Current Research in Geoscience

Original Research Paper

Reconstruction of the Depositional Setting of Tortonian Sediments in the Yowi Field, Shallow Offshore Niger Delta, Using Wireline Logs

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Article history
Received: 26-05-2015
Revised: 04-02-2016
Accepted: 06-02-2016

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Abstract: Well logs and ditch-cuttings information was used to study the subsurface of the Yowi oilfields, shallow offshore, in the eastern Niger Delta sedimentary basin. The essence of the study was to determine the gross depositional environments of selected and-bodies. Electrofacies trends from gamma ray log and mineral composition of ditch-cutting samples were used to reconstruct the depositional environments in the study area. A total of eleven (8) relatively thick sandstones reservoirs penetrated by five representative wells (A9, A12, A6, A4 and A2) occurred within the paralic Agbada sequence in the field. Seven log facies associations deduced from log trends revealed three major environments resulting from fluvial, marine and marginal marine processes. A coarsening upward log motif is interpreted to be deposits resulting from progradation, whereas fining upward trends are transgressive deposits. The presence of glauconite in all the wells in the field from about 1800ft down hole within the Agbada Formation shows that the environments were influenced by marine processes than continental. A predominantly marine, deltaic sequence strongly influenced by clastic output from the delta is inferred for the Yowi Field. Water depths fluctuated considerably and deposition occurred within a variety of littoral and neritic environments ranging from near shore barrier sand complexes to fully marine, outer shelf mudstones. An overall shallowing trend is observed on well log towards the base of the Qua Iboe Shale Member. The upper part of the well between the intervals of 2000 and 2450ft appears to have been deposited in a marginal marine setting. Below this depth down to about 5000ft may indicate relatively shallow marine conditions with normal salinities, well oxygenated bottom waters and periodic access to open marine conditions. Interval above 1800ft is the overlying continental Benin Formation. The associated environments based on log shapes and the presence of glauconite within the studied interval include; offshore/regressive bars, barrier foot, beach and shore face deposits.

Keywords: Electrofacies, Depositional Environments, Agbada Formation, Qua Iboe Shale, Facies

Introduction

Reconstruction of the depositional history of any ancient siliciclastic unit involves determining the dominant sediment dispersal process and the depositional development of the unit in time and space (Amajor and Agbaire, 1989). Different sedimentary units show facies geometries that reflect processes that deposited them. The recognition and understanding of both the processes and their responses is a key factor in the study of sedimentary geology. Consequently, various tools and methods have been used in the reconstruction of depositional environments. Friedman (1967), used grain size characteristics; Davis and Ethridge (1975) used sandstone composition; spontaneous potential and gamma-ray log shape was used by (Galloway, 1968;

DOI: 10.3844/ajgsp.2016.24.35

1989; Krueger, 1968; Pirson, 1970; Selley, 1985; Amajor and Agbaire, 1989). The work of Selley (1978; 1985; Amajor and Agbaire, 1989) identified and interpreted depositional environments based on wireline (gamma-ray) log shapes and aspects of sandstone composition (glauconite, carbonaceous detritus). This study will basically use well logs (gamma ray) and ditch-cutting information to reconstruct the depositional environments of sand-bodies in the Yowi field.

The Niger Delta formations according to Schlumberger (1985), are composed of unconsolidated sands, in which it is often not possible to take cores or to make drill stem tests. However, subsurface investigations are mostly based on logs, with the help of sidewall samples, ditch cuttings and wireline formation tests. Well logs provide essential information and interpretation of the subsurface geology of the area penetrated by boreholes. It provides information on lithology, stratigraphy, structures, reservoir quality, temperature, etc. These information are useful in both regional and local studies of sedimentary basins.

Regional Geologic Setting

The Nigerian pericratonic basin was formed by rift faulting of the Pre-Cambrian (Doust and Omatsola, 1989). The outlines of the Niger Delta are controlled by deep-seated faults along the Benin and Calabar hinge lines. These are structural boundaries delimiting the basin on both the western and eastern parts of the delta. In the south, it is bounded by shale ridges. At least three major sedimentary cycles have been deposited in the basin since early Cretaceous times (Reijers, 2011). The delta started growing during the second cycle between Campanian and Paleocene transgressions. The third sedimentary cycle that occurred during the Paleocene accounted for the formation of the Niger Delta. The deltaic sequence consists essentially of clayey marine sediments overlain by paralic sediments, i.e., mixed continental, brackish water and marine deposits, which are covered by continental sands and gravels. In cross section a time stratigraphic unit of such deltaic sediments is characteristically S-shaped (Merki, 1972).

