Lithofacies and Paleoenvironmental Reconstruction of Wells A & B in Marginal Offshore Niger Delta Using Wireline Gamma Ray Log and Microscopic Grain Analysis

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Abstract

Varying sedimentary environments have led to diverse diagenetic pathways in Niger Delta basin. Integrating wireline gamma log and microscopic grain data analyses to reconstruct the lithofacies and paleoenvironmental conditions allows for a more comprehensive assessment of Well A and Well B, located in the marginal offshore Niger Delta. The gamma ray log provides log signatures of the well's for the identification of distinct lithofacies and depositional environments. Microscopic grain analysis, on the other hand, offers a detailed understanding of the sedimentary textures, composition, and paleoenvironment. By combining these two methods, we aim to: Identify and characterize the lithofacies present in Wells A & B, reconstruct the paleoenvironmental conditions and depositional settings of the wells, gain insights into the geological history and evolution of the Niger Delta. A total number of sixty (60) ditch cuttings from intervals 11140 – 12580 ft of well A and 11620 – 13570 ft of well B and gammar ray log data set were utilized for this study. Schlumberger's Petrel 2010 version software was used for processing the data. From the lithosections and the detailed lithostratigraphic description, the lithology shows siltstone with alternation of sand and shale. The shale is brown to grey in colour and moderately hard. The sand is also grey and whitish in colour. The shift from silt at 12,300ft to sandyshale (90% shale and 10% sand) at 11,800ft and back to sandstone at 11,400ft implies a transition from a low energy level such as lake where fine particles settle slowly out of suspension through a more slightly more energy environment such as marine or deltaic environment leading to the deposition of organic or marine material. Between 13,100ft to 12,400ft, there was an alternation of sand and silt and eventual deposition of sandyshale with 60% shale and 40% sand which also correspond with the gamma ray response having a serrated shape. The lithofacies and environment of deposition of Wells A & B revealed deltaic distributaries, lacustrine, fluvial flood plains and tidal channels which took place in a range of energy zones, from low to high. This demonstrates a wide range of deposition environments, from deltaic to shallow marine to fluvio-marine.

Keywords: Lithosections, well logs, lithofacies, paleodepositional environment

1. INTRODUCTION

Environmental reconstruction and sedimentary analysis are processes which need large range of data such as wireline logs, rock outcrop section, ditch cuttings, core samples, seismic data (Rouby *et al.,* 2011). Lithostratigraphic analysis has helped immensely in providing method of analyzing gross facie distribution and their relation to structure (Emery and Myers 1996). This has also helped to map and identify porosity distribution, lateral variation in permeability and the presence of internal impermeable barriers (Mathew *et al.,* 2020). The Niger Delta is a complex and prolific hydrocarbon province, with rich geological history shaped by various depositional environments and processes (Ameloko, *et al.,* 2019). Understanding the lithofacies and paleoenvironmental conditions of this

region is crucial for optimizing hydrocarbon exploration and production. This study focuses on Wells A & B, located in the Niger Delta, with the objective of reconstructing its lithofacies and paleoenvironmental history. To achieve this goal, we have integrated two complementary approaches: gamma ray log analysis and microscopic grain analysis. The gamma ray log provides a continuous record of the well's geological signature, allowing for the identification of distinct lithofacies and depositional environments. Microscopic grain size analysis, on the other hand, offers a detailed understanding of the sedimentary textures, composition, and paleoenvironmental conditions. By combining these two methods, we aim to: Identify and characterize the lithofacies present in Wells A & B, reconstruct the paleoenvironmental conditions and depositional settings of the wells, Gain insights into the geological history and evolution of the Niger Delta. This integrated approach will provide a comprehensive understanding of the Wells subsurface geology, ultimately supporting informed decisions in hydrocarbon exploration and production.

The gamma ray log is a record of a formation's radioactivity which emanates from naturally occurring uranium, thorium and natural potassium (Ameloko, *et al.,* 2019). Usually, Shales, organic rich shales, volcanic ash and mudstone contain high concentration of radioactive elements than any other sedimentary rocks with API value between 30-80 while clean sandstone, limestone, or dolomite, halite, anhydrites, coal has less than 30 API (typically 5-30 API). (Oluwajana 2019; (Johnson, *et al.,* 2023). Its main use is the discrimination of shale by their high radioactivity. (Johnson, *et al.,* 2023).
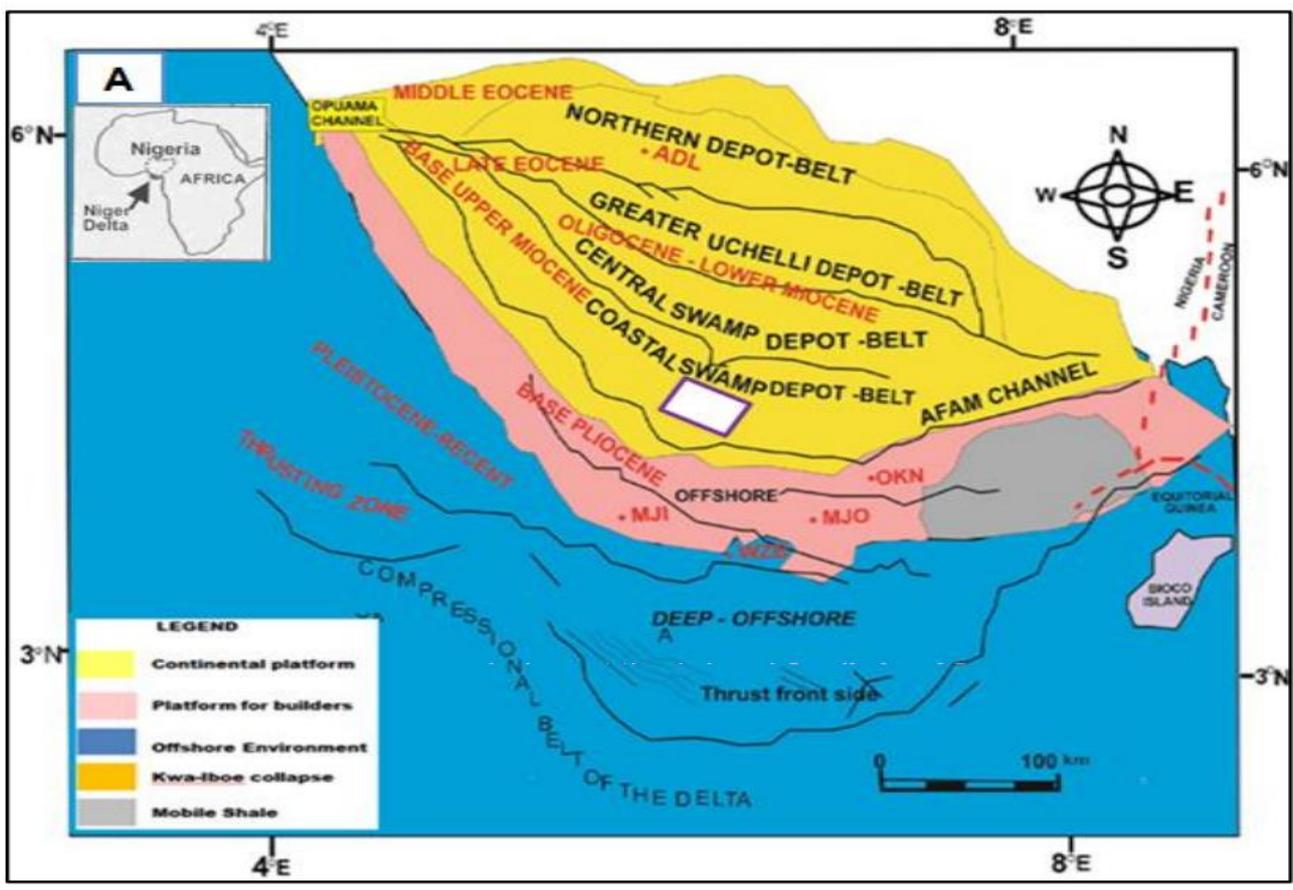
Fig. 1: Location of the study area. Simplified regional geological setting map of the Niger Delta basin, showing the different depobelts (Modified from Saugy and Eyer, 2003).

