Lithologic Characterization of Subsurface Formations Using Well Logs in X Field, Niger Delta, Nigeria

Abeki J. P[1], Egeni Emiyenjuseigha[2]

[1,2] Department of Physics, Niger Delta University, Wilberforce Island, Bayelsa State, Nigeria

ABSTRACT

Lithologic characterization of subsurface formations plays a crucial role in hydrocarbon exploration and effective reservoir evaluation, as it provides insight into the distribution, composition, and properties of underground rock units. In this study, an integrated analysis of gamma ray (GR), spontaneous potential (SP), and resistivity (RT) logs obtained from Well TM-2 (SSTVD) in the X Field of the Niger Delta was carried out to identify lithologic units and delineate potential reservoir zones. The interpretation of these logs reveals a sequence of alternating sandstone and shale layers within the Agbada Formation, which is the principal hydrocarbon-bearing unit in the region. The sandstone intervals are distinguished by relatively low gamma ray readings and high resistivity values, suggesting clean, porous formations with significant hydrocarbon potential due to the reduced conductivity of hydrocarbons. In contrast, shale units exhibit high gamma ray responses and low resistivity values, reflecting their clay-rich composition and low permeability, which makes them effective sealing rocks. the main reservoir interval was clearly identified between depths of 300 ft and 500 ft, where the log signatures indicate favourable conditions for hydrocarbon accumulation. Furthermore, the analysis of log motifs provides valuable information on the depositional environment, with patterns indicating progradational (coarsening upward), retro gradational (fining upward), and aggradational (uniform deposition) sequences, reflecting variations in sediment supply and basin dynamics over time. Overall, the study highlights the reliability and effectiveness of integrated well log interpretation in accurately identifying lithologic units, evaluating reservoir quality, and understanding depositional processes, thereby reinforcing its importance as a fundamental tool in petroleum exploration and development within the Niger Delta Basin.

KEYWORDS

Well logs, Gamma ray, Resistivity, Lithology, Niger Delta, Reservoir

I. INTRODUCTION

The characterization of subsurface formations using well logs remains a cornerstone of petroleum geophysics, providing critical insights into the physical and petro physical properties of rocks encountered during drilling operations. Well logging techniques generate continuous in-situ records that enable geoscientists to evaluate lithology, identify fluid types, and interpret stratigraphic sequences with a high degree of resolution. These logs are indispensable tools in reservoir characterization, as they allow for the delineation of productive zones and the assessment of formation properties such as porosity, permeability, and fluid saturation. Among the various logging tools, the gamma ray log is widely used for lithological discrimination, as it measures the natural radioactivity of formations and effectively distinguishes shale-rich intervals from cleaner sandstones, which typically exhibit lower radioactive content. In addition, resistivity logs play a crucial role in identifying hydrocarbon-bearing formations by measuring the resistance of rocks to electrical current; hydrocarbon-filled reservoirs generally exhibit higher resistivity compared to water-saturated zones. The spontaneous potential (SP) log further complements these measurements by detecting electrochemical differences between borehole fluids and formation waters, thereby aiding in the identification of permeable zones and lithologic boundaries (Buryakovsky et al., 2012).

In the context of the Niger Delta Basin, one of the most prolific hydrocarbon provinces globally, well log analysis is particularly important due to the basin's complex depositional history and thick sequences of interbedded sands and shales. These heterogeneities, resulting from deltaic sedimentation processes, necessitate precise lithologic and petrophysical characterization to optimize hydrocarbon exploration and production. Consequently, accurate interpretation of well logs significantly enhances reservoir management strategies and supports efficient resource exploitation in the region (Tuttle et al., 1999).

II. GEOLOGICAL SETTING

The Niger Delta Basin is stratigraphically composed of three major lithostratigraphic units: the Akata, Agbada, and Benin Formations, each representing distinct depositional environments and playing unique roles in the petroleum system (Doust and Omatsola, 1990). The Akata Formation, which forms the basal unit of the basin, is predominantly made up of thick marine shales deposited in deep offshore settings. These organic-rich shales serve as the principal source rock for hydrocarbon generation, owing to their high total organic content and favorable burial conditions. Overlying the Akata Formation is the Agbada Formation, which is characterized by alternating sequences of sandstones and shales deposited in paralic (transitional) environments such as delta fronts, distributary channels, and shallow marine settings.

