Well Log Analysis for Depositional Environment Interpretation – A Case Study of Ada Field, Central Niger Delta, Nigeria

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ABSTRACT

Well logs acquired while drilling in some parts of Ada field, Central Niger Delta, Nigeria were analysed to determine characteristic patterns or motifs that indicate particular environment of deposition. An understanding of the depositional processes that led to the formation of a specific sedimentary succession could help in determining the best exploration and exploitation method for the resources, that is, oil and gas contained therein. Seven wells, namely ADA-001, ADA-001-ST2, ADA-001-ST3, ADA-002, ADA-003, ADA-003-ST1 and ADA-008 were used for this study. These well data were loaded into Schlumberger Petrel (2018) software version and examined. The Galloway model of sequence stratigraphy was also applied to the dataset and three sequences, Sequence A, Sequence B, and sequence C were interpreted from careful study of parasequences and parasequence sets as observed in the wells. Cylindrical, funnel, bell, symmetrical and serrated log motifs signifying a wide range of environment of deposition including eolian, distributary channel, crevasses splay, delta front, shoreface, fluvial point bar, tidal channel fill, fluvial flood plain and distal deep marine slope were inferred. However, by comparing log motifs with biostratratigaphic data, the most probable depositional environments were determined. The presence of benthic species like *Alabammina-2, Bolivina sp, Cassigerinella-1, Chiloguembelina-3, Globigerina-41, Nonion-4, Uvigerina-5* showed that the clastic successions in Ada field were deposited in delta front, prodelta and open shelf environment of deposition.

Keywords: Depositional Environment, Motifs, Sequence Stratigraphy, Parasequences, Biostratigraphic.

INTRODUCTION

Well logs are detailed records of the lithologic successions penetrated while drilling a well (Delalex and Rueil, 2006). The process of acquiring a well log is referred to as formation evaluation or well logging. A log can be described as the graphical representation of one parameter as a function of another. Most logs come as a function of depth (Baker Hughes, 1996). The log may be either geological logs based on visual inspection of samples brought to the surface or geophysical logs based on physical measurements made by instruments or tools run down the well as it is being drilled or after drilling. Well logs are acquired during exploration or drilling operations to obtain information about mineral resources and groundwater located in subsurface geological formations. Logging operations are also carried out for environmental hazard investigations for landfills and other environmental concerns as well as for geotechnical analysis (Rider, 1986). There are two types of formation evaluation or logging activities that are carried out in oil and gas field operations, these are, cased hole and open hole logging. The objectives of the logging procedure or operations usually determines the type of logging operation that will be conducted. Spontaneous potential and gamma ray are the most basic parameters that are obtained during logging operation. Well logs are essential tools in the oil and gas industry. Most studies that are carried out during exploration, development and production stages rely on well logs for their analysis. They are also commonly used for sequence stratigraphy and pore pressure studies. The data collected during logging operations are restricted to the immediate surroundings of the well in which they are acquired. Log signatures or motifs have been used successfully to study the environment of deposition of lithologic successions in the Niger Delta (Mene and Okengwu, 2020; Nton and Rotimi, 2015). By comparing

The authors wish to express our gratitude to Shell Petroleum Development Company of Nigeria for the dataset used for this study. The efforts of the Department of Petroleum Resources in approving the release of the dataset are also kindly acknowledged. Similarly, the opportunity to use the facilities of the Department of Geology, University of Ilorin for this work is greatly appreciated.

depositional environment inferred from well log patterns with those interpreted from biostratigraphy data, this study adds to the body of knowledge that presume that well log patterns can be used as tools to determine environment of deposition.

Location and Geology of Ada Field

Ada field is located within the Niger Delta which lies between latitude 30 and 60 North and longitude 40 and 90 East. The field falls within the central swamp depobelt (Figure 1). The Niger Delta is located in the Gulf of Guinea with a major geological feature of significant petroleum exploration and production in Nigeria, ranking amongst the world's most prolific petroleum producing deltas (Ugwu, 2015). It occupies the coastal and oceanward part of a much larger and older tectonic feature, the Benue Trough (Reijers, *et al.,* 1997). The hinter land of the Niger Delta consists primarily of ancient rocks of the African shield (Doust and Omatsola, 1990).

The regressive depositional cycles of the delta have progressively migrated southwestwards, leading to the formation of depobelts that reveal the developmental stages of the Niger Delta. (Doust and Omatsola, 1990). The Niger Delta covers an area of about 300,000 km2 with sediment volume of up to 500,000 km3 and the thickness is about 11 km (Kulke, 1995). Sediments in the Delta were supplied in rapid successions from Eocene to middle Miocene (Weber and Daukoru, 1975). Further sedimentation after middle Miocene was controlled by erosion of uplifted hinterland and sea level changes.

The Niger Delta has been divided into three lithostatigrahpic units, namely the marine Akata Formation, paralic Agbada Formation and the continental Benin Formation (Short and Stauble, 1967, Doust and Omatsola, 1990, Reijers *et al.,* 1997, Reijers 2011, Abiola and Olowokere, 2016).

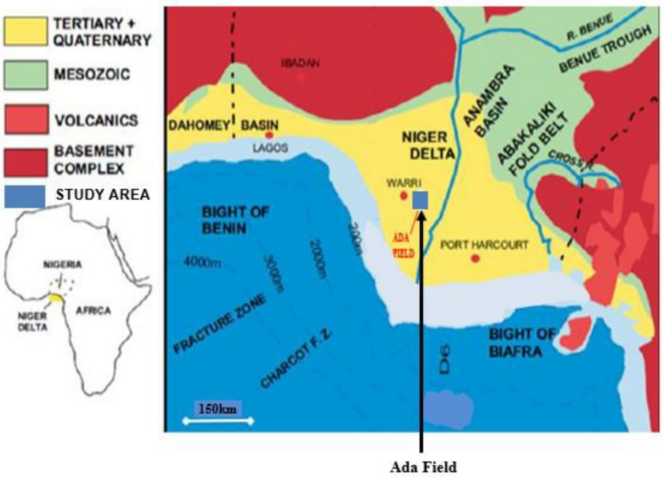

Figure 1: Map of the Niger Delta Showing the Location of Ada Field (Modified After Doust and Omatsola, 1990, Obaje, 2013).

The scope and objectives of this study are:

· Identification of stacking patterns and their corresponding parasequences and parasequence sets

· Building sequence stratigraphy model for Ada field using the Galloway (1989) concept

· Using log motifs and stacking patterns to determine depositional environment

· Validation of depositional environment inferred from well logs with biostratigraphy data

METHODOLOGY

Desk Work and Data Gathering

The desk work involves the review and study of available and relevant information on well logs and the Niger Delta. Previous research works relevant to the study such as thesis and journals were also consulted.

The data for this work was sourced from Shell Petroleum Development Company, Port Harcourt Office through the help of the Department of Petroleum Resources (DPR). The dataset includes suites of well logs and biostratigraphy data.

Dataset and software

The supplied dataset contained Well data for five wells, namely ADA-001, ADA-002, ADA-003, ADA-008 and ADA-009 and five side-track wells ADA-001-ST1, ADA-001-ST2, ADA-001-ST3, ADA-003-ST1 and ADA-003-ST2. One of the main wells, ADA-009 has no usable data and Two of the side-track wells, namely ADA-001-ST1 and ADA-003-ST2 have no well log data. Seven wells, namely ADA-001, ADA-001-ST2, ADA-001-ST3, ADA-002, ADA-003, ADA-003-ST1 and ADA-008 were therefore used for this study. A summary of available well data in the Ada field is presented in Table 1.

Table 1: Available Well Data in Ada Field.

	WELL DATA					
WELL	CALIPER	SP	GR	RESISTIVITY	DENSITY	
ADA-001	A	A	A	NA	NA	
ADA-001-ST1	NA	NA	NA	NA	NA	
ADA-001-ST2	A	NA	A	A	A	
ADA-001-ST3	NA	NA	A	NA	NA	
ADA-002	A	A	A	A	NA	A
ADA-003	A	A	A	A	NA	A
ADA-003-ST1	A	NA	A	A	A	
ADA-003-ST2	NA	NA	NA	NA	NA	NA
ADA-008	A	A	A	NA	NA	NA
ADA-009	A	NA	NA	NA	NA	NA

SP Spontaneous Potential
GR Gamma Ray

A Available
NA Not Available

The well log data were loaded into the Schlumberger Petrel software (2018) version and were processed, analyzed, and interpreted. Microsoft office suites of applications were also employed in the analysis and presentation of results.