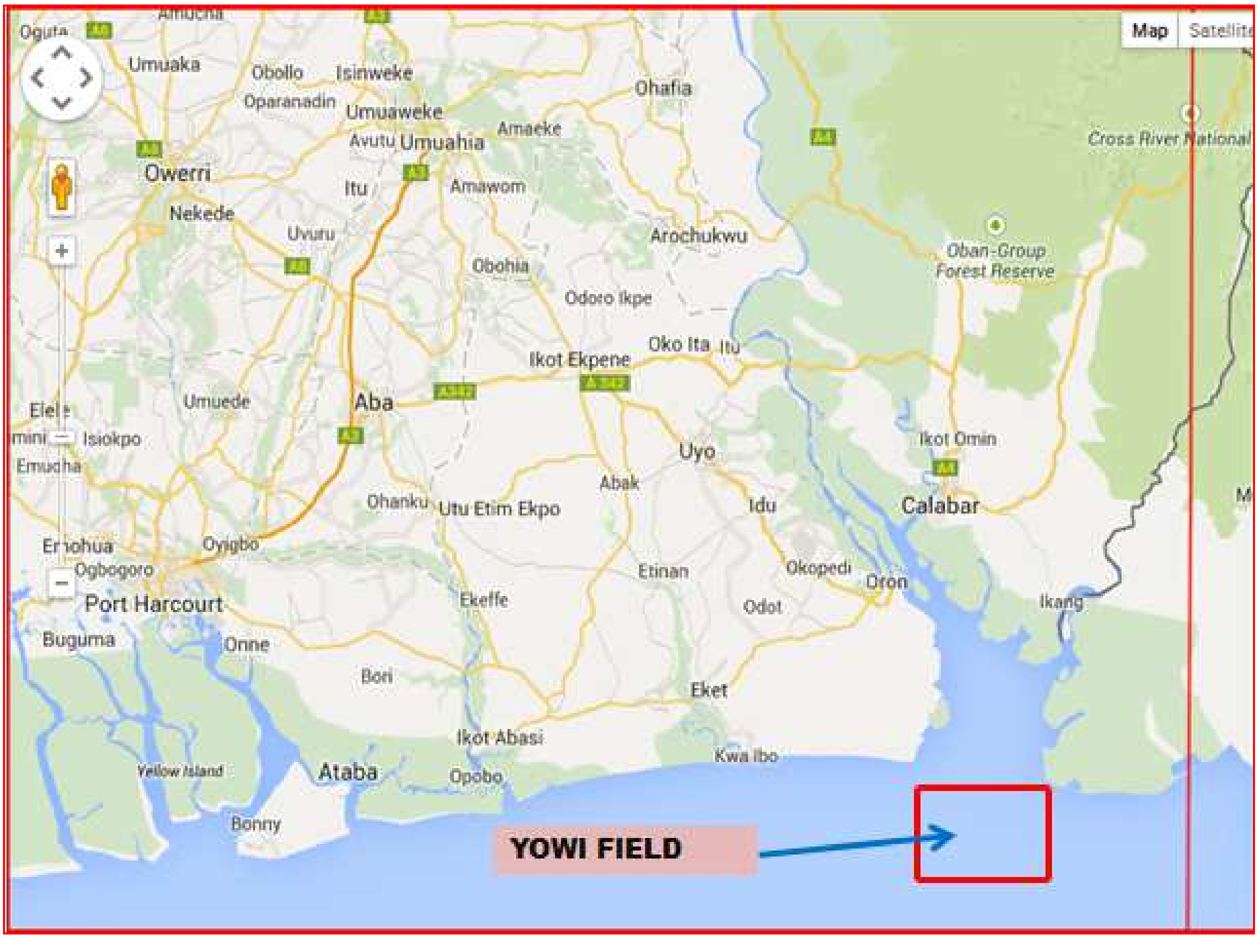

Fig. 1. Map Showing the Study Area (Yowi Field)

Generally, sediments belonging to the Benin Formation represent the subaerially exposed part of the delta. The main prospective interval, the Agbada Formation is a regressive offlap succession that formed under shallow-marine conditions in active depobelts of the delta where subsidence rates were 500-1000 m/Ma (Reijers, 2011). Such depositional rates occasionally resulted in gravity-induced mass transport over the over-pressured Akata shales and as a result triggered large-scale flows of the over pressured shales that became squeezed out, such as also reported from the offshore by (Owoyemi and Willis, 2006; Magbagbeoloa and Willis, 2007). These units form the backbone for the analysis of the cyclicity and the genetic sequences (Reijers**,** 2011).

Four sedimentary units make up the Agbada Formation in the eastern Niger Delta. They are; D-1 sand Member, the Qua Iboe Shale Member (QISM), the Rubble Beds and the Biafra Member. The D-1 sand and the Rubble beds have not been encountered in Yowi oilfield. The thickness of Agbada is about 7000ft in wells A2P2 and A6P1 (two deep wells in the field). The QISM occurs between 1850 and 2000ft in most of the wells and is identified on well log as the first continuous shale with a sharp drop in resistivity showing a transition from fresh water to brackish water zone. The QISM represents an outer shelf and slope member of the Agbada Formation and mainly comprises of shales and slope channel sandstones (Bruso *et al*., 2004). The thickness of the QISM increases progressively seaward from the continental shelf (about 22ft water depth in Yowi field) in Nigeria, up to the deepwater Equatorial Guinea, where it houses turbidite sandstones of the Isongo Formation. The top and base of the QISM are believed to be unconformable.

Study Location

The Yowi field lies within the shallow offshore depobelt in the eastern Niger Delta sedimentary basin (Fig. 1). It is located between latitude 4°38'-4°32'N and longitude 8°18' and 8°35'E, about 30 km from the Cameroon border. The field covers an area extent of approximately 229sq.km (seismic coverage). The field straddles between two fields located in different fault blocks north and south of Yowi oilfield.

Methodology and Dataset

The well logs ASCII was loaded into version 2010 PETREL software and used to generate well log plots. Standard electrofacies was used majorly to infer gross depositional environments of the sand-bodies based on gamma ray log trends. Intervals with high gamma ray values beyond 75°API show a shalier or very fine grained pelitic sedimentary rocks. The sandy intervals have low gamma ray values below 75°API.

Well log data provided for five representative wells (Fig. 2) include Gamma Ray log. Ditch-cutting information complemented well log interpretation. The five representative wells (A9P2, A9P3, A6P1, A2P2 and A8P1) cut across the field from East to West. The various wells and their respective locations were chosen for good geologic control and to establish the lateral continuity of the delineated environments. Wells A9P2 and A9P3 occur on the western flank of the field, well A6P1 is midway between the east and west, whereas wells A2P2 and A8P1 occurred on the eastern flank (Fig. 2).

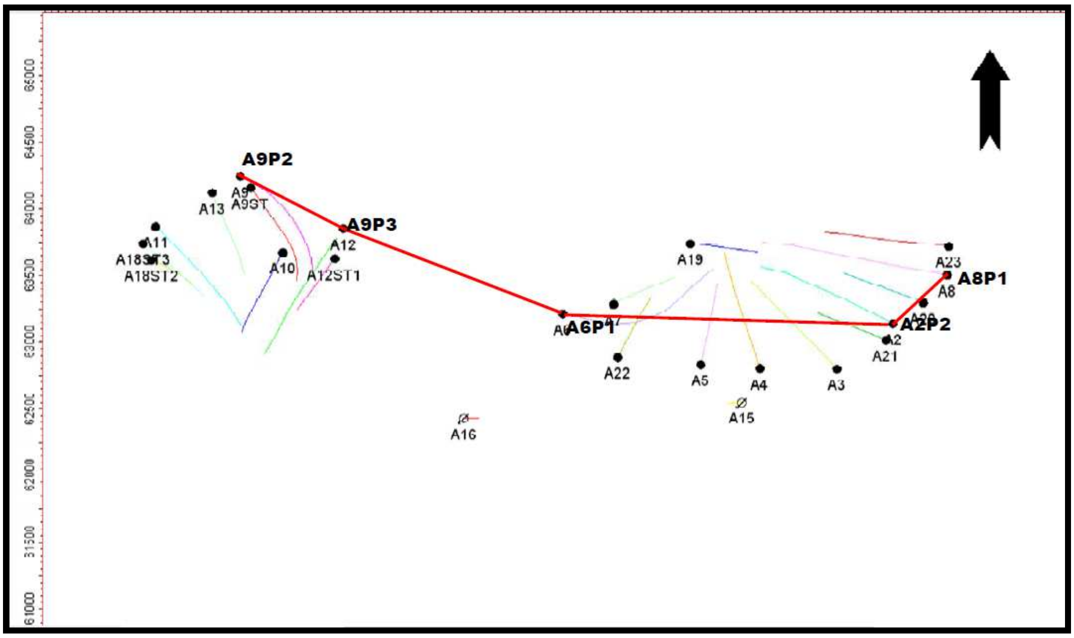

Fig. 2. Well Location Map showing the Line of Section (East to West) across studied wells (A9P2, A9P3, A6P1, A2P2, A8P1) in the Field