This formation constitutes the primary reservoir unit within the basin, as its sandy intervals typically exhibit good porosity and permeability, making them suitable for hydrocarbon accumulation and production. The interbedded shale layers within the Agbada Formation also act as effective seals, creating favorable conditions for trapping hydrocarbons. The uppermost unit, the Benin Formation, consists mainly of continental sands and gravels deposited in fluvial and alluvial environments. These sediments are generally coarse-grained, highly porous, and water-bearing, thus serving primarily as an aquifer rather than a hydrocarbon reservoir (Reijers et al., 1997). Due to its significant reservoir properties and its central role in hydrocarbon accumulation, this study specifically focuses on the Agbada Formation. Its complex alternation of sand and shale layers requires detailed petrophysical evaluation to accurately delineate reservoir quality, fluid distribution, and overall hydrocarbon potential within the Niger Delta Basin.

Figure 1. Map of the study area GIS-produced map (ArcGIS/QGIS style)

III. MATERIALS AND METHODS

A. Data Acquisition

Well log data obtained from Well TM-2 (SSTVD) formed the primary dataset for this study, providing essential subsurface information for lithologic and petrophysical evaluation. The logs utilized include gamma ray (GR), spontaneous potential (SP), and resistivity (RT), which are standard tools in petroleum geophysics for reservoir characterization. These logs offer continuous records of formation properties along the wellbore and are widely applied in identifying lithology, fluid content, and permeability trends within sedimentary basins. The gamma ray log records the natural radioactivity of formations and is particularly effective in differentiating shale from non-shale lithologies. Shale formations typically exhibit high gamma ray readings due to the presence of radioactive elements such as potassium, thorium, and uranium, whereas clean sandstones generally show lower values.

B. Log Interpretation

Lithologic interpretation in this study was primarily based on the gamma ray response, where a cut off value was applied to distinguish between sand and shale intervals. Intervals with low GR values were interpreted as sand bodies, which are potential reservoir units, while high GR values were classified as shale, often acting as seals or non-reservoir zones (Harris et al., 1999). In addition, resistivity logs were employed to evaluate the fluid content within the identified lithologic units. Hydrocarbon-bearing formations typically exhibit higher resistivity compared to water-saturated zones due to the non-conductive nature of hydrocarbons. Therefore, zones with relatively high resistivity values were interpreted as potential hydrocarbon reservoirs. The spontaneous potential (SP) log was used to identify permeable formations and delineate lithologic boundaries. The SP log responds to electrochemical differences between drilling mud and formation water, producing characteristic deflections in permeable zones such as sands. By integrating GR, SP, and resistivity logs, a more reliable interpretation of subsurface lithology and reservoir potential was achieved, enhancing the overall accuracy of formation evaluation in Well TM-2(Harris et al., 1999).

IV. RESULTS AND DISCUSSION

A. Lithologic Units

The lithologic analysis of the studied interval within the Niger Delta Basin reveals a characteristic alternation of sandstone and shale sequences, typical of the Agbada Formation’s paralic depositional environment. This interbedded pattern reflects fluctuations in depositional energy associated with deltaic processes, where sands are deposited in higher-energy settings such as channels and distributary mouths, while shales accumulate in lower-energy environments like floodplains and offshore zones. The sandstone units are clearly distinguished by relatively low gamma ray (GR) values, indicating minimal shale content, and are further supported by moderate to high resistivity readings, which suggest low water saturation and possible hydrocarbon presence. In contrast, shale units exhibit high gamma ray responses due to their radioactive mineral content and generally show low resistivity values, reflecting their conductive nature and poor reservoir quality. These lithologic variations are consistent with established interpretations of clastic sequences in the Niger Delta and similar sedimentary basins.