Data Analysis

Biostratigraphy Data

Biostratigraphy is very important in sequence stratigraphic studies because it holds the key to paleobathymetry, a measure of topography of the ancient ocean floor (Neal *et al.,* 1993). It also affords the opportunity to determine the ages of stratigraphic surfaces. Available biostratigraphic data provided for all the wells consisting of total foram count and benthic diversity were interpreted. Marker fossils were identified by comparing the biostrastrigraphic data with the Niger Delta Chronostratigraphic chart.

The environment of deposition (EOD) was established based on species association (abundance and diversity). Maximum flooding surface (MFS) coinciding with peak diversity and abundance of microfossils and increasing water depth were dated based on the occurrence of marker fossils.

Fossils of planktonic organisms are more widespread than those of benthic organisms and are therefore more useful in establishing regional time correlation (Nichols, 2009). However, in shallow water environments, benthic fossils are used because near shore conditions may be too variable for planktonic fossils (Okosun, 2012).

Benthic species were utilized for bathymetry interpretation in this work. High counts or peaks of foraminifera species are associated with shales deposited during low sedimentation. This usually occurs in the basin during the time of relative sea level rise (Neal *et al.,* 1993; Nichols, 2009).

The interpreted biostratigraphic results were integrated with the wireline log and other available well data. The stacking pattern indicated by the log motif was calibrated with the results of biostratiraphic data to interpret sequences, systems tracts and depositional environment. The maximum flooding surfaces identified from biostratigraphic data correspond to zones with highest gamma ray (GR) count.

Available stratigraphic data was compared with the Niger Delta stratigraphic chart (Figures 2a and 2b) to deduce the time of the maximum flooding surfaces. A comprehensive approach was used for the interpretation of key surfaces. Using available well data, flooding surfaces were picked based on density (where available) and resistivity log signatures. Density and neutron logs are particularly useful where there are possible shale washouts. Biostratigraphic data was used as a control, since fauna abundance and diversity are indicative of positive sea level changes (Posamentier and Vail, 1988).

This work used the Galloway model for the sequence stratigraphy analysis. A lot of work that has been done on the Niger Delta have relied heavily on the Vail *et al.* (1977) approach (Giwa, *et al.,* 2004; Ozumba *et al.,* 2005; Ajayi, et al., 2006; Magbagbeola and Willis, 2007; Obaje, 2013; Bassey *et al.,* 2014).

Galloway (1989) concept of sequence stratigraphy is based on sequences bounded by maximum flooding surfaces. Maximum flooding surfaces are more laterally extensive when compared to other flooding surfaces and most likely to present strong reflections on seismic (Posametier, 2000). The Galloway (1989) model is also referred to as the regressive – transgressive (R-T) model of sequence stratigraphy as opposed to the (T-R), transgressive – regressive model of Embry and Johannessen (1993). The sequence has been widely defined as a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Vail *et al.,* 1977; Posamentier and Vail, 1988; Van Wagoner *et. al.,* 1990; Posamentier and Allen, 1999; Catuneanu *et al.,* 2006). However, to accommodate the various models of sequence stratigraphy, the definition was revised (Embry and Johannessen, 2017) to a succession of strata deposited during a full cycle of change in accommodation or sediment supply (Catuneanu *et al.,* 2009, 2011).

Well Log Data

The well logs were examined to;
i. identify lithologies;
ii. interpret stacking patterns of parasequences and parasequence sets;
iii. identify well log patterns of sedimentary facies (cylindrical, funnel, bell, symmetrical, serrated shapes) to interpret aggrading, prograding and retrograding facies respectively (Figure 3);
iv. interpret and indicate regressive/transgressive cycles and sequence stacking patterns;
v. infer depositional environment (Cant, 1984, Osetoba and Ojo, 2014).

And with the aid of biostratigraphic data, candidate maximum flooding surfaces were mapped, sequences and systems tracts were also delineated.

Well Correlation

The gamma ray log is the most commonly used nuclear log (Horsfall *et al.,* 2018) and measures the natural radioactivity of the formation. It is a useful tool for lithology recognition and differentiation. The electrical conductivity or resistivity of the formation is also an important physical property of the formation that have become increasingly useful in lithology correlation. These

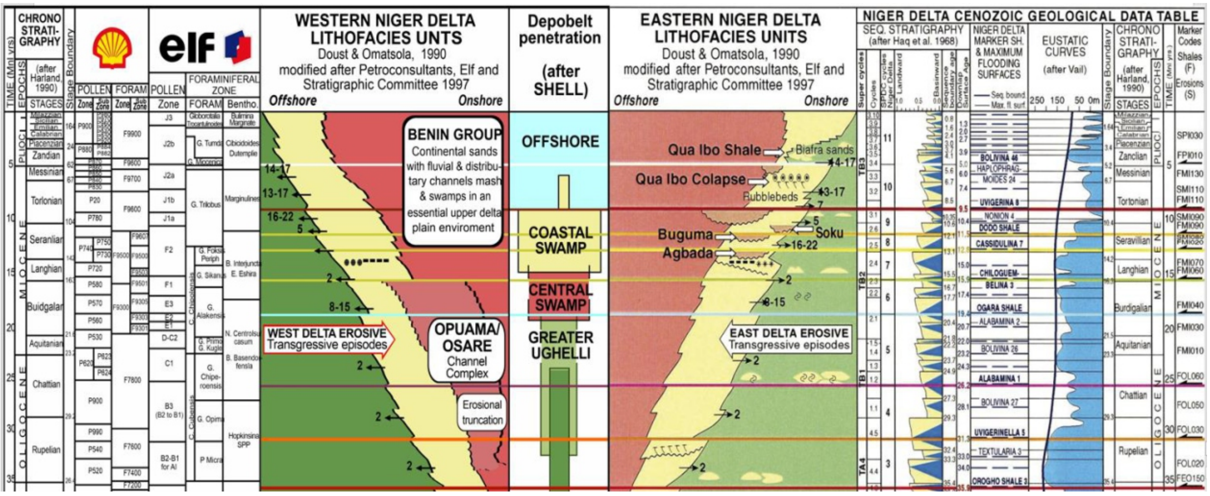

Figure 2a: Niger Delta Stratigraphic Data Sheet (Modified After Reijers, 2011).

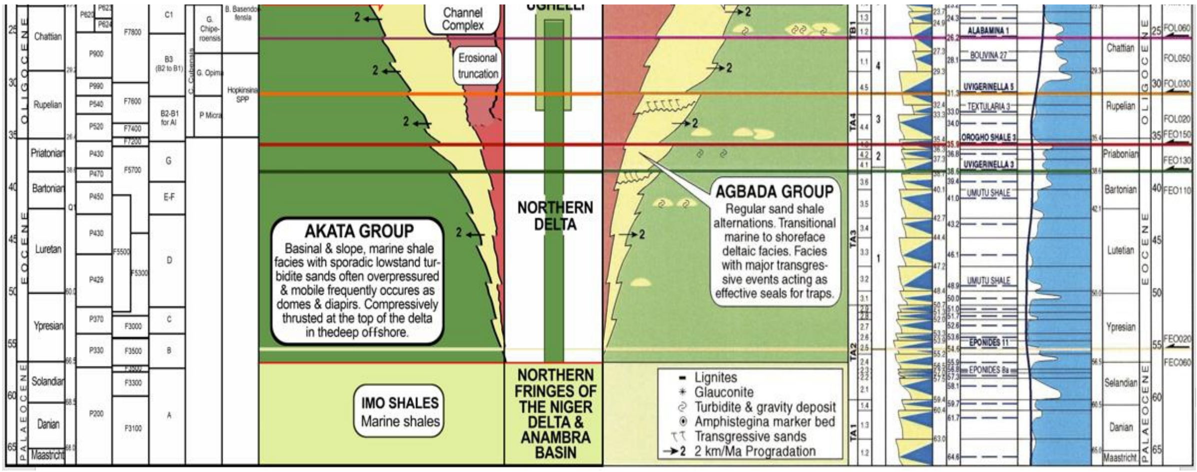

Figure 2b: Niger Delta Stratigraphic Data Sheet, continued (Modified After Reijers, 2011).

