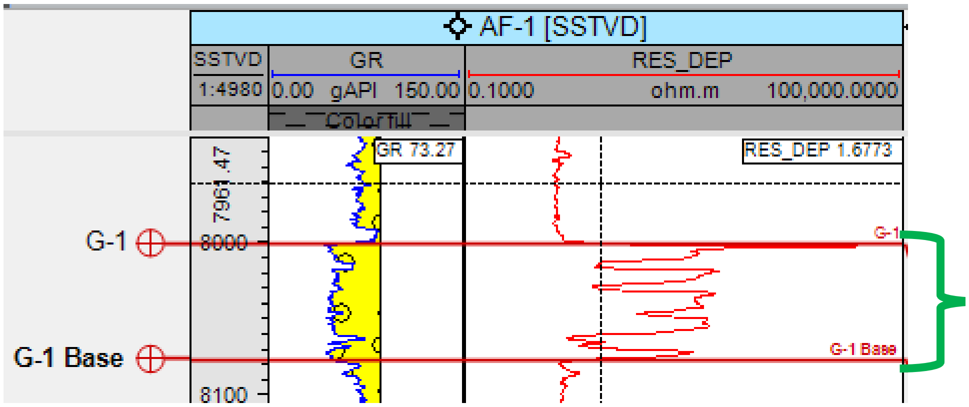


Figure 10: Bell shape Gamma Ray log signature in well AF-4



Serrated shape gamma ray log signature observed at depths between 8000 ft and 8080 ft approximately 80 ft. thick. This indicates aggrading sequence as deep marine lobe.

Figure 11: Serrated shape Gamma Ray log signature in well AF-1

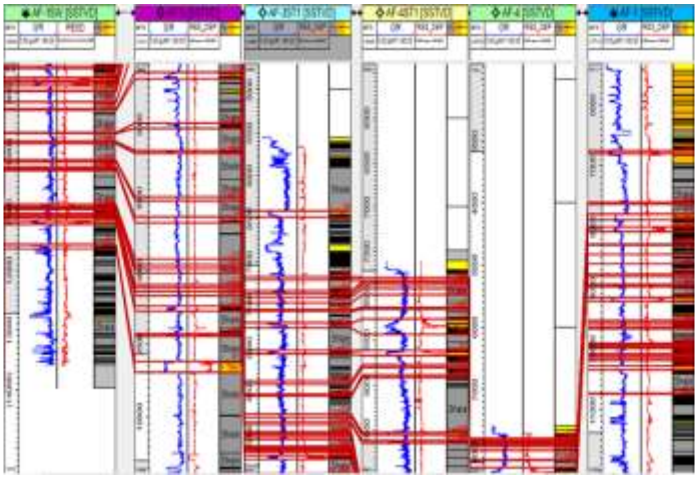


Figure 12: Lithostratigraphic (Sand-to sand) correlation of AFUN Field's hydrocarbon bearing reservoirs

are characterized by both lateral and vertical heterogeneities. The reservoirs could be said to have been smeared by the continuous shale layers that occur between the sand bodies in the study area. The three horizons mapped, namely C4-sand, F1-sand and G1-sand (Fig. 13) were chosen based on the systems tract they belong to, the net pay of the hydrocarbon bearing sand and the sand quality. They are well developed hydrocarbon bearing sands within the Lowstand Systems Tract (LST). This Lowstand Systems Tract (LST) are of both the Lowstand Progading Wedge (LPW) and Lowstand Slope Fan (LSF) complex varieties where overall coarsening and finning upward stacking pattern respectively was observed. Reservoir C4-sand is within LST-3; F1-sand is within LST-6 while the G1-sand is within LST-7. Table 1 shows the relationship between the systems tracts, reservoirs and their respective predicted depositional environment.

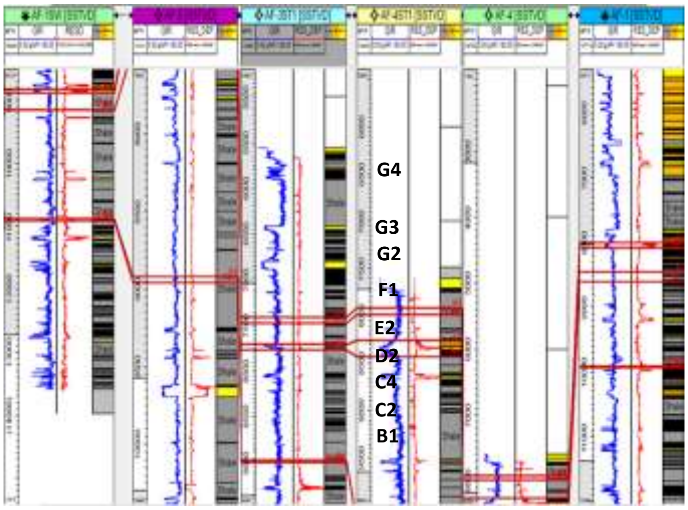


Figure 13: Sand to sand correlation (G1, F1 & C4)

Table 1: Relationship between the systems tracts, reservoirs and their respective predicted depositional environment

SEQUENCE	SYSTEMS TRACTS	RESERVOIRS	INFERRED DEPOSITIONAL ENVIRONMENT PER SEQUENCE	FORMATION
7	HST-7	G4		AGBADA
	TST-7			
	LST-7	G1,G2 and G3	Submarine Fan	
6	HST-6			
	TST-6			
	LST-6	F1	Submarine Fan	
5	HST-5	E2		
	TST-5			
	LST-5	E1	Submarine Fan	
4	HST-4	D2		
	TST-4			
	LST-4	D1	Submarine Fan	
3	HST-3	C5 & C6		
	TST-3			
	LST-3	C1, C2 ,C3 & C4	Submarine Fan	
2	HST-2	B2		
	TST-2			
	LST-2	B1	Submarine Fan	
1	HST-1			
	TST-1			
	LST-1		Submarine Fan	

V. CONCLUSIONS

The sequence stratigraphic analysis of thin reservoirs in the "AFUN" Field was carried out using data integration which involved the interpretation of biostratigraphic data and gamma ray log signature for chronostratigraphic correlation. This was in order to define depositional environment. The wells in the field penetrated early to late Miocene succession of sediments on the basis of biostratigraphic analysis. The depositional sequence of the mapped reservoirs has been divided into three systems tracts namely Lowstand Systems Tracts, Transgressive Systems Tracts and Highstand Systems Tracts. The six (6) Lowstand Systems Tract (LST) that were delineated are of both Lowstand Slope Fan (LSF) and Lowstand Prograding Wedge (LPW) varieties. Consistently, LSF are characterized by six cycles of retrograding event while LPW are characterized by six cycles of prograding event. These system tracts are bounded by three key chronostratigraphic surfaces namely Sequence Boundary (SB), Transgressive Surface (TS) and Maximum Flooding Surface (MFS). Seven (7) depositional sequences based on dated surfaces were identified and correlated across the well logs and mapped on seismic sections. Sequence stratigraphy and analogs were used to predict the depositional environment. Both LSF and LPW are predicted to be Submarine fan deposits which are vertically smeared by pro-deltaic mud. Eleven reservoirs belong to the Lowstand System Tracts and six reservoirs belong to the Highstand System Tracts. The study concluded that the characterization of "AFUN" deep marine reservoir systems could be assessed by lateral and vertical variations in the stacking patters of the submarine fans which affects the shape and scale of the reservoirs and their trapping geometry.

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