Determination of Hydraulic Flow Unit using Integrated Petrophysical Method: A Case Study of Field "X" in the Niger Delta

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Abstract— **Improvement on reservoir description technique is one of the emerging challenges for geoscientist and engineers in a bid to reduce the amount of hydrocarbon left behind pipe. Key to improved reservoir description and efficient hydrocarbon exploitation involve understanding complex variations in pore geometry within different lithofacies. This variation in pore geometrical attributes, provided by core data information on various depositional and diagenetic controls defines the existence of distinct zone (hydraulic units) with similar fluid flow characteristics. Classic description of reservoir rock has been based on subjective geological observations and on empirical porosity-permeability relationships. However, it has been observed that for any porosity within a given reservoir rock, permeability can vary by several orders of magnitude indicating the existence of several flow units. This study is set to use a theoretical methodology in the identification and characterization of hydraulic units within a geological unit (facies) through the integration of core data analysis and well log data analysis. The technique is based on the modified Kozeny-Carmen equation and the concept of hydraulic mean radius. The study documents the theoretical development of proposed technique, validates and characterizes the hydraulic units and present predicted versus actual permeability data to demonstrate the usefulness of the technique.**

I. INTRODUCTION

The key success in a reservoir flow unit is to integrate the geological, petrophysical, engineering and reservoir performance data to describe a flow unit. Bear (1972) defined the hydraulic (pore geometrical) unit as the representative elementary volume of the total reservoir rock within which the geological and petrophysical properties of the rock volume are the same. A hydraulic flow unit (flow unit) is also defined as the representative volume of total reservoir rock within which geological properties that control fluid flow are internally consistent and predictably different from properties of other rocks (Ebanks et al., 1984). Hear et al (1984), also defined flow unit as a reservoir zone that is laterally and vertically continuous, and has similar permeability, porosity, and bedding characteristic. Tiab (2000) also defined hydraulic flow unit as a continuous body over a specific reservoir volume that practically possesses consistent petrophysical and fluid properties, which uniquely characterize its static and dynamic communication with the wellbore. characterization of reservoirs into hydraulic flow units is a practical way of reservoir zonation. The presence of distinct units with particular petrophysical characteristics such as porosity, permeability, water saturation, pore throat radius, storage and flow capacities help researchers to establish strong reservoir characterization. Thus, the earlier in the life of a reservoir the flow unit determination is done, the greater the understanding of the future reservoir performance. Most Niger delta sandstones reservoir tends to be unconsolidated and generally heterogeneous due to its depositional and diagenetic processes variations. The extreme petrophysical heterogeneity found in sandstone reservoirs is demonstrated by the wide variability observed especially in porosity-permeability cross plot of core data analysis. Reservoir characterization method is therefore valuable as it provides a better description of the storage and flow capacities of a petroleum reservoir. Strong reservoir characterization can be established in the presence of distinct units with particular petrophysical properties such as water saturation, permeability, pore throat radius, porosity and storage capacities. The key to enhanced reserves determination and improved productivity is based on the establishment of causal relationships among core-derived data and log-derived attributes. These theoretically correct relationships can then be used as input variables to improved reservoir description.

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II. OBJECTIVE OF STUDY

The objective of this study therefore is to describe and characterize the X field by using available conventional core data and well logs from well 'CPG' in the 'X' field of the Niger Delta oil province. The distribution of distinct reservoirs parameters concerning the petrophysical properties are also taken into consideration for an effective hydraulic flow unit characterization. The petrophysical parameter of interest in this characterization is the **PERMEABILITY.** This study provides a graphical method for easily quantifying reservoir flow unit based on the geologic framework, petrophysical rock and fluid type, storage capacity and reservoir process speed. Using these parameters and graphical tools to outline a quantitative approach to transform rock type based zonation into petrophysical based flow unit that can be used as input into a numerical flow simulator that takes into consideration the foot by foot characteristics of the wellbore.