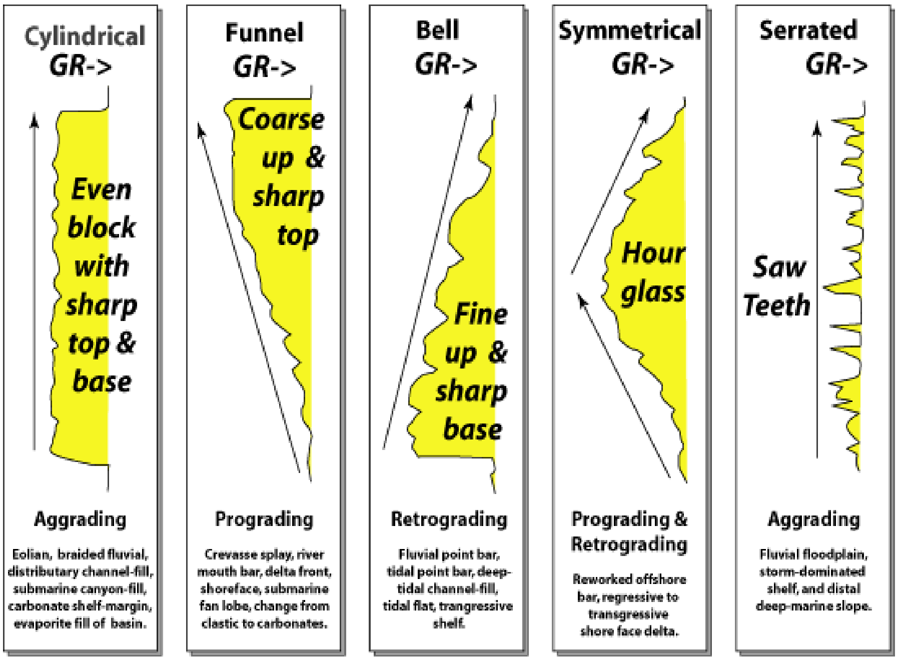

Figure 3: Well Log Patterns of Sedimentary Facies (Kendall, 2005, Mene and Okengwu, 2020).

properties are recorded by wireline or logging while drilling tools (Rider, 1986). Formation resistivity can be used to map lithologies with similar characteristics across all the wells within a field. A good example of this is the base of Benin Formation that can be easily interpreted at the first major resistivity reversal on the resistivity log.

There are three rules that must be considered for a successful well correlation, they are lithologic or depositional environment rules, geological structure rules and local distance rules (STAG, 2005). Lithology rules consider correlating distinct and significant lithology intervals that are clearly seen as a priority. This helps to divide the stratigraphic succession into different packages which can be worked individually. Vakarelov (2016) suggested the use of a datum, for example, the maximum flooding surface for this purpose. Geologic structure rules relate to observable geological structures such as faults that may be evident in the well sections, tie points across wells have to consider apparent discontinuities within the section. The distance rule is about well spacing (Vakarelov, 2016), it requires a great deal of effort to correlate wells that are far apart and do not have adequate well control, this usually happens in exploration drilling when dealing with frontier basins where geologic information may be sparse or unavailable.

Well correlation was carried out with the aid of lithologic logs. The base of the Benin Formation was the first to be picked and correlated, this is easily seen at the first significant resistivity reversal which also in some of the wells coincide with the occurrence of shale. The Benin Formation is made up of continental to coastal plain deposits. It is marked by relatively high resistivity on well logs. The base of Benin Formation marks the transition from Benin to Agbada Formation.

Interpreted maximum flooding surfaces were mapped across the field, they were mapped on the well logs. Since maximum flooding surfaces are synonymous with fauna and flora peak occurrence/ abundance and diversity, maximum flooding surfaces were picked from the biostratigraphic data and their depths matched on the well logs. This was done for all the wells on the correlation panel including those that lack some well log data but have biostratigraphic data in their upper sections like ADA-001 and ADA-001ST2. These aided the division of the lithology succession into different sequences and systems tracts. Interpreted systems tracts and sequences were then mapped and correlated across all the wells appropriately.

Results and Discussion

The Galloway (1989) model of sequence stratigraphy analysis was used to study the lithologic successions in Ada Field. The maximum flooding surfaces were mapped first on well logs and named after the dominant fauna occurrence within the interval using the supplied biostratigraphic data.

Lithologies were interpreted using the gamma ray. The gamma ray log was provided for almost all the wells in Ada Field. From log signatures, sand and shale were interpreted as the lithologies in Ada Field. On the gamma ray log, shale cut off point was set at 70 API. Log data points below 70 API were interpreted to be sand and those above 70 API were interpreted to be shale. Intervals interpreted to be sand or sandstone were coloured yellow while those that were interpreted to be shale were coloured grey in the well section (Figures 4 and 5). Although occurrences of silty or sandy shale and shaly sands have been reported in some wells in the Niger Delta, this cannot be easily interpreted on well logs (Osetoba and Ojo, 2014). However, when well logs are used with the aid of core samples and end of well report consisting of mudlog data, sandy shale, siltstone and shaly sands can be correctly interpreted. A careful study of the well log data and other supplied data led to the mapping of three maximum

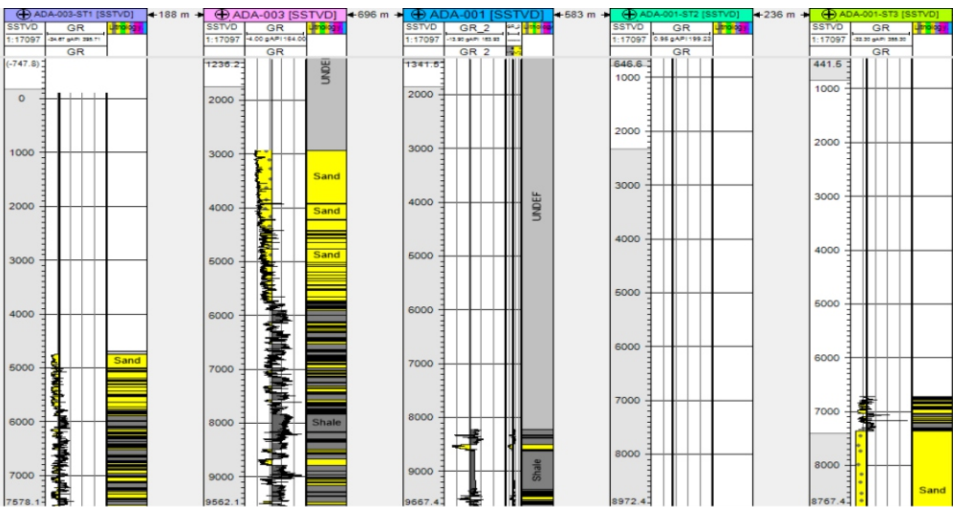

Figure 4: Well Section Showing Wells ADA-003 ST1, ADA-003, ADA-001, ADA-001 ST2, ADA-001 ST3 with Yellow and Grey Colours Indicating Sand and Shale Respectively.

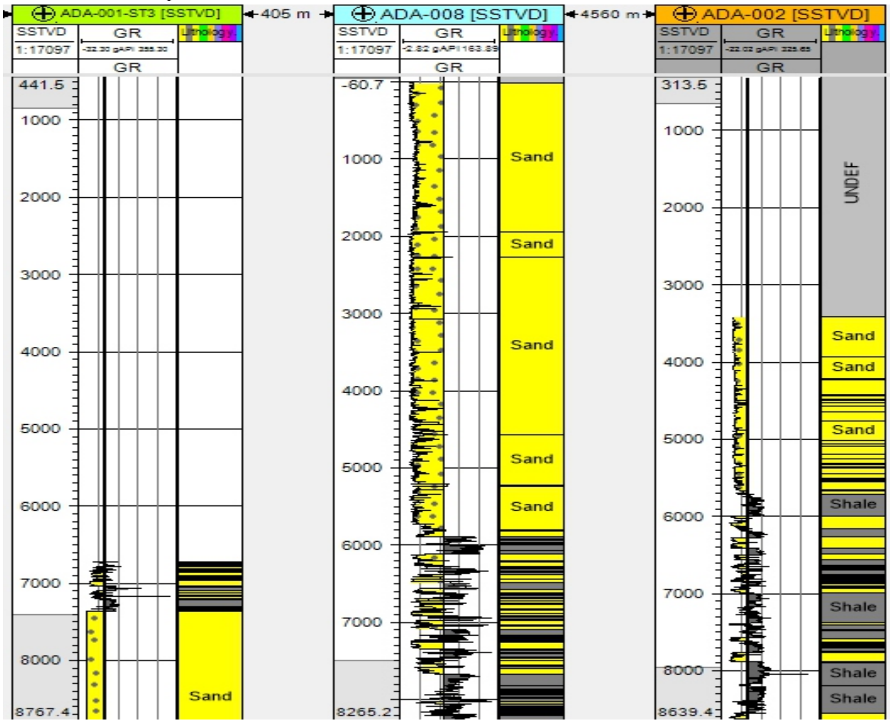

Figure 5: Well Section Showing Wells ADA-001-ST3, ADA-008 and ADA-002 with Yellow and Grey Colours Indicating Sand and Shale Respectively.

