

Petrophysical Evaluation of Langbodo Reservoirs, Niger Delta, Nigeria

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ABSTRACT The Niger Delta basin of Nigeria covers the Langbodo reservoirs which have attracted the interests of several geoscientists for proper petrophysical analysis to obtain their reservoir quality and percentage hydrocarbon (HC) contents. This study integrates petrophysical, geophysical, and geological data to allow for a detailed evaluation of reservoir properties. Wireline logs, which include the density, resistivity, gamma-ray, and neutron logs, were used to determine hydrocarbon zones of the reservoir, calculate porosity, and obtain fluid potential. The methodologies used showed the sand to shale lithologies delineation, effective porosity estimation, and the use of Archie's algorithm for water saturation estimation. Heterogeneity of reservoir was addressed via volumetric evaluations and cross-plots. Seismic analysis revealed structural understanding into HC traps. Results obtained reveal exploitable fluids in the Langbodo reservoirs. The quality of reservoirs shows porosity values existing between 20% and 30%, permeability within 100–500 mD, and negligible water saturation potential. Hydrocarbon-harboring intervals and zones were determined by the presence of values revealing low density and high resistivity. Structural cartography showed anticlinal ends and fault-enhanced traps as salient characteristics assisting HC accumulation.

KEYWORDS: Anticlinal, Cross-plot, Wireline, Petrophysical, Heterogeneity, Lithologies

I. INTRODUCTION

The increase in the demand of hydrocarbon has necessitated a thorough re-evaluation of the existing oilfields so as to maximize their production potentials [1], [2] and [3]. This has got the geoscientists brainstorming in order to put in place production that will match up with the high demand [1]. Petrophysics is the study of the properties (both physical and chemical) of reservoir rocks and the inherent fluids. It seeks to clearly explain the contained pore spaces in rocks and the mechanism of the movement of the fluids therein [2]. A holistic petrophysical analysis involves scientific evaluation of rocks and the fluids

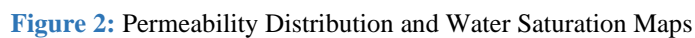
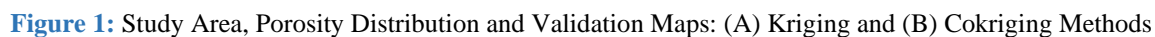
characteristics of water, gas and oil reservoirs by physical samples collection, magnetic, electrical, nuclear and chemical data obtained by logging, coring, drilling and sondes [4], [5], [6] and [7]. The data analysis, evaluation and interpretation require an adequate understanding of physics, geophysics, geology, electronics, mechanics, chemistry and drilling technicalities [8]. Petrophysical evaluation can be thoroughly done on hydrocarbon reservoirs, when rocks parameters such as bulk volume water (BVW), index of movability (IOM), true resistivity (R_t), true conductivity (C_t), water saturation (S_w), hydrocarbon saturation (S_h), porosity (ϕ), Permeability (K) and the shale volume (V_{sh}) are correctly determined by necessary empirical equations [9], [10] and [11]. This is because many of these parameters help to determine the potentials of the reservoirs under study [12]. Hydrocarbon reservoirs are body of rocks that are majorly composed of free space to harbor commercial deposits of organic fluids (majorly hydrocarbon) and have sufficient fluids mobility capability so as to deliver to drilled extraction holes [2]. Rocks located within the subsurface reservoirs are known as reservoir rocks. They are characterized by sufficient permeability and porosity capable of permitting mobility and accumulation of considerable volume of hydrocarbon. Reservoir rocks can be any of metamorphic, sedimentary or igneous rocks which can drain and accommodate hydrocarbons but, in most cases, rocks in the reservoirs are usually sedimentary [2]. This is because of their high permeability, porosity strength and saturation potential. Petroleum production from stratified reservoir rocks is dependent on models built from an in-depth understanding of geology and geophysics [13]. The genuineness of these models is anchored on the reliability of inputted data [14]. It is therefore very important to ascertain the validity of computed petrophysical parameters so as to guide against errors in decision making by engineers as an inappropriate executive resolve made on these values can either overestimate reservoirs potentials that should have been developed and enhanced before exploration or underestimate those that can be explored without having to go through any developmental steps [2]. Thorough studies of Langbodo reservoirs show a predominant composition of deposits of sandstones in deltaic to surface marine basins. These reservoirs reveal changing petrophysical features, determined by sedimentary facies, diagenetic (physical and chemical) processes, and structural characteristics such as fractures and faults. Many researchers have employed seismic properties, core data and well logs to characterize the reservoirs in the Langbodo field [2]. The porosity estimates range is indicative of good storage ability, while the permeability is at most times determined by sorting and grain size. One major peculiarity of the reservoirs is that they are usually water-wet alongside HC saturations changing through depths. Recent breakthroughs in modeling of HC reservoirs and petrophysical evaluation have utilized neural connections and machine learning to enhance the accuracy of attributes predictions [2]. Holistic petrophysical assessment, reservoir management and characterization are done by determining correctly the values of the aforementioned reservoir parameters. Petrophysics can practically be used for two major types of important estimations. These estimations are the original oil/hydrocarbon in place (OOIP) alongside its distribution and the engineering flow estimations. An accurate estimation of the OOIP and that of the engineering flow can be achieved by doing a foot-by-foot estimation of lithology, porosity, net pay, permeability and water saturation [15]. These estimations are important for the variation, distribution and overall idea of the reservoir fluids before taking any decision about exploration [16]. There are several techniques of estimating some of the aforementioned petrophysical parameters. Examples of such are water saturation and porosity. The validity of these parameters can actually be ascertained when different techniques of estimation produced an approximately the same results [17]. Shah et al. [18] did a thorough petrophysical analysis on the Titas field. The shale volume, porosity and the permeability of the gas zones were estimated and the Titas field was found to be rich in gas deposits. The petrophysical evaluation of the field suggests that the field has the potential to enhance and accumulate hydrocarbon. The

reservoirs in the Langbodo field of the Nigeria's Niger Delta basin are very significant hydrocarbon-harboring formations that enhances Nigeria's oil and gas potential [2]. Adequate evaluation of oil and gas reservoirs is very important for proper comprehension of their contents and maximizing their hydrocarbon potential [2]. Petrophysical evaluation involves proper analysis of fluid and rock properties using core data and well logs. These processes are germane to effective characterization of reservoirs [4]. A holistic petrophysical analysis of the Langbodo reservoirs showed accurate estimation of reservoir's salient properties, such as permeability, porosity, hydrocarbon potential and water saturation [19]. Despite the economic importance, the complex geology and depositional environment of the Niger Delta is a major barrier to accurate characterization of the available reservoirs. Several researchers have recorded a lot of successes in evaluating the hydrocarbon reservoirs in the Niger Delta basin, nevertheless, available studies reveal lack of clear integration of petrophysical data which has failed to address the challenges of uncertainties in geophysical parameters, minimizing the effectuality of production and modeling. Unlike previous studies in the Niger Delta, this research encompasses a novel methodological perspective that seamlessly combines different petrophysical data sets. This integration aims to solve the problems of unreliability in geophysical attributes, which have at most times disrupted the functionalities of previous evaluations. While research done in the past has majorly focused on broader regional evaluations, this study solely targets the Langbodo reservoirs. By concentrating on this particular area, it aims to open confined petrophysical features and peculiar behaviors which previous researchers might have failed to consider in their works. This research brings advanced techniques for resource estimation that incorporate state-of-the-art modeling and the latest geophysical data. This advancement is intended to improve recovery forecasts and mitigate the risks associated with HC exploration in the Niger Delta axis of Nigeria. By making available a robust petrophysical assessment, this study not only aims to strengthen theoretical knowledge but also provides practical implications for field development decisions, thereby contributing to more informed and effective operational strategies within the Niger Delta. The research seeks to identify and quantify specific petrophysical features that determine the efficiency of production, which has not been critically looked into in previous studies. Consequently, it aims to incorporate strategies that improve HC recovery and optimize resource management. This research work aimed to solve the problem by providing a robust petrophysical study of the Langbodo reservoirs to facilitate unhindered resource estimation, increased recovery, and informed field developmental decisions.

