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Research Article

ANALYSIS OF DEPOSITIONAL ENVIRONMENTS OF UK FIELD RESERVOIR SANDS IN NIGER DELTA BASIN, NIGERIA

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ABSTRACT

The environments of deposition play a vital role during hydrocarbon formation, migration, trapping and storage. Since the reservoir rocks are a function of their depositional environments, the successful tapping of hydrocarbon from its host rock when wells are drilled depends largely on the petrophysical characteristics of the reservoir rocks which in turn originated from and are influenced by their depositional environment. The reservoir facies in Niger Delta shows a broad range of characteristic sedimentological complexities that gave rise to subsurface geological, drilling and production problems occurring in UK Field. The problems include inaccurate determination of environments of deposition, imperfect stratigraphic correlations and reservoir top uncertainty across the UK Field which are targeted by this research in other to help resolve these challenges facing oil and gas industries in the Niger Delta basin of Nigeria. The research findings will assist in the evaluation of depositional environments and well-to-well lithologic correlation within the UK Field and Niger Delta Basin at large. It will also help to unravel major causes of reservoir top uncertainty in UK Field. Also, it will help in future planning and drilling of new wells within UK Field. The determination of the depositional environments of UK Field reservoir sands were carried out to determine the depositional environment of reservoir sand bodies based on data from seven (7) wells. The determination of depositional environments of sand facies penetrated by wells UK1, UK2, UK3, UK4, UK5, UK6 and UK8 was achieved through a side-by-side comparison of their log suites to standard log motifs. Results of facies analysis showed that the reservoir sands belong to mostly (i) fluvial channel, (ii) barrier bar, (iii) lower-middle shoreface, (iv) distributary mouth bar, (v) distributary channel, (vi) point bar and (vii) tidal channel environments that belonged to parts of a deltaic system. Lithologic correlation result reveals the existence of good correlation among all wells in UK Field due to good geological similarities except well UK8 that failed to correlate perfectly with others thereby establishing the existence of reservoir top uncertainty within UK Field. Therefore, reservoir top uncertainty within UK Field is geologically controlled.

KEYWORDS

Depositional Environments, Reservoir sand facies, log analysis, lithofacies environmental models, correlation and reservoir top uncertainty.

INTRODUCTION

The Niger-Delta basin is the largest known prolific hydrocarbon-producing field in the West African sub-region with commercial reserves discovered both onshore and offshore (Tinker, 1996). The principal goal of reservoir characterization is to derive a special understanding of inter and intra-well heterogeneity that helps to eliminate lots of uncertainties in their environments and petrophysics. Both flow and storage properties of reservoir facies are also provided via reservoir characterization and description (Tinker, 1996). The UK Field is one of the most prolific oil fields in the onshore Niger Delta basin. The structural pattern indicates a synthetic fault system with a West-East axis in the central part of the Macrostructure. The structure is bounded south by a major normal fault and north by a boundary fault. The Field is a hanging wall structural closure, bounded by two converging faults. The structure is also divided into two smaller blocks by a minor synthetic fault. The primary purpose and objectives of this research are to evaluate the depositional environments of UK Field reservoir sands in the Niger Delta Basin, carry out lithofacies analysis and develop models for the depositional facies in the "UK" Field of Niger Delta basin. The reservoir facies of UK Field in the Niger Delta basin show a broad range of characteristic complications and complexities in its sedimentology and depositional environments. These complexities gave rise to subsurface geological, drilling and production problems occurring in UK Field which are targeted by this research. The major problems include the determination of reservoir depositional environments and stratigraphic reservoir top uncertainty across the UK Field. The reservoirs submitted to high stratigraphic reservoir top uncertainty whose causes are yet to be unraveled in the UK Field. The study of reservoirs' environments of deposition amongst other problems has to be carried out using available data from UK Field wells in other to mitigate these challenges in the field. Significantly, this study will assist in the total determination of depositional environments of the reservoirs, well to well lithologic correlation within the UK Field and Niger Delta basin at large. This will also help to unravel the major causes of reservoir top uncertainty. The research outcome will help oil industries in the Niger Delta basin for better future planning and drilling of new wells within UK Field. Finally, the research outcome will make an invaluable contribution to knowledge for geoscientists and oil-producing companies in the Niger Delta basin. The reservoir petrophysical challenges are most times a function of their depositional environments (Webber, 1971). A change in the depositional environment would also mean a change in the reservoir petrophysics either completely or incompletely. Both play a vital role in reservoir viability for hydrocarbon production. Thus, the environment of deposition and the petrophysical properties have to be derived from logs together with a certain number of side wall core samples (Webber, 1971). An examination of electric logs reveals that certain GR and Self-potential (SP) areas of sand zones have characteristic shapes that are of common occurrence. These characteristic shapes reflect significant lithologic properties which are a function of the depositional origin of the corresponding sand body. Consequently, the shape of the GR and SP curve is indicative of the mode of formation of certain sands. From this knowledge, the external form and trend and the primary internal characteristics of the sand body can be estimated (Crain, 2005). A major challenge in hydrocarbon exploration lies in the need for proper mapping of the reservoir including its environment and characterization to determine the economic value of such a field (Aniefok S.A et al., 2020). Extensive descriptions of depositional facies and environments in the Niger Delta Basin are presented in many publications. Some of these include, Amajor and Agbaire (1989), Nton and Adesina (2009), Onyekuru et al, (2012), Reijers (2011) among others. This study, therefore, utilizes these previous research as well as that of Selly (1998) and Amajor and Agbaire (1989) who defined the depositional history of the reservoir sandstones of the Agbada formation in the Akpor and Apara oilfields, eastern Niger Delta using the integration of well logs with ditch cutting samples.

LOCATION OF THE STUDY AREA

The UK Field is a hydrocarbon-producing field located in the western part of Niger Delta and lies within the proximal part of the coastal swamp depobelt (Fig. 1). The field contains eight (8) wells named UK1, UK2, UK3, UK4, UK5, UK6, UK7 and UK8. Well UK 7 was not analyzed since it lacked the basic lithology logs.

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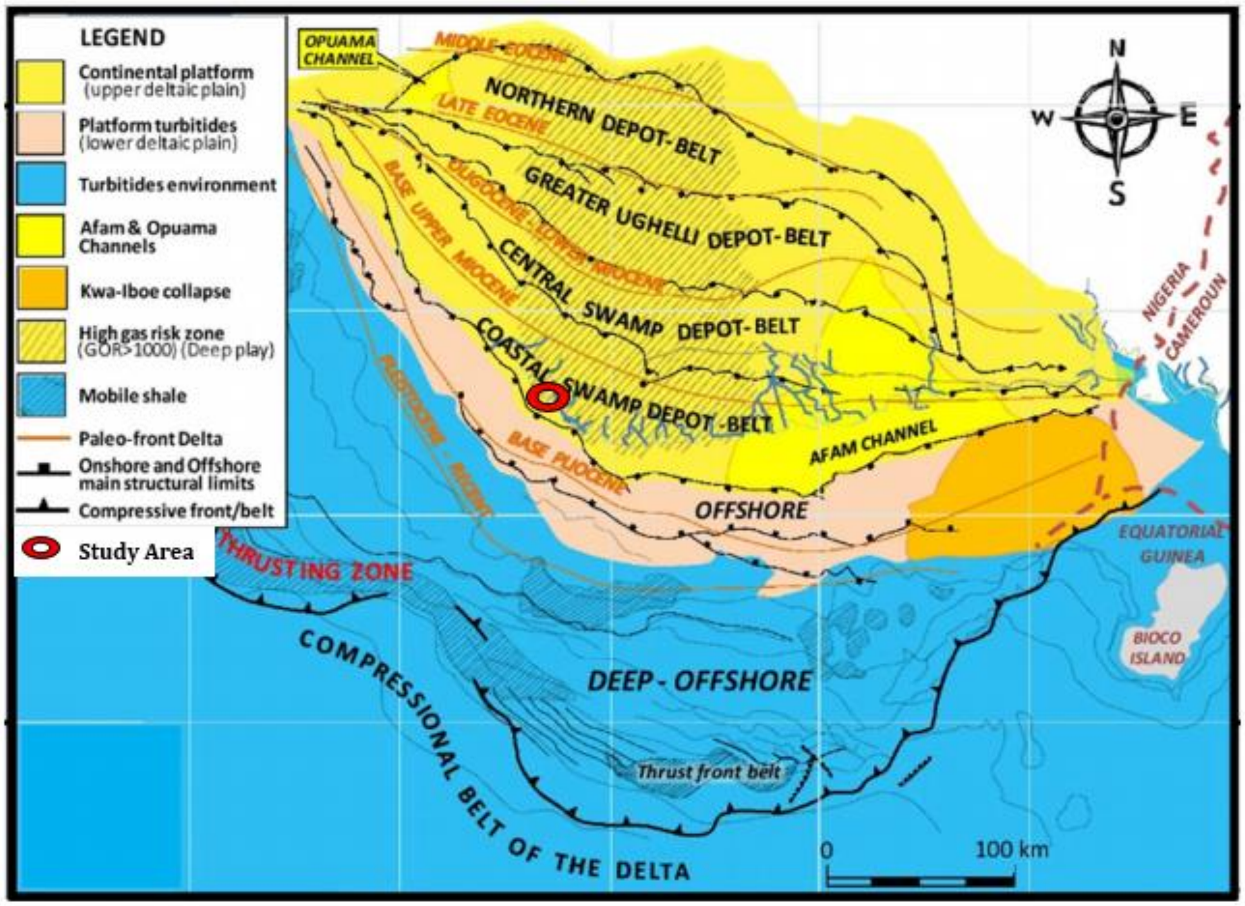

Fig. 1: Niger Delta Depobelts map displaying the Location of UK Field.