flooding surfaces (MFS), the mapped MFS are displayed in Figure 6. These Three maximum flooding surfaces were identified and named after the dominant benthic forams species namely Alabamina-2, Chiloguembelina-3 and Bolivina-25. These formed the bounding surfaces for the sequences. The base of Benin Formation was also mapped. Three sequences were thereafter delineated in the Ada Field, they were named Sequence A, Sequence B and Sequence C from oldest to youngest (Figure 7). Well log patterns showing aggradation, progradation and retrogradation stackings are presented in Figure 8.

Depositional Sequence

Sequences in the Ada field were mapped on well logs. Sequences were determined by;

i. the areas of recorded highest gamma ray log values within an overall shaly interval, signifying a possible condensed section with flora and fauna abundance;

ii. the position and arrangement of parasequences and parasequence sets and maximum flooding surfaces (Van Wagoner, et al., 1990, Osetoba and Ojo, 2014).

Three sequences were interpreted based on the above criteria. The sequences are named from oldest to youngest

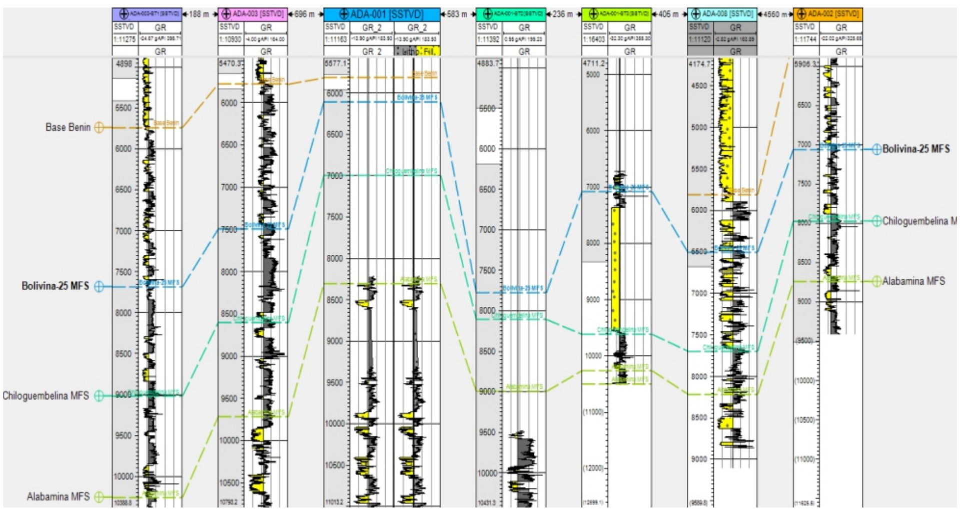

Figure 6: Maximum Flooding Surfaces and the Base of Benin Formation as Interpreted in the Well Logs in Ada Field.

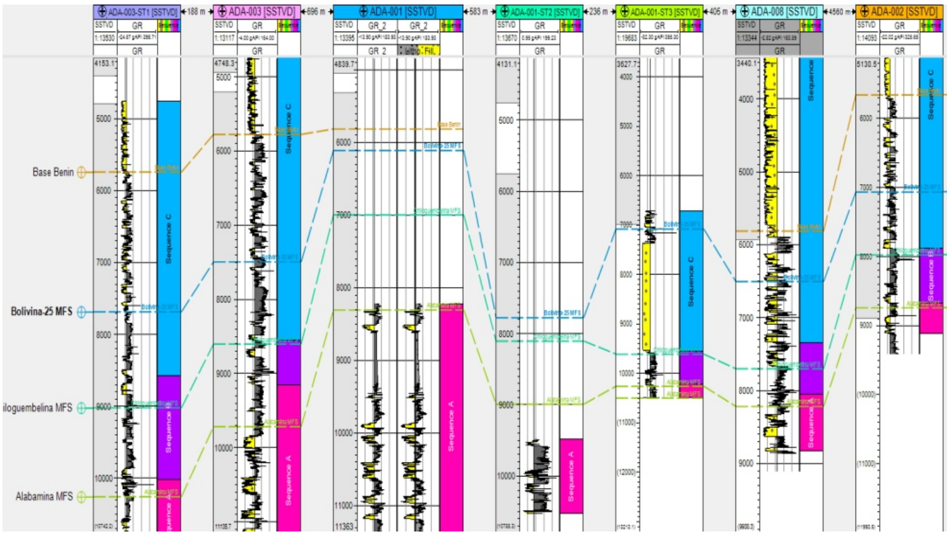

Figure 7: Sequences A, B and C as Interpreted on Well Logs.

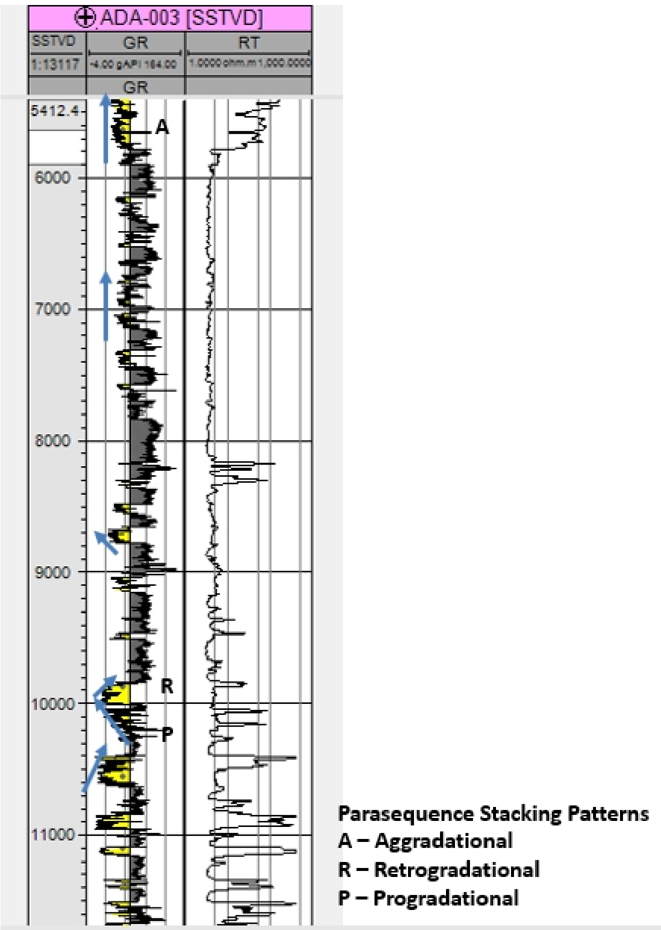

Figure 8: Representative Parasequence Stacking Patterns in Ada Field, Well Logs Showing Aggradational, Progradational and Retrogradational forms.

Sequence A, Sequence B and Sequence C. It is not all the sequences that are represented in all the wells, especially the side-track wells. The sequences as penetrated by the wells in Ada field are discussed below. The Galloway (1989) model of sequence stratigraphy was used for this study and the result is shown in Figure 9. The result of Vail et al., 1977 (Exxon) model, though not the focus of this study is also displayed in Figure 10 for comparison. Galloway suggested the use of maximum flooding surfaces (MFS) as sequence bounding surface, the MFS is agreed to be one of the most extensive and laterally continuous surfaces (Galloway, 1989; Van Wagoner et al., 1990; Posamentier and Vail, 1988; Catuneanu, 2006; Catuneanu et al., 2011).