2. GEOLOGICAL SETTING

The Niger Delta basin (Fig. 1) is a wave dominated delta with a maximum thickness of 12km and an area of 75,000km^2. It is located at the upper part of the Gulf of Guinea on the West African continental margin regressive clastic sediments (Doust and Omatsola; Rouby *et al.,* 2011). The opening of the Gulf of Guinea, which created room for sediment buildup, was linked to the deposition in the Niger Delta Basin. The delta clastic wedge was created along a triple junction system's failing arm during the early Cretaceous breakup of Gondwana and ultimate separation of the African and South American plates (Whiteman, 1982; Ibe and Ezekiel, 2018).The deposition in the Niger Delta Basin was associated with opening of the Gulf of Guinea that produced accommodation space for sediment accumulation. The delta clastic wedge produced along a failed arm of a triple junction system which originally developed during the breakup of the Gondwana and the eventual separation of the South American and African plates in the early Cretaceous, (Whiteman, 1982; Ibe and Ezekiel, 2018). The southwestern and southeastern arms of the rift system then developed into the West Africa passive continental margin, and the third failed arm formed the Benue Trough (Nwajide, 2013). The southern basin of Nigeria has undergone three depositional cycles since its onset in early Cretaceous (Short and Stauble, 1967; Osokpor and Ogbe, 2019). The first phase of the cycle is the marine incursion in the pre-Albian that ended with a brief gentle folding phase in the Santonian age. The second cycle commenced with the growth of a proto-Niger delta in the Campanian age and terminated with a Paleocene marine transgression in the northern part of the delta (Whiteman, 1992; Nwajide, 2013) while the third depositional cycle started when the Cenozoic Niger Delta began to prograde southward in the late Paleocene to Recent time with an aggressive transportation of sediment by an extensive drainage system of the Niger-Benue river through the Anambra Basin north of Onitsha and to a lesser degree, the Calabar drainage system through the Afikpo Basin (Short and Stauble, 1967; Evamy et al., 1978; Etu-Efeotor, 1997; Nwajide, 2013). This prograding sedimentation of the delta resulted in the development of five offlapping depositional bodies known as depobelts, namely; Northern Delta; Greater Ughelli; Central Swamp; Coastal Swamp; and Offshore Depobelts, (Doust and Omatsola, 1990; Tuttle et al., 1999; Saugy and Eyer, 2003).

The stratigraphic fill of the Niger Delta basin is composed primarily of three lithostratigraphic units that extend across the whole delta (Obafemi *et al.,* 2020) (Fig. 2). These include basal marine pro-delta Akata Formation, the middle shallow-marine delta-front Agbada Formation and, the overlying youngest continental, delta plain Benin Formation (Doust and Omatsola 1990; Adojoh *et al.,* 2020). The Akata Formation, a prodeltaic lithofacies of Paleocene to Recent in age is composed primarily