II. METHODOLOGY

A. STUDY AREA

The Langbodo field and Reservoirs are located in the Niger Delta region of Nigeria. The Niger Delta basins stand tall as one of the most prolific HC provinces in the world [20]. The Niger Delta, by location exists in the southern region of Nigeria, approximately covers about 75,000 km², made up of a complex connection of depositional features such as fluvial divisions, deeply rooted marine basins and deltaic plains [21]. The Niger Delta basin is known for its rich oil and gas potential, portraying it as a focal point for HC exploitation and development [22].



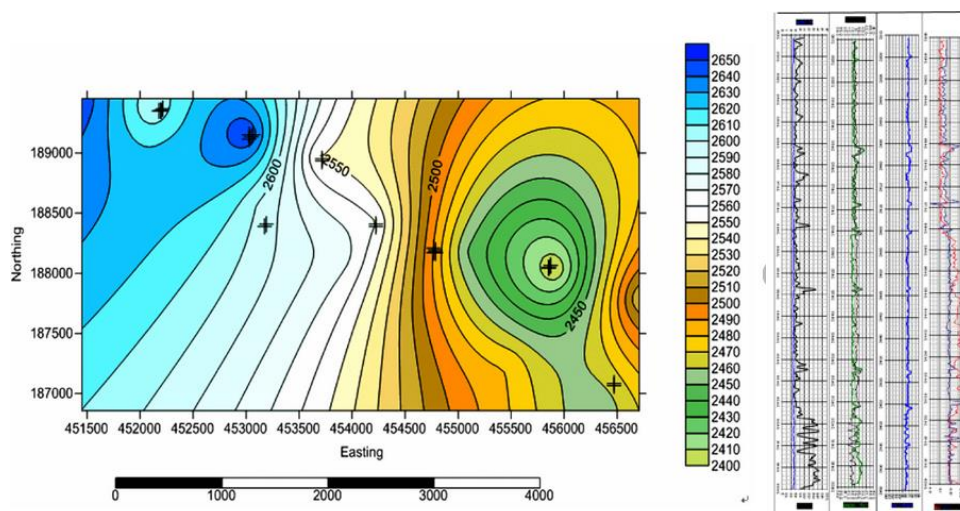


Figure 4: Map Showing Depth Correlation with other Petrophysical Properties and suites of Wireline logs from Langbodo Field

B. GEOLOGICAL AND GEOGRAPHICAL FEATURES

The Langbodo field is located within the region's central depobelt, a basin known for its thick depositional sequences showing the ancient Eocene to the recent times. These deposits are obtained originally from the Benue Trough and other adjacent locations, conveyed by the tributaries of the Niger River. The Reservoirs, are specifically, situated within complex structural segments of the plains, characterized by rich sand connective systems. depositional anticlines, and accumulate faults.

The Lithostratigraphic sequence of the Niger Delta is made up three formations:

- Akata Formation:** This composed significantly of marine shales deposits as the primary sediments which are the source rocks [23].
- Agbada Formation:** This formation is the main reservoir segments, made up of interstratified sandstones and shaly deposits occurring in interfingering continental and marine deposits to deltaic settings [24].
- Benin Formation:** This comprises connective and overbank sandy sediments and formations originating from a rapid accumulation of materials such as gravel, sand, clay and silt often conveyed and deposited by flowing streams and rivers. This formed the top layer of the delta's sequence [25].

The petroliferous Langbodo reservoirs share the same features with the Agbada Formation. These reservoirs are renowned for their promising reservoir potential, coupled with high porosity permeable sandstones compounded with shales serving as seals [26].

C. B. STRUCTURAL CHARACTERISTICS

The Niger Delta province is a highly productive petroleum region well distinguished for its complex stratigraphic and structural layers, which influences significantly, the HC potential [27]. The structural attributes of the reservoirs, situated within this province, play a crucial role in the characterization of potential reservoirs and HC entrapment. The outline below shows the major structural features related with the area studied:

a) Provincial Tectonic Build-up

- Growth Faults:** The Niger Delta is dominated by a syndepositional developed faults resulting from differential sediment subsidence and loading, which expands into the study area.

- ii. Rift System: The Niger Delta province results from the rifting and consequent passive boundary progression during the dissociation of the South American and African plates in the early cretaceous period.

b) Reservoir Structural Traps

- i. Anticlinal Roll-Over: The delta is associated with listric developed faults, which are prevalent trapping structures in the Niger Delta [28].
- ii. Fault Seals: Faults existing in the Niger Delta area usually plays the role of both seal and migration pathways, based on their throw, orientation, and related clay sediment [28].
- iii. Anticlinal Structures: Hydrocarbon reserves of the Langbodo usually occurs in arch-like shape traps resulting from differential compression and faulting [2].

D. FAULTS SYSTEM

- i. Fault Blocks: The area covered by the reservoirs is segmented into blocks of fault which resulted from the extensive system of faults, producing compartmentalized sections of the area with varying petrophysical features and connectivity.
- ii. Listric Faults: These are upward, curved and concave faults that are common in the study area. This influenced the deposition structure and deposition of the reservoirs in the Langbodo field.

E. STRUCTURAL INTERACTION AND SEDIMENTARY ACCUMULATION

- i. Subsidence and Compaction: Differential compression of sediments over previous structural faults or highs snowballs into the formation of minor folds and distorted structures [4].
- ii. Deltaic Procedures: The interaction between tidal, marine and fluvial procedures in the Niger Delta determines sediment accumulation and structural distortion [1].

F. DISTORTION ZONES

The distortion zone in the reservoirs of the Langbodo field is a key structural characteristic determining petrophysical properties and reservoir features. The Niger Delta is a tectonically reactive region, with prevalent wide-ranging folding, diapiric, and faulting structures originating from the interaction between sediment accumulation, subsidence, and territorial stress patterns. These distortion zones are important in managing HC movement, accumulation, and confining mechanisms [2].

In the Langbodo field, distortion parts may show as fractured or faulted regions, impacting fluid migration and reservoir longevity. Faults usually act as barriers or conduits due to their non-sealing or sealing nature, significantly affecting permeability, porosity, and hydrocarbon potential. Analysis of these zones is important for proper comprehension of reservoir classification and enhancement of field improvement strategies.

G. DATA ACQUISITION

Data used for this study were originally sourced from the reservoirs in the Langbodo field situated in the Niger Delta region of Nigeria and kept in the data bank of the Department of Geology, Obafemi Awolowo University, Ile-Ife. The dataset is made up of well log data, which include resistivity, density, gamma-ray (GR), neutron porosity, sonic, and density logs, alongside core data and important pieces of petrophysical information made available by the operating establishment. The identification of lithology and estimation of volume of shale were done utilizing the GR log, while the resistivity logs helped in the evaluation of the HC saturation. Density and neutron logs were used for the derivation of porosity while correlating the permeability estimates with results from core analysis where present. In addition, seismic field data covering the Langbodo field were sourced to give structural insights and help in the reservoir boundaries' delineation. The well depths, locations, and stratigraphic details were cross-index with regional geological investigations to facilitate data consistency and integrity. All data were quality checked to cancel outliers and reduce errors during analyses.