Sequence A

This is the oldest sequence. The lowstand systems tract of this sequence is generally characterised by low gamma ray and resistivity values. This is the only sequence penetrated by ADA-001 and ADA-001-ST2, this is mainly because gamma ray and resistivity data for the wells are limited and only starts from 8,230 ft (2,508 m) for ADA-001 and 9,500 ft (2,895 m) for ADA-001-ST2. The lowstand system tract is essentially of serrated log pattern that seem to thicken towards the middle but finally thins out into the transgressive system tract. Faunal abundance is generally low.

Transgressive system tract for this sequence generally consists of high gamma ray values between 70 API and 130 API values. The log motif is essentially finning upward with a few intercalations of sands. The transgressive system tract is capped by the Alabamina-2 (20.7 Ma) maximum flooding surface.

In ADA-002, Sequence A starts with the lowstand systems tract at about 9,124 ft (2,781 m) with serrated gamma ray log pattern, low fauna assemblages are recorded within this interval. Directly overlying the LST is the

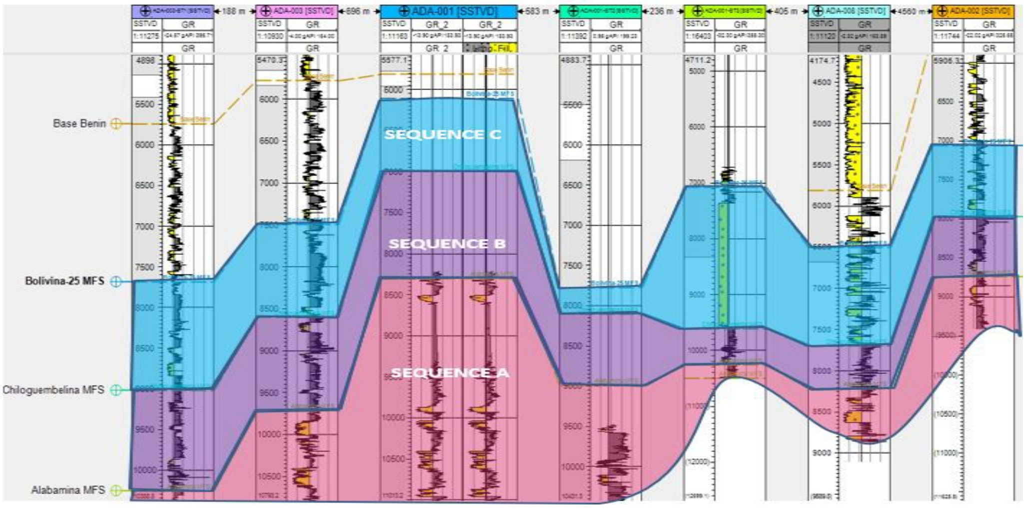

Figure 9: Genetic Sequence Stratigraphy Model on Ada Field Well Logs
MFS are the bounding surfaces for the genetic sequence stratigraphy model.

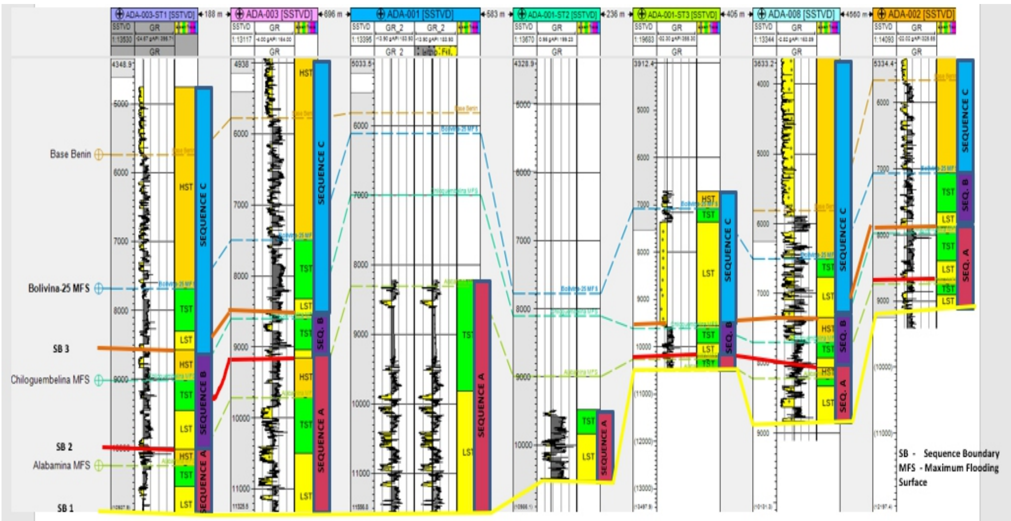

Figure 10: Vail *et al.,* 1977, Vail and Mitchum, 1977 (Exxon) Type Sequence Stratigraphy Model on Ada Field Well Logs
Sequence boundaries are the bounding surfaces for the Exxon model of sequence stratigraphy. The MFS are located within the sequence.

transgressive system tract for this sequence. Gamma ray log values range from 87 API to 124 API. The transgressive systems tract is capped by the Alabamina-2 maximum flooding surface at 8,741 ft (2,664 m). A short highstand systems tract of about 83 ft (25 m) starts from the MFS and ends at 8,677 ft (2,644.7 m).

In both ADA-003 and ADA-003-ST1, serrated log signatures with some occasional channel progradational stacking pattern indicative of channel type sedimentary facies are interpreted to indicate the lowstand systems tracts. This systems tract is predominantly made up of sandstone with some intercalations of shale in both wells, there are however more occurrences of sandstone in the sidetrack, ADA-003-ST1 than the main well. The LST terminates at 10,474 ft (3,192 m) in ADA-003 and 10,557 ft (3, 217 m) in ADA-003-ST1 where log signatures grades into retrogradational stacking pattern to indicate the start of the transgressive system tract. The TST is almost entirely composed of shale but for occasional occurrences of sandstone within the overall finning upward parasequence sets. The maximum flooding surface is interpreted to be at 9,722 ft (2,963 m) in ADA-003 and 10,269 ft (3,130 m) in ADA-003-ST1. This MFS is dated by Alabamina-2 (20.7 Ma). Aggradational stacking patterns continues on top of the MFS as the highstand systems tract. In both wells, shale is the dominant lithology in the HST, this together with the aggrading nature of the sedimentation indicate a slow and gradual fall in the sea level at the time of deposition of the sediments

(Posamentier, 2000). Sequence A in ADA-008 is made up of lowstand systems tract (LST), transgressive system tract (TST) and highstand system tract (HST). The lowstand system tract has a thin blocky base overlain by intercalations of shale with variable gamma ray API values. There are three major sand bodies that are separated by shale intervals with the thickest sand body located in the middle part of the systems tract. The sand is about 135 ft (41 m) thick. This systems tract is made up of both aggrdational and progradational stacking pattern, with the prograding clastic sediments being predominant. The transgressive surface is seen at 8,404 ft (2,561 m) being the beginning of the transgressive systems tract for the sequence. This sequence has a short TST interval that measures 116 ft (35 m) from 8,336 ft (2,540 m) to 8,220 ft (2,505 m). It is entirely made up of retrogradational fining upward parasequence sets. Very thin beds of sandstone are seen within the shale in this systems tract due to the dominant retrograding forces. The maximum flooding surface defined by Alabamina-2 is at 8,211 ft (2,502 m). The highstand systems tract is composed of both retrograding and aggrading stacking patterns. A few intercalations of sandstone seen within the systems tract means that there were occasions of coarse clastic sediment deposition within the systems tract (Neal et al., 1993). This stacking pattern continues until the next sequence.

Sequence B

While ADA-001 and ADA-001-ST2 lack well log data in both sequence B and sequence C, these sequences are well represented in ADA-001-ST3. Sequence B in ADA-001-ST3 starts at 10,210 ft (3,112 m) with a characteristic blocky log pattern. Retrogradational stacking patterns above the lowstand systems tract is indicative of the transgressive systems tract. The transgressive systems tract is bounded below by a downlap surface at 9,921 ft (3,024 m). Within the system tract, high gamma ray values are predominant and range between 74 API and 120 API. The suite of well logs for ADA-001-ST3 does not include the resistivity log.