Results

Five representative wells correlated across the field show good lateral continuity of key horizons (Fig. 3). The selection of the wells at various points was to enhance good geologic control and establish the lateral continuity of the delineated environments. Wells A9P2 and A9P3 occur on the western flank of the field, well A6P1 is midway between the east and west, whereas wells A2P2 and A8P1 occurred on the eastern flank. The east and west are separated by a distance of approximately 7 km. The eastern part of the field shows a higher sand development compared to the western part containing thicker shales (Fig. 3).

Table 1 gives a lithologic description of the ditch-cutting samples of key sand horizons. A significant aspect of the lithologic description is the presence of glauconite that has environmental significance. This mineral consistently occurred abundantly in all the sections of the well from below the Qua Iboe Shale Member (QISM) down to the total depth of the wells across the field. The QISM is the first marine shale capping the paralic Agbada Formation. Traces of pyrite suggest a reducing environment corroborating a deposition of sediments within the marine realm with the presence of glauconite. Carbonaceous detritus and the presence of mica indicate the proximity of provenance and that the sediments were derived from the continent.

Description of Gamma Ray Log Facies

Studies of modern sedimentary environments (Selley 1985; Amajor and Agbaire, 1989; Chow *et al*., 2005) revealed that vertical profiles of grain size from a specific environment have certain characteristics. For instance, prograding deltas and barrier bars deposit display an upward-coarsening grain size profiles (Fig. 4). Three prominent trends identified on well log that helped to delineate the various depositional settings are: coarsening upward trend representing deltaic facies (N4, N5 and N6 reservoirs in Fig. 4); fining upward trend showing transgressive facies; boxcar gamma ray log motif of regressive barrier bar/beach deposits (Fig. 6 and 7). Each sand body tend to be laterally continuous across the field (Fig. 3), a typical feature of beach, barrier and shore face depositional profile.