H. B. TECHNIQUES OF ANALYSIS

The six identified wells in the Langbodo reservoir were labelled LGD-01, LGD-02, LGD-03, LGD-04, LGD-05, and LGD-06 with respective zone, depth, lithology, porosity, permeability, water saturation and net pay thickness. The three wireline logs used for this research were labelled Langbodo 1, Langbodo 2 and Langbodo 3 with intervals well marked and distinguished for identification.

I. ANALYSIS OF LOG

Analysis of logs was a key integral component in the holistic petrophysical evaluation of the reservoirs in the Langbodo area of the Niger Delta. The initial aims were to estimate the water saturation, permeability, and porosity of the reservoirs, which are germane to characterizing HC potential. Wireline logs, which include the resistivity, density, gamma ray, sonic, and neutron porosity logs, were used to obtain the aforementioned parameters.

J. ESTIMATION OF POROSITY

Porosity (ϕ) was estimated using the neutron porosity and density logs, with corrections introduced for fluid effects and lithology. The density (ρ) log showed the bulk density (ρ_b), which was thereafter compared with the fluid density (ρ_f) and matrix density (ρ_m) to estimate the effective porosity with the relation. The (ρ_{sh}) represents the density of adjacent shale body.

$$\phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} - V_{sh} \left\{ \frac{\rho_m - \rho_{sh}}{\rho_m - \rho_f} \right\}. \quad (1)$$

The neutron porosity log was used as a cross-check, and the combination of both logs enhanced the accuracy in the heterogeneity of the lithologies.

K. PREDICTION OF PERMEABILITY

The Permeability (K) was calculated indirectly employing empirical comparisons with the porosity and the irreducible water saturation obtained from the resistivity and the porosity logs. The Timur-Coates and Schlumberger methods were used to estimate the permeability (K) in clastic reservoirs which typified the ones in the study area. The estimated permeability values were confirmed against core data if available.

L. DETERMINATION OF WATER SATURATION (S_w)

The estimation of water saturation was done using the Archie algorithm:

$$S_w^n = \frac{a \cdot R_w}{\phi^m \cdot R_t} \quad (2)$$

The R_w represents the formation water resistivity, R_t stands for the true formation resistivity, and the Archie constants a , m , and n respectively represents tortuosity factor, cementation exponent and saturation exponent. The m and n were calibrated for the lithology of the reservoir. The data for the R_t were obtained from the resistivity log while that of R_w were provided by the close water zones or the analysis of formation water. Results obtained from the analysis of log were combined with core analysis measurements and other relevant geological data to confirm the petrophysical models and boost confidence in characterization of reservoir. The aforementioned discoveries formed the basis for quantifying HC volumes and examining the productivity strength of the Langbodo reservoirs.

M. RESERVOIR ZONATION AND QUALITY ASSESSMENT

Identification and delineation of high-quality HC-bearing zones within the reservoirs of the Lagbodo area were carried out after conducting reservoir zonation and quality assessment processes. The process of zonation was driven by some important petrophysical parameters, which include porosity, water saturation, and permeability, obtained from well log data. The zones with effective porosity (ϕ_e) values ranging from 20 to 30%, permeability which occurs within the range of 100 to 500 (mD), and insignificant water saturation value which is less than 10% were taken as high-quality intervals of reservoir. The delineation procedure was characterized by the utilization of well log data, including neutron-density, gamma ray, sonic, and resistivity logs. The gamma ray logs were used to distinguish shales from clean

reservoir sands, while the resistivity logs were employed for the identification of hydrocarbon-harboring zones. The use of the neutron-density crossplots gave additional confirmation of fluid type and porosity. Petrel version 2010 and Techlog version 2023 were used for the quantitative analysis. This includes the integration of log interpretations and estimation of key reservoir parameters. Implemented algorithms in the tools were utilized to respectively calculate the permeability and porosity from sonic and neutron-density log responses, while the Archie's equation was employed to estimate the water saturation. The non-pay and pay zones were classified by a cut-off analysis done based on the known thresholds for permeability, water saturation and porosity. The flow zone indicators (FZI) and the reservoir quality indices (RQI) were carried out to assess the identified reservoirs zones for quality, so as to properly confirm their HC production potential using reservoir quality indices (RQI) and flow zone indicators (FZI) to confirm their potential for hydrocarbon production. Statistical and graphical results obtained from the software were studied and analyzed to facilitate reliability and consistency in the delineated zones.

H. CROSS-VALIDATION OF WELL LOG INTERPRETATIONS

The accuracy and reliability of well log interpretations employed in evaluating the petrophysical attributes of the reservoirs in the study area, the process of cross-validation was carried out following the procedure which involved comparing petrophysical properties such as permeability, water saturation and porosity which are derived from logs, with values obtained from production data and core analysis. Extracted core samples from the Langbodo reservoir intervals were critically analyzed in the laboratory to pave way for measurements of fluid and rock properties with high resolution. The primary statistical metrics used for cross-validation include Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R-squared (R^2). These metrics allowed for a quantitative assessment of the accuracy of the well log-derived petrophysical properties against the core analysis and production data. The dataset was divided into two subsets: a training set, which was used to derive the petrophysical properties from the well logs, and a validation set, which included core samples and production data for comparative analysis. This approach ensured that the assessment of well log interpretations remained unbiased and robust. A k-fold cross-validation technique was utilized, wherein the dataset was partitioned into k subsets. For each iteration, one subset was reserved as the validation data while the remaining k-1 subsets were utilized for training. This method allowed multiple evaluations of the model's performance, providing a more stable and generalizable estimate of the accuracy of the interpretations. The comparisons between the log-derived properties (permeability, water saturation, and porosity) and the corresponding values from core analysis and production data were subjected to statistical analysis. Correlation coefficients were calculated to determine the strength and direction of relationships between the variables. Additionally, regression analysis was performed to model and predict the relationships between the derived properties and measured parameters, helping reveal underlying patterns and validating our interpretations. Graphical methods such as scatter plots and residuals analysis were employed to visualize the relationships between the well log-derived petrophysical properties and the core analysis data. These visualizations aided in assessing model fit and identifying any potential outliers or inconsistencies within the data. The results of the statistical analyses informed the overall assessment of the reliability of the well log interpretations. The derived metrics and visual analyses established confidence in the petrophysical attributes assigned to the Langbodo Reservoirs, ultimately contributing to more informed decision-making regarding reservoir evaluation and production strategies. By employing these statistical methods, we aimed to enhance the credibility of the well log interpretation process, ensuring that our findings regarding the petrophysical attributes of the Langbodo reservoirs are both accurate and reliable. The following steps were included in the workflow:

- a) **Calibration of Core-to-Log:** Permeability data and Core-originated porosity were plotted against corresponding values from well log, such as neutron, resistivity, and density logs. Cross-plots alongside statistical metrics, which include the correlation coefficients and the root mean square error (RMSE), were employed to determine the consistency between the values in the datasets. Log data were adjusted to log interpretation models to establish an alignment with core-derived data.
- b) **Integration of Production Data:** Where present, production test obtained results, like the fluid types and flow rates, were integrated as an added layer of confirmation. The saturation profiles and interpreted

fluid contacts from well logs were cross-checked against corresponding production indicators to facilitate consistency.

- c) **Quality Control Process:** The process of quality control was carried out to determine the variations that exist between log-originated and core-obtained characteristics. This was with a view to identifying the discrepancies or potential biases. This iterative process of validation gave room for petrophysical models refinement and reduced the uncertainty that usually occur with reservoir characterization.

The process of cross-validation involved the integration of production and core data. This further facilitated a more reliable well log interpretation process, giving rise to a more robust information about the reservoir properties. Following this procedure ensured the accurate representation of the petrophysical models with the reservoir's underground characteristics, ensuring better developmental plans and management of the reservoir.