III. Statement of Problem

The importance of permeability in reservoir charcterization and investment decision making can not be overstated. Knowledge of permeability and permeability distribution is critical to effective reservoir description and characterization. The prediction of pemeability in hetrogeneous sandstone from well logs and core data represents difficult and complex problem, thus a basic correlation between porosity and permeability can not be established due to the fact that porosity is generally independent of grain size while permeability is strongly dependent on grain size. Measurement of permeability has been of utmost concern considering the fact that permeability can only be measured when a well is cored as there is low percentage of cored wells due to technical and economic reasons thus the prediction of permeability is required.
Several researchers have undertaken studies in which core data have been correlated with log data with a view to establishing unique core-log relationship from which permeability can be correctly estimated. Permeability is an important rock property and one of the most difficult of all petrophysical properties to determine and predict (Johnson, 1994). For a petroleum engineer, an accurate estimate of permeability is essential because permeability is a key parameter that controls strategies of well completion, production, and reservoir management. Also knowledge of rock permeability and its spatial distribution throughout the reservoir is of utmost importance to reservoir characterization.
Amaefule, et. al., (1993) stated that core data provide information on various depositional and diagenetic controls on pore geometry, and the variations in pore geometry attributes lead to the existence of separated zones (hydraulic flow units) with similar flow properties. They proposed a method based on Cozeny-Karmen equation and the concept of hydraulic mean radius in which core porosity and core permeability values determined from routine core analyses are used. These data are used to determine reservoir quality index (RQI), and flow zone indicator (FZI). The determination of these values can be transformed to hydraulic flow units by means of combination of petrophysical, geologic and statistical analyses. These hydraulic flow units are correlated to well logging responses in order to establish regression models for permeability estimations in the uncored wells or intervals. The Amaefule et al (1993) method was employed in this study.

IV. Methodology

In order to define a petrophysical based reservoir characterization and zonation, the best representative data of the studied reservoir must be obtained. The methods for obtaining such data can be listed as

- well logging,
- conventional core analysis

This method and their applications are employed to construct a hydraulic flow unit zonation within the reservoir of interest. The techniques applied in this research include the basic geologic framework of the study area, the petrophysical properties of the formation (sandstone), analyses of core-plug data, interpretation of well logging data. The hydraulic flow zone was obtained through a combination of these techniques and the Amaefule et al's (1993) method. The research methodology is summarized as follows;

V. Available Data

The formation of interest is a well (CPG) in the X field of the Niger Delta region. The conventional open-hole well logging data are utilized. The well has conventional Gamma Ray (GR), Neutron Porosity (PHIN), Bulk Density (RHOB) and Resistivity (R-LLD, R-LLS and R-MSFL) log data.
Well log for the well was available in conventional forms. The logs were read by 1 meter increments. The interpretations included only the Agbada formation. The log data for the well as read by 1 meter increments. Lithology discriminations were the first interpretations. Shale volume calculations, porosity determinations from sonic logs, neutron logs and density logs followed shale calculations. Necessary cross-plots for porosity determinations and corrections were constructed. Microsoft excel was used to generate logs.

VI. Well Logging Data Analysis

Surface geological methods help to identify interesting surface structures which could possibly contain fluids, but they are unable to predict whether these fluids are hydrocarbons. So far, there is no other solution than to drill a well to exactly determine the presence of hydrocarbons below the surface. However, drilling is a capital intensive process with numerous risks and uncertainty; a drilling process can come up with a dry hole or non commercial quantity of hydrocarbon. Formation evaluation tests can be utilized in order to analyse the contents of some subsurface sections, rather than drill a well. Formation evaluation is the process of using borehole measurements to evaluate the characteristics of the subsurface reservoirs, such as determining the physical properties of reservoirs and their contained fluids. Four categories are available for formation evaluation

