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Permeability Prediction in Wells Using Flow Zone Indicator (FZI)

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Abstract

Estimation of permeability values in uncored wells but logged intervals is a worldwide challenge usually encountered in all reservoirs. Permeability estimation is a major risk task in petroleum engineering, as it is a necessity for reservoir description and performance (fluid flow).

Permeability obtained from core measurement is usually limited due to the high cost of getting core samples and toilsome analysis required, scoring only being done for certain good sections and well logs are used for predicting permeability in sections where core permeability are unavailable. This makes core derived permeability cost effective and feasible.

For this work, statistical and graphical measurement was considered for estimating permeability. Statistical methods employing regression model and flow zone indicator (FZI) were utilized in establishing a mathematical correlation between core data and well logs using equations obtained from plotted graphs. FZI_{mean} values obtained from the log-log plot of RQI against Φ_z, was used to classify the well into different hydraulic flow units (HFUs).

Statistical methods were tested using a sample size of over 960 measured permeability data gotten from five wells in an oil field, located in the Niger Delta region of Nigeria. Results obtained from classifying data into hydraulic flow unit using FZI showed better correlation R^2 compared to the regression model.

Keywords: Well logs; Hydraulic Flow Units; Flow Zone Indicator; Permeability; Cores.

1. Introduction

Over the years the prediction of permeability in non-homogeneous and anisotropic formations has been a challenge, because of the availability of limited and confined numbers of core and well log data's. Permeability prediction is affected by variations in reservoir properties like type and sorting of rock materials, mineralogy of rock matrix, pore throat size and so forth. Stratigraphic and petrographic analysis of cores in combination with correlations of logs and major rock types were initially used to describe various sedimentary bodies that have distinct chemical, physical, and biological characteristics in the formation. The key to a better reservoir characterization and exploitation begins with the understanding of the differences in pore geometry within various lithofacies. These differences have lead to a further subdivision known as flow units. A flow unit is a "mappable portion of the total reservoir within which geological and petrophysical properties that affect the flow of fluids are consistent and predictably different from the properties of other reservoir rock volumes" [1]. Flow units are a function of Flow Zone Indicator (FZI), Reservoir Quality Index (RQI) and Normalized Porosity (Φz).

Estimation of permeability using mathematical functions and correlations to show relationships between the well log and core data have being done in the past by traditional methods. Permeability computation by flow units and FZI concept offer a better estimation compared to the customary regression founded average relationships. The Niger Delta Basin has many abandoned or marginally productive oilfields in the region. Mostly, production records are nonexistent which hinders further exploitation and development pursuit. Using the flow unit concept of flow zone indicator and flow units, a substantial development in permeability prediction from log data has been achieved for reservoirs located in the Niger Delta [2].

2. Method

The flow unit concept [2] was adopted for segmenting the reservoir into different unique petrophysical types. Each unique reservoir type has a specific FZI value. Bear [3], defined the hydraulic (pore geometrical) unit as the characteristic fundamental volume of the entire reservoir within which petrophysical and geological properties of the reservoir are the same. Hearn *et al.*, [4] defined flow units as reservoir zones that are vertically and laterally continuous, and possess the same bedding, porosity, and permeability qualities.

Amaefule *et al.*, [2] developed a technique for formations containing similar flow units. This technique is based on a modified Kozeny-Carmen equation which gives a theoretical basis for the dependence of permeability in pore structures. Entreating the mean hydraulic radius concept, Kozeny and Carmen [5] considered the reservoir to be made up of a pack of capillary tubes. Poiseuille's and Darcy's laws were combined to derive a link between permeability and porosity, shown in Eq. 1:

$$K = \frac{{\emptyset_e}^3}{(1-\emptyset_e)^2}\left(\frac{1}{F_s\tau^2S_{gv}^2}\right) \quad (1)$$

where K is permeability in μm^2; $\emptyset_e$ is effective porosity in fractional bulk volume; Fs is a shape factor (Fs=2, for a circular cylinder); τ is tortuosity; Sgv is surface area per unit grain volume in μm^{-1}.

Eq. 1 can be written in field units as:

$$0.0314\sqrt{\frac{K}{\emptyset_e}} = \left(\frac{\emptyset_e}{1-\emptyset_e}\right)\left(\frac{1}{\sqrt{F_s}\tau S_{gv}}\right) \quad (2)$$

However, if permeability is to be presented in millidarcy (mD), then new relationships can be defined:

$$RQI\ (\mu m) = 0.0314\sqrt{\frac{K}{\emptyset_e}} \quad (3)$$

$$\emptyset_z = \left(\frac{\emptyset_e}{1-\emptyset_e}\right) \quad (4)$$

$$FZI = \frac{1}{\sqrt{F_s}\tau S_{gv}} = \frac{RQI}{\emptyset_z} \quad (5)$$

where FZI is the flow zone indicator; RQI is the reservoir quality index and $\emptyset_z$ is the pore volume-to-grain volume ratio.