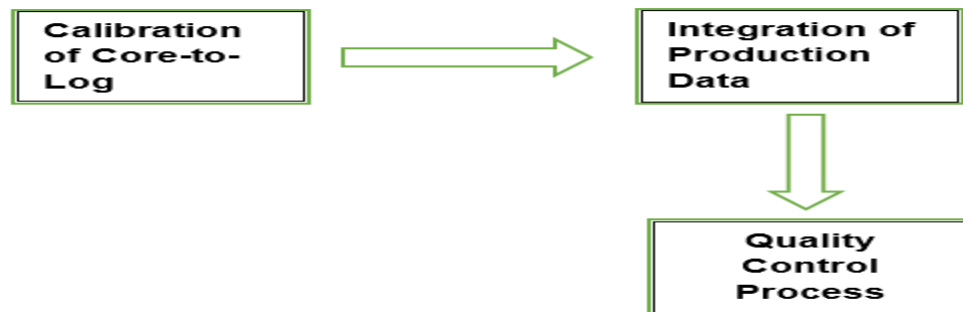


Figure 5: Workflow of Steps involved in the Cross-Validation of Well Log Interpretations.

I. MAPPING AND VISUALIZATION

Petrophysical and structural maps, including that of permeability and porosity, were generated to give a spatial knowledge about the properties of identified Langbodo reservoirs. The process of mapping involved the integration of well log and core data with the seismic analysis interpretations. Petrophysical parameters derived from well logs, such as permeability, water saturation and porosity, were inputted for spatial interpolation. The techniques of interpolation were employed to establish seamless distributions of property across the Langbodo reservoir. The suitability of the kriging and inverse distance weighting (IDW) methods were examined and the kriging was ultimately preferred for its additional ability to give spatial variability and establish optimal values. In a bit to ensure accuracy and consistency in the distributions, geostatistical analysis was carried out. This includes the variogram modeling to fully understand the spatial relationships. This process was conducted employing **Petrel** version 2010 and **ArcGIS Enterprise 10.9**. Derivation of structural maps from seismic analysis interpretations was carried out by incorporating horizons and faults for reservoir geometry's delineation. Grids from interpolated property was thereafter overlaid on the structural framework to generate petrophysical maps. The finally generated maps were visually complemented with contour lines and color gradients to show the salient reservoir properties' variations. These maps play crucial roles in the identification of potential HC-bearing zones, assessment of reservoir qualities, and guidance of field developmental planning.

J. STATISTICAL AND COMPARATIVE ANALYSIS

The statistical and comparative analyses were used to examine the petrophysical properties of the reservoirs and findings are validated against analogous reservoirs for comparisons. The analysis of salient petrophysical parameters which include permeability, water saturation, shale volume and porosity was done employing descriptive and inferential statistical techniques. The integration of core, production test and well logs data was also ensured to facilitate an all-encompassing analysis. Boxplots, histograms, and

frequency distributions, were employed to examine the extent of variability and measure the central tendencies of the reservoir parameters. The relationship between the reservoir properties and their observed dependencies on depositional environments and lithology. Regression analytic models were thereafter built to ascertain from well logs' data, the indicators of reservoir quality, with major emphasis on the link between permeability and porosity. Langbodo reservoirs, randomly selected analog reservoirs in the Niger Delta basin and reservoirs from similar geographycal locations worldwide were studied for proper comparisons. This entailed statistical matching of ranges, standard deviations, and mean values of petrophysical features. Cluster analysis and cross-plots were used to determine the deviations and similarities in reservoir characteristics, giving insights into the Langbodo reservoirs' relative qualities and performance. Further validation of the statistical findings was done by comparing analog reservoir case studies and trends of published datasets. This comparison enhanced the reliability of interpretations done and also gave a wider context for proper petrophysical evaluation. The incorporation comparative and statistical analyses in the study, facilitated robust characterization of reservoirs in the Langbodo field and established their importance within the wider framework of reservoirs of the Niger Delta.

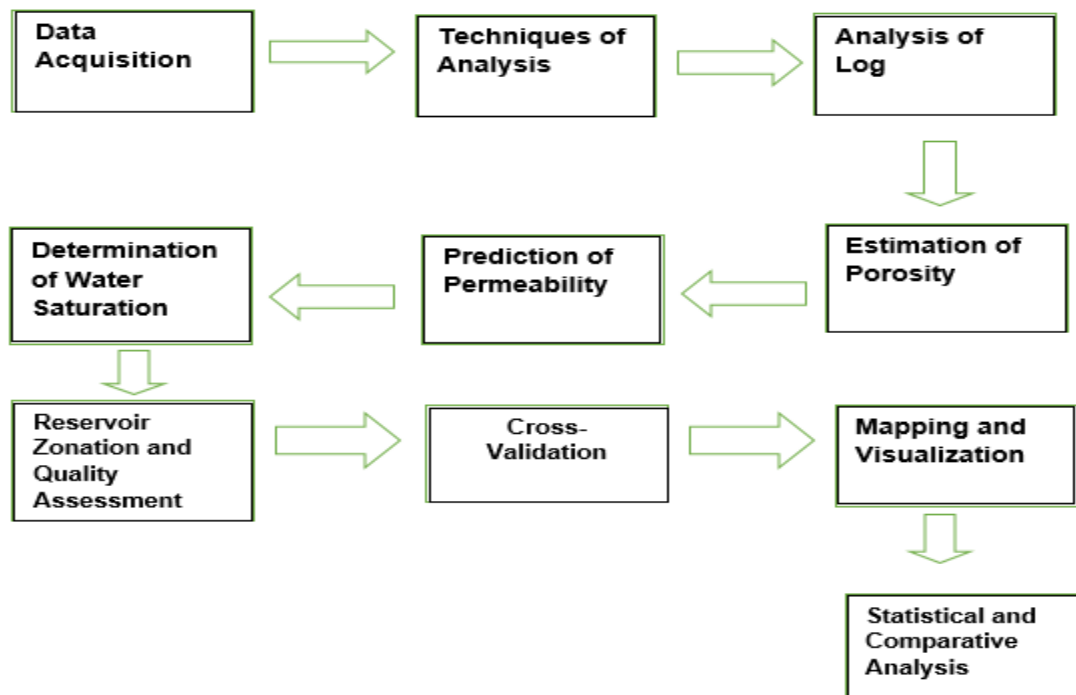


Figure 6: Workflow Showing Petrophysical Evaluation Process.

III. RESULTS AND DISCUSSION

A. DATA ACQUISITION

The evaluation process made use of well log data, which include resistivity, gamma ray, neutron- sonic, and density logs, accompanied by core samples for appropriate calibration. These obtained datasets gave rise to robust contributions for reservoir zones delineation and assessment of salient petrophysical properties such as permeability, water saturation, and porosity.

Table 1: Langbodo Reservoirs Petrophysical Data

Zone	Well ID	Depth (ft)	Lithology	Porosity (%)	Permeability (mD)	Water Saturation (%)	Net Pay Thickness (ft)
B	LGD-01	7,900	Sandstone	25.5	450	18.5	47
C	LGD-02	7,920	Shale	14	13	65	0
B	LGD-03	7,950	Sandstone	28.3	500	12.3	60
A	LGD-04	7,970	Sandstone	21.8	330	22.6	50
C	LGD-05	8,000	Shale	10.7	10	80	0
B	LGD-06	8,010	Sandstone	26.6	480	15.3	58

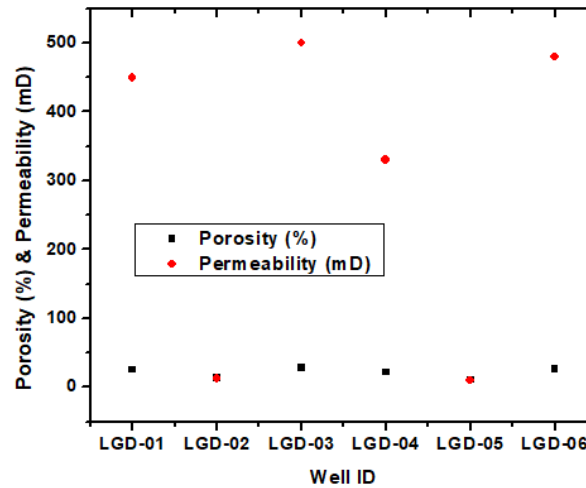


Figure 7: Relationship between Porosity and Permeability.