of marine shales with turbidite sands and continental slope channel fills (Doust and Omatsola 1990). It is estimated to be up to 7 km thick and generally considered as the source rock of the Niger Delta. The middle paralic Agbada Formation, estimated to be over 3.7km thick and ranges in age from Eocene to Recent (Tuttle *et al.,* 1999; Avbovbo, 1978) is primarily composed of delta-front lithofacies and characterized by intercalations of sand and shale. The sandstone reservoirs facies within this formation are mostly shoreface and channel sands with minor shales in the upper part, and alternation of sands and shales in the lower part (Doust and Omatsola 1990). This unit serves as the hydrocarbon reservoir within the basin with sand percentage ranging from 30 to 70% (Doust and Omatsola 1990). The deltaic sequence is capped by the topmost Benin Formation that is Oligocene to Recent in age, about 2km thick and is made up of continental fluvial sands (Avbovbo 1978; Doust and Omatsola 1990; Owolabi et al. 2019). Adegoke *et al.,* (2017) described the formation as friable, white, fine to coarse and pebbly, poorly sorted sand with lignites occurring as thin streaks or as finely dispersed fragments.
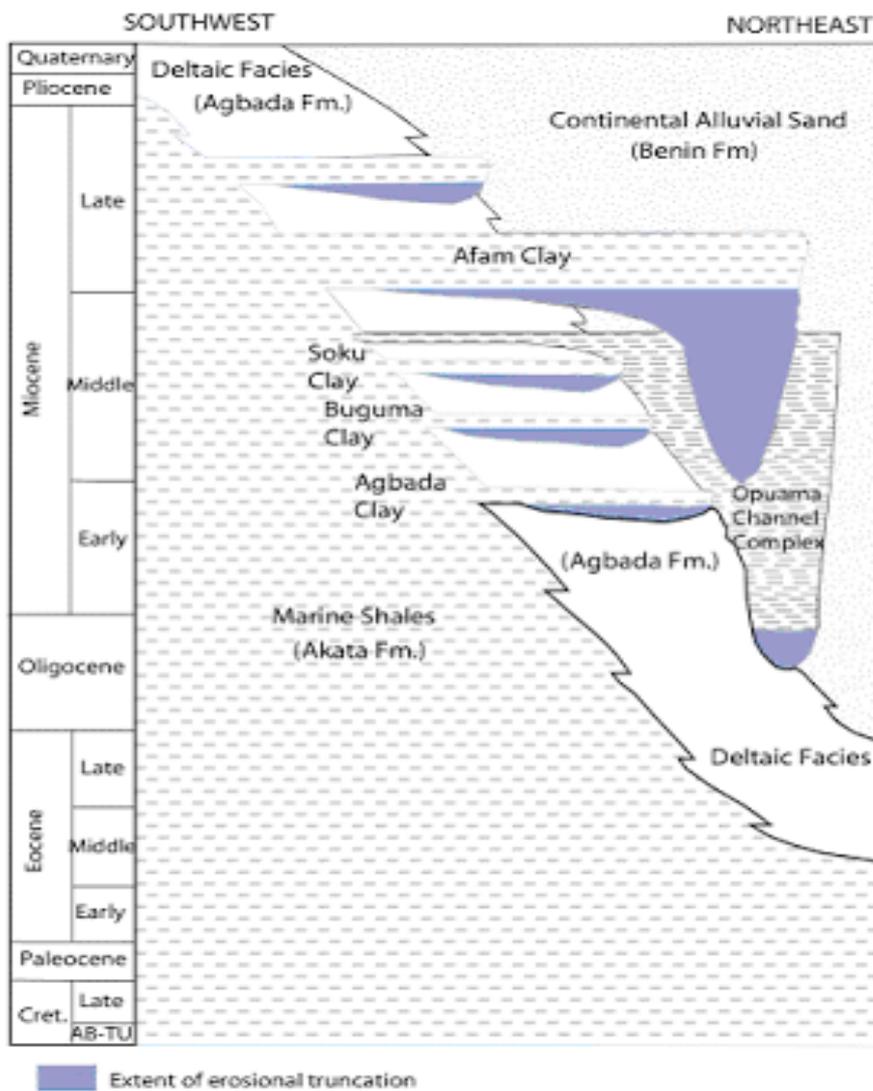

Fig. 2: Stratigraphic data sheet of the Niger Delta. Source: Adapted from Adegoke, et. al., 2017).

3. MATERIALS AND METHODS

3.1. Materials

A total number of sixty (60) ditch cuttings from intervals 11140 – 12580 ft. of well A and 11620 – 13570 ft. of well B collected at 40ft intervals drilled in the Niger Delta were utilized for this study. Other materials used includes; charts, microscope and camera, and computer software (Stratabug, Corel draw, Surfer and Microsoft Excel). Laboratory analysis were carried out in Crystal Age Laboratory Lagos and Novena University EPS laboratory Ogume.

3.2. Methods of Study

Microscopic Analyses: The samples were washed samples with water to free it from drilling mud and allowed to dry in an ambient temperature for 3 days. Thereafter, 50g of each samples was treated with one teaspoonful of anhydrous sodium carbonate for thorough disintegration, enough water was added to cover the samples and allow to stand for few hours. The sample was then sieved and dried in an oven for 60mins at 40^0C. Sedimentological analysis was carried out on the samples by visual inspection using binocular microscope and comparing it with a known standard. Physical characteristics such as colour, texture and sizes were noted taking into consideration published lithofacies description of the Niger Delta as well as lithofacies models of Webber and Daukoru (1975) and Whiteman (1982).

Wireline Log: Geophysical logs from two wells A and B were used for this study. Schlumberger's Petrel 2010 version software was used for processing the data. The two wells logs were placed against each other to facilitate correlation and assessment of data quality. The following techniques were adopted for the data analysis:

Lithology Identification: The gamma ray logs were used for lithology identification. Gamma ray log records the radioactivity of the formation encountered in the boreholes. Shale lithology is usually associated with high gamma ray radioactive response while sandstone lithology is associated with low gamma ray value. (Johnson, *et al.,* 2023; Jina, *et al.,* 2020). The gamma ray log is also used as measures for grain size and subsequently for inferring depositional energy. Thus coarse-grain sand, which contains little mud, will have low gamma ray value, while a fine mud will have a high gamma ray value.

Well Log Facies Identification: The shape of gamma ray log signatures is a basic tool for the interpretation of lithofacies and depositional environments. Four types of gamma ray trends or shapes

can be recognized when examining the log curves. The basic gamma ray log shapes are shown in Fig. 3. and they are as follows:

Funnel shape: This is a cleaning up trend and it represents a gradual upward decrease in gamma response. It is known as the prograding process and in deep water settings, this shape indicates an increase in sand contents (Johnson, *et al.,* 2023; Jina, *et al.,* 2020; Krassay, 1998). This shape also represents a gradual change from clastic to carbonate deposition. In shallow marine environments, this trend typically signifies a transition from shale-rich to sand-rich lithology, accompanied by an upward increase in depositional energy, characterized by shallowing-upward and coarsening.

Bell shape: This exhibits upward finning trend and it is a gradual upward increase in gamma ray response. It is known as a retrograding process (Jina, *et al.,* 2020; Krassay, 1998). This type of curve may reflect upward fining which is an indication of a lithology change from sand to shale. This trend is an indication of a decrease in depositional energy. In the deepwater environment, this curve reflects the waning of submarine fans and submarine channel that is reducing of sand content. In non-marine settings, upward fining predominates within meandering or tidal channel deposits, indicating a decrease in fluid velocity within a channel (coarser sediments at the base of the channel). In shallow-marine environments, this trend typically signifies upward deepening and a decrease in depositional energy (shoreline retreat) (Krassay, 1998; Alao *et al.,* 2013).

Cylindrical or Block shape: This type of trend is associated with low gamma ray value having sharp boundaries and no internal change. It is also known as an aggrading process. This type of curve is common in fluvial channel sands, turbidites and in a submarine canyon fill (Alao *et al.,* 2013).