The maximum flooding surface is interpreted to be at 9,611 ft (2,929 m), this coincides with the Chiloguembelina-3 maximum flooding surface. This maximum flooding surface marks the base of the highstand system tract for this sequence. The highstand systems tract is just about 30 m thick. It is likely that most of the highstand systems tract has been eroded before the deposition of the overlying lowstand systems tract of the next sequence. Sequence B in ADA-002 has the bounding surface at 8,741 ft (2,664 m) which is the Alabamina-2 maximum flooding surface as the lower boundary. This sequence consists of the highstand systems tract, lowstand systems tract and transgressive systems tract.

Log patterns for highstand systems tract are both retrogradational and aggradational. They are more aggradational than the overlying lowstand systems tract. During the deposition of the highstand systems tract, the rate of accommodation compared to sedimentation had started to reduce (Catuneanu, 2006) and this consequently gave rise to more deposition of coarse clastics in the lowstand systems tract. As water level began to rise, a transgressive surface was formed at 8,387 ft (2,556 m), the transgressive systems tract continued to build until the next maximum flooding surface at 7,974 ft (2,430.5 m) which is the upper bounding surface for sequence B and lower bounding surface for the last sequence as seen in this well. ADA-003 and ADA-003 ST1 have similar architectures in sequence B except that the sequence is longer in ADA-003 ST1 than ADA-003. The lowstand systems tract for both wells have minimal fauna occurrences while the transgressive systems tract have abundant fauna content culminating at the Chiloguembelina-3 MFS at 8,599 ft (2,621 m) in ADA-003 and 9,019 ft (2,749 m) in ADA-003 St1.

Sequence B in ADA-008 consists of the lowstand, transgressive and highstand systems tracts. Progradational stacking patterns in the lowstand systems tract gave way to retrogradational,

In ADA-002, Sequence A starts with the lowstand systems tract at about 9,124 ft (2,781 m) with serrated gamma ray log pattern, low fauna assemblages are recorded within this interval. Directly overlying the LST is the transgressive system tract for this sequence. Gamma ray log values range from 87 API to 124 API. The transgressive systems tract is capped by the Alabamina-2 maximum flooding surface at 8,741 ft (2,664 m). A short highstand systems tract of about 83 ft (25 m) starts from the MFS and ends at 8,677 ft (2,644.7 m).

In both ADA-003 and ADA-003-ST1, serrated log signatures with some occasional channel progradational stacking pattern indicative of channel type sedimentary facies are interpreted to indicate the lowstand systems tracts. This systems tract is predominantly made up of sandstone with some intercalations of shale in both wells, there are however more occurrences of sandstone in the sidetrack, ADA-003-ST1 than the main well. The LST terminates at 10,474 ft (3,192 m) in ADA-003 and 10,557 ft (3, 217 m) in ADA-003-ST1 where log signatures grades into retrogradational stacking pattern to indicate the start of the transgressive system tract. The TST is almost entirely composed of shale but for occasional occurrences of sandstone within the overall finning upward parasequence sets. The maximum flooding surface is interpreted to be at 9,722 ft (2,963 m) in ADA-003 and 10,269 ft (3,130 m) in ADA-003-ST1. This MFS is dated by Alabamina-2 (20.7 Ma). Aggradational stacking patterns continues on top of the MFS as the highstand systems tract. In both wells, shale is the dominant lithology in the HST, this together with the aggrading nature of the sedimentation indicate a slow and gradual fall in the sea level at the time of deposition of the sediments (Posamentier, 2000). Sequence A in ADA-008 is made up of lowstand systems tract (LST), transgressive system tract (TST) and highstand system tract (HST). The lowstand system tract has a thin blocky base overlain by intercalations of shale with variable gamma ray API values. There are three major sand bodies that are separated by shale intervals with the thickest sand body located in the middle part of the systems tract. The sand is about 135 ft (41 m) thick. This systems tract is made up of both aggrdational and progradational stacking pattern, with the prograding clastic sediments being predominant. The transgressive surface is seen at 8,404 ft (2,561 m) being the beginning of the transgressive systems tract for the sequence. This sequence has a short TST interval that measures 116 ft (35 m) from 8,336 ft (2,540 m) to 8,220 ft (2,505 m). It is entirely made up of retrogradational fining upward parasequence sets. Very thin beds of sandstone are seen within the shale in this systems tract due to the dominant retrograding forces. The maximum flooding surface defined by Alabamina-2 is at 8,211 ft (2,502 m). The highstand systems tract is composed of both retrograding and aggrading stacking patterns. A few intercalations of sandstone seen within the systems tract means that there were occasions of coarse clastic sediment deposition within the systems tract (Neal et al., 1993). This stacking pattern continues until the next sequence.

Sequence B

While ADA-001 and ADA-001-ST2 lack well log data in both sequence B and sequence C, these sequences are well represented in ADA-001-ST3. Sequence B in ADA-001-ST3 starts at 10,210 ft (3,112 m) with a characteristic blocky log pattern. Retrogradational stacking patterns above the lowstand systems tract is indicative of the transgressive systems tract. The transgressive systems tract is bounded below by a downlap surface at 9,921 ft (3,024 m). Within the system tract, high gamma ray values are predominant and range between 74 API and 120 API. The suite of well logs for ADA-001-ST3 does not include the resistivity log.

The maximum flooding surface is interpreted to be at 9,611 ft (2,929 m), this coincides with the Chiloguembelina-3 maximum flooding surface. This maximum flooding surface marks the base of the highstand system tract for this sequence. The highstand systems tract is just about 30 m thick. It is likely that most of the highstand systems tract has been eroded before the deposition of the overlying lowstand systems tract of the next sequence. Sequence B in ADA-002 has the bounding surface at 8,741 ft (2,664 m) which is the Alabamina-2 maximum flooding surface as the lower boundary. This sequence consists of the highstand systems tract, lowstand systems tract and transgressive systems tract.

Log patterns for highstand systems tract are both retrogradational and aggradational. They are more aggradational than the overlying lowstand systems tract. During the deposition of the highstand systems tract, the rate of accommodation compared to sedimentation had started to reduce (Catuneanu, 2006) and this consequently gave rise to more deposition of coarse clastics in the lowstand systems tract. As water level began to rise, a transgressive surface was formed at 8,387 ft (2,556 m), the transgressive systems tract continued to build until the next maximum flooding surface at 7,974 ft (2,430.5 m) which is the upper bounding surface for sequence B and lower bounding surface for the last sequence as seen in this well.

ADA-003 and ADA-003 ST1 have similar architectures in sequence B except that the sequence is longer in ADA-003 ST1 than ADA-003. The lowstand systems tract for both wells have minimal fauna occurrences while the transgressive systems tract have abundant fauna content culminating at the *Chiloguembelina-3* MFS at 8,599 ft (2,621 m) in ADA-003 and 9,019 ft (2,749 m) in ADA-003 ST1.

Sequence B in ADA-008 consists of the lowstand, transgressive and highstand systems tracts. Progradational stacking patterns in the lowstand systems tract gave way to retrogradational, W

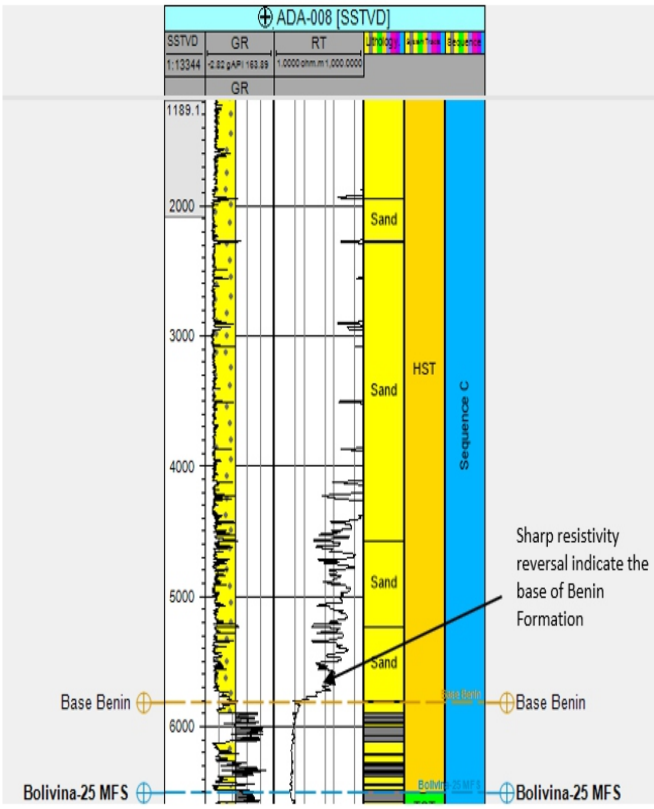

Figure 11: ADA-008 Showing the Sharp Resistivity Reversal Indicating the Base of Benin Formation.