GEOLOGY AND FORMATIONS OF THE STUDY AREA

The morphology of the Niger Delta changed from an early stage, spanning the Paleocene to Early Eocene, to a later stage of delta development beginning in Miocene time. Early coastlines were concave to the sea and basement topography strongly affected depositional patterns (Doust and Omatsola, 1989). Progradation of the Delta happened along two major axes. The first paralleled the Niger River, where sediment supply superseded subsidence rate. The second, smaller than the first, became active basinward of the Cross River during the Eocene to Early Oligocene. Late stages of deposition began in the early to Middle Miocene, as these separate eastern and western depocenters merged. In Late Miocene, the delta prograded far enough that shorelines became broadly concave into the basin. This rapid delta progradation generated underlying unstable shales through accelerated loading. These shales grew into diapiric walls, deforming overlying strata (Doust and Omatsola, 1989). Local uplift was caused by the resulting complex deformation structures, which led to major erosion events into the leading progradational edge of the Niger Delta. During sea level low stands, many deep canyons, now clay dominated, cut into the shelf were analyzed to have developed majorly. The best known are the Afam, Opuama, and Qua Iboe

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Canyon fills (Reijers, et al., 1997 and Tuttle, et al., 1999). Short and Stauble (1967) based on sand/shale ratios estimated from subsurface well logs defined the Niger Delta clastic wedge formations. The three major lithostratigraphic units (Akata, Agbada and Benin formations) defined in the subsurface of the Niger Delta (Lawrence, et al., 2002) showed a gross upward-coarsening clastic wedge. Dominantly marine, deltaic and fluvial environments respectively are the major environment where these formations were deposited (Weber and Daukoru, 1975; Weber, 1987). Surface equivalent units to these three formations are stratigraphically outcropping in southern Nigerian (Nwajide 2013, Short and Stauble, 1967).

AKATA FORMATION

The Akata Formation consists of dark grey shales and silts with scarce streaks of sand that may be of turbidite flow origin. The formation is estimated to be 6,400 m thick in the central area of this clastic wedge (Doust and Omatsola, 1989). Marine planktonic foraminifera showed a shallow marine shelf depositional setting starting from Paleocene to Recent in age (Doust and Omatsola, 1989). The shales are referred to as the Imo Shale in the northeastern area of the delta where it occurred as a surface lithostratigraphic unit. The formation also cropped out offshore in diapers within the continental slopes. The basal portions of the Akata formation are typically over-pressured. Akata shales shoal vertically into the Agbada Formation and were interpreted as prodelta and deeper water deposits (Stacher, 1995) (Doust and Omatsola, 1989).

AGBADA FORMATION

The Agbada Formation occurred all over the Niger Delta clastic wedge. Its maximum thickness is about 3,900 m and the age spans from Eocene to Pleistocene (Doust and Omatsola, 1989). The surface lithostratigraphic equivalent in southeastern Nigeria is regarded as the Ameki Group and the Ogwashi-Asaba Formation. The lithologies are largely made up of sand alternations, silts and shales with progressive upward variations in grain size and bed thickness. The strata were believed to have developed in fluvial-deltaic environments (Stacher, 1995, Doust and Omatsola, 1989).

BENIN FORMATION

The Benin Formation represents the topmost part of the clastic wedge of the Niger Delta, from the Benin-Onitsha area in the north to the present coastline (Short and Stauble, 1967). The top of the formation is the current subaerially-exposed delta top surface, and its base is defined by the top of the youngest underlying marine shales which covers a depth of about 1400m. The formation's age ranges from Oligocene to Recent (Short and Stauble, 1967). Shallow parts of the formation are entirely made-up of non-marine sands deposited in an alluvial or upper coastal plain environment during the progradation of the delta (Doust and Omatsola, 1989). The formation thins basinward and ends near the shelf edge. The modern Niger Delta is a mixed wave, tide and fluvial deltaic system (Cathles et al., 2003). The delta is reworked by wave action along an arcuate coast with barrier islands, back-barrier lagoons, and channel ridges. The coastline of the lower Niger Delta plain is bordered by thick mangroves. Incised into this coastline are numerous tide-dominated coastal estuaries that have gradually been infilled with sediments following the Holocene sea-level highstand (Cathles et al., 2003). Localized slumps and canyons that bypass sediments into deeper waters marked the present delta front and continental slope. Within reservoir intervals of Niger Delta deposits, details of

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deltaic features are difficult to decipher and a good analog is indicated by the modern spread of distributary channels, estuary fills, shoreface, back-barrier lagoonal sediments and delta plain deposits.

MATERIALS AND METHODOLOGY

For the extensive analysis and study of the depositional environment of UK Field, data from seven (7) wells within the field were used. The data includes (1) complete well log suites containing GR, SP, resistivities (induction medium (ILM), induction deep resistivity (ILD), attenuation resistivity (ATR) and phase shift resistivity (PSR)), bulk density, neutron-density, sonic, caliper, and thermal neutron porosity data which were given in ASCII format, (2) well information such as wellheads, depths, well surface coordinates and Kelly bushing (KB) for all the wells, (3) survey and deviation data (TVD), (4) seismic surveys with coordinates, seismic sections and volume, (5) migrated velocity data, and Time-depth data/check-shots. Computation, plotting and analysis of the above data were carried out using Petrel software, Surfer and Microsoft Office Packages. The depth was given in meters but was converted to feet. The conversion was done by multiplying depth in meter (m) with a conversion factor of 3.281 to get its equivalent in feet. The method involves importing ASCII data for seven (7) wells into Petrel software for plotting to generate the needed log suites for each well. The log suites of GR, SP, Resistivity, Neutron, Sonic, Caliper and Bulk Density were generated which displayed facies' signatures for seven (7) wells within the UK Field. The seven (7) wells include UK1, UK2, UK3, UK4, UK5, UK6 and UK8. A detailed study was carried out on logs to identify reservoirs' depositional environments based on the curve shapes of the GR and SP log. Reservoir sand facies were identified with the help of GR log (lithological log), resistivity (electrical logs) and porosity logs (neutron, density and sonic logs). The signatures of GR and SP logs for the seven (7) wells were compared to standard index electro-facies logs. The standard index electro-facie logs adopted includes General Gamma Ray Response to Variations in Grain Size (Kendall 2003; modified from Emery 1996), General Gamma Ray Response to Variations in Grain Size and Depositional Setting (Kendall 2003; modified from Malcon Rider, 1999), Classification of Electrofacies for deltaic environments using GR logs (Schlumberger, 1985), Symmetrical descriptive classification of basic SP log shapes (Nanz and Wilson, 1959) and Index of basic SP log shapes (Crain, 2005). These were used to infer the characteristic environments of deposition for the reservoir sand facies. The type of contact existing between different facies in UK Field was decided using Nanz and Wilson (1959) standard logs.

RESULTS AND DISCUSSION

Depositional Environment Analysis Result

Detailed results of the depositional environment analysis are presented below for well UK1 (Table 1, Fig. 2), UK2 (Table 2, Fig. 3), UK3 (Table 3, Fig. 4), UK4 (Table 4, Fig. 5), UK5 (Table 5, Fig. 6), UK6 (Table 6, Fig. 7) and well UK8 (Table 7, Fig. 8). The abundance of the depositional environments based on frequency for UK Field was analyzed (Tab. 8, Fig. 9). The conceptual geologic models for the depositional environment as inferred from the analysis were also presented (Fig. 10 and Fig. 11).

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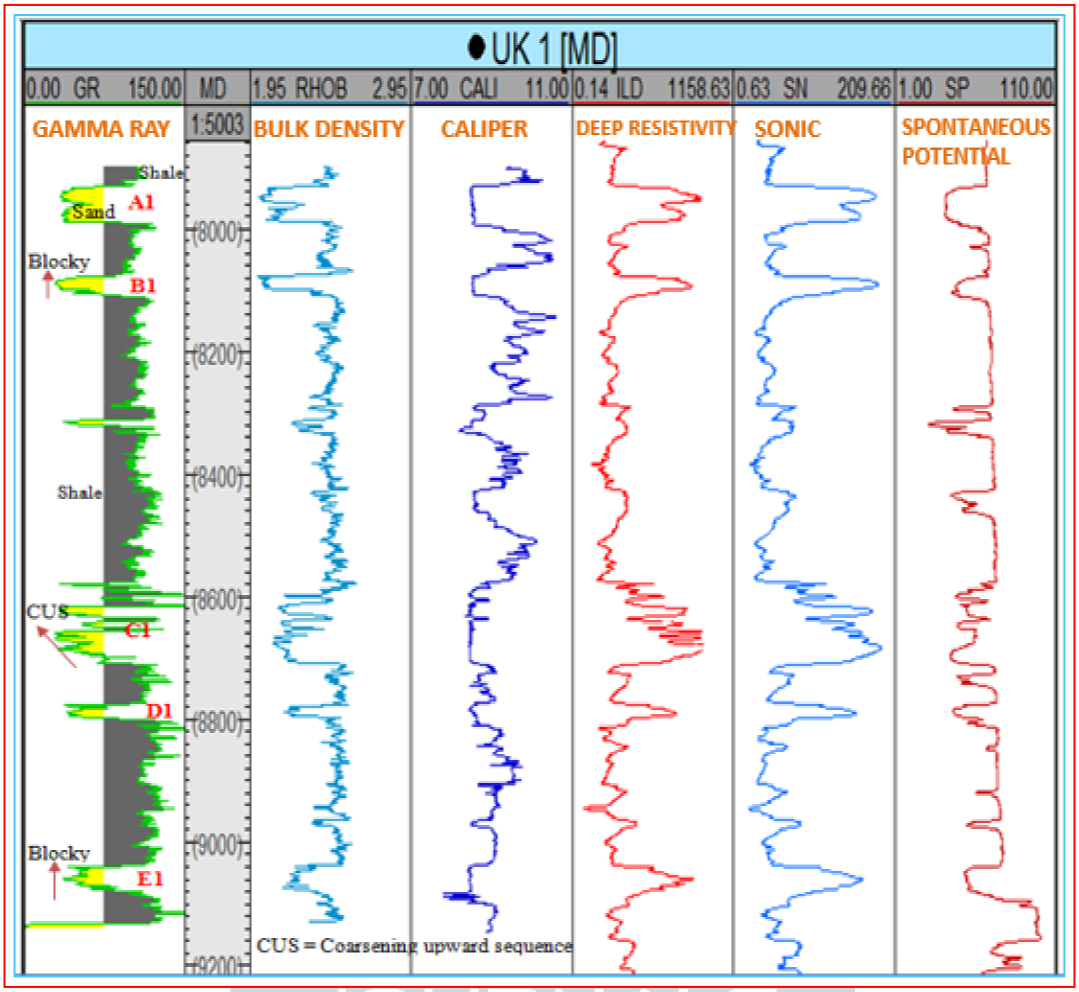

Fig. 2: UK1 log suites for reservoirs A1, B1, C1, D1 and E1.