Symmetrical trend: This type of trend is associated with a gradual decrease and then a gradual increase in gamma values (Abdel-fattah, *et al.,* 2022). It is an indication of a progradation, retrogradation of clastic sediments and a submarine fan. A change in the energy of deposition is also an indication in the environment of deposition (Abdel-fattah, *et al.,* 2022; Johnson, *et al.,* 2023; Jina, *et al.,* 2020; Krassay, 1998). Stability in the gamma ray curve is a result of little or no variation in the depositional environment. This characteristics of the gamma ray curve are also very important. The gamma ray may be smooth, serrated or complex. The nature of the upper and lower contacts of the curves is also very important in the interpretation (Krassay, 1998).

Shape	Smooth	Environments	Serrated	Environments
Cylindrical Represents uniform distribution		Aeolian dunes Tidal sands Fluvial channels		Deltaic distributaries Turbidites channels Proximal deep-sea fans
Bell shape Fining upwards sequences		Tidal sands Alluvial sands Braided streams Fluvial channels Point bars		Lacustrine sands Deltaic distributaries Turbidites channels Proximal deep-sea fans
Funnel shape Coarsing upward		Barrier bars Beaches Crevasse splays		Distributary mouth bars Delta marine fringe Distal deep-sea fans

Fig. 3: Gamma Ray Signatures with corresponding Depositional Environments (Alao *et al.,* 2013)

4. RESULTS AND DISCUSSION

4.1 Results

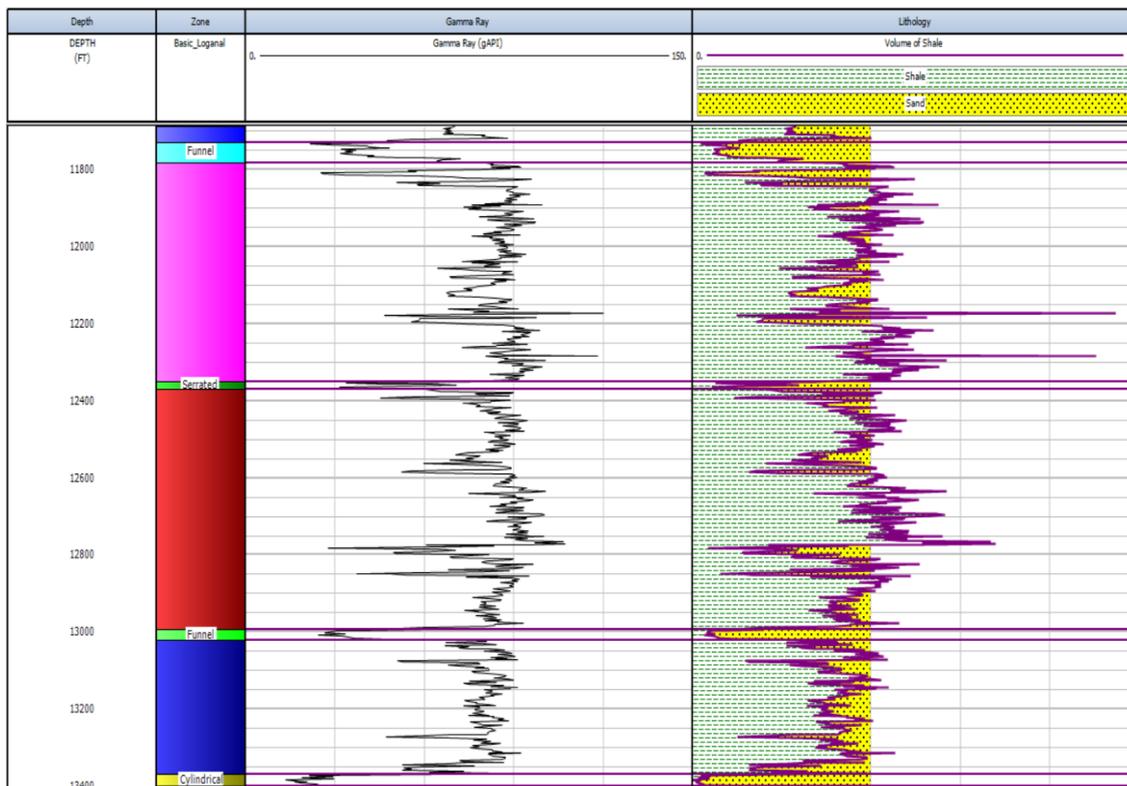Figures. 4 and 5 below show the gamma ray signature for well A.
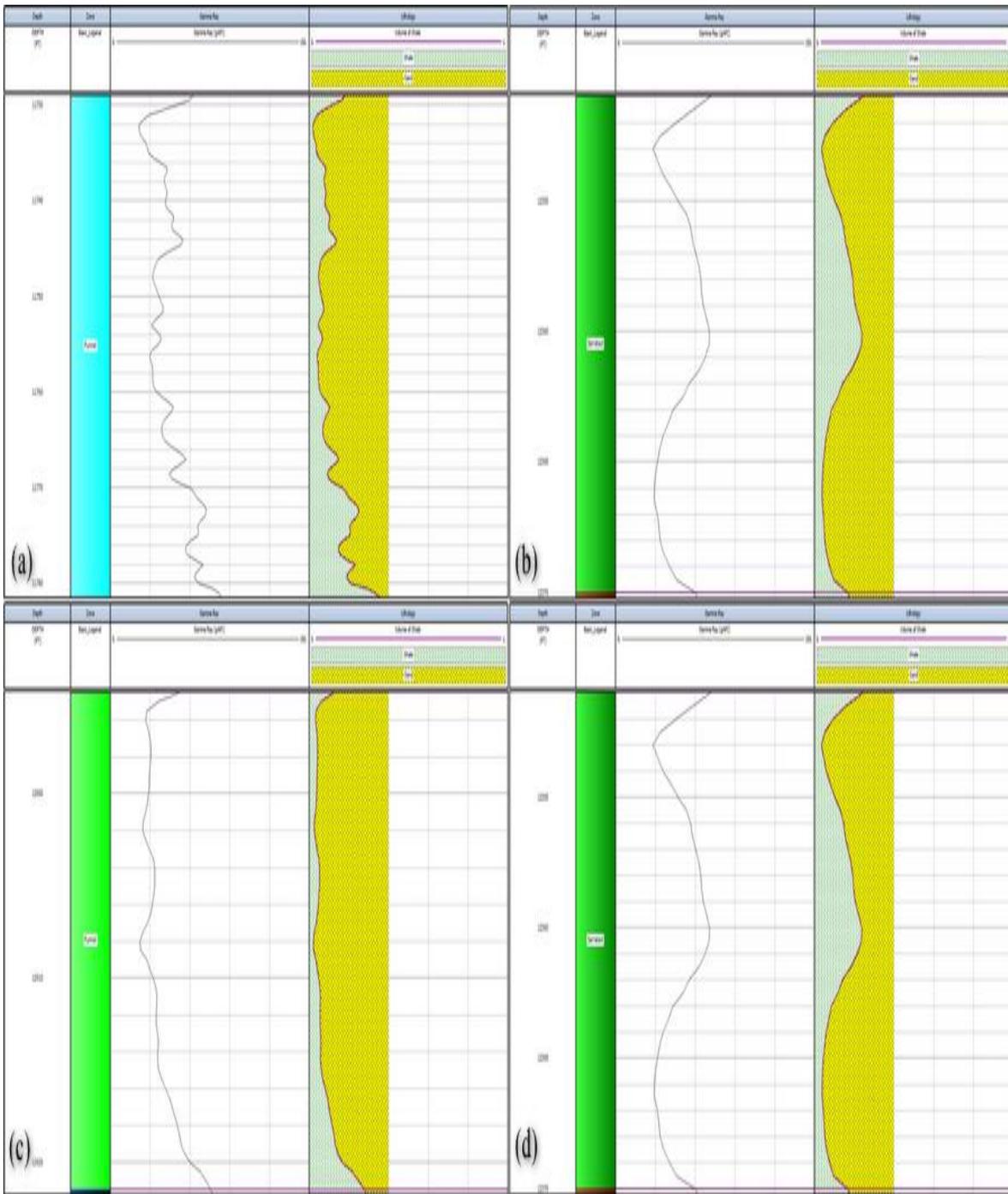