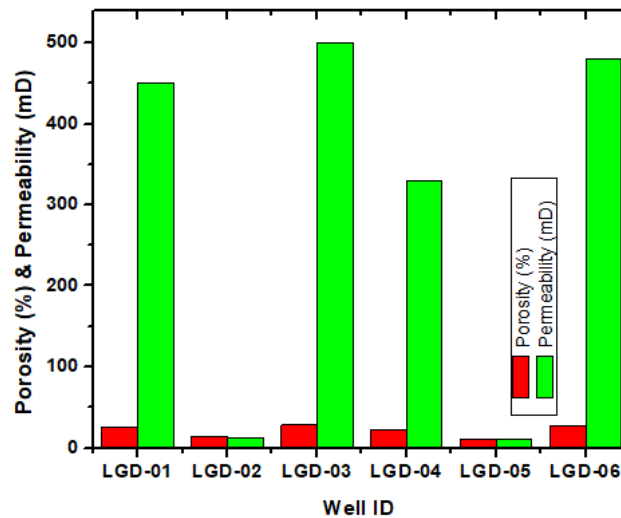


Figure 8: Relationship between Porosity and Water Saturation in each of the Wells.

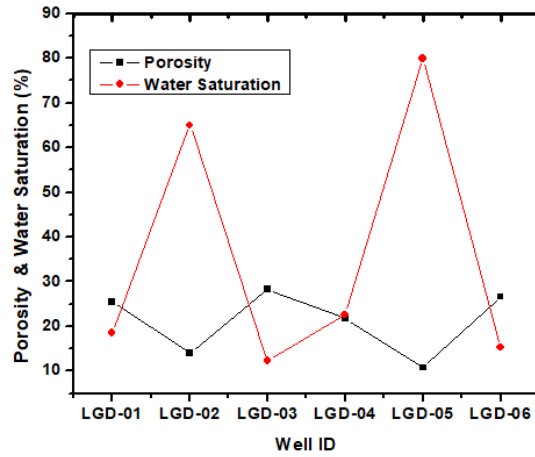


Figure 9: Relationship between Porosity and Water Saturation.

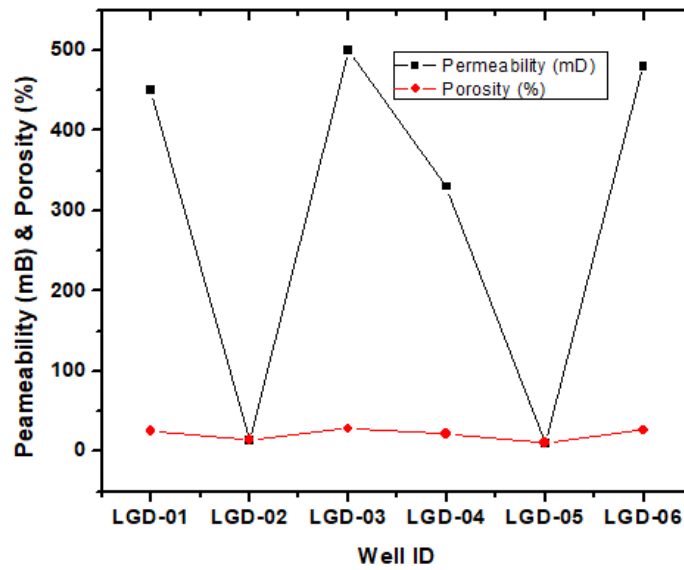


Figure 10: Relationship between Permeability and Porosity.

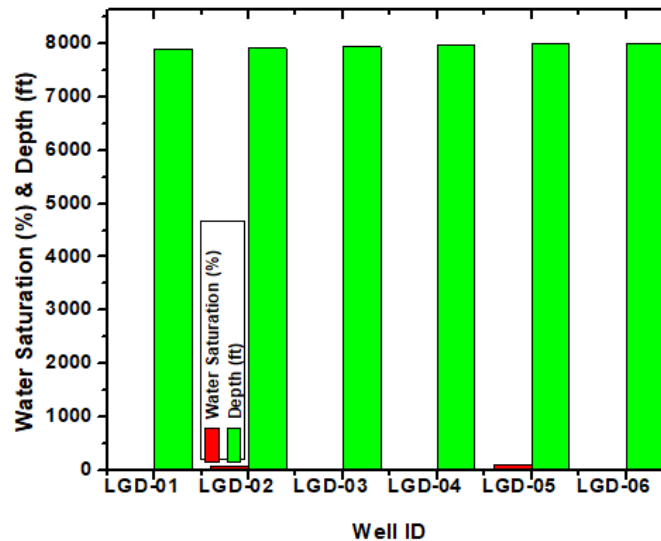


Figure 11: Relationship Water Saturation and Depth in each of the Wells

Figures 7, 9 and 10 show a scatter and a cross plot of the relationship between porosity and permeability in different zones of the Langbodo reservoirs. In LGD-01, LGD-02, LGD-03, LGD-04, LGD-05 and LGD-06, The porosity and permeability show a respective range of (14 - 28.3%) and (10 – 500 mD). The zone A and B of the reservoir revealed a high hydrocarbon potential as the porosity and permeability respectively occurred in ranges of (20-30% and 100-500 mD). This is in line with the work of Thomas *et al.* [29], Ojo *et al.* [30] and that of Obidike and Chiazor [31]. Thomas *et al.* [29] examined the petrophysical evaluation of H-field in the Niger Delta region of Nigeria. Results obtained revealed the presence of clastic reservoirs with water saturation ranging from 8 to 30% while the hydrocarbon saturation showed a range of 70 to 92% which is indicative of a high permeability value as seen in this work. Ojo *et al.* [30] worked on the petrophysical evaluation of Osaka field of the Niger Delta. This was done by identifying four wells in three reservoirs of the field and each of these wells was correlated to obtain the needed petrophysical parameters. The water saturation values range from 15 to 65% in the first well, 26 to 65% in the fourth well while the hydrocarbon saturation in the first, second, third and fourth well showed values with respective ranges of (53–84%), (54–62%), (40–69%) and (60–74%) which is indicative of an exploitable HC field with high permeability. Obidike and Chiazor [31] evaluated the petrophysical parameters and depositional potential of the reservoir sand of an oil rich region of the Niger Delta. The three identified reservoirs showed a water saturation range of 19 to 44% and a high permeability range which revealed a good site for HC exploration, production and management. Figures 8 and 11 respectively show the relationship between porosity and water saturation and that of water saturation and depth. Figure 6 shows porosity values which ranges from 14% to 28.3% and water saturation values which ranges from 12.3% to 80%. The hydrocarbon rich zones (A and B) have values ranges 12.3% to 22.6% which is indicative of HC saturation range of 77.4% to 87.7%. Figure 11 shows a range of depth from 7900 to 8010 ft with water saturation values of 12.3% to 80%. The A and B zones also appeared within the aforementioned depths of the reservoir. This is similar to the work of Frank and Ugochukwu [32] and Nton and Adeyemi [33]. Frank and Ugochukwu [32] examined the petrophysical evaluation of reservoir properties using core and logs data analysis. The porosity of the identified reservoir ranges between 22% to 31% and the water saturation at less than 45% which implies a HC saturation of less than 55% and high HC prospectivity. Nton and Adeyemi [33] looked into the evaluation of the reservoirs of the AD field of the Niger Delta. The water saturation ranges of 19% to 39% were compared across depth in feet (ft). Result obtained showed that the AD field has a very high hydrocarbon content which can be exploited for economic and other purposes. Findings of this research indicate that the porosity of the Langbodo reservoirs ranges between 20% and 30%, with water saturation

