# Reservoir Permeability Determination Using Porosity Logs (Otumara Field)

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**Abstract—***This study explores various techniques for applying well logs and other data to the problem of predicting permeability in uncored wells in Otumara fields, Onshore Southern Niger Delta. Data utilized for the study included well logs and core data. Lithology was determined from gamma ray log. Hydrocarbon presence was determined using resistivity log while porosity was determined from density log. The results from wireline logs revealed that the cored sections are predominantly sandy. Effective porosity ranged from 0.02 to 0.33 with an average of 0.24±0.05 in Otumara field. Meanwhile on average, core effective porosity is 0.24±0.02 in Otumara field. These results show good agreement between log-determined and core-determined porosity for the cored section of the wells in Otumara field. Five empirical methods (Tixier, Timur, Coates and Dumanoir, Owolabi and Aigbedion) were applied to compute permeability as a function of computed porosity and irreducible water saturation in hydrocarbon bearing sands from both fields. These results were validated using average core permeability (202.66mD for Otumara field) and a linear regression model generated from core permeability versus log porosity plot (229.35mD for Otumara and field). The average permeability recorded for Timur, Coates and Dumanoir, Tixier, Aigbedion and Owolabi are 1.83, 5.71, 31.18, 2.59 and 1842.36mD for Otumara field. These results showed that Tixier, Timur, Aigbedion, Coates and Dumanoir models all underestimated permeability in Otumara oil fields. Although Owolabi's empirical model overestimated permeability in Otumara field by 9.09%. Linear regression models generated revealed that they are better predictors of permeability in the uncored wells. All other empirical methods failed in predicting permeability accurately and this is because, adjustments to constants for these models were not possible. This study therefore recommends the use of the generated linear regression model for a more accurate estimation of permeability in uncored wells in Otumara field.*

**Index Terms—**Permeability, Porosity, Density, logs, Water Saturation, Darcy, Liner Regression Model, Uncored Wells, Core Data Analysis, Emperical Models.

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## 1. INTRODUCTION

The permeability of a rock is one of the most important parameters necessary for effective reservoir characterization and management (Onyekonwu & Ekpoudom, 2004; Bloch, 1991). Therefore, accurate knowledge of its distribution in the reservoir is critical to accurate production performance prediction. Its importance is reflected by the number of available techniques typically used for its estimation which includes well log evaluation, core measurements, and well testing. Permeability measurements from cores are direct measurement of these properties. But a reservoir without core data is often associated with uncertainties as these properties have to be log derived. Of all the formation parameters that petroleum engineers use, permeability is one of the most important. In the oil and gas industry, it is used to determine whether a well should be completed and brought on line (Allen et al. 1988). It is also essential in overall reservoir management and development (e.g., for choosing the optimal drainage points and production rate, optimizing completion and perforation design, and devising Enhanced Oil Recovery patterns and injection conditions).

Permeability of a formation is affected by factors such as porosity and pore space characteristics, types, amount and distribution of clay minerals, rock matrix composition and size of matrix grains (Balan & Mohaghegh, 1995).

Even though permeability is a very important reservoir property, it is the most difficult property to determine and predict. Several researchers including Osborne (2004), Timur (1968), Coates and Dumanoir (1981), Yao (2003) and Tixier (1949) have proposed models for permeability determination in an uncored reservoir using well logs. These models are based on correlation between permeability, porosity and irreducible water saturation. Irreducible water saturation being a function of the rock characteristics. This present research utilizes well logs in the determination of permeability from one oil field in the Onshore Niger Delta.