Fig. 4: Gamma ray log for Well A

Fig. 5: Sand units in well A

Table 1 and Figure 4 provided presents data from Well A, showing the various sand units, detailing various lithological formations and their corresponding Gamma Ray (GR) log responses and volume of shale.

Table 2 and Fig.6, highlighting the lithological formations in Well B, their corresponding Gamma Ray (GR) log responses, and volume of shale characteristics

Table1 Gamma Ray and Volume of Shale Characteristics of Lithological Formations in Well A

Well A		Curve	Gamma Ray	Volume of Shale
		Units	gAPI	
Funnel Sand 1	Top: 11729 ft,	Min	21.587	0.019
	Bottom: 11781.5 ft,	Max	84.136	0.358
	Net: 53 ft	Mean	45.620	0.106
Serrated Sand	Top: 12351 ft,	Min	28.026	0.035
	Bottom: 12370 ft,	Max	71.754	0.246
	Net: 19.5 ft	Mean	48.140	0.117
Funnel Sand 2	Top: 12994.5 ft,	Min	22.328	0.020
	Bottom: 13021.5 ft,	Max	75.992	0.281
	Net: 27.5 ft	Mean	36.630	0.068
Cylindrical Sand	Top: 13369.5 ft,	Min	12.805	0.000
	Bottom: 13400.5 ft,	Max	73.758	0.262
	Net: 31.5 ft	Mean	26.346	0.038

4.2. Gamma Ray Log Result Discussion for Well A

Funnel Sand 1: This lithological unit exhibits a coarsening upward trend, indicated by a gradual upward decrease in gamma response, as shown in Fig. 5a. In shallow marine environments, such a trend suggests a transition from shale-rich to sand-rich lithology, accompanied by an increase in depositional energy and shallowing-upward (Nelson *et al.,* 2021). The volume of shale decreases gradually from a mean of 0.106 to 0.019, reflecting the coarsening of the sediment.

Figures 6 and 7 below show the gamma ray signature for well B. *Serrated Sand:* Similar to Funnel Sand 1, Serrated Sand also shows a cleaning-up trend with a gradual decrease in gamma response, as shown in Fig. 5b. The volume of shale decreases from a mean of 0.117 to 0.035, indicating a shift towards sand-rich lithology and higher depositional energy.

Funnel Sand 2: This lithological unit displays a coarsening upward, consistent with the previous formations, as shown in Fig. 5c. The volume of shale decreases gradually from a mean of 0.068 to 0.020, suggesting a transition towards sand-rich lithology and increased depositional energy (Olatunbosun, *et al.,* 2019; Nelson *et al.,* 2021).

Cylindrical Sand: In contrast to the cleaning-up trend observed in the previous formations, Cylindrical Sand exhibits a boxcar trend characterized by low gamma and sharp boundaries with no internal change, as shown in Fig. 5d. This suggests a stable lithological composition, commonly

observed in fluvial channel sands, turbidites, and aeolian sands (Krassay, 1998; Alao *et al.,* 2013). The volume of shale remains relatively constant, indicating minimal variability in lithology.