Table 1: Result of depositional environment analysis for well UK1

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A1	7948 - 7890	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
B1	8064 -8035	Blocky/cylinderical	Smooth curve with gradational upper contact and abrupt lower contact (G/A Sm).	Fluvial channel and barrier bar

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C1	8662 - 8533	Funnel with blocky top	Serrate curve with abrupt upper contact and gradational lower contact (A/G Se).	Shoreface
D1	8752 - 8729	Blocky/cylinderical	Serrate curve with abrupt upper and lower contacts (A/A Se).	Tidal channel
E1	9030 - 8992	Blocky/cylinderical	Serrate curve with abrupt upper contact and gradational lower contacts (A/G Se).	Tidal channel
CUS: Coarsening upward sequence. **FUS:** Fining upward sequence. **A:** Abrupt, **G:** Gradational, **Sm:** Smooth, **Se:** Serrated.				

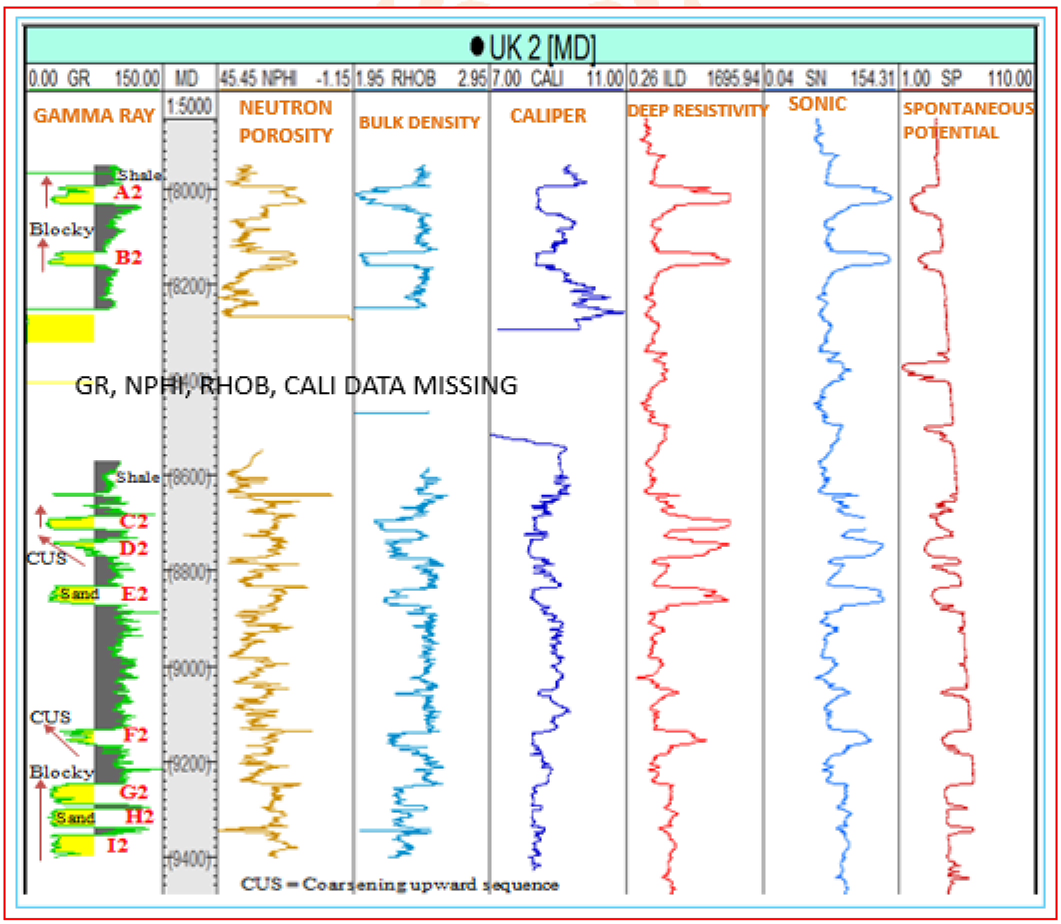

Fig. 3: UK2 log suites for reservoirs A2, B2, C2, D2, E2, F2, G2, H2 and I2.

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Table 2: Result of depositional environment analysis for well UK2

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A2	8011 - 7974	Blocky/cylindrical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
B2	8140 - 8111	Blocky/cylindrical	Smooth curve with abrupt upper contact and abrupt lower contact (A/A Sm).	Fluvial channel and barrier bar
C2	8694 - 8666	Blocky/cylinderical	Smooth curve with abrupt upper contact and abrupt lower contact (A/A Sm).	Fluvial channel and barrier bar
D2	8748 - 8713	Funnel with blocky top	Serrate curve with abrupt upper and gradational lower contacts (A/G Se).	Shore face
E2	8850 - 8813	Blocky/cylinderical	Smooth curve with abrupt upper contact and abrupt lower contact (A/A Sm).	Fluvial channel and barrier bar
F2	9145 - 9114	Funnel (CUS)	Serrate curve with abrupt upper contact and gradational lower contact (A/G Se).	Distributary mouth bar
G2	9269 - 9227	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
H2	9317 - 9280	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
I2	9380 - 9334	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
CUS: Coarsening upward sequence. **FUS:** Fining upward sequence. **A:** Abrupt, **G:** Gradational, **Sm:** Smooth, **Se:** Serrated.				

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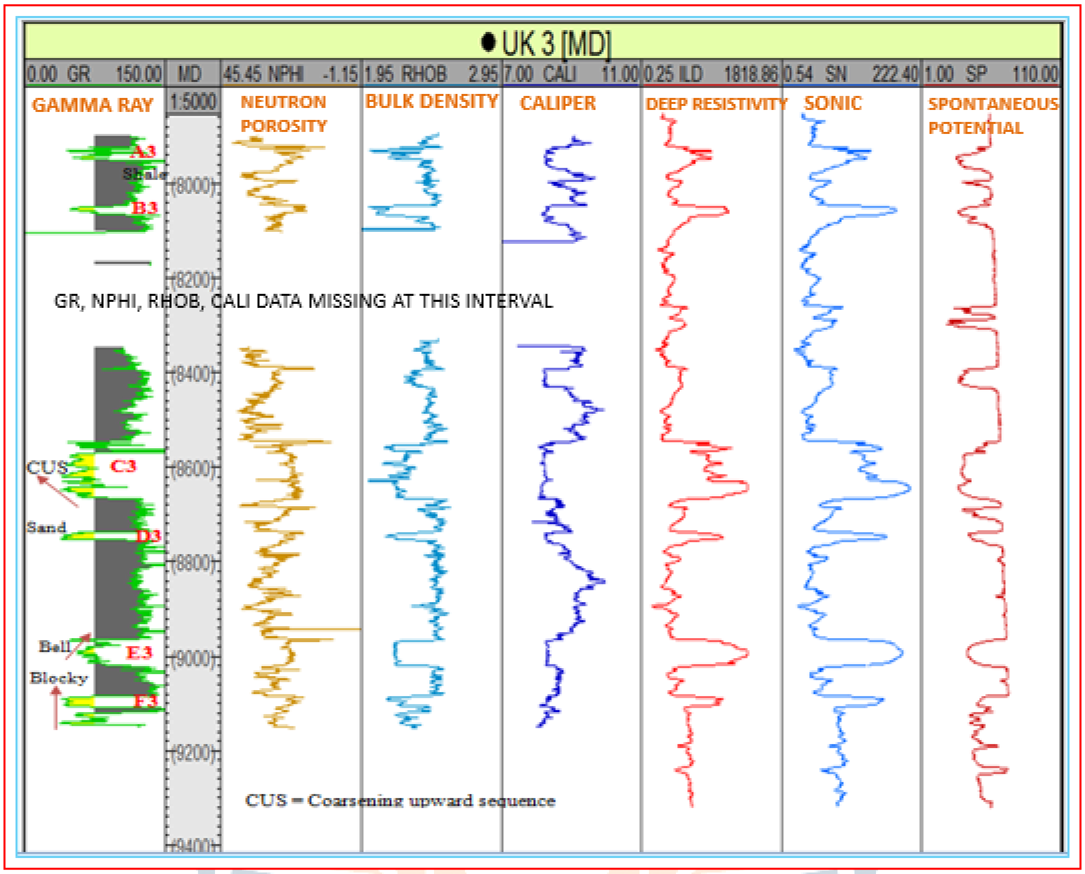

Fig. 4: UK3 log suites for reservoirs A3, B3, C3, D3, E3 and F3.

Table 3: Result of depositional environment analysis for well UK3

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A3	7943 - 7917	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
B3	8062 - 8041	Blocky/cylinderical	Smooth curve with abrupt upper contact and abrupt lower contact (A/A Sm).	Fluvial channel and barrier bar
C3	8660 - 8540	Funnel with blocky top	Serrate curve with abrupt upper contact and gradational lower contact (A/G Se).	Shoreface

D3	8749 - 8730	Blocky/cylinderical	Smooth curve with gradational upper contact and abrupt lower contact (G/A Sm).	Tidal channel
E3	9013 - 8958	Bell (FUS)	Serrate curve with gradational upper and lower contacts (G/G Se).	Distributary channel and point bar
F3	9140 - 9079	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar

CUS: Coarsening upward sequence.
FUS: Fining upward sequence.
A: Abrupt.
G: Gradational.
Sm: Smooth.
Se: Serrated.