Niger delta is the case study in this work and is found in the Gulf of Guinea and it extends across the-Niger-Delta Province. Among the largest deltas in the world, the depo-belts within the Niger Delta Province form one of the largest prolific deltas which cover a total area of about 300,000 km$^2$ (Kulke, 1995). Detailed discussion on the history, evolution, and structural features of the Niger Delta can be found in the works of Allen (1964), Hospers (2005) and Whiteman (1982). Stoneley (1966) and Burke et al. (1972) analyzed and discussed the mega tectonic setting of the Niger Delta. The syn-sedimentary tectonics of the Tertiary delta was extensively described by Evamy et al. (1978). Detailed studies on tectonics, stratigraphy, depositional environment, petrophysics, sedimentology and hydrocarbon potential are well documented in the literature (Weber & Daukoru 1975; Doust & Omatsola 1990; Reijers & Nwajide 1996, among others). The modern Niger Delta has distinctive basinward variations in structural style that define; (1) an inner extensional zone of listric growth faults beneath the outer shelf; (2) a translational zone of diapirs and shale ridges beneath the upper slope; and (3) an outer compressional zone of imbricate toe-thrust structures beneath the lower slope (Hooper et al. 2002).Detailed discussion of the Structural pattern of the Niger Delta Province is seen in Nwajide, 2013; stratigraphy is given in Stacher, 1995 and Avbovbo, 1978; Tectonics and Structure is seen in Lehner & De Ruiter, 1977; the lithology is analyzed in Hospers, 1965 and Reijers, 1997; the Depo-belts is given in Stacher, 1995 Doust & Omatsola, 1990; the Hydrocarbon source is articulated in Evamy, 1978.

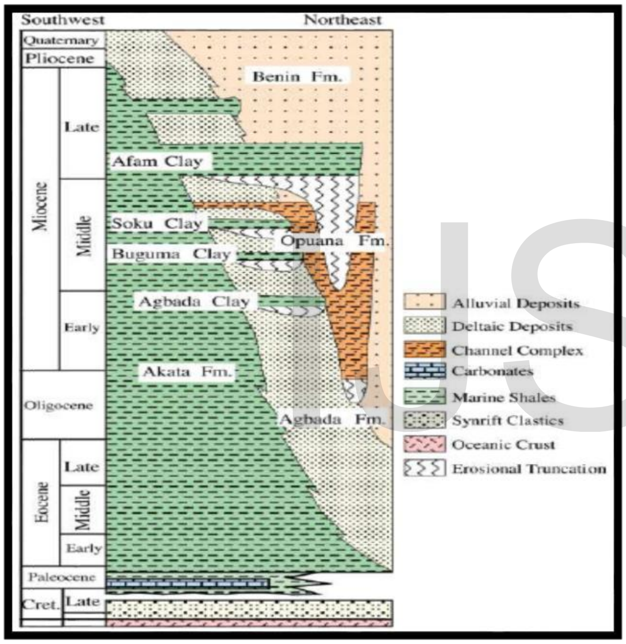

**Figure 1: Stratigraphic Column showing the various stratigraphic units of the Niger Delta basin(Doust & Omatsola, 1990).**

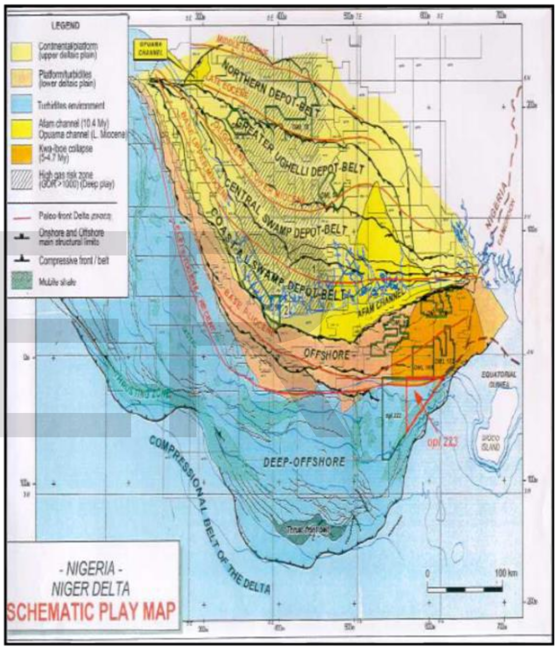

**Figure 2: Showing the Niger Delta Depo-belts (Steele et al. 2009)**

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The Petrophysical Logs includes Gamma Ray Log, Neutron Log, Sonic Log, Resistivity log and Density log - The electron density index for a pure element, which is proportional to the electron density, is defined as:

$$\rho e = \rho b \times \left[\frac{2Z}{A}\right] \qquad (1)$$

Fresh water filled with limestone formation of high purity to give an apparent density is used to calibrate the density tool and is related to the electron density index by:

$$\rho a = 1.0704\rho e \; - \; 0.1883 \qquad (2)$$

For limestones, dolomites and liquid filled sandstones, the apparent density read by the tool is essentially equal to bulk density of the formation. Clean formation bulk density is given by:

$$\rho b = \emptyset_{\rho f} + \emptyset_{ma}(1 - \emptyset) \qquad (3)$$

Well log is very essential with respect to its interpretation to describe the geophysical parameter along a well bore. Successful development of a hydrocarbon reservoir depends largely on well logging. Measurements from a well log is essential in the life of a given well because it has absolute influence on the decision for the well location and the formation evaluation. Well logging in Petroleum Engineering is very useful for Rock typing and petrophysical studies, Geological environment identification, Reservoir fluid contact location, Detection of fractures, Estimation of hydrocarbon in place, Estimation of recoverable hydrocarbons, Estimation of water salinity, Determination of average reservoir pressure, Determination of porosity or pore size distribution, Feasibility of water flooding studies, Mapping of reservoir quality, Probability assessment of inter-zone fluid communication, Monitoring of reservoir fluid movement.

The porosity of a reservoir rock is defined as that fraction of the bulk volume of the reservoir that is not occupied by the solid framework of the reservoir. This can be expressed in mathematical form as (Tiab & Donaldson, 2004):

$$\emptyset = \frac{V_b - V_{gr}}{V_b} = \frac{V_p}{V_b} \qquad (4)$$

Porosity are affected by several factors such as Uniformity of grain size, Degree of cementation or consolidation, Amount of compaction during and after deposition, methods of packing. In Engineering, porosity is classified into Total (Absolute) and Effective porosity depending upon which pore spaces are measured in determining the volume of these pore spaces.

Well Log Porosity can be determined through Sonic Porosity (Wyllie (1963), given as;

$$\emptyset = \frac{t_{LOG} - t_{ma}}{t_f - t_{ma}} \qquad (5)$$

Typical Values are Sand ($\Delta t_{matrix}$= 182 msec/m), Lime ($\Delta t_{matrix}$ x = 156 msec/m),Dolomite ($\Delta t_{matrix}$= 143 msec/m), Anhydrite ($\Delta t_{matrix}$= 164 msec/m).

When the formations are not sufficiently compacted, the observed $\Delta t$values are greater than those that correspond to the porosity according to the time-average formula, but the f versus *t* relationship is still approximately linear. In these cases, an empirical correction factor, *Cp*, is applied to Equation 2.5 to give a corrected porosity, $\emptyset_{SVcor}$:

$$\emptyset_{SVcor} = \frac{t - t_{ma}}{t_f - t_{ma}} \times \frac{1}{C_p} \qquad (6)$$

The value of $C_P$ is given approximately by dividing the sonic velocity in nearby shale beds by 328. However, the compaction correction factor is best determined by comparing $\emptyset_{SV}$ with the true porosity obtained from another source.

There several Factors affecting sonic, Neutron and density porosity interpretation such as Lithology, Shale, Fluid Type, Compaction, Secondary Porosity, Borehole Effect, Mudcake.

Porosity from Density log is given as;

$$\emptyset_D = \frac{\varrho_{ma} - \varrho_b}{\varrho_{ma} - \varrho_f} \qquad (7)$$

Porosity from Neutron log is expressed mathematically as;

$$\log_{10}\emptyset = aN + B \qquad (8)$$

Permeability detailed classic definition and analysis are described by Darcy (1856) and Tiab & Donaldson (2004) and factors affecting permeability includes compaction, pore size, sorting, cementation, layering and clay swelling. It can be determined through direct measurement, regression methods, virtual measurements and empirical methods.

Rock formation permeability is the most important parameter that indicates how efficient the reservoir fluids flow through the rock pores to the wellbore. The only direct means of permeability measurement has always been through the analysis of core plugs, but due to the huge cost associated with their acquisition, other indirect methods have been turned to. In the absence of cores, several workers have developed empirical approaches in the determination of permeability from well logs which are more readily available for all drilled wells. Of all the reservoir properties, permeability is the only parameter that cannot be determined directly from well logs, but can only be derived from porosity. This makes it the most difficult property to determine and also predict, thereby a problem. The huge importance placed on permeability in reservoir production and management has made it imperative for accurate prediction models to be put in place for its determination. Hence, in this study five permeability models were evaluated and validated using core derived petrophysical properties.

The aim of this work is to determine the permeability of reservoirs using porosity logs and this is been achieved by the determination of the reservoir and non-reservoir rocks using well logs, determination of porosity using well logs, computing of the reservoir permeability using

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various models and the validation of permeability models using core permeability.