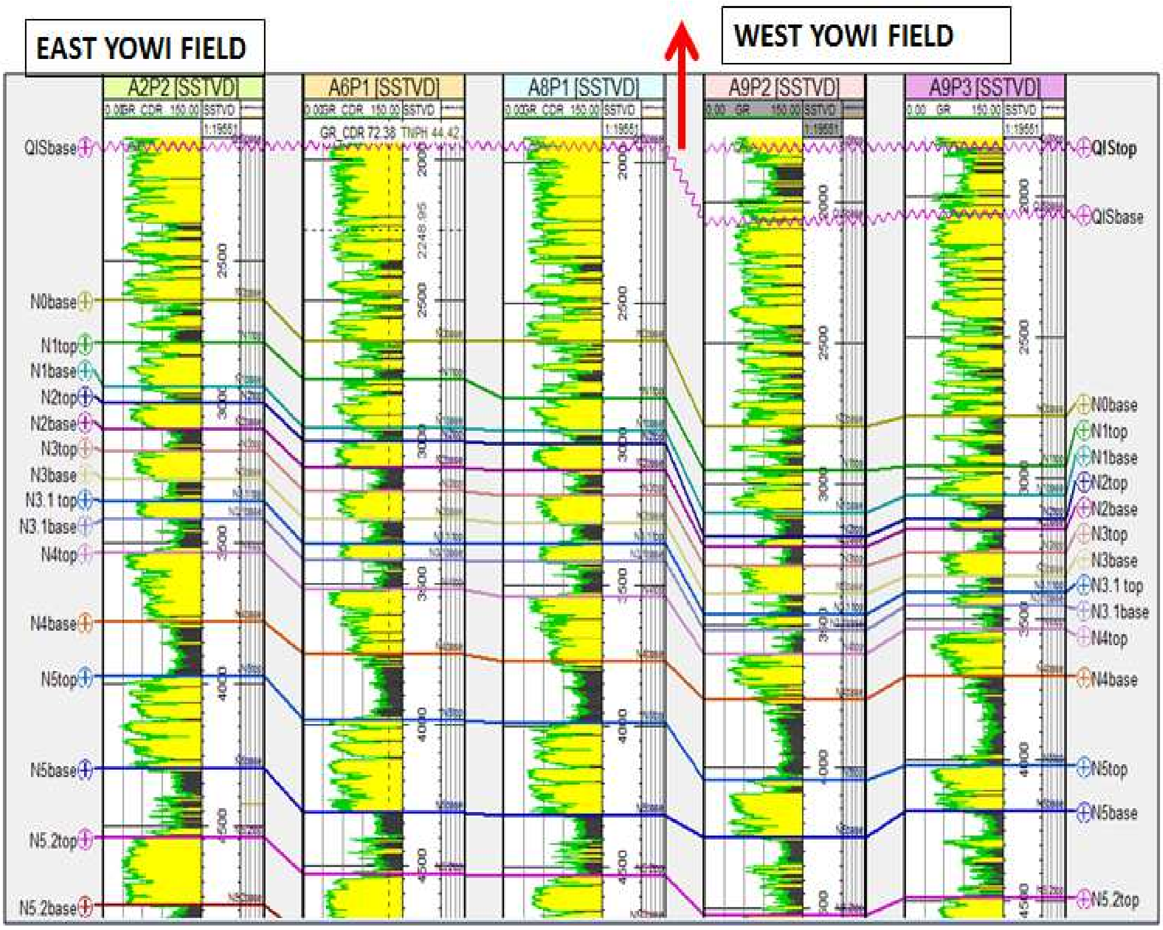

Fig. 3. Litho-correlation for five representative wells across the Field

DOI: 10.3844/ajgsp.2016.24.35

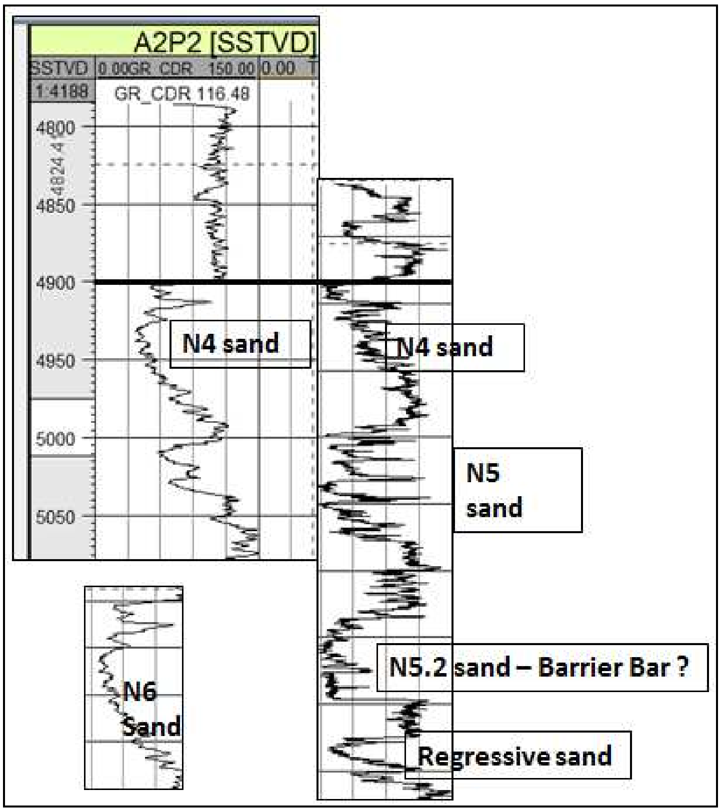

Fig. 4. Gamma Ray Log Trends of Reservoirs indicating certain environments (N4 and N6 are regressive bars; N5 shows stacked regressive units; N5.2 Barrier bar?)

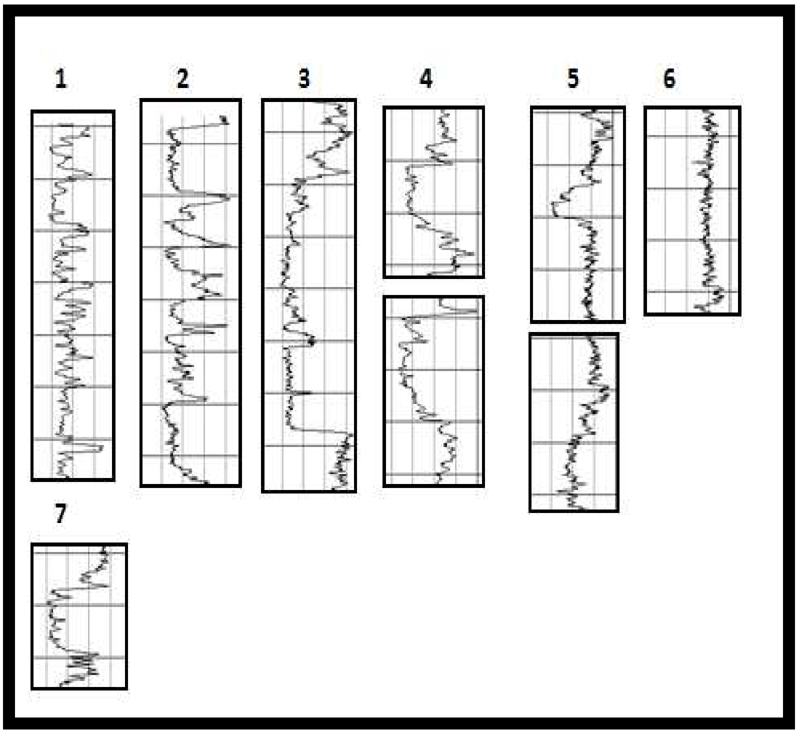

Fig. 5. Gamma ray log motifs in association

The thick shale segments within each sequence are interpreted to be shelf or deep marine deposits. A combination of log trends is grouped to interpret association of facies.

Well Log Facies Association

Seven main gamma-ray facies associations (Fig. 5) were established using gamma-ray log stacking patterns (1) spiky or mixed, (2) blocky and coarsening-upward (3) blocky and fining-upward (4) coarsening upward (5) fining upward (6) erratic and (7) blocky. The log facies descriptions below have been grouped into facies associations that are genetically related. This will be used to infer depositional environments in the field. These associations of facies form the primary basis of inferring the depositional setting under which the sediments were deposited and preserved. The gamma-ray facies associations represent environments that range from deltaic front to shallow marine in the Yowi field.

Facies Association 1

This facies is characterized by spiky or mixed gamma ray log signature, which may represent middle or lower deltaic plain environment (Fig. 5).

Facies Association 2

This facies consists of both a blocky pattern in association with a coarsening-upward trend. It may represent amalgamated fluvial or estuarine channels resulting from seaward progradation of continental sediments (Fig. 5).

Facies Association 3

This contains a blocky unit at the base with a fining upward trend typical of fluvial channel, distributary channel or a fluvial or tidally influenced delta.

Facies Association 4

This unit displays a spiky and coarsening upward trend that represents a prograding deltaic deposit. This could be shoreface deposit, mouth bar or tidal bar. According to the methods reported in Selley (1998), the environments of coarsening upward successions can be put into three general categories: (1) regressive barrier bars, (2) prograding submarine fans, (3) prograding deltas or crevasse splays.

The first two environments, regressive barrier bars and prograding submarine fans are commonly deposited with glauconite and shell debris (Selley, 1985; 1998; Nelson and James, 2000). There is glauconite debris present in the samples, therefore, there is the possibility of the first two environments (regressive barrier bars or prograding submarine fans) and we can infer that the paleoenvironments of the funnel shape facies in Yowi Field belongs to regressive barrier bar sand (Fig. 4). However, one of the main differences between a prograding delta and a crevasse splay is the deposition scale; the prograding delta is comparatively large. According to the identification system of Selley (1985; 1998), the paleoenvironment of funnel-shaped successions with carbonaceous detritus can be identified as a prograding delta or a crevasse splay. The thickness of all of the thin funnel-shaped successions is less than 8 meters, which allow us to narrow down the identification of the paleoenvironment to a crevasse splay of a deltaic channel. Less than eight meters seems too thin to be of a prograding delta.