Depositional Environment

Biostratigraphic data show the presence of Alabamina-2, Chiloguembelina-3 and Bolivina-25 and other forms which are characteristic of the Niger Delta. These marker species (Reijers, 2011; Fowora, 2017) were used to name the maximum flooding surfaces.

In addition, well log patterns were also studied in conjunction with biostratigrpahic data to determine the environment of deposition. Different patterns of Ada well log motifs and their possible depositional environments are shown in Figures 12 to 16 below. Gamma ray logs are not only useful for differentiating lithologies, their log motifs or patterns are also helpful in inferring environments of deposition (Nwagwu *et al.,* 2019). It is however important to note that log patterns were not solely relied on for the interpretation of environment of deposition, interpretations from log motifs were compared with results from biostratigraphic data analysis to confirm depositional environment. Since similar log motifs can be seen in different depositional settings (Kendall, 2005, Mene and Okengwu, 2020), it is necessary to use additional tools for a determinative depositional environment interpretation (Rider, 1986). Table 2 shows the integration of available data set and interpreted depositional environment. The clastic successions within the Ada field were interpreted to be deposited within shallow water, inner to outer neritic environment of deposition (Figure 17).

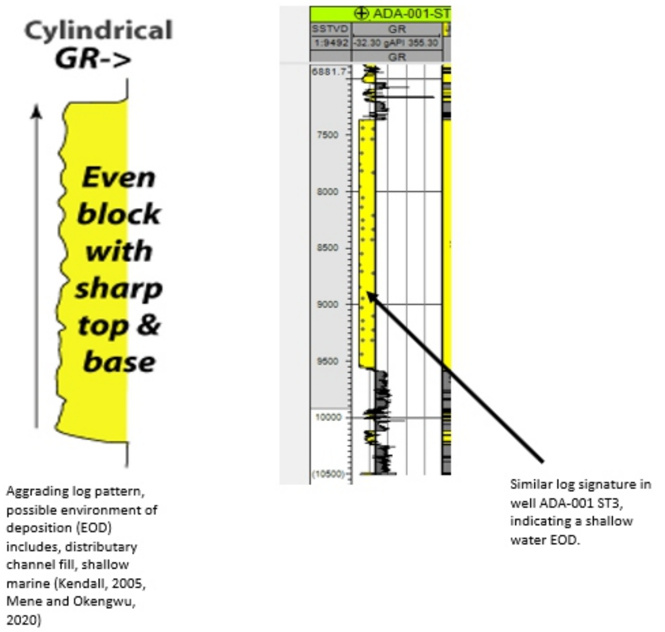

Figure 12: Blocky Log Signature in ADA-001 ST3 Indicating a Possible Shallow Water Environment of Deposition.

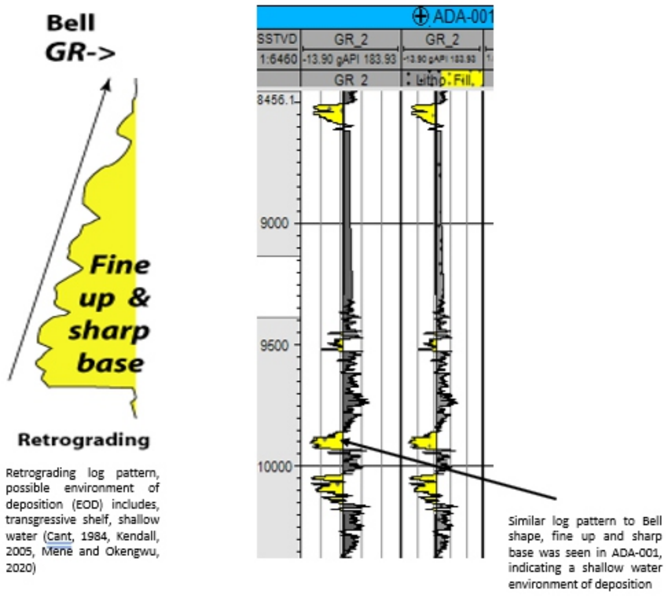

Figure 13: Fine up and Sharp Base Log Motif Seen in ADA-001 Well Signifying a Transgressive Shelf, Shallow Water EOD.

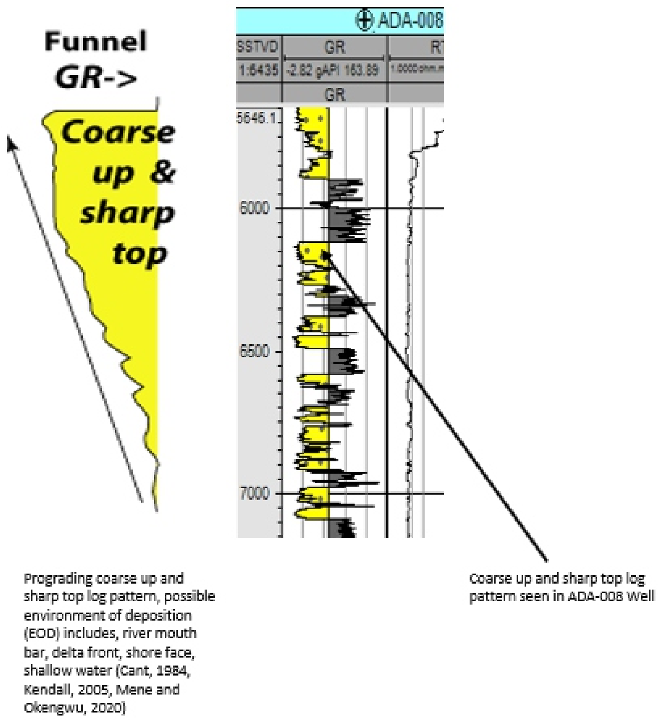

Figure 14: Coarse Up and Sharp Top Log Pattern Seen in ADA-008 Well Signifying a Shore face, Shallow Marine EOD.

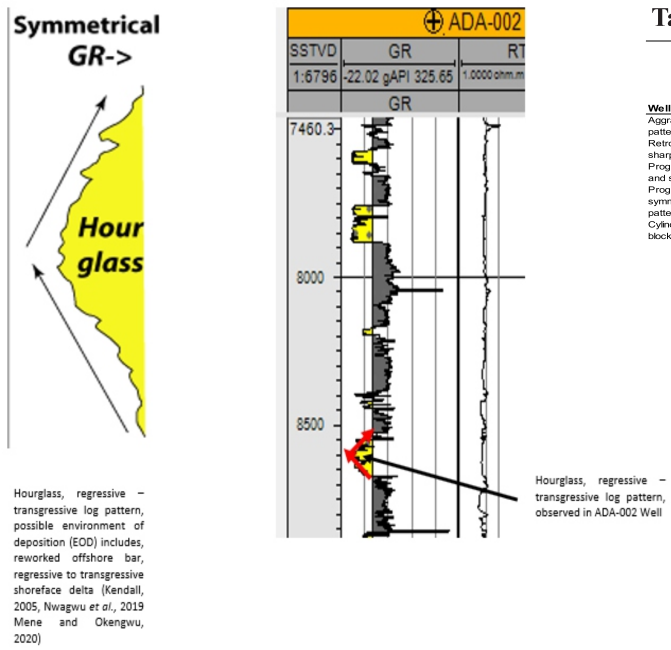

Figure 15: ADA-002 Well Showing Log Pattern Indicating a Regressive-Transgressive Shoreface Delta Depositional Environment.