levels below 30% in the high HC zones of the reservoirs. These properties are comparable to those found in several significant hydrocarbon reservoirs around the world. For instance, the North Sea and the Permian Basin in the United States exhibit similar ranges of porosity (typically around 20% to 30%) and moderate water saturation levels, indicating a favorable hydrocarbon saturation. The high porosity values in our study suggest a substantial capacity for hydrocarbon storage, consistent with findings from productive fields in these regions. With an implied hydrocarbon saturation of less than 55%, our results align with reservoirs known for high-quality hydrocarbon assets, such as those in the Gulf of Mexico. In many of these regions, similar saturation metrics correspond with productive reservoirs that yield significant volumes of oil and gas. The results from Frank and Ugochukwu [32] and Nton and Adeyemi [33] suggest that the Langbodo Reservoirs also possess the potential for high hydrocarbon content, which is further supported by the comparatively low water saturation levels reported. Globally, reservoirs such as the Brent Group of the North Sea and the various fields in the Norwegian Continental Shelf have been extensively studied and often show water saturation levels in the range of 20% to 40%, which is reminiscent of our findings in the AD field (19% to 39% water saturation). This similarity in water saturation levels suggests that the Langbodo Reservoirs may share geological characteristics with these prolific producing basins and are thus worthy of further investigation. From an economic perspective, high hydrocarbon saturation combined with favorable porosity has been a characteristic of commercially viable oil and gas fields worldwide. The economic potential inferred from the petrophysical evaluation of the Langbodo Reservoirs indicates that similar hydrocarbon-rich reservoirs could lead to significant exploitation opportunities. The reference to high hydrocarbon content in the AD field indicates that, like the reserves in key global regions, the Langbodo Reservoirs may also offer substantial economic benefits. The Niger Delta's geology shares similarities with other deltaic environments, such as the Mississippi River Delta and the Sundarbans in India. These regions often exhibit complex subsurface structures and reservoir characteristics influenced by deltaic sedimentation processes. Therefore, understanding how our findings relate to reservoirs in these settings may provide valuable insights into the geological and operational challenges one might encounter during exploration and production. In conclusion, our petrophysical evaluation of the Langbodo Reservoirs not only underscores the reservoirs' significant potential but also places them within the broader context of global reservoir characteristics. By comparing our findings with recognized hydrocarbon provinces worldwide, we can strengthen the argument for further exploration and exploitation of the Langbodo Reservoirs, recognizing both their similarities and unique features.

Table 2: Core Data Summary Table for Langbodo Reservoirs

Depth (m)	Lithology	Porosity (%)	Permeability (mD)	Water Saturation (%)	Hydrocarbon Indication
2460	Sandstone	29.5	490	13	Oil and Gas
2485	Shale	13	9	47	None
2510	Sandstone	25.8	380	9	Oil and Gas
2535	Sandstone	28.1	420	12	Oil and Gas
2560	Shale	16.4	16	60	None
2585	Sandstone	23.6	330	11	Oil and Gas
2700	Sandstone	27.3	460	7	Oil and Gas
2825	Shale/Silt	20.5	55	48	None

Table 3: Langbodo Reservoir Zones Classification Table

Zone	Porosity (%)	Permeability (mD)	Water Saturation (%)	Reservoir Quality	Remarks
Excellent	26 - 30	450 - 500	< 8	Very High	Highly productive Zone
Good	23 - 26	350 - 450	8 - 25	Moderate to high	Commercially viable Zone
Fair	18 - 23	200 - 350	25 - 30	Moderate	Marginally economic Zone
Poor	< 18	< 200	> 30	Very Low	Non-commercial Zone

Table 4: Well Log Data

Depth (m)	Gamma Ray (GR, API)	Resistivity (RT, ohm-m)	Porosity (PHI, %)	Permeability (mD)
100	40	10	21	210
120	65	13	23	300
130	60	15	22	250
140	50	19	24	450
150	75	20	20	200
160	65	24	18	180

B. METHODS OF ANALYSIS

Well log interpretation was combined with calibration of core samples and cross-plots for the derivation of permeability, water saturation, and porosity. The estimation of water saturation was done using the Archie's equation while the permeability prediction was made possible by several empirical relationships in petrophysics. GR-cutoff values, combined with resistivity and neutron-density signatures were also employed for reservoir zonation.

C. RESERVOIR ZONATION PROCESS AND QUALITY CHECKING

The Reservoirs of Langbodo were divided into three major zones (A, B, and C). This division was dependent on petrophysical features. Zones A and B of the reservoir showed high quality with range values from 22% to 28% in porosity and 150–450 mD of permeability, conforming with targeted thresholds. Quality slightly lower than that of zones A and B was experienced with Zone C. The C zone has an average of 18% porosity and a lowered permeability of less than 100 mD. A negligible water saturation value of less than 15% was recorded across the zones which further confirmed little or no impediments to fluid flow.

D. MAPPING, CROSS-VALIDATION, AND VISUALIZATION

Maps generated from properties distribution in the Langbodo reservoirs were obtained employing seismic-to-well combined workflow alongside appropriate techniques for geostatistical interpolation. These maps showed vertical and lateral heterogeneity. The zone A revealed more uniform features when compared to zones B and C of the reservoir. The process of cross-validation between core-measured and log-derived values revealed a strong correlation of ($R^2 > 0.85$), substantiating the dependability of the interpreted reservoir properties. Figure 12 shows the Niger Delta continental margin showing the distribution of the Langbodo reservoirs.

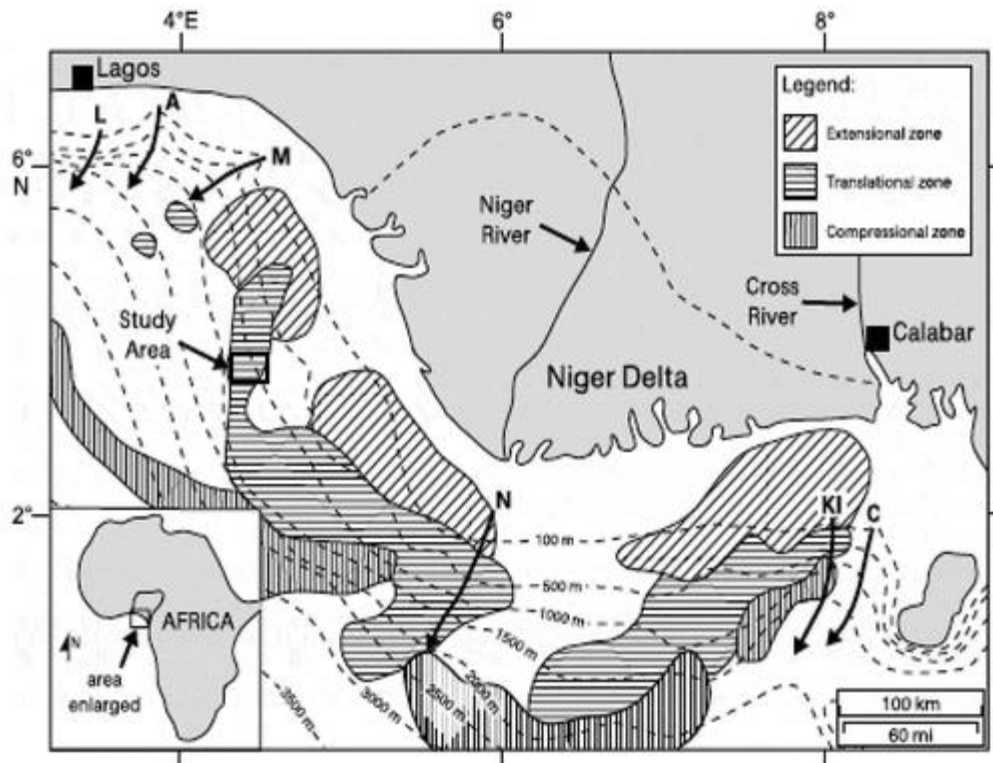


Figure 12: The Niger Delta continental margin showing Langbodo Reservoirs (After Damuth, [34])