The trends observed in the Gamma Ray log responses and volume of shale provide valuable insights into the lithological characteristics and depositional environments within Well A. The coarsening upward trends in the Funnel Sands suggest transitions towards sand-rich lithology and increased depositional energy, whereas the boxcar trend in the Cylindrical Sand indicates a stable lithological composition (Alao *et al.,* 2013).
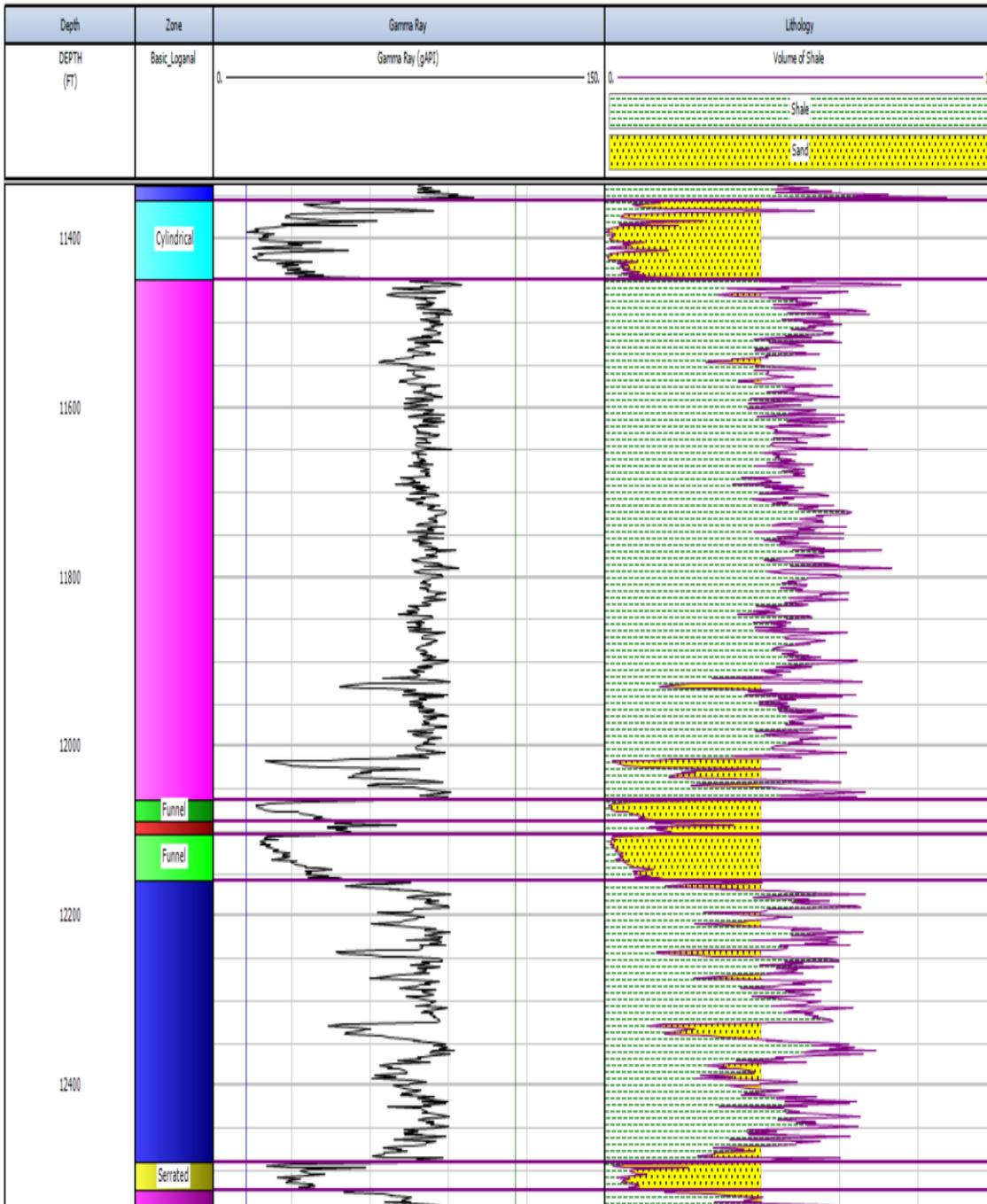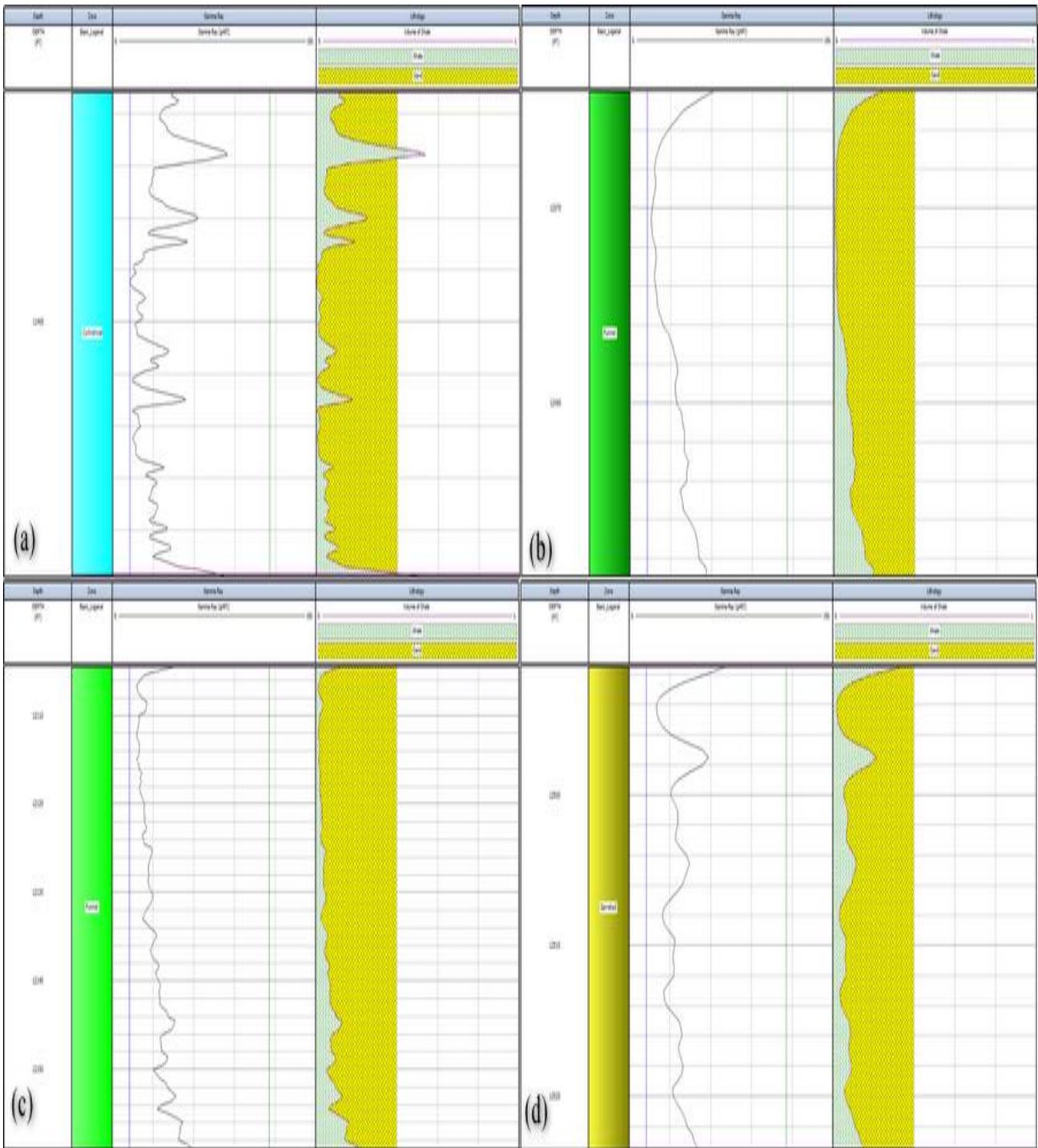

Fig. 6: Gamma ray log for Well B

Fig. 7: Sand units in Well B

4.3. Gamma Ray Log Result Discussion For Well B

Cylindrical Sand: This lithological unit exhibits a boxcar trend in the GR log, characterized by low gamma and sharp boundaries with no internal change as shown in Figure 4.6a. This indicates a stable lithological composition, commonly found in settings such as fluvial channel sands, turbidites, and aeolian sands (Krassay, 1998; Alao *et al.,* 2013). The volume of shale remains relatively constant across this formation, suggesting minimal variability in lithology and consistent depositional conditions (Alao *et al., 2013*).