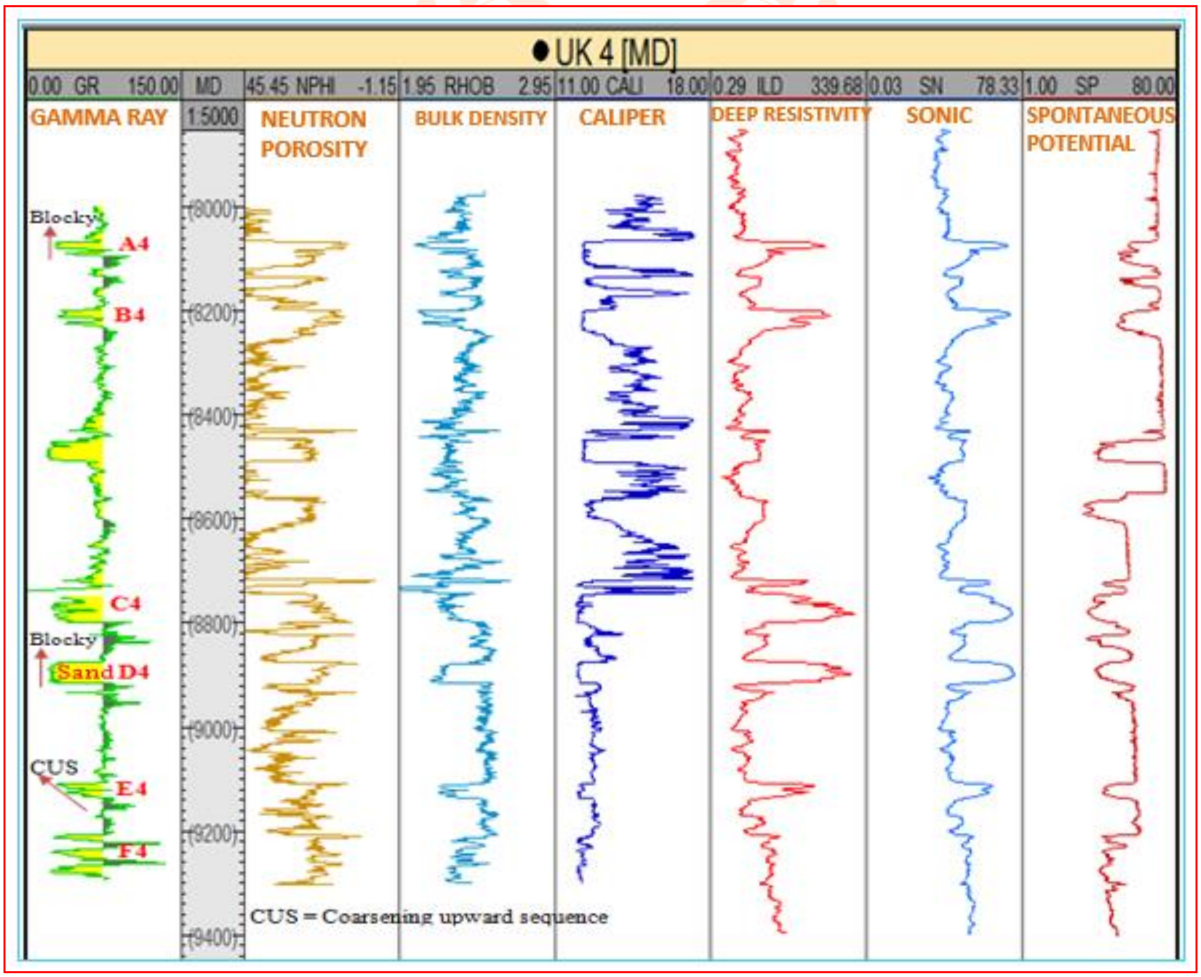

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Table 4: Result of depositional environment analysis for well UK4

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A4	8072 - 8018	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
B4	8212 - 8175	Blocky/cylinderical	Smooth curve with abrupt upper contact and gradational lower contact (A/G Sm).	Fluvial channel and barrier bar
C4	8777 - 8694	Blocky/cylinderical	Serrate curve with abrupt upper contact and abrupt lower contact (A/A Se).	Tidal channel
D4	8894 - 8850	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
E4	9115 - 9085	Funnel (CUS)	Serrate curve with abrupt upper contact and gradational lower contact (A/G Se).	Distributary mouth bar
F4	9270 - 9185	Funnel (CUS)	Serrate curve with abrupt upper contact and gradational lower contact (A/G Se).	Distributary mouth bar
CUS: Coarsening upward sequence. **FUS:** Fining upward sequence. **A:** Abrupt. **G:** Gradational. **Sm:** Smooth. **Se:** Serrated.				

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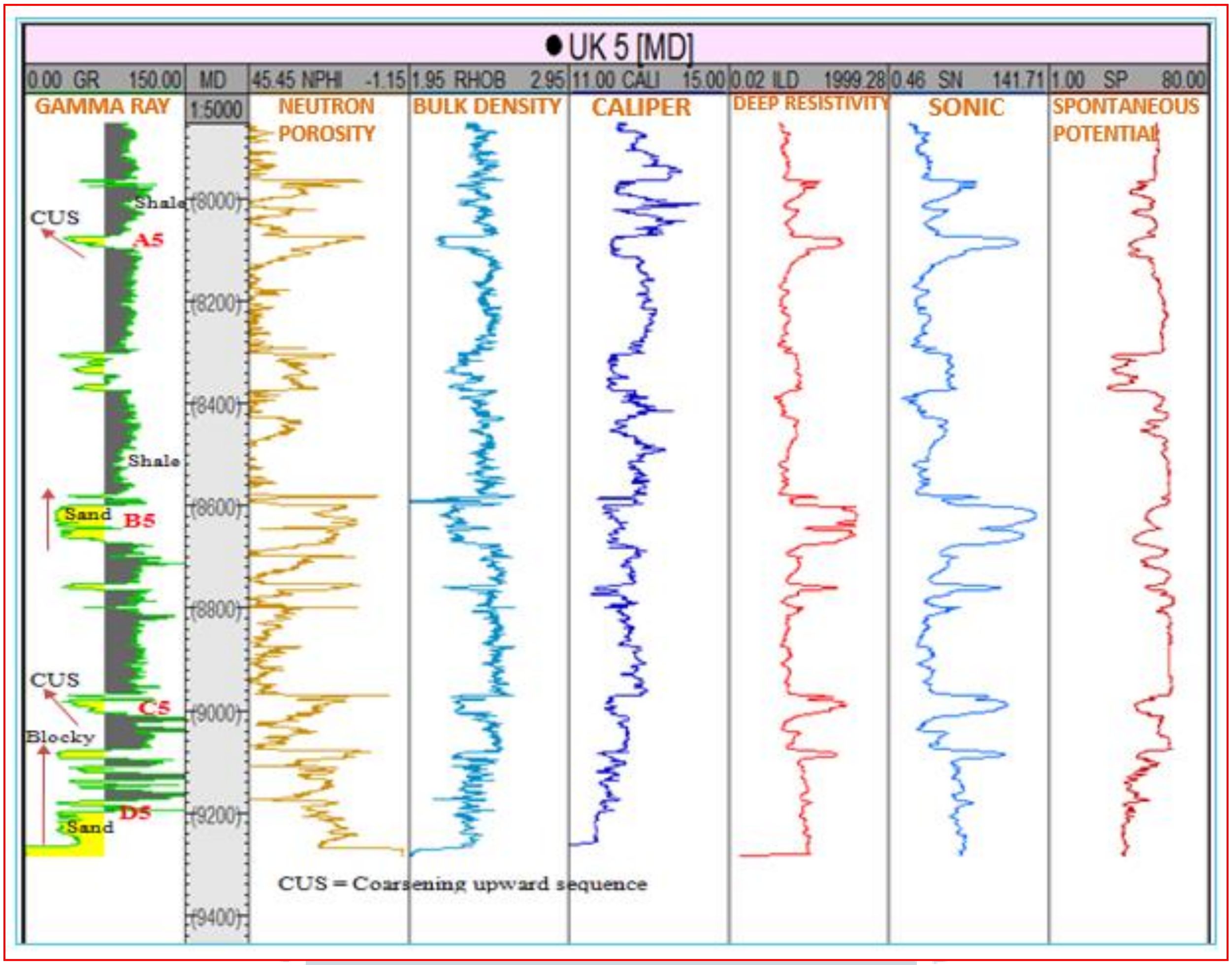

Fig. 6: UK5 log suites for reservoirs A5, B5, C5 and D5.

Table 5: Result of depositional environment analysis for well UK5

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A5	8077 - 8052	Funnel	Serrate curve with abrupt upper and gradational lower contacts (A/G Se).	Distributary mouth bar
B5	8652 - 8558	Blocky/cylindrical	Serrate curve with abrupt upper contact and abrupt lower contact (A/A Se).	Tidal channel

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C5	8986 - 8949	Funnel (CUS)	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Distributary mouth bar
D5	9245 - 9056	Blocky/cylindrical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
CUS: Coarsening upward sequence. **FUS:** Fining upward sequence. **A:** Abrupt. **G:** Gradational. **Sm:** Smooth. **Se:** Serrated.				