Facies Association 5

The characteristic of this unit displays a sharp lower contact with a gradational top. It is a transgressive unit. The bell shaped succession usually occurs in three types of environments: Tidal channels, turbidite fills and fluvial or deltaic channels. Tidal channels and turbidite fills also commonly include glauconite and shell debris (Nelson and James, 2000). The only bell shaped successions with carbonaceous detritus are deposited in environments of fluvial or deltaic channels (Selley, 1985).

Facies Association 6

This is erratic in nature. It may represent a lower deltaic plain to shallow marine shelf deposits.

Facies Association 7

Log facies of this unit has sharp upper and lower contact (blocky). The thickness of the boxcar motifs in all the studied intervals is less than 25 m. Mudlog report shows that the lithologies of these sections are mostly sandstones (off white to creamy white, grey in part, translucent to transparent, very fine to fine, occasionally medium grained, sub-rounded to rounded, sub-spherical, primarily calcareous cement, argillaceous in part poorly to moderately sorted) (Table 1). In the Yowi field, the boxcar shaped gamma-ray log reoccurred in all the wells with average thickness of 58ft in well A2P2 between the intervals of 3357-3412, 5286-5344, 5750-5813, 6047-6110 and 6848-6903ft. Carbonaceous matter, mica and glauconitic materials are also present in the successions (Table 1).

The boxcar shaped gamma-ray log (unit E in Fig. 6 and 7) indicates the truncation or rapid termination of deposition at the upper and bottom boundaries. Three general categories of environments can deposit boxcar-shaped successions (Selley, 1985; 1998). These three environments are tidal sand wave, grain flow fill and delta distributary channel. The first two environments, tidal sand wave and grain flow fill commonly deposit with glauconite and shell debris (Nelson and James, 2000). Only the delta distributary channel associates with carbonaceous detritus. Therefore, the boxcar gamma ray log motif with carbonaceous detritus indicates a deltaic distributary channel, according to the well log identification system of Selley (1985; 1998).

DOI: 10.3844/ajgsp.2016.24.35

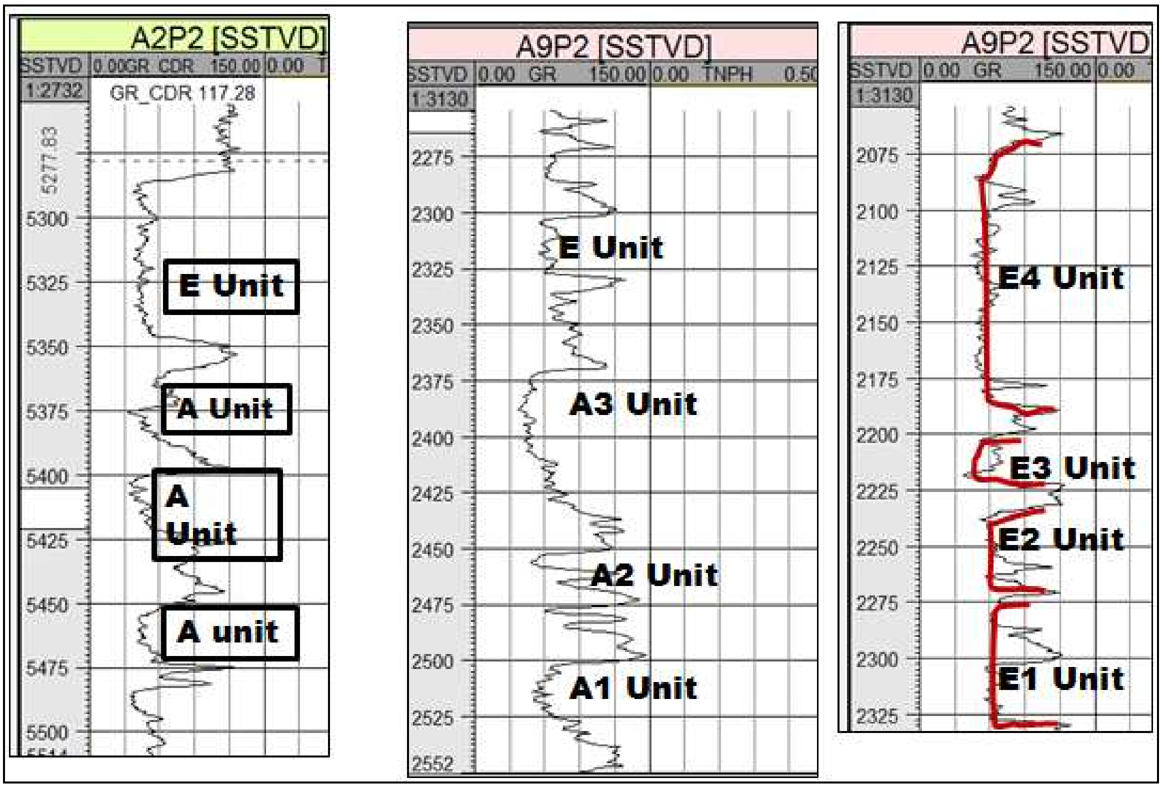

Fig. 6. Representative Units for environments (AUNITS: Sharp upper boundary with gradational base-Stacked Coastal Barriers-funnel shape; E UNIT: The E Unit shows a blocky/cylindrical shape with minor serration. These units display a stacked/amalgamated channel system)

Table 1. Ditch-cuttings description of reservoirs

Reservoirs	Core description	Remark
5018-5021	**Sandstone:** Light to medium brown, friable, clear, translucent, light brown, quartz grains, very fine, slightly silty, sub rounded to rounded, well sorted, glauconitic, carbonaceous speckles, micaceous, good porosity and permeability. Oil Shows: Very light brown oil stain, very dull yellow fluorescence, weak diffuse white cut fluorescence, no residue, faint Hydrocarbon odour.	Regressive Bar
5027-5033	**Silty Sandstone:** Light to medium grey brown, friable, clear, translucent, opaque, quartz grains, very fine, silty in part, with thin Siltstone laminae, sub rounded to rounded, well sorted, micaceous, glauconitic, carbonaceous speckles, traces of pyrite, moderate to good porosity and permeability. Oil Shows: Very light brown oil stain, moderate yellow white fluorescence, slow streaming to weak diffuse white cut fluorescence, no residue, faint Hydrocarbon odour.	Lower part of a regressive bar
5042-5045 (N5.2 Reservoir) Well A2P2	**Sandstone:** Medium to dark brown oil saturated sandstone, clear, translucent, medium brown, friable to loose quartz grains, very fine to fine, predominantly very fine, sub rounded to rounded, very well sorted, excellent porosity and permeability, micaceous, trace glauconite, trace carbonaceous speckles. Oil Shows: Medium brown oil stain, intense bright yellow fluorescence, instant blooming milky white cut fluorescence, light brown residue. Very strong Hydrocarbon odour.	Top N5.2 sand-A Regressive bar

A distributary channel is an irregular, divergent stream flowing away from the main stream in a delta. Distributary channels are often choked by stream deposition and produce new distributary channels. This is the reason for the formation of a boxcar log motif for distributary channels.