E. STATISTICAL AND COMPARATIVE ANALYSIS

Statistical analyses revealed that 75% of the values obtained for porosity appeared within the desired range of 20–30% alongside an average value of 320 mD as permeability. Comparing these values with analogue reservoirs in the Niger Delta, similar qualities and trends were revealed. Findings from the Langbodo reservoirs further validate the viability of the field as an economic target for HC exploitation, considering the excellent storage capacity and the flow properties of the reservoirs.

V. CONCLUSION

The identified reservoirs were all mapped and matched across the field. The variation in the thickness of these reservoirs wasn't a barrier for making useful developmental decisions to improve their qualities. Light intercalations of shale which are capable of impeding fluid flow were noticed in almost all of the reservoirs. All the delineated reservoirs contained considerable deposits of oil mixed with some quantities of water. Minor presence of oil was recorded across some intervals as water saturation potential increase particularly in Langbodo 3. The distribution of oil decreases from the eastern to the western part of the field. There were no records of gas deposits in the field. The petrophysical assessment of the reservoirs in the Langbodo field has shown significant HC potential, aided by good reservoir parameters. The values of the porosity range consistently from 20% to 30% at different stages of the evaluation, indicating the presence of well-developed spaces or allowances capable of harboring substantial amount of hydrocarbons. Moreover, permeability estimations which occur within 100 mD and 500 mD show the excellent fluid migration properties of the Langbodo reservoirs and also ensured efficient HC recovery. There is also a negligible water saturation capacity in the Langbodo reservoirs indicating the hydrocarbon dominance within the intervals evaluated, making the identified reservoirs major candidates for exploitation and development. The validation of hydrocarbon bearing zones was made possible by the presence of high resistivity and low density values which are major markers of hydrocarbon accumulation characteristics. These discoveries were supported by structural cartography, revealing anticlinal features and traps enhanced by faults as major geological characteristics enhancing HC preservation and entrapment. The traps structural configuration

provides a detailed foundation for the accumulation of hydrocarbon, minimizing leakage and migration risk. The combining effect of the structural and petrophysical awareness of the reservoirs underscore the high HC potential of the Langbodo field. The combination of advantageous quality, HC potential, and structural fairness situates the field as a hopeful prospect for constant production and exploration activities. The results obtained did not only broaden the understanding of the reservoir fluid mobility but also show the strategic importance of the Langbodo reservoirs in enhancing HC resource base of the petroliferous region of Nigeria. The petrophysical evaluation of the Langbodo reservoirs has significant implications for reservoir management and HC production. The presence of well-developed spaces with high porosity values (20% to 30%) and excellent fluid migration properties (permeability estimates between 100 mD and 500 mD) suggests that the reservoirs have the potential to support high rates of hydrocarbon production. From a reservoir management perspective, these findings imply that the Langbodo field can be optimized for maximum hydrocarbon recovery through optimized well placement and completion strategies to target high-porosity and high-permeability zones, implementation of enhanced oil recovery (EOR) techniques, such as water injection or gas injection, to maximize sweep efficiency and oil recovery and development of a robust reservoir monitoring and surveillance program to track fluid movement and optimize production. Furthermore, the excellent fluid migration properties of the reservoirs suggest that the Langbodo field is suitable for various HC production scenarios, including primary recovery, secondary recovery, and tertiary recovery. Overall, the petrophysical evaluation of the Langbodo reservoirs provides valuable insights for reservoir management and HC production, highlighting the potential for the Langbodo field to become a significant contributor to Nigeria's hydrocarbon production. Machine learning algorithms can be employed in future to develop predictive models that can estimate reservoir properties (e.g., porosity, permeability) based on seismic data, well logs, or other input parameters. Reservoir Characterization using Unsupervised Learning techniques (e.g., clustering, dimensionality reduction) can help identify patterns in the data that may not be immediately apparent through traditional analysis methods. This could lead to new insights into the reservoir's structure and behavior. By training machine learning models on the existing dataset, we can develop a system that can estimate porosity and permeability values for new wells or reservoirs, potentially reducing the need for expensive and time-consuming measurements. Machine learning algorithm can be to improve the accuracy of geostatistical models, such as Gaussian process regression or Markov chain Monte Carlo simulations, for reservoir characterization. The available dataset of porosity and permeability can for instance be integrated into the Gaussian process regression (GPR) and Markov chain Monte Carlo (MCMC) simulations. We can use GPR to model the relationship between the depth and the porosity/permeability values.

ACKNOWLEDGEMENT

We will like to thank the Department of Geology of the Obafemi Awolowo University, Ile-Ife for providing us with the data used for this research.

REFERENCES

- [1] C. N. Nwankwo and Y.K. Saadu, "Petrophysical evaluation and volumetric estimation within central swamp Depobelt, Niger Delta, using 3-D seismic and well logs", *Egyptian Journal of Petroleum*, Vol. 27, No. 4. pp. 427 – 437, 2017.
- [2] I. Aigbedion and S.E. Iyayi, "Environmental effect of mineral exploitation in Nigeria", *International Journal of Physical Sciences*, Vol. 2, No. 2. pp. 33 – 38, 2007.
- [3] R. Farajzadeh, S. Kahrobaei, B. De Zwart and D. Boersma, "Life-cycle Optimization of Hydrocarbon Fields: Thermoeconomics Perspective", *Sustainable Energy Fuels*, Vol.3, No.11. pp. 3050 -3060, 2019.
- [4] U.P. Ugwu, K.O. okengwu and A.E. Jones, "Petrophysical Evaluation for Development of a Marginal Oil Field in the Onshore Niger Delta, Nigeria", *Scientia Africana*, Vol. 21, No.1. pp.123 -132, 2022.
- [5] F.B. Onita and P. Iriogbe, "Theoretical advancements in operational petrophysics for enhanced reservoir surveillance", *Engineering Science & Technology*, Vol. 5, No. 8. pp.2576 – 2588, 2024.