B. Reservoir Identification

Reservoir identification within the studied well interval highlights the main hydrocarbon-bearing zone between 300 ft and 500 ft. This interval is characterized by a combination of low gamma ray values, high resistivity readings, and moderate spontaneous potential (SP) deflection. The low GR values confirm the presence of relatively clean sandstone with minimal shale intercalation, while the elevated resistivity suggests the likelihood of hydrocarbon saturation, as hydrocarbons are poor conductors of electricity compared to formation water. Additionally, the moderate SP deflection indicates good permeability, which is essential for fluid flow within the reservoir. The integration of these log responses strongly suggests that this interval represents a clean, porous, and permeable sandstone unit with significant hydrocarbon potential. Such zones are principal targets for exploration and production, as they offer favourable conditions for hydrocarbon accumulation, storage, and extraction within the Agbada Formation.

C. Log Interpretation Panel

Figure 2 and3 presents a comprehensive multi-track petro physical log panel used for detailed lithologic and reservoir interpretation within the Niger Delta Basin. The panel integrates gamma ray (GR), resistivity (RT), and spontaneous potential (SP) logs alongside an interpreted lithology column, providing a holistic view of subsurface characteristics. This type of integrated log display is essential in petroleum geophysics, as it allows for the correlation of different physical properties and enhances the accuracy of formation evaluation. The gamma ray log serves as the primary indicator of lithology, distinguishing between shale and sandstone based on natural radioactivity levels. Low GR values correspond to cleaner sand units, while high values indicate shale-rich intervals. In the presented panel, the interval between 300 ft and 500 ft is clearly defined by consistently low gamma ray readings, suggesting a dominantly sandy lithology with minimal shale content.

The resistivity log further strengthens this interpretation by showing elevated resistivity values within the same interval, which is typically indicative of hydrocarbon saturation. Since hydrocarbons are poor electrical conductors compared to saline formation water, zones with high resistivity are often associated with oil or gas accumulation. The spontaneous potential (SP) log complements these observations by exhibiting moderate deflection within the reservoir interval, which signifies the presence of permeable formations capable of fluid movement. The combined response of low GR, high RT, and noticeable SP deflection strongly supports the identification of a clean, porous, and permeable sandstone reservoir. The shaded section in Figure 2 highlights this main hydrocarbon-bearing zone, emphasizing its significance for exploration and production. Overall, the multi-track log panel provides a clear visualization of lithologic variations and reservoir properties, enabling a reliable interpretation of subsurface formations and facilitating informed decision-making in reservoir development.

D. Depositional Environment

The depositional environment of the studied interval can be effectively interpreted through log motif analysis, which examines the shapes and trends of gamma ray log signatures to infer sedimentary processes. In the Niger Delta Basin, such analyses are particularly valuable due to the basin's complex deltaic system characterized by fluctuating sediment supply and energy conditions. Three principal log motifs are identified in this study: funnel-shaped, bell-shaped, and cylindrical patterns, each representing distinct depositional settings. Funnel-shaped patterns, characterized by a progressive decrease in gamma ray values upward, indicate coarsening-upward sequences typically associated with pro gradational environments such as delta fronts or advancing shorelines. These sequences suggest an increase in depositional energy over time, resulting in the accumulation of coarser sediments like sand.

Conversely, bell-shaped patterns display an upward increase in gamma ray values, reflecting fining-upward sequences that are indicative of retro gradational settings. These environments are commonly associated with channel abandonment or transgressive phases, where energy conditions decrease and finer sediments such as silt and clay are deposited. Cylindrical or blocky patterns, on the other hand, represent relatively uniform gamma ray values throughout the interval and are interpreted as aggradational deposits.

These typically form in stable depositional conditions such as distributary channels or point bars, where sediment supply and energy levels remain relatively constant over time. The presence of these diverse log motifs within the study area highlights the dynamic nature of sedimentation in the Niger Delta, controlled by variations in sea level, sediment influx, and tectonic influences. Collectively, these patterns provide valuable insights into the stratigraphic architecture and reservoir distribution within the basin.