- mud logging
- coring and core analysis
- drillstem testing
- well logging

The easiest way of getting reservoir data at the very beginning of the study can be considered as well logging, which mainly contributes to formation evaluation. The main objectives of the well logging is to identify the reservoirs, estimate the hydrocarbons in place, and estimate the recoverable hydrocarbons, but the data provided from well logs also help so many studies besides their main objectives.
In our X field, the conventional open-hole well log was available. This log is used to examine the lithological-mineralogical composition and the petrophysical properties such as porosity and water saturations. Besides the use of raw log data, some crossplots are utilized based on log parameters used to understand the nature of porosity. Obtained well log parameters are also run as input for the geostatistical methods, in order to correlate with core data for permeability estimations.

VII. Core Data Analysis

The reservoir characterization should include core analyses that help researchers to understand the reservoir parameters such as porosity type, porosity distribution, and permeability. All data gained from the core data analyses were observed carefully and comparisons were made with other available data. For an efficient reservoir characterization, all available data of core analyses, well logging, and production tests were combined.

VIII. Core Plug Permeability Analysis

The ability of the formation to conduct fluids is known as permeability. The measurement of permeability is a measure of the fluid conductivity of the particular material (Amyx, et.al,1960). Darcy's equation is used to define fluid flow in porous media.

$$K = \frac{Q}{A} \cdot \frac{\mu L}{\Delta P}$$

(1)

where,
Q is the flow rate in (cc/sec)
A is the cross-sectional area in (cm2)
L is the length (cm)
ΔP pressure difference in (atm)
μ is viscosity of the fluid in (cp)

Core permeability measurements must be carefully carried out in order to obtain results that are representative of the cored the formation. Core permeability in this study was determined by means of gas permeability tests to avoid reaction between the core sample and the fluid. It must also be kept in mind that, when the core is taken out from the reservoir, all of the confining pressures which attributes to overburden pressures are removed. Compaction of the core due to overburden pressure may cause as much as a 60 percent reduction in the permeability of various formations (Amyx, et.al, 1960).

IX. Depth Matching

Depth adjustment was performed using Microsoft excel controls, this allowed the achievement of consistency on the depth of the log and core. The data set were shifted to the proper depth and then matched each set of data individually. The core depth were matched to the wireline log depth by comparing the total spectral gamma derived from the log and core data.

X. Identification of Hydraulic Units and Permeability Prediction from Core and Log Data

The hydraulic quality of a rock is controlled by pore geometry which is a function of mineralogy (i.e. type. abundance, morphology and location relative to pore throat) and texture (i.e., grain size. grain shape, sorting. and packing). Various permutations of these geological attributes often indicate the existence of distinct rock unit with similar pore throat attribute: Determination of these pore throat attributes is central to accurate zoning of reservoir into units with similar hydraulic properties. The mean hydraulic unit radius (r_{mh}) concept is the key to unraveling the hydraulic units and relating porosity, permeability and capillary pressure.

$$R_{mh} = \frac{Cross-sectional\ Area}{Wetted\ perimeter} = \frac{Vol\ open\ to\ flow}{Wetted\ surface\ area}$$

(2)

For a circular cylindrical capillary tube

$$R_{mh} = \frac{r}{2}$$

(3)

By invoking the concept of the mean hydraulic radius, Kozeny and Carmen considered the reservoir rock to be composed of a buddle of capillary tubes. They then applied Poisseeuille's and Darcy's Laws to derive a relationship (Eq. 4) between porosity and permeability. The primary assumption in their derivation is that "the Level time of a fluid element in a capillary tube is equal to that in a REV." and that porosity is effective.

$$k = \frac{\emptyset_e r^2}{8\tau^2} = \frac{\emptyset_e}{2\tau^2} = \left(\frac{r}{2}\right)^2 = \frac{\emptyset_e {r_{mh}}^2}{2\tau^2}$$

(4)

The mean hydraulic radius (r_{mh})can be related to the surface area per unit grain volume (Sgv) and effective porosity ($\emptyset_e$) as follows

$$S_{gv} = \frac{2}{r} = \left(\frac{\emptyset_e}{1-\emptyset_e}\right)\frac{1}{r_{mh}} = \left(\frac{\emptyset_e}{1-\emptyset_e}\right)$$

(5)

Substituting Eq. 4 for r_{mh} in Eq. 3, Kozeny and Carmen obtained the following relationship

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

(6)

Where k is in μm^2 and $\emptyset_e$is a fraction.