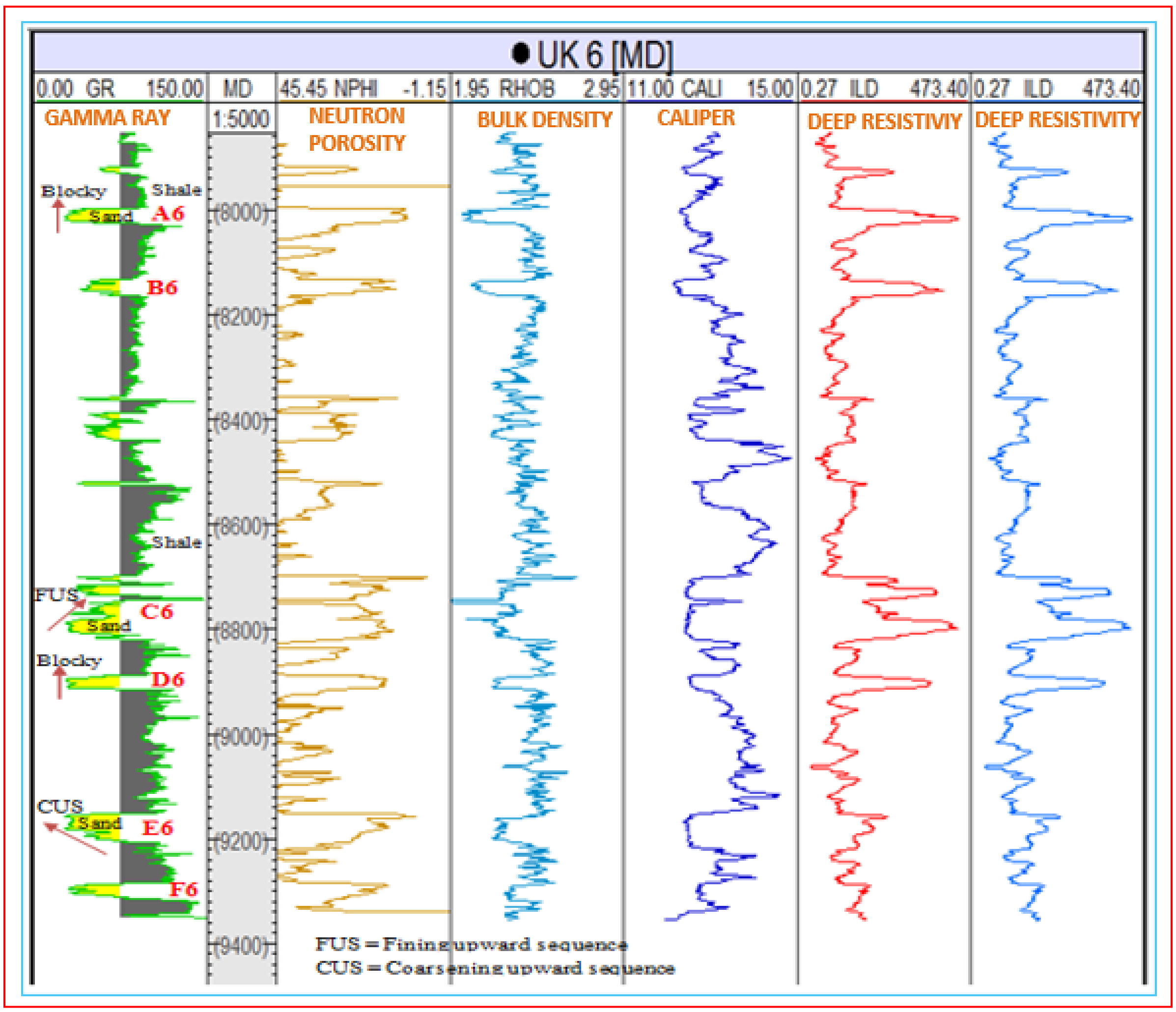

Fig. 7: UK6 log suites for reservoirs A6, B6, C6, D6, E6 and F6.

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Table 6: Result of depositional environment analysis for well UK6

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A6	8003 - 7974	Blocky/cylinderical	Smooth curve with abrupt upper and lower contacts (A/A Sm).	Fluvial channel and barrier bar
B6	8140 - 8111	Blocky/cylinderical	Serrate curve with abrupt upper contact and abrupt lower contact (A/A Se).	Tidal channel
C6	8796 - 8676	Bell (FUS)	Serrate curve with abrupt upper contact and gradational lower contact (G/A Se).	Distributary channel and point bar
D6	8891 - 8865	Blocky/cylinderical	Smooth curve with gradational upper contact and abrupt lower contact (A/A Se).	Tidal channel
E6	9182 - 9131	Funnel (CUS)	Serrate curve with abrupt upper contact and gradational lower contacts (A/G Se).	Distributary mouth bar
F6	9290 - 9262	Funnel (CUS)	Serrate curve with abrupt upper contact and gradational lower contacts (A/G Se).	Distributary mouth bar

CUS: Coarsening upward sequence.
FUS: Fining upward sequence.
A: Abrupt.
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Sm: Smooth.
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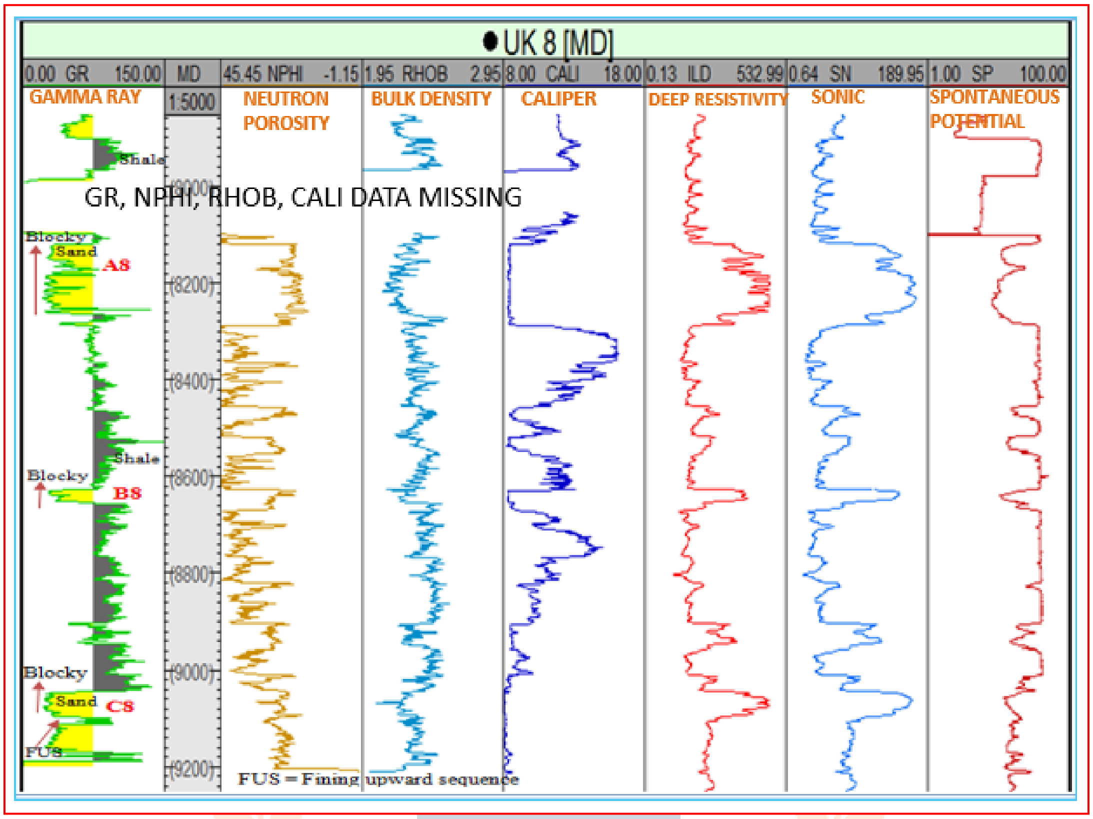

Fig. 8: UK8 log suites for reservoirs A8, B8 and C8.

Table 7: Result of depositional environment analysis for well UK8

Reservoir	Reservoir Depth Interval (Ft)	Classification of reservoir GR Log Shape (C.S. Kendall 2003; Malcon and Rider, 1999; Emery 1996).	Descriptive analysis of log signature (Nanz and Wilson, 1959).	Interpreted Facies' Depositional Environment
A8	8274 - 8105	Blocky/cylindrical	Serrate curve with abrupt upper and lower contacts (A/A Se).	Fluvial channel and barrier bar
B8	8641 - 8612	Blocky/cylindrical	Smooth curve with abrupt upper contact and abrupt lower contact (A/A Sm).	Fluvial channel and barrier bar
C8	9177 - 9032	Bell with blocky top	Serrate curve with abrupt upper contact and gradational lower contact (G/A Se).	Distributary channel and point bar

CUS: Coarsening upward sequence.
FUS: Fining upward sequence.
A: Abrupt.
G: Gradational.
Sm: Smooth.
Se: Serrated.

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Table 8: Abundance of Depositional Environments in Uk Field Based on Frequency

Depositional Environments	*Frequency*
Fluvial Channel/Barrier bar	19
Shoreface	3
Tidal Channel	7
Distributary Mouth bar	7
Distributary Channel and Point bar	3
Total	39