Discussion

Depositional Settings and Sedimentology

The major lithologic tools used here to identify the various lithostratigraphic units in the field are well log (gamma ray log) and drill-cutting samples description.

DOI: 10.3844/ajgsp.2016.24.35

Core and ditch cutting sample description are very diagnostic on lithology types and define the depositional settings of only certain stratigraphic intervals used to calibrate the well log. Three sections have been identified in the field base on gamma ray log expressions: The section above 1800ft showing erratic and jagged gamma ray log motif, which is the Benin Formation. The Benin sand is not affected by the growth fault and shows continuous parallel seismic reflection pattern. Underlying the Benin sand is the first thick continuous shale of approximately 150ft thick that cuts across the field, the Qua Iboe Shale Member (QISM); and the last section on the well log displays repeated alternations of sand and shales from the base of the QISM to about 8950ft in well A2P2. This is the Agbada Formation.

Well Log Expression of Fluvial-Related Environments

The well log attribute of the continental fluvial environment of the Benin Group shows a jagged log motif, a typical characteristic of siliciclastic fluvial environment. It occurred above the base of Qua Iboe Shale Member (QISM) at 1850ft. A variety of subenvironments within this setting include; channel fills, flood plain, braided stream, meandering channels, point-bar, etc. For example, typical sand beds indicating the meandering fluvial systems consist of an alternation of fining-upward (Fig. 5-7) channel fills and mud dominated floodplain deposits. Braided fluvial systems are often composed of amalgamated channel fills, which confer a blocky pattern to the well logs; in contrast, other types of rivers, including fine-grained meandering or flashy ephemeral, produce a more irregular, jagged type of motif on well logs (Fig. 6). Relatively thin (± meter scale) coarsening-upward trends may also be observed in fluvial successions in relation to crevasse splays, especially in low-energy and confined meandering-type rivers (Catuneanu, 2006). The ditch cutting description for the sandy section shows sand dominated by Quartz grains.

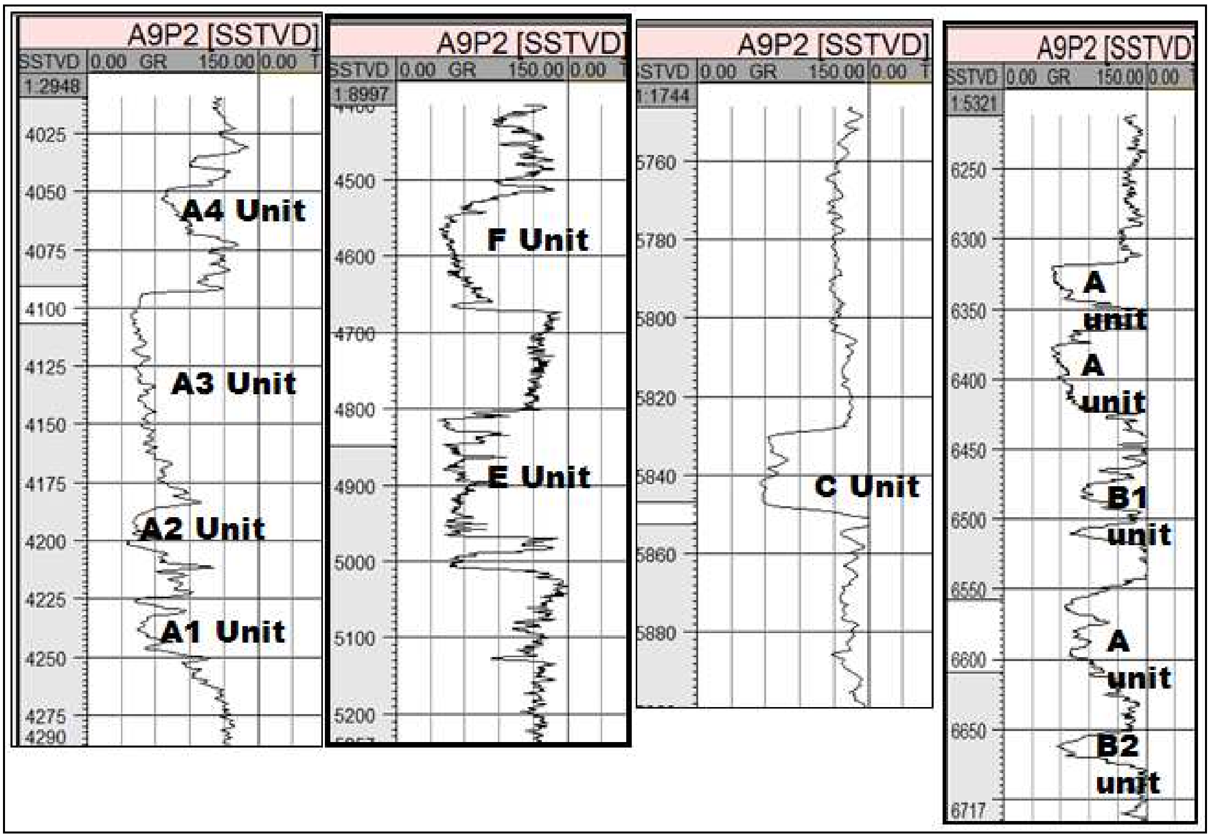

Fig. 7. A UNIT: This unit display stacked coarsening upward successions. The trend shows a funnel shape with sharp upper contact and gradational lower boundary underlain by thick shale unit, likely shelf mud. This suggests a prograding depositional setting (deltaic). E UNIT: The shape is blocky and serrated. Has sharp upper and lower contacts and both overlain by thick shales. F UNIT: The shape of this unit is crescentic. Have gradational upper and lower contacts. C UNIT: This has a boxcar shape. The upper and lower contacts are sharp and occur within thick shales. Possibly a channel within the slope setting or a sandy wave dominated shelf. B UNIT: It is crescent in shape. It displays weak gradational top and base, and underlain by thick continuous shale (B2 Unit)