The generalized form of the Kozeny-Carmen relationship is given by Eq. 7

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

(7)

Where
F_s is the shape factor (2 is for a circular cylinder).

The term $F_s\,\tau^2$ has classically been referred to as the Kozeny constant. For ideal, uniform and unconsolidated rocks, Carmen and Leverette computed the value of this term to be about 5. However. Rose and Bruce showed that this term $F_s\,\tau^2$could vary from 5 to 100 in real reservoir rocks which is a function of the geological characteristic of porous media and varies with changes in pore geometry. The Kozeny constant is a variable "constant" which varies between hydraulic units, but is constant within a given unit.

The variability of the Kozeny constant can be addressed in the following manner by dividing both sides of the equation by porosity and then taking the square root of both sides result in

$$\sqrt{\frac{K}{\emptyset_e}} = \left\{\frac{\emptyset_e}{1-\emptyset_e}\right\}\left\{\frac{1}{F_s\ \tau\ S_{gv}}\right\}$$

(8)

Where
K is in μm^2

Permeability expressed in milidarcy and porosity as a fraction will be

$$RQI = 0.0314\sqrt{\frac{K}{\emptyset_e}}$$

(9)

Where
RQI is the reservoir quality index
0.0314 is the constant square root of the conversion factor from μm^2 to md
$\emptyset_e$ is the effective porosity

The normalized porosity $\emptyset_z$ is the pore volume to grain volume ratio,

$$\emptyset_z = \left(\frac{\emptyset_e}{1-\emptyset_e}\right)$$
(10)

Thus FZI (flow zone indicator) is designated and is given by

$$FZI = \frac{1}{\sqrt{F_s \tau S_{gv}}} = \frac{RQI}{\emptyset_z}$$
(11)

Substituting these variables into Eq.8 and taking the logarithm of both sides results in

$$\log RQI - \log \emptyset_z + \log FZI$$
(12)

On a log-log plot of RQ1 versus $\emptyset_z$ the samples with similar FZl values will lie on a straight line with unit slope while sample with different FZ1 values will lie on other parallel line. The value of the FZ1 constant can be determined from the intercept of the unit- slope straight line at $\emptyset_z$=1. Samples that lie on the same straight line have similar pore throat attributes and thereby, constitutes a unique hydraulic flow unit. Each line is a hydraulic flow unit and the intercept of this line with normalized porosity is equal to 1 ($\emptyset_z = 1$) is the mean FZI for that hydraulic flow unit.

The basic idea of the hydraulic flow unit classification approach is to identify groups of data that forms unit slope straight line on a log log plot of RQI versus $\emptyset_z$. The permeability of a particular sample point is then calculated using the mean FZI valve of that hydraulic flow unit and the corresponding sample$\emptyset$.

The relation for this process is

$$K = 1014FZI^2 \left\{\frac{\emptyset_e^3}{(1-\emptyset_e)^2}\right\}$$
(13)

Permeability estimation is typically obtained from cores and well log measurement and well testing. As core sampling and well testing are expensive and often only available for a limited number of wells. A common approach is to present permeability using well logs by establishing a correlation based on the data from cored wells. Given this essentially empirical approach, geological compatibility procedures must be used for a reliable calculation of permeability distribution in wells.