Eq. 2 can be rewritten as:

$$RQI = \emptyset_z \times FZI \quad (6)$$

Taking the logarithm of both sides of Eq. 6 results in:

$$\text{Log } RQI = \text{Log } \emptyset_z + \text{Log } FZI \quad (7)$$

Equation 3-5 are used to derive the values for plotting a log-log plot based on (Eq. 7) for RQI versus $\emptyset_z$. All data with similar FZI values will be on a straight line with unit slope. Data with different FZ1 values will be on other lines. FZI_{mean} can be calculated from the intercept of the unit slope straight line at $\emptyset_z = 1$. All data on the same straight line can be said to have similar pore throat features and thereby making a hydraulic unit. Moreso, Eq. 8 below, can be used to calculate the permeability of a specific data point in a hydraulic unit using the FZI_{mean} and the corresponding data porosity.

$$K = 1014\ (FZI_{mean})^2\left(\frac{{\emptyset_e}^3}{(1-\emptyset_e)^2}\right) \quad (8)$$

Previous researchers have employed statistical methods/approach based on changes/variations in permeability to zone/characterize reservoirs into layers. The basic challenge encountered by those methods is that geological attribute that governs reservoir zonation are being neglected. The Flow Zone Indicator (FZI) is a sole parameter that mixes the geological attributes of mineralogy and texture in the separation of unique hydraulic flow units.

3. Results and discussion

In this paper, statistical and graphical methods were tested using a data size of over 900 measured core and log data obtained from wells in an oilfield, located in the Niger Delta region of Nigeria.

Initially, a semi-logarithmic cross plot of core permeability against core porosity was plotted as shown in Fig. 1. A trendline equation obtained from this plot was used in the estimation of permeability for the cored sections of the well using corresponding porosity data. Fig. 1 shows a lot of scattering, clearly indicating that porosity alone is insufficient to explain variation in permeability. A linear correlation (R^2=0.3969) was obtained, indicating a poor linear relationship between core permeability and porosity. The poor correlation can be attributed to the fact that the trendline passes through few points of the many scattered points, clearly indicating the existence of more than one group of data, also could be attributed to variation in lithology (presence of more than one rock type). Therefore, this conventional relationship between core porosity and permeability cannot be relied upon for accurate estimation of permeability values from porosity data.

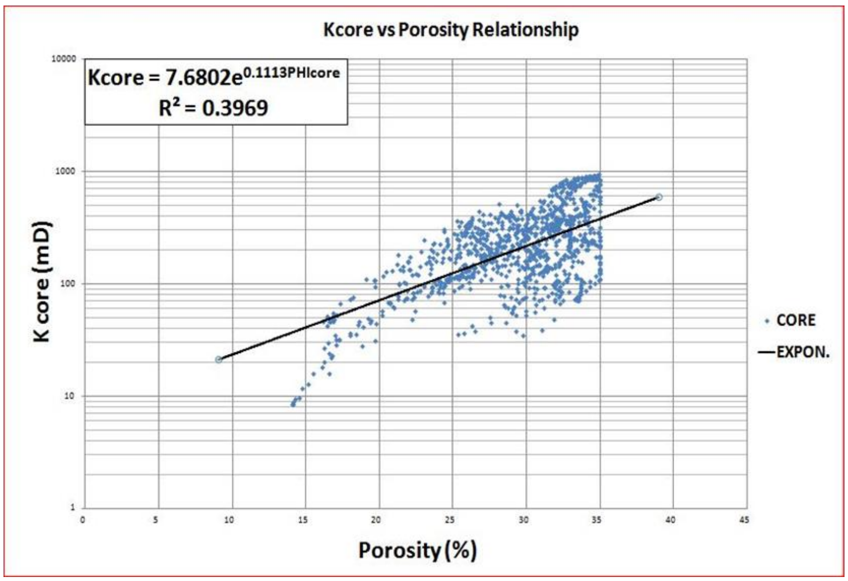

Fig. 1. The core permeability against core porosity

3.1. Porosity-Permeability relationship based on Flow Unit (FU) Concept

To determine the number of flow units, three (3) different ways were applied, and results were compared:

1. Histogram Analysis

Plotting the data of flow zone indicator in the form of a histogram, a normal distribution will be gotten which represents "n" hydraulic flow units. Fig. 2 shows the superposition of multiple log-normal distributions, showing more than one group of data. However, individual distributions are not distinct on the histogram due to the overlapping of data.