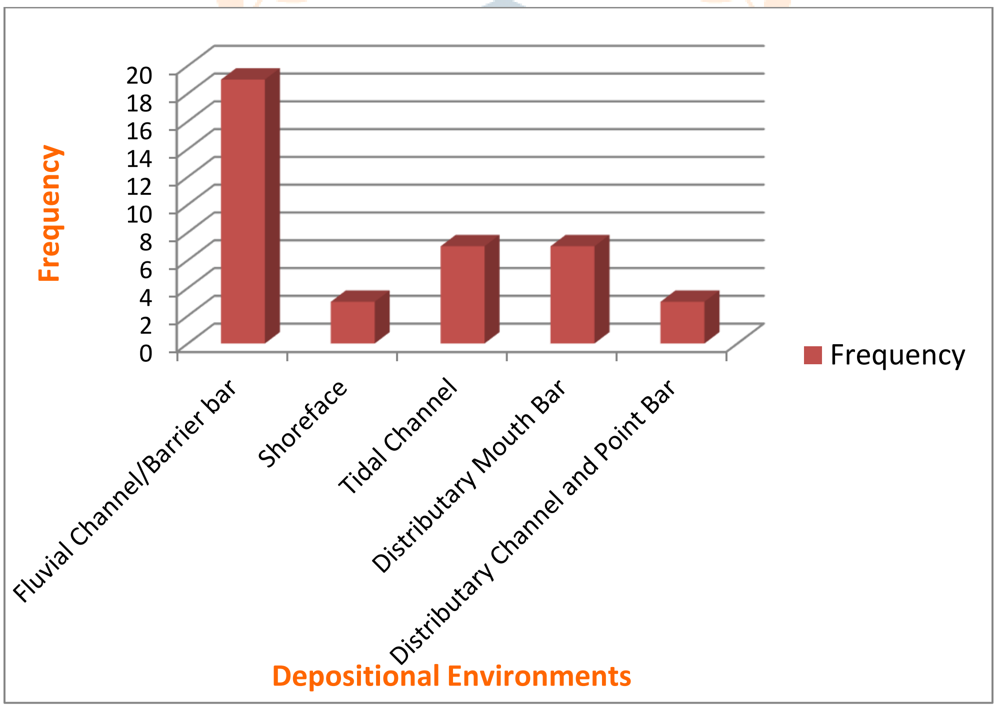

Fig. 9: Abundance of Depositional Environments in Uk Field Based on Frequency

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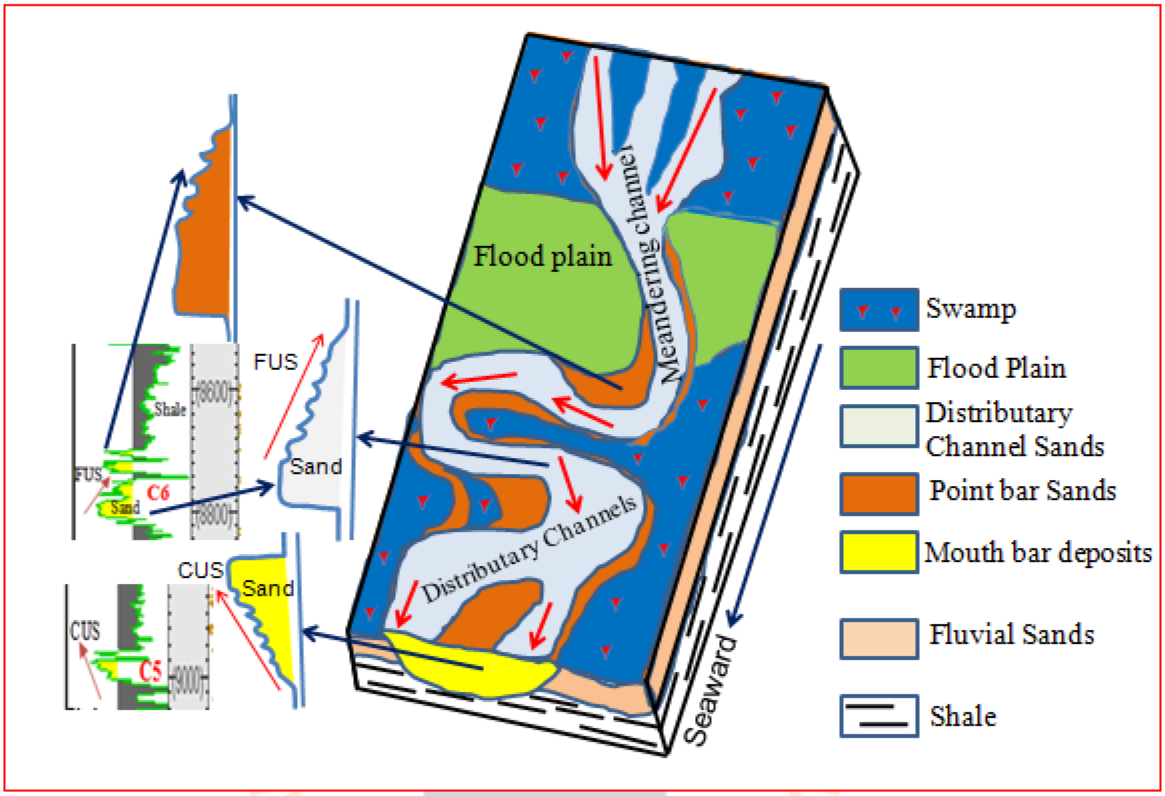

Fig. 10: Conceptual Lithofacies model of Fluvial, Distributary Channel, Point Bar and Mouth Bar Environments

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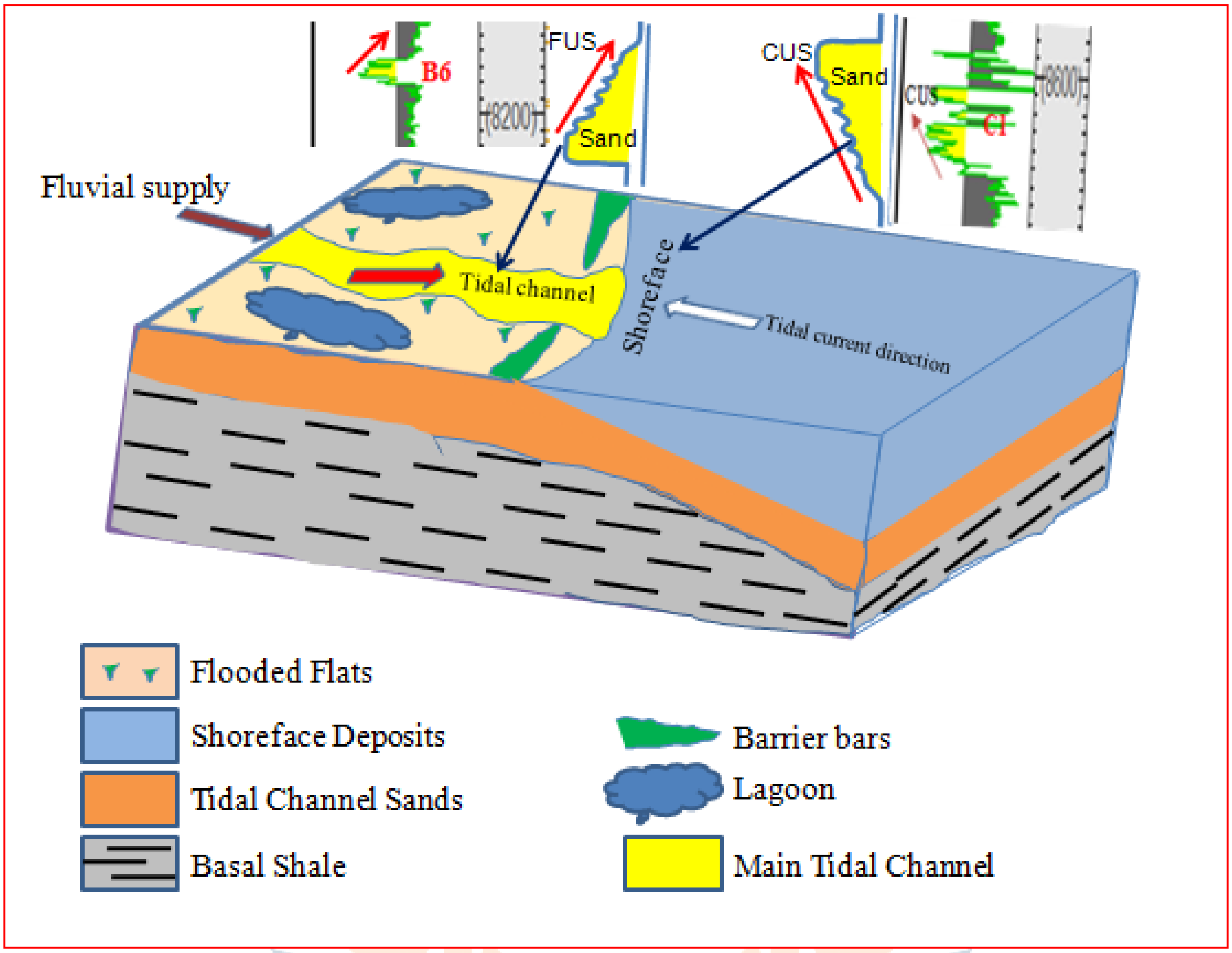

Fig. 11: Conceptual Lithofacies model of Tidal Channel and Shoreface Environments

5.2 WELL LOG CORRELATION

The lithologic correlation result for the wells in UK Field is presented in Fig. 11 below while the structural Map displaying the major fault running East to West and minor fault trends in UK Field with the various well locations is presented in Fig. 12.

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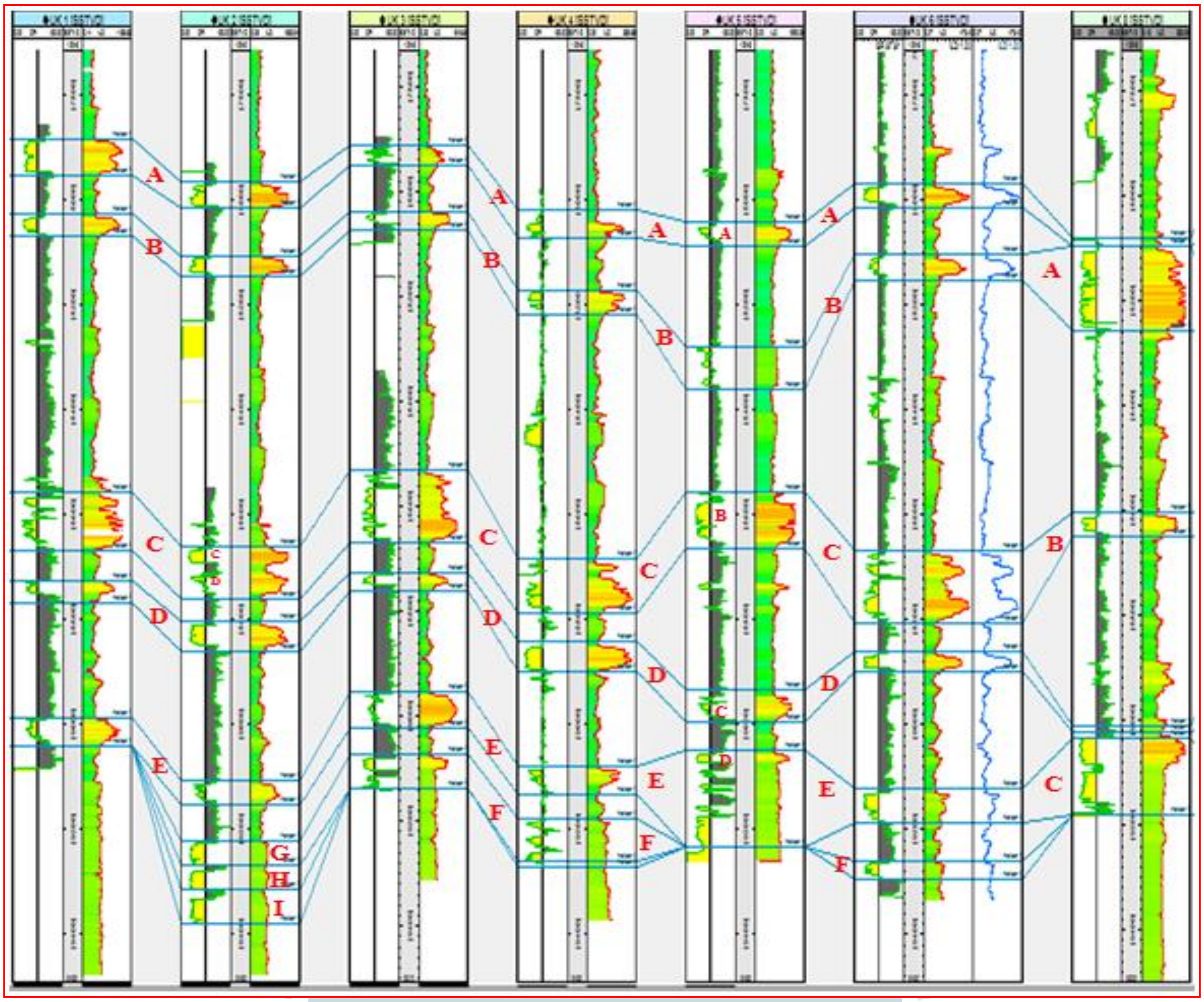

Fig. 12: Lithologic correlation across wells UK1, UK2, UK3, UK4, UK5, UK6 and UK8 in UK Field, Niger Delta.