Table 2 Gamma Ray and Volume of Shale Characteristics of Lithological Formations in Well B

Well B		Curve	**Gamma Ray**	**Volume of Shale**
		Units	gAPI	
Cylindrical	Top: 11356 ft,	Min	12.731	0.000
	Bottom: 11448.5 ft,	Max	84.384	0.537
	Net: 93 ft	Mean	32.642	0.078
Funnel 1	Top: 12064 ft,	Min	15.711	0.007
	Bottom: 12089 ft,	Max	61.413	0.240
	Net: 25.5 ft	Mean	32.248	0.069
Funnel 2	Top: 12104.5 ft,	Min	17.730	0.012
	Bottom: 12159 ft,	Max	59.542	0.224
	Net: 55 ft	Mean	30.578	0.059
Serrated	Bottom: 12491.5 ft,	Min	20.002	0.018
	Top: 12523.5 ft,	Max	70.349	0.333
	Net: 32.5 ft	Mean	36.230	0.083

Funnel Sand 1 and Funnel Sand 2: Both lithological units display a coarsening upward trend in the GR log, indicated by a gradual upward decrease in gamma response as shown in Figure 4.6b and 4.6c. This trend typically signifies a transition from shale-rich to sand-rich lithology and is associated with increased depositional energy and shallowing-upward features (Olatunbosun, *et al.,* 2019; Nelson *et al.,* 2021). The volume of shale decreases gradually in both formations, reflecting the transition towards sand-rich lithology and higher depositional energy.

Serrated Sand: Similar to Funnel Sand formations, Serrated Sand also shows a cleaning-up trend in the GR log, suggesting a transition towards sand-rich lithology and increased depositional energy, as shown in Figure 4.6d. The volume of shale decreases gradually, further supporting the shift towards sand-rich lithology and higher depositional energy.

The trends observed in the GR log responses and volume of shale provide valuable insights into the lithological characteristics and depositional environments within Well B. The cleaning-up trends in the Funnel Sands indicate transitions towards sand-rich lithology and increased depositional energy, while the boxcar trend in the Cylindrical Sand suggests a stable lithological composition (Jina*, et al.,* 2020).

4.4. Lithostratigraphic Results Discussion

From the lithosection A in fig. 4.1 and the detailed lithostratigraphic description, the lithology shows siltstone with alternation of sand and shale. The shale is brown to grey in colour and moderately hard.

The sand is also grey and whitish in colour. This formation can be referred to as Agbada formation owing to the alternation of sand and shale (Short and Stauble 1967). The sand stone is fine to medium grained and are unconsolidated. The alternation of sandstone and shale are as a result of sediment supply causing transgression and regression (Short and Stauble 1967).
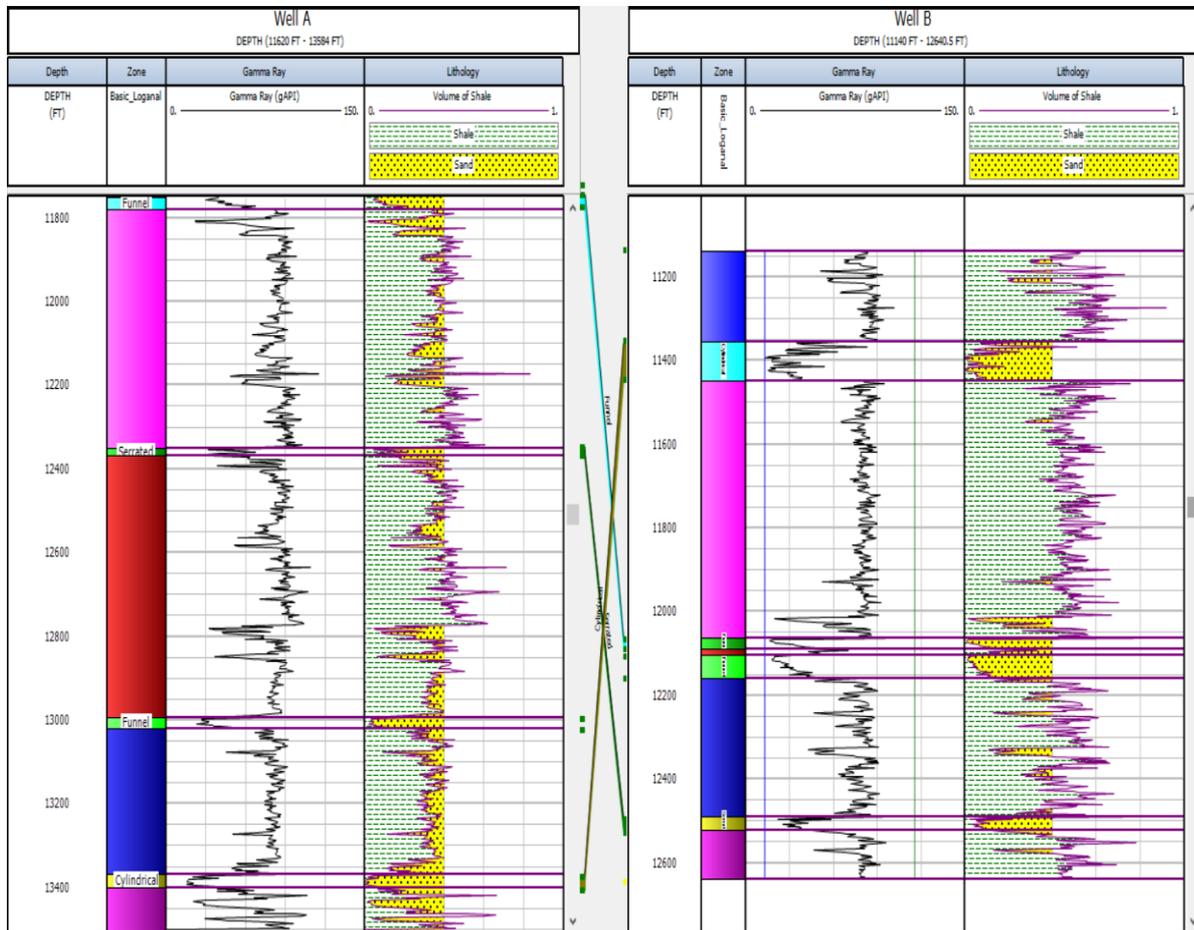

Fig. 8. Well tie for Well A and B

Fig. 8: shows well ties based on Gamma Ray responses, three types of variations were identified based on the grain size, as Funnel, Serrated and Cylindrical, with the Funnel shape been the predominate shape within the two wells.