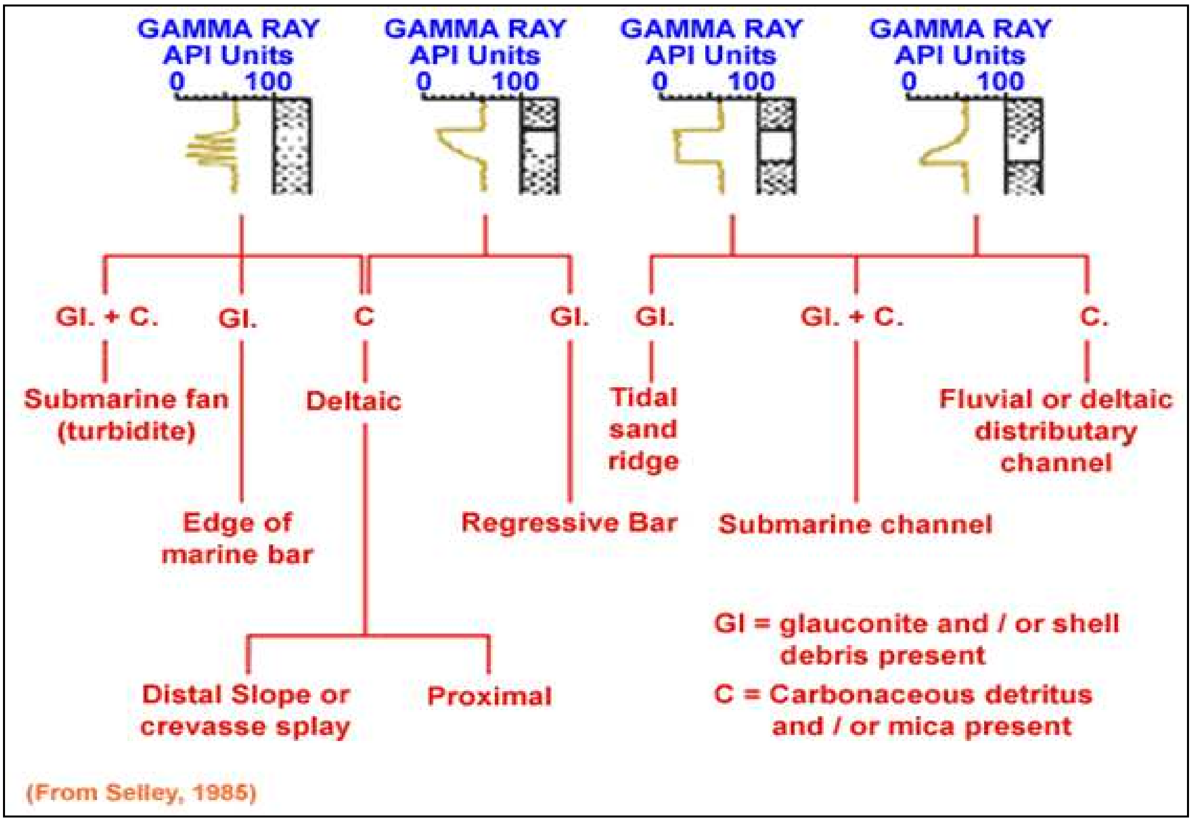

Fig. 8. Characteristic log motifs combined with aspects of the reservoir composition (after Selley, 1978; 1985)

The grains are clear to white, yellow, opaque, transparent to translucent, medium, coarse, very coarse grained to pebbly size in part, sub angular to sub-rounded, poorly sorted grains with the presence of lignite streaks and carbonaceous detritus. The absence of glauconite and presence of carbonaceous materials in this section confirms its fluvial origin in conformance with Selley (1985) (Fig. 8). The claystone component are light grey in colour, soft to firm, sub blocky-blocky, sticky, washable, silty and non-calcareous. Lignite streaks are also present. Lignitic materials indicate continental environment (floodplain). Traces of glauconite begin to occur at about 1400ft and increasing in percentage beyond this depth. This is towards the top of QISM showing the incursion/interaction of marine process.

Deltaic Front Environments and Log Characteristics

The deltaic front environment is highly unstable due to the variety of processes operating within this realm. A combination of marine and fluvial influences account for the depositional styles within the marginal marine. Studies on modern sedimentary environments revealed that vertical profiles of grain size from a specific environment have certain log characteristics (Selley, 1985). For instance, prograding deltas and barrier bar deposits have upward-coarsening grain size profiles (Fig. 9). The vertical profiles may also be of use in lithofacies analysis. Gamma ray motifs with a bell-shape reflects a gradual vertical transition from shale to sandstone, whereas an upward increase in sand-size is indicative of a gradual change in the energy level of the depositional milieu, and no unique SP-curve pattern is representative of any specific depositional environment (Amajor and Agbaire, 1989). However, when these patterns are integrated with the presence or absence of glauconite and/or carbonaceous detritus from cuttings, a more meaningful and reliable interpretation emerges (Selley, 1978) (Table 1 and Fig. 8). The presence of glauconite is noticed in all the wells in the Yowi field from about 1800ft, which is about the base of Agbada Formation in the field. The highest occurrence of glauconite is reported at 2005ft. It has been consistently recorded throughout the Yowi Field area from the uppermost part of the Agbada sand sequence down hole, signifying a more marine influence than fluvial or deltaic. The associated environments based on log shapes and the presence of glauconite within this interval in the Yowi field include offshore/regressive bars, barrier foot, beach and shore face deposits (Table 1 and Fig. 8-10).