## 2. Materials and Methods

### 2.1 Experimental (Analytical) and Numerical Approach

### 2.1.1 Materials

#### 2.1.1.1 Data Requirement

The following dataset were used for this study;

Well logs for two fields (Otumara fields).Logs include Gamma ray, resistivity and density logs.

Core derived effective porosity and permeability for a cored interval from 2500.92 to 2527.92 m in Otumara Field

### 2.1.2 Methods

Data loading and quality check was carried out and then the identification of the lithology. The core porosity was validated. Then I further generated the permeability model, linear regression permeability model and then validated the models and it aided in selection of a permeability model for a field wide development.

#### 2.1.2.1 Shale volume determination (Vsh)

The gamma ray log was used in this study to calculate the volume of shale by first determining the gamma ray index ($I_{GR}$) using Asquith and Gibson, (1982) linear relationship as follows:

$$GR_{index} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}} \qquad (9)$$

#### 2.1.2.2 Porosity determination

The fluids that are contained in pores of sedimentary rocks could either be oil, water or gas. In this study, **total porosity** was calculated using the density log as follows;

$$\phi_T = \frac{\rho_{ma} - \rho_{bulk}}{\rho_{ma} - \rho_{fl}} \qquad (10)$$

The **effective porosity** is responsible for flow in a reservoir rock. It is calculated using total porosity and shale volume as follows;

e = ∅_T×(1-V_SH) (11)

#### 2.1.2.3 Model Development for Permeability Estimation

There are three methods utilized globally for permeability determination and includes; empirical models, regression method (linear and multiple) and virtual measurements (Nuclear Magnetic Resonance and Fuzzy logic). In this study, five empirical models were utilized for permeability estimation. They include Timur (1968) model, Coates and Dumanoir (1981) model, Tixier (1949) model, Aigbedion (2004) and Owolabi et al., (1994) empirical model. Permeability is mainly controlled by pore throat size, but in an intergranular rock that is itself strongly dependent on grain size (Kennedy, 2015). These models are based on the correlation between permeability, porosity and irreducible water saturation. Irreducible water saturation ($S_{wirr}$) for Niger Delta reservoirs ranges from 0.142 to 0.2.

The models for permeability estimation are presented as follows;

✓ **Model 1: Tixier (1969) Model:**

Tixier (1949) permeability model is given as follows;

$$K^{-1/2} = 250\frac{\phi^{\varepsilon}}{S_{wirr}} \qquad (12)$$

✓ **Model 2: Timur (1968) Model:**

Timur (1968) proposed an equation for permeability in the form;

$$K = 0.136\frac{\phi^{4.4}}{S_{wirr}^{\ 2}} \qquad (13)$$

✓ **Model 3: Coates and Dumanoir (1981) Model:**

Coates and Dumanoir (1981) proposed the following formula for permeability:

$$K^{-1/2} = 100\frac{\phi^{\varepsilon}(1 - S_{wirr})}{S_{wirr}} \qquad (14)$$

✓ **Model 4: Owolabi et al., (1994) Model:**

Permeability was also estimated using Owolabi et al. (1994) empirical model. This model is widely used in the Niger Delta Sedimentary basin. The equation is as follows;

$$K = 307 + 26552(\phi^2) - 34540(\phi \times S_{wirr})^2 \qquad (15)$$

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✓ **Model 5: Aigbedion (2004) Model:**

After analyzing several core samples from certain oil fields in the Niger Delta, Nigeria, Aigbedion (2004) proposed the following correlation for permeability estimation;

$$Log\ K = 20.83565 + 13.069\phi \qquad (16)$$

The permeability results obtained from these empirical models were then compared with those derived from cores.

### 2.1.2.4 Linear Regression Model

Porosity and permeability measurements provided for the available core samples were plotted graphically. Based on the generated correlation coefficients, a relationship between porosity and permeability is generated as follows;

For Otumara-25 Well;

$$Log\,(K) = 2813.2(\phi - 466.61 \qquad (17)$$

The linear relationship equation was then used to generate permeability values for the uncored sections of the cored well. These results were again compared with permeability values generated from the empirical models.