2. Normal Probability Analysis

However, to support and determine the boundaries of each one of the groups represented in Fig. 2, it is essential to make a probability plot. A distinct straight line showing the normal distribution is formed on the probability plot, the number of HFUs in the reservoir is determined by the number of straight lines on the probability plot. Shown in Fig. 3, is a normal probability plot of FZI, from which five (5) group of HFU are distinguished, and FZI boundaries are estimated.

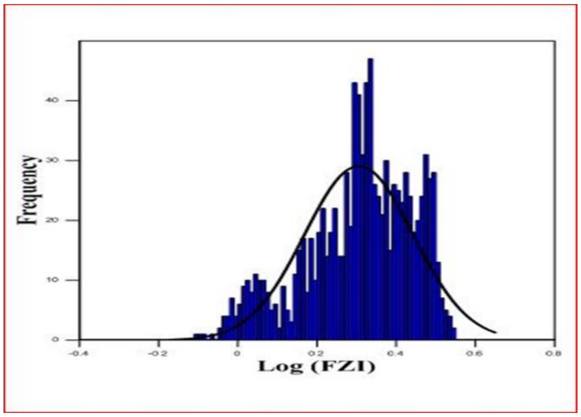

Fig. 2. Histogram of the logarithm of FZI

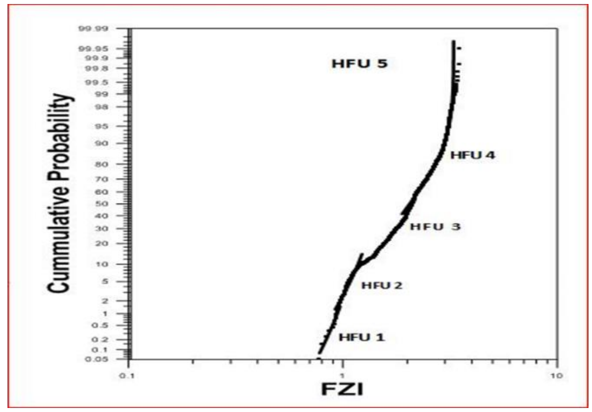

Fig. 3. Normal Probability plot of logarithm of FZI

3. Using Least-Square Regression

Basically, RQI and FZI values were calculated from gathered core data and a log-log plot of RQI versus $\emptyset_z$ was made, which is shown in Fig. 4. Unitary slope lines were drawn through sections of data according to it mean FZI values, where the intercept ($\emptyset_z$=1) is the mean FZI for each section. This method is summarized as the following steps:

1. Calculate the RQI values and $\emptyset_z$ from Eq. 3 and 4, respectively, using the core data given in Fig. 1.
2. Plot RQI vs. $\emptyset_z$ in logarithmic space as Fig 4.
3. Choose a sensible initial guess of the intercept of each straight line equation: the mean value of each HFU (or each FZI).
4. Allocate core sample data to the each straight line.
5. Re-compute the intercept of each HFU employing the least squares regression equations.
6. Compare the current and old values of the intercept for every straight line. Update the intercept values provided the difference is not within the acceptable tolerance and repeat step 4.
7. Repeat steps 3 through 6 until the optimal location of each straight line is found in which the error sum of squares is a minimum for the desired number of HFUs.