XI. Results and Discussions

Following the method as detailed in Amaefule et al (2003) in combination with Kozeny-Carmen equation. The following results were obtained. Tables of data showing the different hydraulic flow unit, correlation of the core data and well log data which were depth match and stress corrected. The different calculation of the parameters used such as RQI, FZI, % porosity, predicted/calculated permeability and normalized porosity were used to identify the hydraulic flow unit. The table 1 to 7 shows the identification of the various hydraulic flow unit for each reservoir zonation in the appendix.

XII. Identification of Hydraulic Flow Unit

Available well log data and core data were combined to yield a single data set for this analysis. The core depth was matched to the wireline log depth by comparing the total spectrum/gamma ray derived from the log and core data.

The proposed zonation process was developed form stressed core porosity and klinkerberg permeability data from the cored zone interval. Three parameters were calculated normalized porosity, RQI, and FZI based on the modified Kozeny-Carmen equation. All the data were sorted out based on their FZI parameter value in an increasing order to determine the number of hydraulic flow unit. On the cross plot of RQI versus $\emptyset_z$ normalized porosity, seven (7) flow units were delineated with unique FZI constant for each unit (see Figure 1). These equation were developed assuming a matrix system where the porosity and permeability are intergranular/intercrystalline which means they may not be sufficient for more complex formation.

All samples with similar FZI values lies on a straight with slope equal to 1 which means they have the same pore throat attributes and thereby constitute a hydraulic unit. The mean valve of FZI was determined from the intercept of the unit slope straight line with$\emptyset_z = 1$. The FZI also incorporate the geological attributes of texture and mineralogy in the discrimination of distinct pore geometrical facies. Based on this process, 7 hydraulic flow unit were identified within the cored interval (Figure 1).

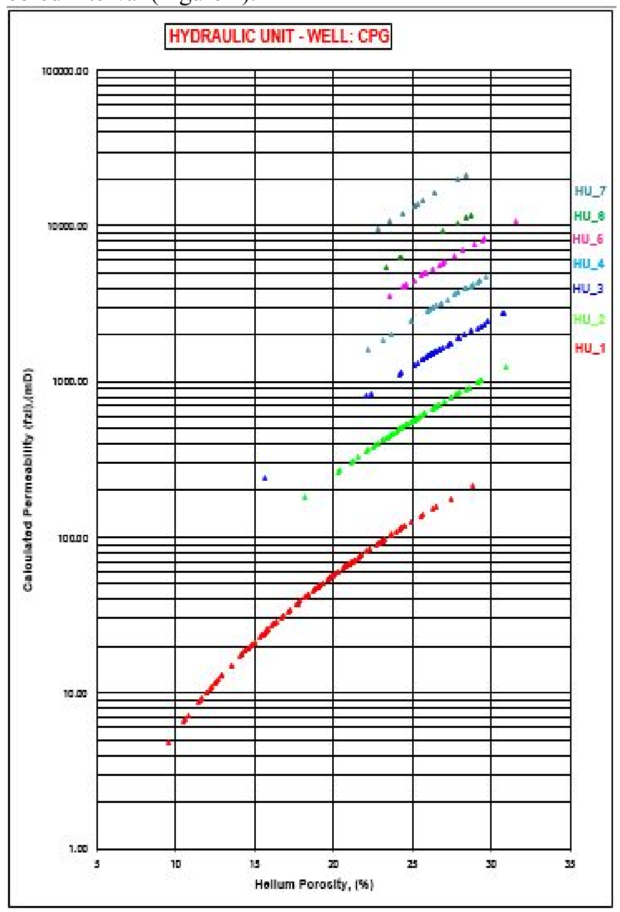

Figure 1 Crossplot of RQI versus Porosity for various hydraulic unit

XIII. Comparison of Core Permeability and Predicted/Calculated Permeability for The Uncored Zone/Interval

The comparison of the core permeability and predicted permeability was carried out based on the hydraulic flow unit by comparing the core and predicted permeability against depth. All samples of the predicted permeability is similar to that of the core permeability because it overlies each other indicating that the predicted permeability is almost the same as the core permeability thus the comparison can be used to predict permeability for the uncored zone/interval.