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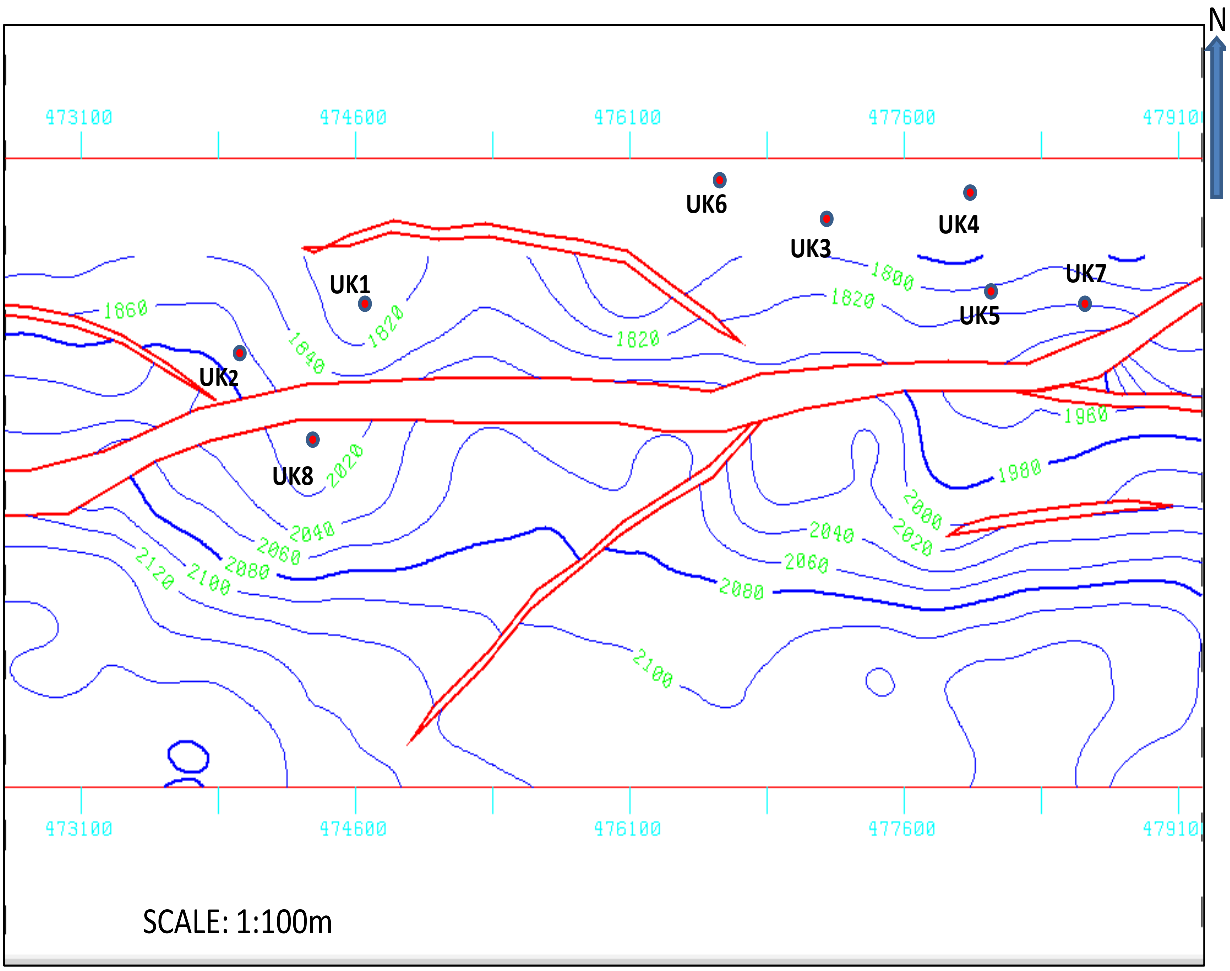

Fig. 13: Structural Map of UK Field showing UK1, UK2, UK3, UK4, UK5, UK6, UK7 and UK8 within Niger Delta.

DISCUSSION

Depositional Environment

Detailed results of the depositional environment analysis for UK Field have been presented in the previous chapter (chapter four) for UK1 (Table 1), UK2 (Table 2), UK3 (Table 3), UK4 (Table 4), UK5 (Table 5), UK6 (Table 6) and UK8 (Table 7). The study of the gamma-ray (GR) log response for seven (7) wells in UK Field identified thirty-nine (39) reservoir sands. The result also discovered that the facies encountered corresponded to fluvial, deltaic and shoreline depositional environments. The determination of depositional environments of the sand facies penetrated by the UK1, UK2, UK3, UK4, UK5, UK6, UK7

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and UK8 wells was achieved through analysis of their GR lithologic logs. The result is presented for UK1 in Fig. 2, UK2 in Fig. 3, UK3 in Fig. 4, UK4 in Fig. 5, UK5 in Fig. 6, UK6 in Fig. 7 and UK8 in Fig. 8. Further statistical analysis was carried out on the inferred depositional environment to determine their abundance within UK Field in Niger Delta basin of Nigeria (Tab. 8, Fig. 9). The research discovered that environments of fluvial channel/barrier bar are the most abundant in UK Field within the Agbada Formation (Fig. 9).

UK FIELD DEPOSITIONAL ENVIRONMENT INTERPRETATION

The study of the gamma-ray (GR) log response for seven (7) wells in UK Field discovered thirty-nine (39) reservoir sands and suggested that the facies encountered corresponded to fluvial, deltaic and shoreline environments (Figs. 9 and 10). The reservoirs contain several stacked systems derived mostly from the lateral migration of a channel system. The depositional environment of these facies making up the reservoirs as inferred from their log curve shapes were discovered to be composed of sands generated mainly by (i) fluvial channel, (ii) barrier bar, (iii) lower-middle shoreface, (iv) distributary mouth bar, (v) distributary channel, (vi) point bar and (vii) tidal channels (See Figs. 2, 3, 4, 5, 6, 7, 8, 10, 11, and Tabs. 1, 2, 3, 4, 5, 6, 7 above). This suggests that the UK Field falls within the paralic environment and its reservoirs are concentrated within the Agbada Formation in the Niger Delta. The research discovered that the field-wide discontinuity of the processes that generated these facies, uneven-spread nature of the processes with their associated facies, faulting and the conditions under which they occurred are all responsible and accounted for the reservoir top lithologic uncertainties encountered within the UK Field in Niger Delta. Therefore, reservoir top lithologic uncertainty within the UK Field is geologically controlled. Both depositional systems and facies displacement during deposition assisted in creating syndepositional faulting. The duo gave rise to both stratigraphic and structural traps found within the UK Field. Analysis of the log suites indicated that the log motifs of the study area fall mostly into three categories of (i) funnel-shaped, (ii) bell-shaped and (iii) blocky/cylindrically-shaped logs (Figs. 10 and 11).

FUNNEL-SHAPED SUCCESSIONS

The funnel motif shows coarsening or cleaning upwards of reservoir sands and also a gradual movement away from low energy to higher energy regime of a depositional medium. The funnel shape which represents coarsening upward sequence facies is always marked by a gradational lower boundary and abrupt or sharp upper contact. The result of gamma-ray log analysis shows that the funnel-shaped succession log pattern occurred in reservoir sand C1 of well UK1, reservoir sands D2 and F2 of well UK2, reservoir sand C3 of well UK3, reservoir sands E4 and F4 of well UK4, reservoir sands A5 and C5 of well UK5, and reservoir sands E6 and F6 of well UK6. Most of the funnel-shaped GR logs identified in the study displayed smooth curves such as reservoirs F4, and C5 (Figs. 5 and 6) while others showed serration such as reservoirs F2, E4, A5, E6, F6 (Figs. 3, 5, 6, 7). These facies belong to the distributary mouth bar depositional environment (Fig. 10). Some of the reservoirs consisted of a combination curve shape, made up of a set of both minor thin blocky shapes stacked on top of a thick major basal funnel motif, a condition in which the reservoir's overall GR log shape still displays a funnel signature that represents gross coarsening upward sequence, such are found in reservoirs C1, D2 and C3 (Figs. 2, 3, 4). This group belongs to the shoreface (Lower - Middle) depositional

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environment (Fig. 11). This combination curve shape may indicate gradual changes or abrupt changes from one environment to another. The reservoirs are then said to be made up of sands of distributary mouth bar environment stacked on top of sands of shoreface environment (Figs. 10 and 11). The sand of this environment is referred to as hybrid sands. In an ideal world, facies analysis should be based on a detailed petrographic and sedimentological study of cores, but this method is not useful in regions, fields and situations where cores are not provided. Since cores of the UK Field were not available, the technique proposed by Selley (1985, 1998), Nanz and Wilson (1959) and Crain (2005) in the interpretation of the depositional paleo-environment of sand bodies from log motifs was strictly applied in this study.

Selley's (1998) methods reported that the environments of coarsening upward sequences can be classified as regressive barrier bars. Crain (2005) and, Nanz and Wilson (1959) proposed that a barrier bar sand unit is distinguished by a generally smooth funnel-shaped GR curve which is produced by homogenous sand increasing moderately in grain size upward and having a gradational lower contact and an abrupt upper contact. The gradation in grain size is most probably directly related to decreasing wave energy with increasing water depth. The wave and longshore currents that deposit barrier bars appear to be more constant and uniform than most other sand–depositing current systems. Etu-Efeotor (1997) proposed that funnel shape logs are products of beach sands, barrier bar sediments and stream bars which characterizes a deltaic environment. The interbeds of sand and shale are related in large part to the flood cycles, sand being deposited by the stronger currents of flood stages and silty clays by the weaker currents of low water stages (Nanz and Wilson, 1959).