Lithostratigraphic Units: The lithostratigraphic section of the wells are based on results of analysis and description of ditch cutting samples and information gathered from microscopic analysis. The lithologies are mainly sandstone, shale and siltstone.
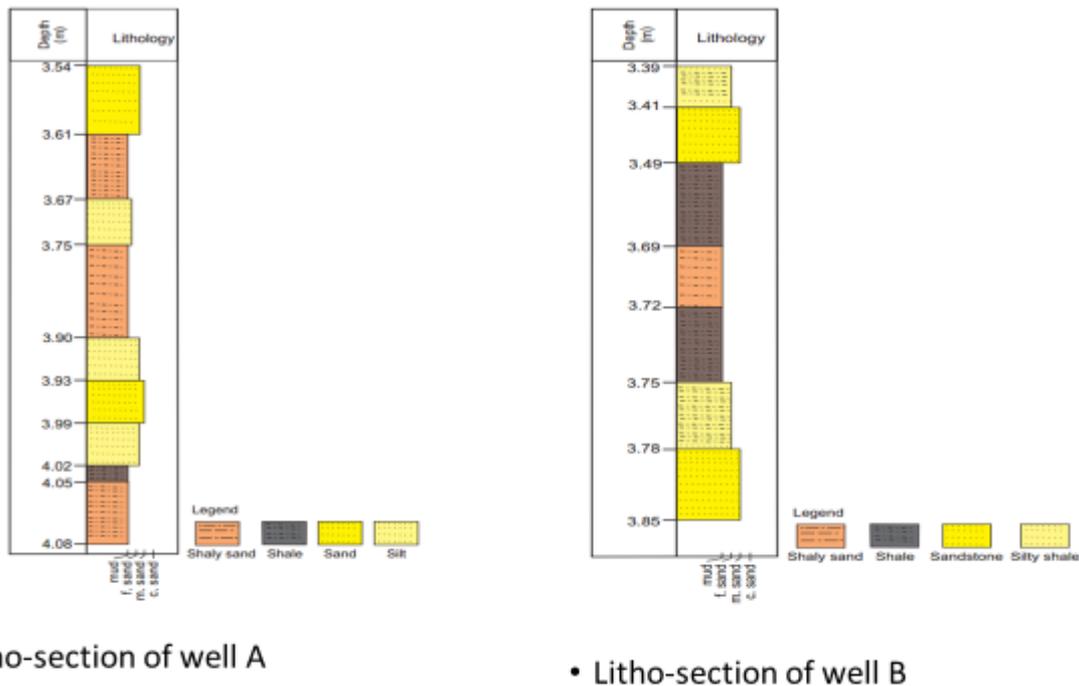
Fig. 9: Lithosections of well A and Well B.

From the litho-section A in Figure 9a and the detailed lithostratigraphic description, the shift from silt at 12,300ft to shaly sand (90% shale and 10% sand) at 11,800ft and back to sandstone at 11,400ft implies a transition from a low energy level such as lake where fine particles settle slowly out of suspension through a more slightly more energy environment such as marine or deltaic environment leading to the deposition of organic or marine material (Short & Stauble 1967). The transition back to sandstone could be due to increased sediment supply or change in sediment transport dynamics (Short & Stauble 1967). This variation also correspond with the gamma ray log of well A in Fig 4a funnel sand 1 where the lithological unit exhibits a cleaning up trend indicated by gradual upward decrease in gamma response. This suggest a transition from shale rich to sand rich lithology (Krassay 1998).

Between 13,100ft to 12,400ft, there was an alternation of sand and silt and eventual deposition of sandyshale with 60% shale and 40% sand which also correspond with the gamma ray response having a serrated shape. This indicate a stable environment possibly lacustrine (Krassay 1998). At the base from 13,400ft to 13,300ft, there is sandyshale with shale on top from 13,300ft to 13,250ft and an eventual deposition of silt from 13,250ft to 13,100ft. This lithology correspond with the cylindrical shape observed from the gamma ray log at the same depth.

For the litho-section B in fig. 8b, it has almost similar lithology with fig.8a with shale, silt and sand as its lithology. From the base, about 13,350ft, we have sand deposit which gradually shifted to silt and finally shale with intercalation of silt at a depth of 12,400ft. this suggest a transition or influx of marine deposit. When correlated with well A, they have similar lithologic character and concides with

the gamma log having cylindrical-serrated shape at same depth. At the upper part of the litho-section 12,100ft, there is a shift from shale to silt and sand which suggest a change in environmental conditions towards a higher energy environment. Since shale is deposited in low energy environment such as deep marine or lake bottom while silt and sand are associated with high energy. The shift from shale could indicate change in sediment supply leading to the deposition of coarser grains.

5. CONCLUSIONS

The lithofacies and environment of deposition of wells A and B have been described. The study area is within the Agbada formation owing to the alternation of sand and shale interpreted from the gamma ray logs in the study area. Four sand bodies were identified from the gamma ray log. The gamma ray curves and the stacking patterns of the logs were used to characterize and interpret the depositional environment. This study has further emphasized the importance of the gamma ray logs in lithofacies and depositional environment analysis. The shale is brown to grey in colour and moderately hard. The sand is also grey and whitish in colour. The shift from silt at 12,300ft to sandyshale (90% shale and 10% sand) at 11,800ft and back to sandstone at 11,400ft implies a transition from a low energy level such as lake where fine particles settle slowly out of suspension through a more slightly more energy environment such as marine or deltaic environment leading to the deposition of organic or marine material. Between 13,100ft to 12,400ft, there was an alternation of sand and silt and eventual deposition of sandyshale with 60% shale and 40% sand which also correspond with the gamma ray response having a serrated shape. This indicate a stable environment possibly lacustrine. The lithofacies and environment of deposition of Wells A & B revealed that the environment of sediments deposition includes deltaic distributaries, lacustrine, fluvial flood plains and tidal channels which took place in a range of energy zones, from low to high. This demonstrates a wide range of deposition environments, from deltaic to shallow marine to fluvial settings.

DECLARATION OF INTEREST

Authors have declared that no competing interests exist.

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