## 3. Results and Discussion

### 3.1 Results of Porosity determination

The average total and effective porosity determined from conventional wireline logs for the cored portion of the Otumara-25 well in Otumara Field are presented in Table 1 and 2 and compared with core derived effective porosity values. The detailed results on conventional log and core derived petrophysical parameters are presented in the appendix of this study. In Otumara field, effective porosity ranges from 0.02 to 0.33 with an arithmetic mean and standard deviation (SD) of 0.24±0.05, while core derived effective porosity ranged from 0.20 to 0.29 with mean and standard deviation of 0.24±0.02. Figure 3shows good agreement between log-determined and core-determined porosity for the cored wells of the field. These results show that density logging tool is very good for porosity measurements.

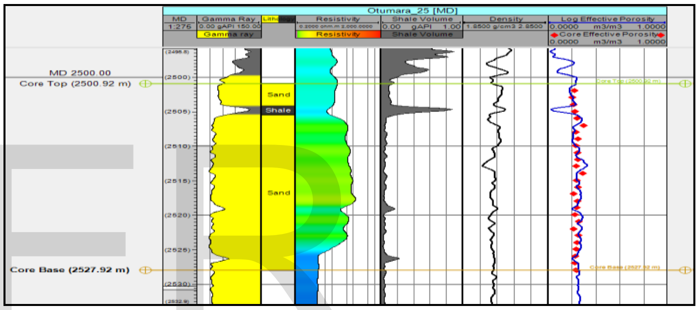

**Figure 3: Log derived effective porosity compared with core derived effective porosity for Otumara-25 well in Otumara field.**

### 3.2 Empirical Models

The five empirical methods (Tixier, Timur, Coates and Dumanoir, Owolabi et al., and Aigbedion) were applied to compute permeability as a function of computed porosity and water saturation in hydrocarbon bearing reservoirs from Otumara field. Table 2 shows the average statistical results of permeability computed using the various empirical models compared with core permeability and linear regression model. Core permeability results are presented in the appendix of this study. Figure 4 shows a comparison of core and empirically computed permeability versus depth for Otumara fields.

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**Table 1: Results of average well log petrophysical parameters compared with core derived porosity for Otumara-25 well**

| Parameters | Gamma Ray | Resistivity | Density | Gamma Ray index | Shale Volume | Log Total Porosity | Log Effective Porosity | Core Effective Porosity |
|---|---|---|---|---|---|---|---|---|
| | (gAPI) | (Ohm.m) | (g/cm³) | | (frac.) | (frac.) | (frac.) | (frac.) |
| Minimum | 27.39 | 2.25 | 2.08 | 0.11 | 0.03 | 0.18 | 0.02 | 0.20 |
| Maximum | 124.40 | 129.39 | 2.35 | 0.95 | 0.87 | 0.34 | 0.33 | 0.29 |
| Arithmetic Mean | 42.84 | 46.05 | 2.22 | 0.24 | 0.09 | 0.26 | 0.24 | 0.24 |
| Geometric Mean | 40.76 | 30.25 | 2.21 | 0.22 | 0.06 | 0.26 | 0.23 | 0.24 |
| Sample variance | 274.42 | 992.49 | 0.00 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 |
| Standard deviation | 16.57 | 31.50 | 0.05 | 0.14 | 0.12 | 0.03 | 0.04 | 0.02 |
| Median | 37.64 | 48.16 | 2.21 | 0.20 | 0.05 | 0.27 | 0.25 | 0.23 |

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**Table 2: Results of permeability determination using empirical models compared with core derived permeability in Otumara-25 well**

| Parameters | Timur (1968) | Coates and Dumanoir (1981) | Tixier (1949) | Aigbedion (2004) | Owolabi et al., (1994) | Core Permeability | Regression model |
|---|---|---|---|---|---|---|---|
| Minimum | 0.33 | 0.57 | 9.97 | 1.54 | 321.57 | 100.62 | 32.82 |
| Maximum | 5.56 | 7.76 | 68.17 | 3.67 | 3048.51 | 366.67 | 456.74 |
| Arithmetic Mean | 1.83 | 5.71 | 31.18 | 2.59 | 1842.36 | 202.66 | 229.35 |
| Geometric Mean | 1.62 | 5.54 | 29.40 | 2.56 | 1763.35 | 191.35 | 207.47 |
| Sample variance | 0.82 | 1.12 | 109.63 | 0.16 | 217883.12 | 4771.67 | 7983.97 |
| Standard deviation | 0.90 | 1.06 | 10.47 | 0.39 | 466.78 | 69.08 | 89.35 |
| Median | 1.74 | 5.93 | 30.86 | 2.62 | 1905.63 | 202.15 | 239.68 |