BLOCKY/CYLINDRICALLY – SHAPED SUCCESSIONS

The blocky-shaped gamma ray log signature occurred in reservoirs A1, B1, D1, E1 of well UK1(Fig. 2), reservoirs A2, B2, C2, E2, G2, H2, I2 of well UK 2 (Fig. 3), reservoirs A3, B3, D3, F3 of well UK3 (Fig. 4), reservoirs A4, B4, C4, D4 of well UK4 (Fig. 5), reservoirs B5, D5 of well UK5 (Fig. 6), reservoirs A6, B6, D6 of well UK6 (Fig. 7) and reservoirs A8, B8 of well UK8 (Fig. 8). The blocky-shaped GR log is visualized same as boxcar log pattern in the context and application of this study. The depositional environment for this blocky/cylindrical/boxcar ranges from a tidal channel (Fig. 11) for smooth blocky shapes, to fluvial channel and barrier bar environments (Figs. 10 and 11) for serrate blocky shapes within deltaic systems. Consequently, the blocky-shaped GR log motifs are the most abundant diagnostic log signature within the UK Field, since it has the highest frequency across all the wells. The log is uniquely characterized by both abrupt upper and lower contacts that represent sharp stratigraphic facies' boundaries. The blocky/cylindrical/boxcar-shaped GR log displays the truncation or rapid termination of deposition at the upper and bottom demarcations. According to Selley (1985, 1998), boxcar–shaped successions can be deposited by three general categories of environments. The three environments include tidal sand wave, grain flow fill, and distributary channel. Since the second environment is associated with shell debris, we may exclude the possibility of the grain flow fill environment, and can infer that the paleoenvironment of the block-shape successions belongs to the tidal channel, fluvial channel and barrier bar within deltaic systems (Figs. 10 and 11). Blocky-shaped channel sand units are represented by smooth and serrate blocky-shape GR curves (Crain, 2005; Nanz and Wilson, 1959). The smooth cylinder-shaped GR indicates homogenous sand with an abrupt lower

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erosional contact and an abrupt upper contact as observed in reservoir sands A1, A2, B2, C2, E2, G2, H2, I2, A3, B3, F3, A4, D4, D5, A6 and B8. The serrate cylinder represents sand and shale interbeds with an abrupt lower erosional contact and an abrupt upper contact. Much of the deposition probably occurred at the bottom of the channel, and the formation of thick deposits was possible because of continuous subsidence during deposition. The fluvial distributary channel sand units which contain serrate blocky/cylinder-shaped GR curves were deposited in channels with non-uniform current velocities resulting in contiguous deposition of sands and silty clays as observed in reservoir sands D1, E1, C4, B5, B6 and A8. In UK Field of Niger Delta, some exceptionally rare cases exist where a generally smooth cylinder-shaped GR may have a very thin gradational upper boundary (reservoirs B1, D3, D6) and a very thin gradational base (reservoirs E1, B4) represented by a relatively thin termination zone of serrate bell-shaped GR development. Such a GR curve may represent tidal channel, barrier bar (Fig. 11), and fluvial channel (Fig. 10) depositions that are coincident with subsidence in the lower part and distributary fill due to abandonment in the upper part.

BELL – SHAPED SUCCESSIONS

The bell motif generally represents a fining upward sequence, dirtying upwards facies and gradual decline from high energy at the base to upward lower-energy condition. The gamma-ray log of reservoir sand E3 in well UK3 (Fig. 4), reservoir sand C6 in well UK6 (Fig. 7) and reservoir sand C8 of well UK8 (Fig. 8) shows bell motifs. Both reservoirs E3, C6 and C8 bell signatures displayed serrate curves. Reservoir C6 has an abrupt lower contact with gradational upper contact; while reservoir E3 differed by possessing thin gradational basal and thick gradational upper contacts. The depositional environment for both reservoirs E3 and C6 was inferred to be a distributary channel and point bar. Reservoir C8 has a thick blocky signature on top of its bell. This indicates fluvial facie channel deposits stacked on top of point bar facies (Fig. 10). The depositional environment of reservoir E3 in well UK3, C6 in well UK6 and C8 of well UK8 was inferred by comparing the gamma-ray log signature with standard log motifs. Facies of this type of environment starts with coarse grains at the transition base and proceeds with fine to very fine grains that indicate low to very low energy conditions towards the top. Combination curve shape, which may indicate gradual changes or abrupt changes from one environment to another or from one type of contact to another was observed in reservoir C6 of well UK6 and C8 of well UK8. There exists the development of thin blocky-shaped log signature within C6 and C8 reservoirs, which indicates an ingress of fluvial sand facies within distributary and point bar deposits (Fig. 10). The upper part of the C6 reservoir eventually continued building up and ended with sands that displayed gradual bell-shaped pattern at the top, which represents a fining upward sequence.

WELL LOG LITHOLOGIC CORRELATION

Lithologic correlation of the seven wells (UK1, UK2, UK3, UK4, UK5, UK6 and UK8) was carried out using their GR and resistivity logs that indicated facies of sand and sealing shales in the UK Field of Niger Delta. The GR log was primarily used for correlation while the resistivity was used to cross-check the accuracy of the result of the GR correlation within the same depth and interval. Resistivity log during correlation reveals hydrocarbon bearing zones within the sand facies hosting them. The correlation result of the two logs (Fig. 12) though presented on one correlation panel altogether shows an identical section nature for both. This indicates a high degree of resolution for the

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correctness of the correlation result. From the correlation result, there exists a good correlation among wells UK1, UK2, UK3, UK4, UK5 and UK6 due to good geological similarities but well UK8 failed to perfectly correlate with them (Fig. 12). There is a major fault running East-West in the UK Field that subdivided the UK Field into two major fault blocks and depo centres (Fig. 13). Each of the major fault blocks in UK Field also displayed streaks of minor faulting. Further analysis of the various well locations on the base map reveals that well UK8 is located on a different fault block and depo centre (Fig. 13). The correlation deduced that (i) facies on different fault blocks do not share the same stratigraphic make-up, and (ii) facies that occur within the same depo centre/fault block tend to be similar in their stratigraphy but different from facies of adjacent fault blocks. This may be probably due to different evolutionary processes and structural barriers. In UK Field, the minor and major faults truncated the even deposition of sedimentary facies, giving rise to both structural and stratigraphic traps within Agbada Formation in the UK Field. The correlation established the existence of stratigraphic reservoir top uncertainty within UK Field in the Niger Delta. This was observed in wells UK1 where facies of reservoir C are stacked together as one reservoir body (C1), whereas in UK2 the facies of reservoir C is split into two separate distinct reservoir bodies of C2 and D2 by a thick marker shale (Fig. 12). Same stratigraphic reservoir top uncertainty was observed in well UK5 where facies of reservoir B is missing. The facie was either probably not deposited due to discontinuity of the facies depositional process or may have been eroded by stronger fluvial processes that were active after it was deposited. The UK Field displayed the existence of strong genetic similarities across its facies. The seven wells contain reservoirs that are genetically and laterally equivalent throughout the study. The study recommends a proposal for closer drilling of new wells in between the older ones. The correlation panel showed how the surfaces correlated along dip and strike directions at certain depths within the UK Field depositional basin, thus depicting basin geometry and depositional sequences across the UK Field. The displayed correlation panel (Fig. 12) indicated that the stratigraphic column appears to be dipping in an N-S direction and striking in the E–W direction. Deposition of reservoir sand facies tends to be thicker in the north and thins out towards the south as seen in wells UK1, UK2, UK3 and UK4. The maker sealing shales in UK Field is simultaneously and gradually thinning out in the northerly direction and thickening in the southerly direction as seen in wells UK5, UK6 and UK8. This shows a shift from a top paralic environment to a pure basal marine depositional environment for UK Field.

CONCLUSION AND RECOMMENDATIONS

CONCLUSION

The study of the gamma-ray (GR) log response for the seven (7) wells in UK Field identified thirty-nine (39) reservoir sands. The facies encountered corresponded to the shoreline and deltaic environments. Facies examination shows that the paleoenvironments of the reservoir sands in UK Field belong to mostly (i) fluvial channel, (ii) barrier bar, (iii) lower-middle shoreface, (iv) distributary mouth bar, (v) distributary channel, (vi) point bar and (vii) tidal channels that belong to parts of a deltaic system. The research discovered that the depositional environments and reservoir sand facies of fluvial-distributary channel/barrier are the most abundant in the Agbada Formation of UK Field within the onshore Niger Delta basin. Three main log facies of funnel, blocky and bell-shapes were majorly recognized in the UK Field using the wireline logs from the wells. The research discovered that the field-wide discontinuity of the processes that generated the facies, uneven-spread nature of the processes with their associated facies and structural displacement of the geologic blocks were all responsible and accounted for the lithologic uncertainties encountered within the UK Field in the Niger Delta basin. Therefore, lithologic uncertainty within the UK Field is geologically controlled. From the correlation result, there exists a good correlation among wells UK1, UK2, UK3, UK4, UK5 and UK6 due to good geological similarities but well UK8 failed to perfectly correlate with them and therefore established the existence of lithologic uncertainty partly within UK Field in Niger Delta. The study recommends closer drilling of new wells in between the older ones due to reservoir top lithologic uncertainty and reservoir sand horizontal discontinuity. The research could not explore the use of core samples due to their non-availability and therefore recommends the use of core samples for future review of the depositional environments of the UK Field.

RECOMMENDATION

The research outcome on the depositional environment will be of invaluable aid to evaluating the environment of deposition and reservoir top uncertainty for wells within UK Field, Niger Delta Basin. The outcome can also be used for future projections on drilling challenges, lithologic correlation, economic viability, forecasting and production capabilities for new wells within UK Field and adjacent Fields.

Most of the challenges in the UK Field such as reservoir top lithologic uncertainty can be managed using high-resolution stratigraphic logs such as Oil base image log (OBIL), Magnetic Resonance Image log (M-RIL) to identify thin and unclean reservoirs.

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Authors' Contributions:

Dr. Uhuo Kenneth Friday: Carried out the Ph.D. research from which this paper was written based on new findings. He analyzed the data, interpreted and wrote the manuscript.

Prof. Okoro Anthony Uwaoma and Dr Igwe Ezekiel Obinna: Supervised, coordinated the research and read the manuscript.

Mr. Ukandu James Sunday: Also reviewed and made much technical inputs in the work.

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