E. Porosity and Compaction

Porosity variation with depth is a critical factor in reservoir evaluation, as it directly influences the storage capacity and productivity of hydrocarbon-bearing formations. In sedimentary basins such as the Niger Delta Basin, porosity generally decreases with increasing depth due to the effects of compaction and diagenesis. As sediments are progressively buried, the overburden pressure increases, causing grains to rearrange into a tighter packing configuration and expelling pore fluids. This process leads to a reduction in pore space and, consequently, a decline in porosity. The rate of porosity reduction, however, varies depending on lithology, grain size, and mineral composition.

Shale formations tend to exhibit a more rapid decrease in porosity compared to sandstones due to their finer grain size and higher compressibility. The clay minerals in shales are more susceptible to compaction, resulting in significant pore collapse even at relatively shallow depths. In contrast, sandstones, which are composed of coarser and more rigid grains such as quartz, retain their pore structure more effectively under increasing pressure. As a result, sandstones generally maintain better reservoir quality at greater depths compared to shales. Additionally, diagenetic processes such as cementation and dissolution can further modify porosity by either reducing pore space through mineral precipitation or enhancing it through the removal of soluble materials.

According to Olowokere and Ojo (2011), the interplay between compaction and diagenesis plays a crucial role in determining the ultimate reservoir quality of sedimentary formations. Understanding these processes is therefore essential for accurate prediction of reservoir performance, particularly in deeply buried sequences where porosity preservation becomes increasingly critical for hydrocarbon exploration and production.