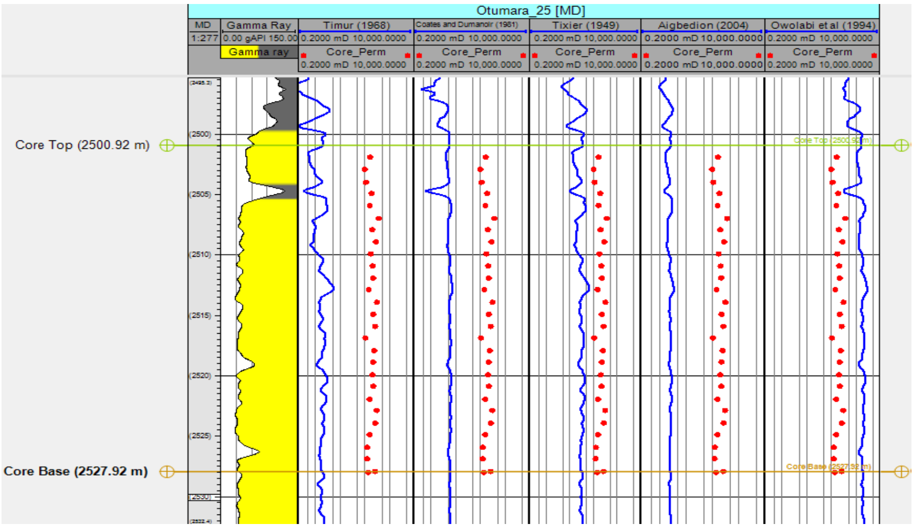

**Figure 4: Permeability models developed using empirical models and linear regression model compared with core permeability for Otumara-25 well in Otumara Field**

In Otumara field, the estimated permeability using Timur's model ranges from 0.33 to 5.56 mD, with arithmetic mean and SD of 1.83±0.90 mD. Coates and Dumanoir estimated permeability ranged from 0.57 to 7.76 mD with mean and SD of 5.71±1.06 mD.Tixier's modelled permeability values ranged from 9.97 to 68.17 mD with mean and SD of 31.8±10.47 mD. Owolabi et al. revealed permeability values that ranged from 321.57 to 3048.51 mD and has average and SD values of 1842.36±466.78 mD. Also, Aigbedion's estimated permeability values ranged from 1.54 to 3.67 mD and has arithmetic mean and standard deviation values of 291±0.38 mD. Meanwhile core permeability values ranged from 100.62 to 366.67 mD with mean and SD values of 202.66±69.08 mD in Otumara field. These results show that permeability values are underestimated by Timur's model, Coates and Dumanoir's model, Tixier's model and Aigbedion's model, while Owolabi's model overestimated permeability values for the cored interval. This can clearly be seen in Figure 4 as there is a wide gap between the empirical models and core permeability. All the empirical models failed to give reasonable permeability values close to those obtained from core (Table 2 and Fig. 4). This shows that, in the absence of acquired cores, none of the empirical modelling approaches can be used to estimate permeability values in Otumara field.

### 3.3 Linear Regression model

Simple linear regression model offered porosity-permeability relationships presented in equation 17 for Otumara field. The equations were generated from a cross-plot of core porosity versus core permeability (Figs. 5). These equations were used to generate permeability curves shown on Figure 5. A linear regression model provided the best fit for the results. For Otumara field, permeability estimated using the regression model for the cored section of Otumara-25 well ranged from 32.82 to 456.74 with mean and SD of 229.35±89.35 mD. The average results obtained from the regression model is 125 times greater than Timur's model, 40 times greater than Coates and Dumanoir model, 7 times greater than Tixier model and 88 times greater than Aigbedion model. Meanwhile, Owolabi's model exceeded the average permeability estimated with the regression method by over 9 times. There is a very close match between permeability derived using regression method and the actual core permeability. This shows that in Otumara field, apart from the regression method, none of the empirical methods are effective for permeability estimation. Figures 6 shows a comparison between log derived permeability and the linear regression models generated for the wells in Otumara field. Inspection of these figures and Tables 2 above shows that regression models performs better than empirical methods. In Otumara-25 well, the linear model only estimated permeability values for the sandy sections of the reservoir. No results were generated for the shaly intervals because of the reduced/absence of effective porosity in shales. Inasmuch as all empirical model either overestimated or underestimates permeability, they showed very good correlation with permeability from the regression model in Figures 7 and gives the average arithmetic permeability determined using all methods.