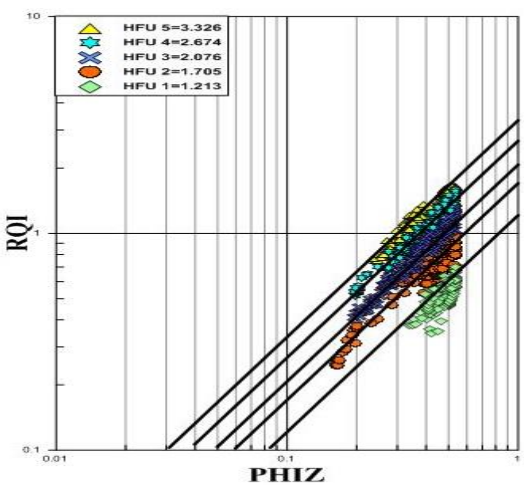

Fig. 4. Plot of reservoir quality index vs. normalized porosity

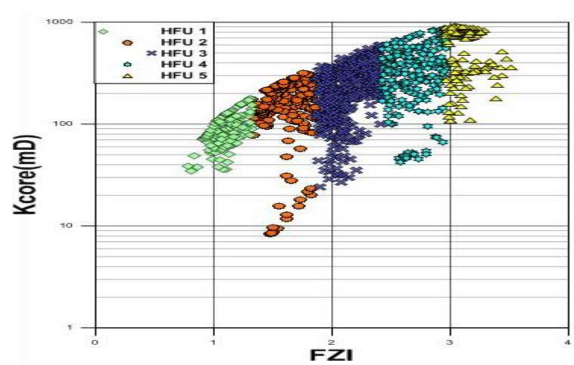

Fig. 5. Plot of permeability vs. FZI showing HFUs

Five (5) hydraulic flow units can be identified from the given core data, as shown in Fig. 4. Segments with similar flow properties fall into the same HFU. The coefficient of determination (R^2) obtained from these fittings are closer to one (1), showing better correlations compared to linear regression models. Classification of these data into their respective HFUs reduces the scatter point of the regression lines, thereby resulting in an improved trendline equations and a better coefficient of determination. Fig. 5 is a plot of core permeability versus FZI generated for the five HFUs; again it was observed that each segment with similar flow attributes falls into the same HFU.

The mean FZI values obtained are used to compute permeability using Eq. 8. A comparison between core permeability and computed permeability using individual FZI_{mean} value is shown in Fig. 6, where the 45° line showing an almost perfect correlation was obtained. A square correlation coefficient of 0.957 was obtained from the regression trendline.

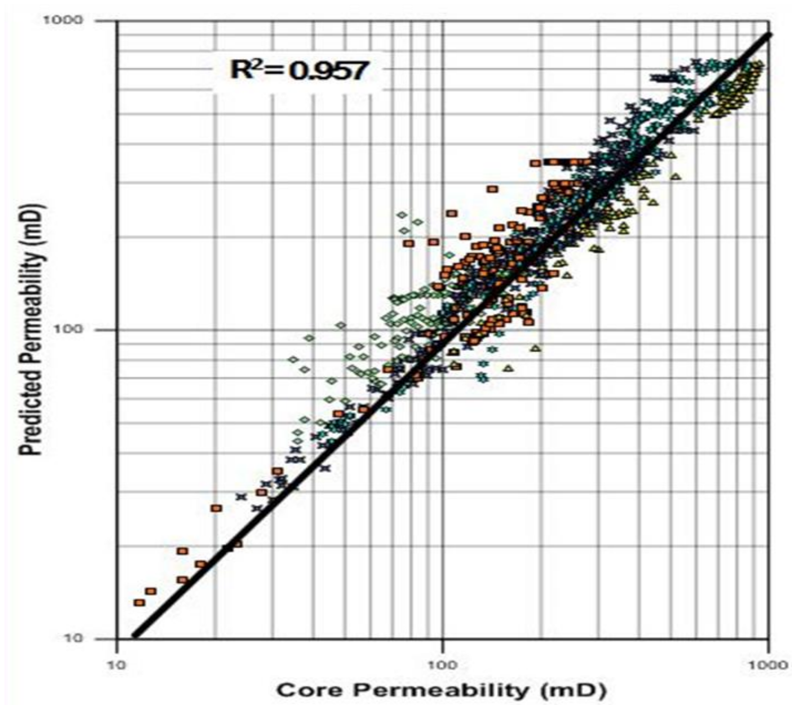

Fig. 6. Core permeability vs. calculated permeability after HFU definition

4. Conclusion

From the results obtained the following conclusions are drawn:

1. An effective parameter for identifying flow unit is the Flow zone indicator since it is dependent on the radius of pore throat and porous medium geometry that are associated with petrophysical rock type.
2. Permeability prediction using regression analysis tends to give a poor linear connection between permeability and porosity. Therefore, regression analysis is unreliable in permeability prediction.
3. The least-square regression approach for estimating the number of flow units minimizes the visual and personal errors common in the histogram and normal probability analysis.
4. FZI permeability prediction model gives a good correlation coefficient (R^2 = 0.957).

Nomenclature

F_S	*shape factor*	*RQI*	*reservoir quality index*
FZI	*flow zone indicator*	S_{gv}	*surface area per grain volume*
HFU	*hydraulic flow unit*	*Ø*	*porosity, fraction*
K	*permeability*	*Øe*	*effective porosity*
N	*normal distribution*	τ	*tortuosity factor*
R^2	*coefficient of determination*		

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