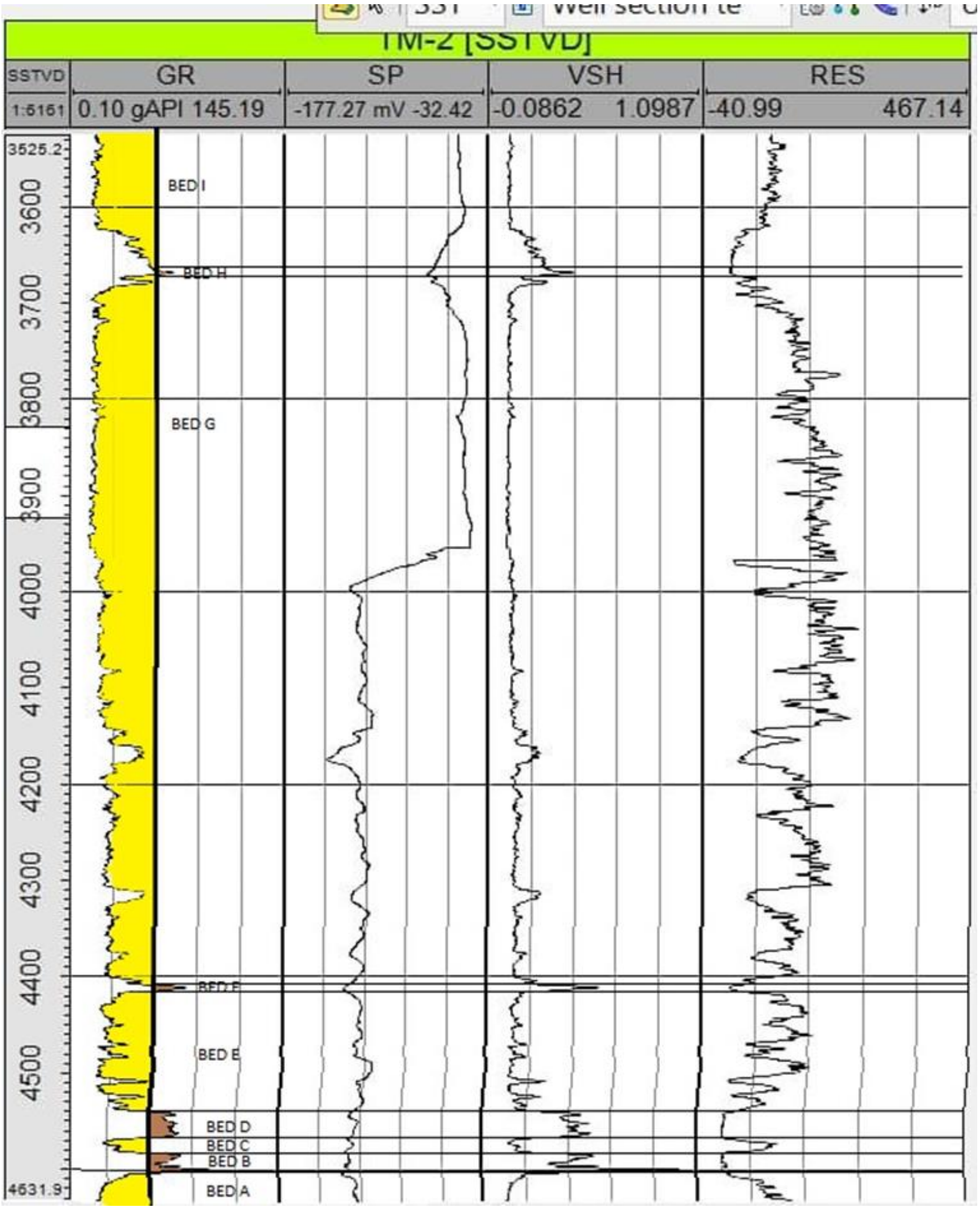

Figure 2: The well top Gamma ray, Spontaneous Resistivity, Volume of Shale and Resistivity logs from Well TM-2 (SSTVD)