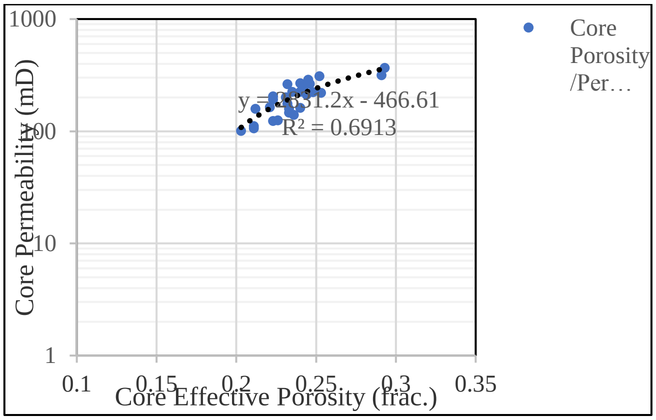

**Figure 5: Core Porosity-Permeability cross-plot for Otumara-25 well showing a strong linear relationship**

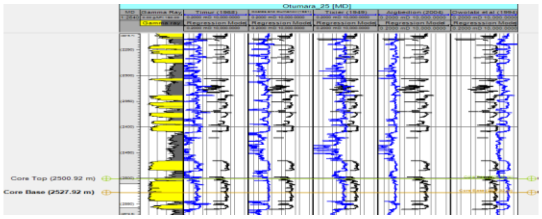

**Figure 6: Comparison between empirical models and regression model for permeability estimation in Otumara-25 well.**

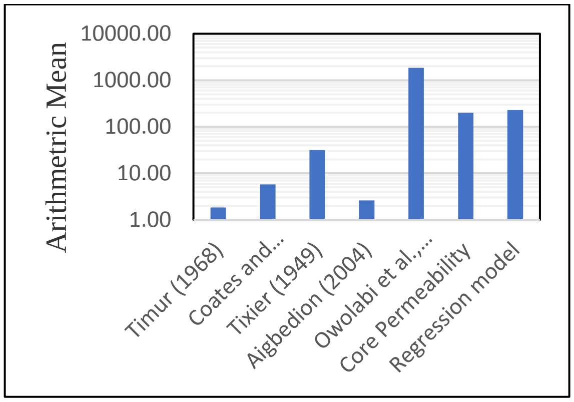

**Figure 7: Models utilized in estimating permeability compared with core permeability for Otumara-25 well.**

## 4. Conclusion

Empirical model for permeability prediction relates permeability with effective porosity and irreducible water saturation. These parameters are often estimated from analysis of cores in the laboratory and some of them can be estimated from well logs. Various empirical models have been utilized in this study for the prediction of permeability and validated using core permeability. Empirical models utilized includes; Timur (1968) model, Coates and Dumanoir (1981) model, Tixier (1949) model, Aigbedion (2004) empirical models underestimated permeability and Owolabi et al. (1994) overestimated permeability. Linear regression models developed for Otumara field revealed a good match with core permeability. All other empirical model underestimated permeability when compared with the linear regression model but Owolabi's permeability model overestimated permeability in Otumara field. Although these models showed deviations from the linear regression model, a strong positive inter-relationship with the linear models is observed. This indicates that if the constants utilized in these models are modified, they can all serve as good estimators for permeability in Otumara field.

This study revealed that among the methods utilized that;

- ✓ The linear regression model which utilizes actual porosity and core permeability in its development gives the best outcomes
- ✓ In the absence of cores, Owolabi et al. (1994) empirical model has proved to fail in being a reliable estimator in the Otumara field since it overestimated permeability.
- ✓ All other empirical model utilized have performed poorly in predicting permeability.

This study has shown that Linear regression model can be developed by using cross-plot of core permeability versus porosity logs to estimate permeability in the uncored wells in Otumara field where the relationship is linear.

This study therefore recommends the use of the generated linear regression model in the estimation of permeability in uncored wells in Otumara field.

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