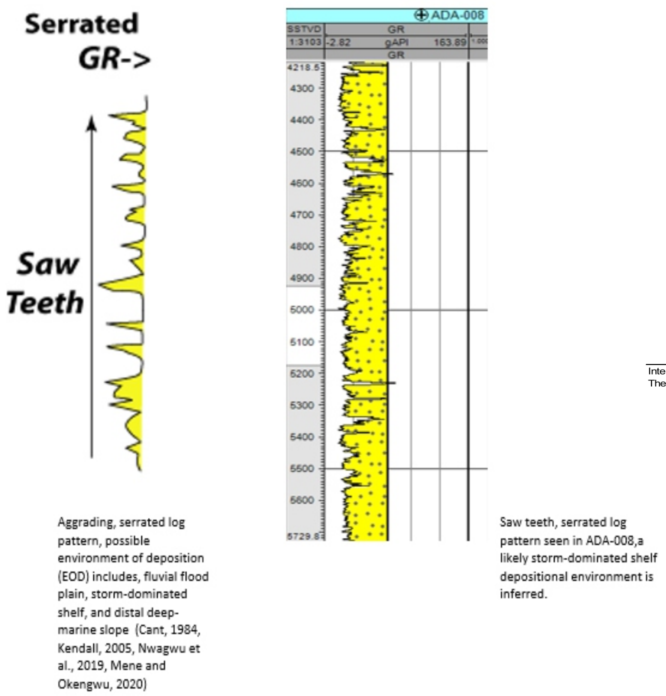

Figure 16: ADA-008 Well Showing Log Pattern Signifying a Probable Storm-dominated Shelf Depositional Environment.

Table 2: Ada Field Environment of Deposition.

Well Log		Biostratigraphic data		
Well log Patterns	**Inferred Depostional Environment (Cant, 1984; Kendall, 2003; Magbagbeola a Willis, 2007; Mene and Okengwu, 2020)**	**Depth**	**Species**	**Depostional Environment Giwa 2004; Reijers, 2011; Okosun, 2012, Anifowose, 2018**
Aggrading, serrated, saw teetl pattern.	Fluvial flood plain, storm-dominated shelf, and distal deep-marine slope	6100	*Bolivina 25*	Inner Neritic to Middle Neritic
Retrograding, bell, fine up and sharp base log pattern	Transgressive shelf, Shallow water		*Globigerina spp.*	Shallow water
Prograding, funnel, coarse up and sharp top log pattern.	River mouth bar, delta front, shore face, shallow marine.		*Nonion 4*	Outer Neritic
Prograding and retrograding, symmetrical, hourglass log pattern,	Reworked offshore bar, regressive transgressive shoreface delta		*Valvulineria 1a*	Shallow water
Cylindrical, aggrading log, even block with sharp top and base	Distributary channel fill, Shallow marine		*Cassidulina norcrossi*	Shallow water
			Eponides 1a	Shallow water
			Textularia 11	Inner Neritic
			Uvigerina sparsicostata	Middle Neritic to Outer Neritic
		6730	*Globigerina 41*	Shallow water
			Valvulineria 1a	Inner Neritic water
			Chiloguembelina 3	Shallow water
			Spiroloculina 2	Inner Neritic water
		8380	*Rotalia 1a*	Shallow water
			Globigerinoides 1	Shallow water
			Echinoid remains	Shallow water
			Bolivina 26	Inner to outer Neritic
			Cassigerinella 1	Inner Neritic water
			Globigerina 20	Shallow water
			Globigerina 41	Shallow water
		8440	*Haplophragmoides spp.*	Shallow water
			Nonion 6	Shallow water
			Uvigerina 6	Inner Neritic water
			Cassidulina norcrossi	Shallow water
			Globigerinoides 1	Shallow water
			Echinoid remains	Shallow water
			Bolivina 26	Inner Neritic water
			Cassigerinella 1	Inner Neritic water
			Globigerina 20	Shallow water
			Alabammina 2	Shallow water
			Globigerina 41	Shallow water
		8770	*Haplophragmoides spp.*	Shallow water
			Globigerina spp.	Shallow water
			Rotalia 1a	Shallow water
		9000	*Haplophragmoides spp.*	Shallow water
			Globigerina spp.	Shallow water
			Bolivina 29	Shallow water
			Nonion 4	Outer Neritic
			Uvigerina sparsicostata	Middle Neritic to Outer Neritic
			Bolivina 26	Middle Neritic to Outer Neritic
			Globigerina 41	Shallow water
			Nonion spp.	Shallow water
		9400	*Globigerina spp.*	Shallow water
			Rotalia 1a	Shallow water
			Bolivina 29	Inner Neritic water
			Uvigerina sparsicostata	Middle Neritic to Outer Neritic
			Nonion spp.	Inner Neritic water
			Textularia 3	Shallow water
		9680	*Haplophragmoides spp.*	Shallow water
			Globigerina spp.	Shallow water
			Bolivina spp.	Shallow water
			Gastropoda .	Shallow water
			Uvigerina spp.	Shallow water
			Eponides 1a	Inner Neritic to Middle Neritic
			Quinqueloculina spp.	Inner Neritic
			Globigerina 41	Shallow water
			Textularia 3	Shallow water
		10060	*Haplophragmoides spp.*	Shallow water
			Bolivina spp.	Shallow water
			Rotalia 1a	Shallow water
			Cassidulina norcrossi	Shallow water
			Uvigerina spp.	Shallow water
			Eponides 1a	Inner Neritic water
			Uvigerina sparsicostata	Shallow water
			Quinqueloculina spp.	Inner Neritic
			Textularia spp.	Inner Neritic water
			Bolivina 26	Shallow water
			Globigerina 41	Shallow water
			Textularia 3	Shallow water
			Alabammina 2	Shallow water
		10840	*Haplophragmoides spp.*	Shallow water
			Globigerina spp.	Shallow water
			Bolivina 29	Shallow water
			Textularia 11	Shallow water
			Uvigerina sparsicostata	Middle Neritic to Outer Neritic
			Textularia 3	Shallow water
			Lenticulina grandis	Inner Neritic to Middle Neritic
			Bolivina spp.	Shallow water
			Cassidulina norcrossi	Shallow water
			Uvigerina spp.	Shallow water
			Eponides 1a	Inner Neritic to Outer Neritic
			Echinoid remains	Shallow water
			Quinqueloculina spp.	Shallow water
			Bolivina 26	Shallow water
			Cassigerinella 1	Shallow water

Interpreted Environment of Depostion
The clastic successions within the Ada field were interpreted to be deposited within shallow water, inner to outer neritic environment of deposition

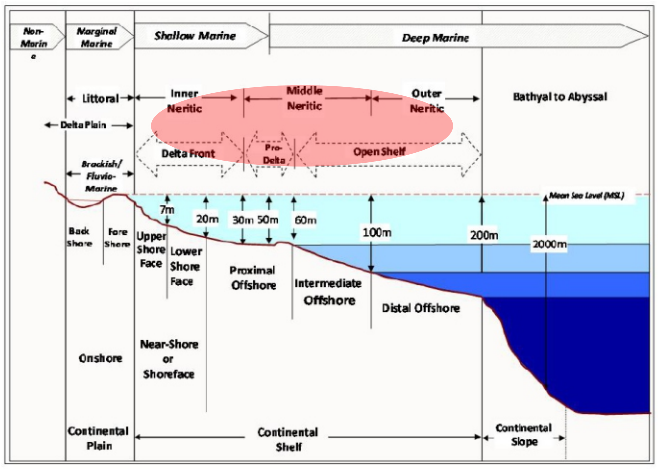

Figure 17: Depositional Environments and Bathymetric Ranges Used in Paleoenvironmental Interpretations (Modified After Allen, 1965 and Okosun *et al.,* 2012)

Ada Field environment of deposition was interpreted to be inner neritic to outer neritic, delta front, prodelta and open shelf (Highlighted with red oval)

CONCLUSION

Well log patterns, shapes and motifs have been used to infer depositional environments of the clastic successions in Ada Field, Central Niger Delta, Nigeria.

Sequence stratigraphy of Ada field contained three sequences, namely sequence A, B and C respectively. It is not all the sequences that contained the traditional lowstand systems tract, transgressive systems tract and highstand systems tract. This may be due to erosional truncations and periods of non-deposition of sediments.

A careful observation and study of the various stacking patterns helped to determine the different parasequences and parasequence sets within each sequence. These include progradational, retrogradational and aggradational parasequences with their separate coarsening up and finning up lithologic successions.

From the different stacking patterns of parasequences and parasequence sets, a range of environment of deposition including distributary channel, crevasses splay, delta front, prodelta, shoreface, fluvial point bar, tidal channel fill, fluvial flood plain and distal deep marine slope were inferred.

The presence of benthic species like *Alabammina-2, Bolivina sp, Cassigerinella-1, Chiloguembelina-3, Globigerina 41, Nonion-4, Uvigerina-5* in the field indicate that the clastic successions are delta front, prodelta and open shelf deposits in inner neritic to outer neritic environment of deposition.

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