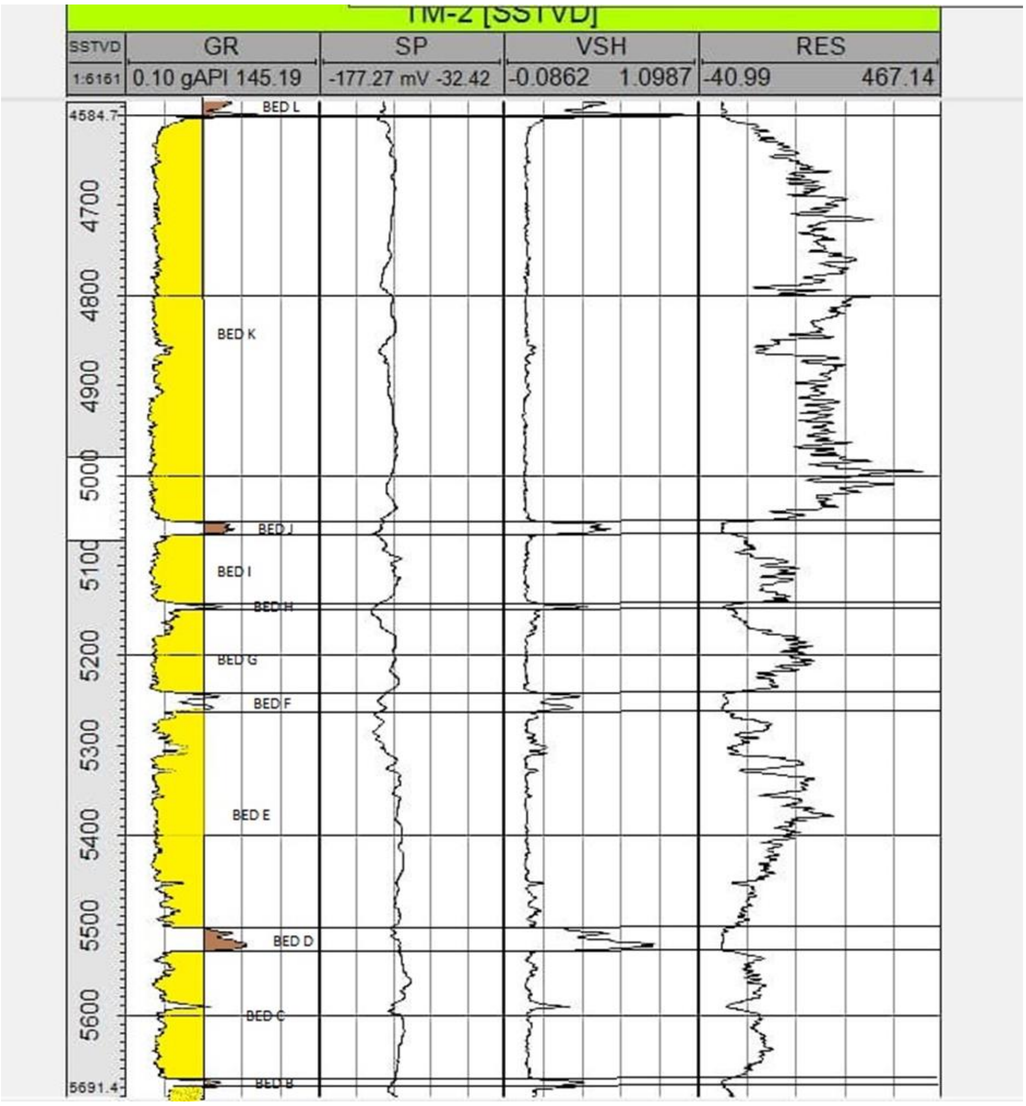

Figure 3: Gamma ray, Spontaneous Resistivity, Volume of Shale and Resistivity logs from Well TM-2 (SSTVD)

Table 1: Description of Lithologies from Well TM-2 (SSTVD) in X Field within the Agbada Formation, Niger Delta Basin

Upper Interval

Beds	Lithology	Thickness (ft)	Environment	Interpretation
L	Shale	20	Shallow marine	Thin impermeable shale layer with low SP and resistivity, and high Vsh.
K	Sand	450	Cylindrical	Thick sandstone with low Vsh, moderate SP (moderate permeability), and high resistivity indicating hydrocarbons.

J	Shale	30	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
I	Sand	60	Cylindrical	Sandstone with low Vsh, moderate SP, and variable resistivity indicating oil and water presence.
H	Shale	20	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
G	Sand	30	Bell-shaped	Fining-upward sandstone with low Vsh, moderate SP, and variable resistivity (oil/water).
F	Shale	30	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
E	Sand	240	Cylindrical	Sandstone with low Vsh, moderate SP, and variable resistivity (oil/water).
D	Shale	30	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
C.	Sand	130	Cylindrical	Sandstone with low Vsh, moderate SP, and low resistivity indicating water saturation
B	Shale	10	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
A	Sand	11.44	Thin sand layer	Thin sand unit with limited reservoir significance.

Lower Interval

Beds	Lithology	Thickness (ft)	Depositional Environment	Interpretation
I	Sand	25.2	Funnel-shaped	Coarsening-upward sandstone with low Vsh, high SP (high permeability), and low resistivity (water-bearing).
H	Shale	10	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
G	Sand	750	Cylindrical	Thick sandstone with low Vsh, variable SP (low–high permeability), and variable resistivity indicating oil and water.
F	Shale	10	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
E	Sand	120	Serrated	Sandstone with low Vsh, low SP (low permeability), and low resistivity (water-bearing).
D	Shale	20	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.
C	Sand	20	Funnel-shaped	Thin coarsening-upward sandstone with low Vsh, low SP, and low resistivity (water-bearing).
B	Shale	20	Shallow marine	Thin impermeable shale with low SP and resistivity, high Vsh.

A	Sand	30	Aggrading sand	Thin sandstone with low Vsh, low SP (low permeability), and low resistivity (water-bearing).

The table presents a detailed lithologic description of Well TM-2 within the Agbada Formation in the Niger Delta Basin, highlighting the vertical distribution of sand and shale units across upper and lower intervals. The sequence is characterized by alternating sandstone and shale layers, which is typical of deltaic environments. Shale units are generally thin, laterally continuous, and interpreted as shallow marine deposits with high shale volume (Vsh), low spontaneous potential (SP), and low resistivity, indicating their impermeable nature and role as cap rocks or seals. In contrast, sandstone units vary significantly in thickness and depositional patterns, including aggrading (cylindrical), retro gradational (bell-shaped), and pro gradational (funnel-shaped) sequences, reflecting fluctuating depositional conditions. Thick sand bodies such as Beds K (450 ft) and G (750 ft) are notable reservoir zones, exhibiting low Vsh, moderate to high SP, and high or variable resistivity, suggesting good porosity, permeability, and hydrocarbon potential. Some sand units, however, show low resistivity, indicating water saturation rather than hydrocarbons. The vertical stacking pattern suggests repeated transgressive-regressive cycles, influencing reservoir quality and fluid distribution. The table provides valuable insight into reservoir heterogeneity, seal integrity, and depositional processes, which are critical for hydrocarbon exploration and reservoir evaluation in the Niger Delta.