- [6] E. Mahmoud, I. Abubakar, H. Moaz, H. Amjed, A. Kareem, M. Mohamed, E. Ammar and A.E. Radwan, "A review on the applications of nuclear magnetic resonance (NMR) in the oil and gas industry: laboratory and field-scale measurements", *Journal of Petroleum Exploration and Production Technology*, Vol. 12, No. 1. pp. 2747 – 2784, 2022.
- [7] R.H. Allawi and M.S. Al-Jawad, "An Empirical Correlations to Predict Shear Wave Velocity at Southern Iraq Oilfield", *Journal of Petroleum Research and Studies*, Vol. 12, No.1. pp. 1 – 14, 2022.
- [8] J. O. Alao, K. M. Lawal, B. B. M. Dewu and J. Raimi, "The evolving roles of Geophysical Test sites in Engineering, Science and Technology", *Acta Geophysica*, Vol. 72, No. 1. pp. 161 – 176, 2023.
- [9] J. I. Omigie and G.I. Alaminikuma, "Petrophysical Evaluation of Reservoirs for Hydrocarbon Reserve Estimation in Eastern Central Swamp Depobelt, Niger Delta", *Malaysian Journal of Geosciences (MJG)*, Vol. 4, No. 2. Pp. 79 – 85, 2020.
- [10] U.C. Omoja and T.N. Obiekezie, "Evaluation of Petrophysical Parameters of Reservoir Sand Wells in Uzot-Field, Onshore Niger Delta Basin, Nigeria", *Journal of Applied Science and Environmental Management*. Vol. 25, No. 2. pp.157 - 171, 2021.
- [11] D.S. Adepehin, F.F. Magi, A.I. Odudu, M.O. Adelayi, and K. Suleiman, "Shale Volume Effect on Hydrocarbon Prospectivity of Green Field, Niger Delta, Nigeria", *Physic Access*, Vol. 2. No. 1. pp. 37 – 53, 2022.
- [12] L. T. Nkwanyang, O. A. Ehinola, J. E. Takem, P. Nguema, S. E. Makoube, and G. M. Chongwain, "Depositional Setting and Petrophysical Evaluation of Reservoir of the K-field in the Western offshore Depobelt, Rio Del Rey basin, Cameroon", *International Journal of Geoscience*, Vol. 9, No. 9. pp. 528 – 546, 2018.
- [13] H. J. Kloosterman and P.L. Pichon, "The Role of Geophysics in Petroleum Resources Estimation and Classification - New Industry Guidance and Best Practices", *The Leading Edge*, Vol. 31, No. 9. pp. 997 – 1120, 2012.
- [14] M. Cabrera, J. Ninic and W. Tizani, "Fusion of Experimental and Synthetic Data for Reliable Prediction of Steel Connection Behaviour Using Machine Learning", *Engineering with Computers*, Vol. 39, No. 4. pp. 3993 – 4011, 2023.
- [15] A.I. Diab, O. Sanuade and A.E. Radwan, "An Integrated Source Rock Potential, Sequence Stratigraphy, and Petroleum Geology of (Agbada-Akata) Sediment Succession, Niger Delta: Application of Well Logs Aided by 3D Seismic and Basin Modeling" *Journal of Petroleum Exploration and Production Technology*, Vol.13, No. 22. pp. 237 – 257, 2023.
- [16] M. Zeyghami and M. A. T. Sarvestani, "Comprehensive Methodology for Reservoir Cut-off Determination", *Journal of Petroleum Exploration and Production Technology*, Vol. 13, No. 2. pp.1551 – 1573, 2023.
- [17] K.S. Taber, "The Use of Cronbach's Alpha When Developing and Reporting Research Instruments in Science Education", *Research in Science Education*, Vol. 48, No. 1. pp. 1273 – 1293, 2018.
- [18] M. D. S Shah, M. D. H. R. Khan, A. Rahman, M.D.R. Islam, S.I. Ahmed, M.I. Molla and S. Butt, "Petrophysical Evaluation of Well Log Data for Reservoir Characterization in Titas Gas Field, Bangladesh: A Case Study", *Journal of Natural Gas Science and Engineering*, Vol.10, No. 1. pp. 1 – 13, 2021.
- [19] D. S. Adepehin, O. A. Dasho, M. I. Amanyi, A. B. Babinisi, A. O. Salawu, S. O. Adikwu, E. D. Onoja and I. A. Ngbede, "Composite Estimation of Permeability in Identified Hydrocarbon Reservoirs of Langbodo Field Niger Delta, Nigeria", *Physics Access*, Vol. 2, No. 1. pp. 19 -25, 2022.
- [20] G. O. Emujakporue, "Assessment of Hydrocarbon Potential in Owem Field in Niger Delta, Nigeria", *International Journal of Geosciences*, Vol. 7, No. 3. pp. 335 – 344, 2016.
- [21] J. Danwazan, K. J. Egunjobi and R. O. Akinwande, "Integrated Modelling and Reservoir Characterization of Ataga Field, Niger Delta Basin, Nigeria", *International Journal of Geosciences*, Vol.14, No. 5. pp. 450 – 466, 2023.
- [22] C. C. Ugbor, "Evaluation of Hydrocarbon Reservoir in the "SIMA" Field of Niger Delta Nigeria from Interpretation of 3D Seismic and Petrophysical Log Data", *International Journal of Geosciences*, Vol.14, No. 1. pp. 94 – 107, 2023.
- [23] B. A. Olisa, "Investigation of Petroleum Source Rock Potential and Maturity in Pologbene-001 from Resistivity and Density Logs, Northern Depobelt Eocene Deposits, Niger Delta, Nigeria", *Scientific Research Journal*, Vol. 6, No. 8. pp. 81 – 88, 2018.

- [24] K.E. Kouadio, S. Abrakasa, S.S. Ikiensikimama and T. Botwe “Source Rocks Characterization of Agbada and Akata Formations in the Niger Delta, Nigeria”, *European Journal of Environment and Earth Sciences*, Vol. 1, No. 4. pp. 4 – 38, 2020.
- [25] G. d’Almeida, C. Kaki and J. Adeoye, “Benin and Western Nigeria Offshore Basins: A Stratigraphic Nomenclature Comparison”, *International Journal of Geosciences*, Vol. 7, No. 2. pp. 177 – 188, 2016.
- [26] L. C. Amajor, “Aquifers in the Benin Formation (Miocene—Recent), Eastern Niger Delta, Nigeria: Lithostratigraphy, Hydraulics, and Water Quality”, *Environmental Geology and Water Sciences*, Vol. 17, No. 1. pp. 85 – 101, 1991.
- [27] T. M. Asubiojo and S. E. Okunuwadje, “Petrophysical evaluation of reservoir sand bodies in Kwe field onshore eastern Niger Delta”, *Journal of Applied Sciences and Environmental Management*, Vol. 20, No. 2. pp. 383 – 393, 2016.
- [28] L. L. Alexander and J. W. Handschy, “Fluid Flow in a Faulted Reservoir System: Fault Trap Analysis for the Block 330 Field in Eugene Island, South Addition, Offshore Louisiana” *American Association of Petroleum Geology Bulletin*, Vol. 82, No. 3. pp. 287 – 411, 1998.
- [29] T. A. Harry, C. E. Etim and A. E. Okechukwu, “Petrophysical Evaluation of H-field, Niger Delta Basin for Petroleum Plays and Prospects”, *Sciend*, Vol. 69, No. 2. pp. 119 – 129, 2023.
- [30] A. O. Ojo, O. E. Babafemi and O. E. Olabisi, “Petrophysical Evaluation and Hydrocarbon Prospectivity Determination of Osaka Field, Niger Delta, Nigeria”, *FUPRE Journal of Scientific and Industrial Research*, Vol. 8, No. 1. pp. 124 – 135, 2024.
- [31] C. C. Obidike and F. I. Chiazor, “Petrophysical Evaluation and Depositional Environments of Reservoir Sands in an Oil Producing Field, Onshore Niger Delta, Nigeria”, *Journal Applied Science and Environmental Management*, Vol. 27, No. 4. pp. 639 – 645, 2023.
- [32] O.A. Frank and D.U. Ugochukwu, “A Petrophysical Properties Evaluation Study of a Niger Delta Field Using Well Logs and Core Data”, *August, Oriental Journal of Physical Sciences*, Vol. 9, No. 1. pp. 53 – 61, 2024.
- [33] M. E. Nton and M. O. Adeyemi, “Evaluation of Hydrocarbon Reserve in AD Field, Offshore Niger Delta”, *Open Journal of Geology*, Vol. 11, No. 5. pp. 155 – 174, 2021.
- [34] J.E. Damuth, “Neocene gravity tectonics and depositional processes on the deep Niger Delta continental margin”, *Marine and Petroleum Geology*, Vol.11, No. 3. pp. 320–345, 1994.