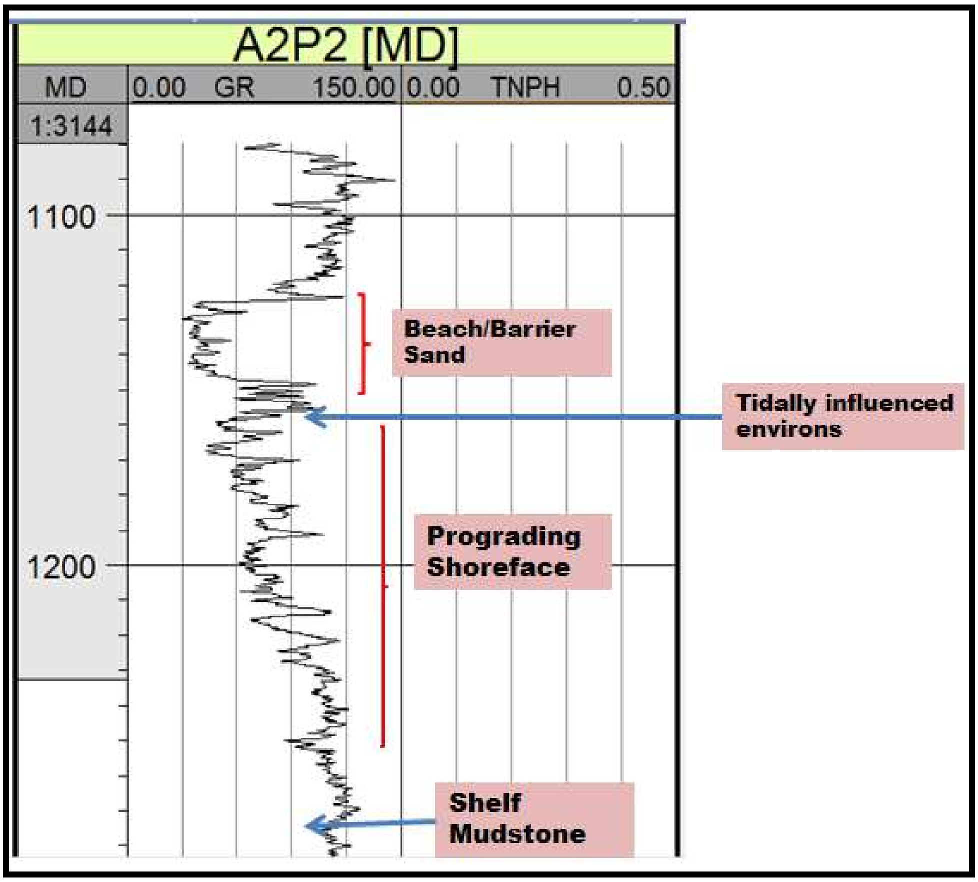

Fig. 9. Deltaic related environments (beach/ barrier bar and prograding shoreface

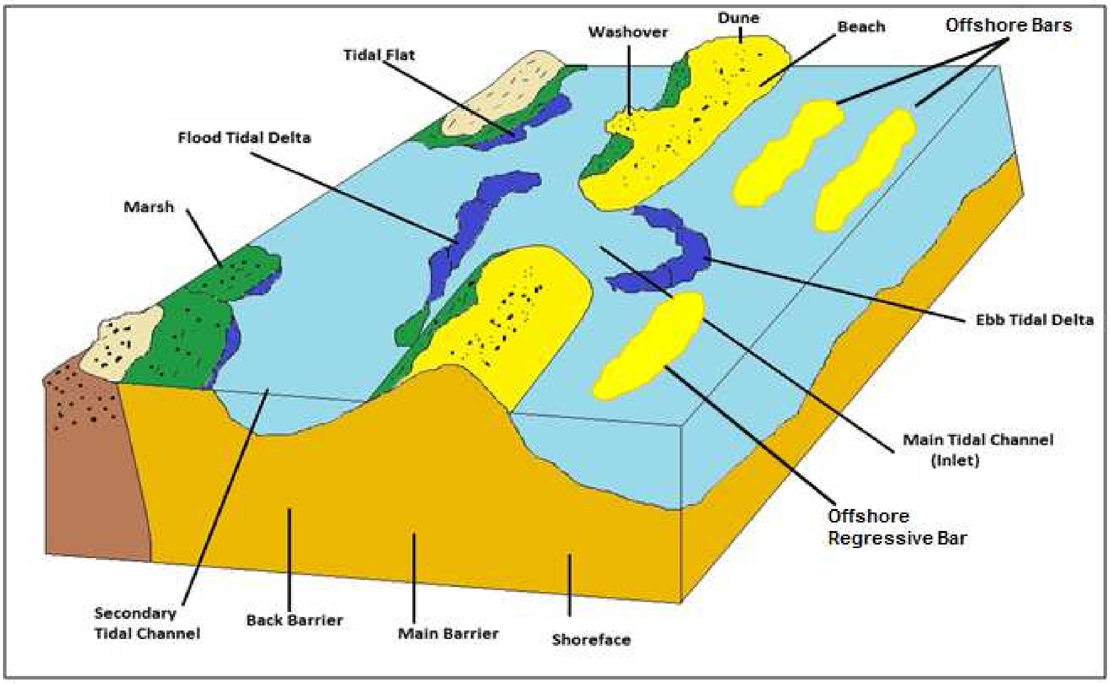

Fig. 10. Depositional model for the yowi field

The overall stacking pattern/trend represented on gamma ray log shows a coarsening upward succession. This is typical of a deltaic depositional setting where sediments from the continent build out or are moved seaward (basin ward shift in facies). In the upper sequence of the field, stacked regressive sand showing rapid deposition are noticed between 2000 and 3300ft (Fig. 4 well A2P2). They are parasequence sets belonging to the High stand Systems Tracts (HST).

The generalized deposition model for the Yowi field shows different environments affected by variety of processes ranging from wave action, long shore currents, tidal action and fluvial process (Fig. 10). The sediments were derived from the continent and deposited within the shallow marine environment through distributary channels. The sediments upon arrival within the shoreface got reworked by wave action to form beach ridges/dunes. Long shore currents reworked the sediments into longitudinal bars that are laterally extensive and running parallel to coastline. Subaqueous migration of regressive sands form the offshore bars. Most of the log facies units displaying erratic/fining upward motifs are representatives of tidal events.

Conclusion

A predominantly marine, deltaic sequence strongly influenced by clastic output from the Niger Delta is inferred for the Yowi Field. Water depths fluctuated considerably and deposition occurred within a variety of littoral and neritic environments ranging from near shore barrier sand complexes to fully marine and outer shelf mudstones. An overall shallowing trend is observed on well log towards the base of the Qua Iboe Shale Member. The upper part of the well section between 2000 and 2450ft appears to have been deposited in a marginal marine setting. Below this level down to about 5000ft on the well log may indicate paleobathymetric depth of relatively shallow marine conditions with normal salinities, well oxygenated bottom waters (photic zone) and periodic access to open marine (oceanic) conditions (Selley, 2000). Interval above 1800ft is the overlying continental Benin Formation.

Acknowledgement

The authors wish to acknowledge the O.B Lulu Briggs Chair in Petroleum Geoscience at the Institute of Petroleum Studies, University of Port Harcourt, Nigeria, for providing the platform for this research.

Funding Information

Funding for this research was generously supported by Engr. LeBari Nania.

Author's Contributions

Prince Suka Momta: Undertook the PhD research from which this manuscript was developed and written.

Minapuye Isaac Odigi: Supervised the PhD work, read and revised the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that the second author read and approved the manuscript, and that there are no ethical issues.

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