V. CONCLUSION

This study demonstrates that well log analysis remains a highly effective and reliable tool for lithologic characterization and reservoir evaluation within the Niger Delta Basin. By integrating key petrophysical logs such as gamma ray (GR), resistivity (RT), and spontaneous potential (SP), a comprehensive understanding of subsurface formations was achieved. The gamma ray log played a crucial role in differentiating lithologies, enabling the clear identification of sandstone and shale units based on variations in natural radioactivity. Clean sandstones were associated with low GR values, while shale intervals exhibited higher readings due to their clay content. The resistivity log further enhanced the interpretation by distinguishing fluid types within the formations, as hydrocarbon-bearing zones typically display higher resistivity compared to water-saturated layers. The spontaneous potential log provided valuable insights into permeability and formation boundaries, with characteristic deflections indicating the presence of permeable sand bodies.

The combined interpretation of these logs allowed for the accurate delineation of lithologic units within the Agbada Formation, which is known for its interbedded sand-shale sequences and significant reservoir potential. The main reservoir interval was successfully identified between 300 ft and 500 ft, characterized by low gamma ray values, high resistivity, and moderate SP deflection. These log responses are indicative of a clean, porous, and permeable sandstone formation with favorable conditions for hydrocarbon accumulation. The identification of this interval highlights its potential as a productive reservoir zone, capable of supporting hydrocarbon exploration and development activities.

The study underscores the importance of well log interpretation as a fundamental technique in petroleum exploration and reservoir management. Accurate analysis of log data not only improves the understanding of subsurface geology but also reduces uncertainty in decision-making processes related to drilling and production. Overall, the findings reinforce the critical role of integrated well log analysis in evaluating reservoir quality and optimizing hydrocarbon recovery in complex sedimentary basins such as the Niger Delta.

ACKNOWLEDGEMENTS

The authors acknowledge the Department of Physics, Niger Delta University, for providing support and resources for this study.

REFERENCES

[1] Aigbedion, I., and Iyayi, S. E. (2007). Formation evaluation of Oshioka field using geophysical well logs. Middle-East Journal of Scientific Research, 2(3–4), 107–110.

[2] Buryakovsky, L., Chilingar, G. V., and Aminzadeh, F. (2012). Petroleum geology: Theory and practice. Gulf Professional Publishing.

[3] Doust, H., and Omatsola, E. (1990). Niger Delta. In J. D. Edwards and P. A. Santogrossi (Eds.), Divergent/passive margin basins (pp. 201–238). American Association of Petroleum Geologists.

[4] Harris, N. B., Freeman, K. H., Pancost, R. D., White, T. S., and Mitchell, G. D. (1999). Depositional systems from well logs: An integrated approach to interpreting subsurface facies. Sedimentary Geology, 125(1–2), 123–140. https://doi.org/10.1016/S0037-0738(99)00015-3

[5] Olowokere, M. T., and Ojo, S. J. (2011). Porosity prediction using compaction curves. International Journal of Geosciences, 2(4), 512–520. https://doi.org/10.4236/ijg.2011.24054

[6] Ophori, D. U. (2015). A simulation of large-scale groundwater flow in the Niger Delta, Nigeria. Environmental Geosciences, 14(4), 181–195.

[7] Reijers, T. J. A., Petters, S. W., and Nwajide, C. S. (1997). The Niger Delta Basin. Elsevier.

[8] Tuttle, M. L. W., Charpentier, R. R., and Brownfield, M. E. (1999). The Niger Delta petroleum system. U.S. Geological Survey Open-File Report 99-50-H. U.S. Geological Survey.