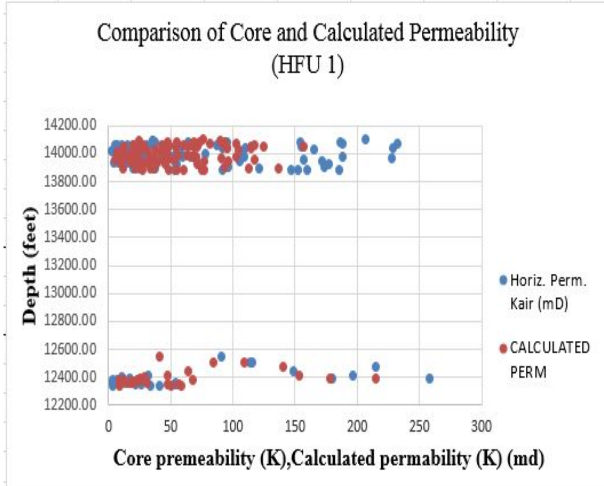

Figure 1 Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 1

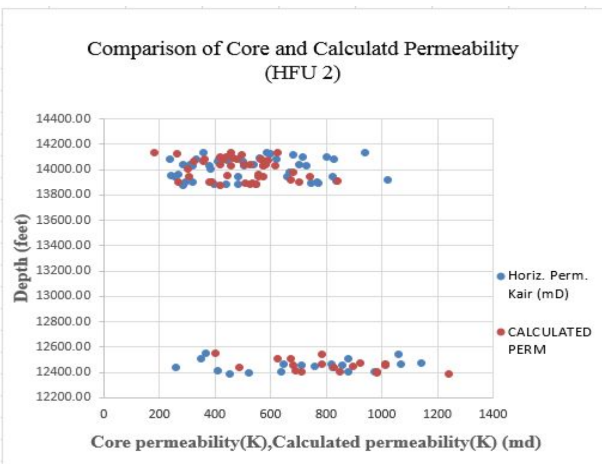

Figure 2 Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 2

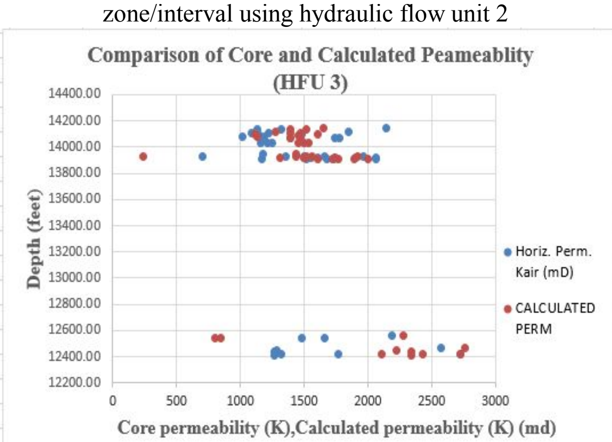

Figure XIII Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 3

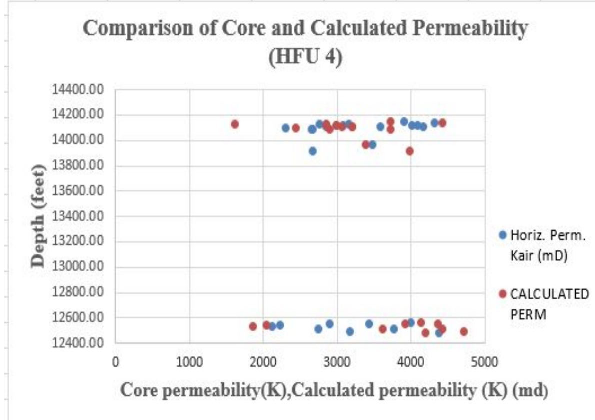

Figure 3 Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 4

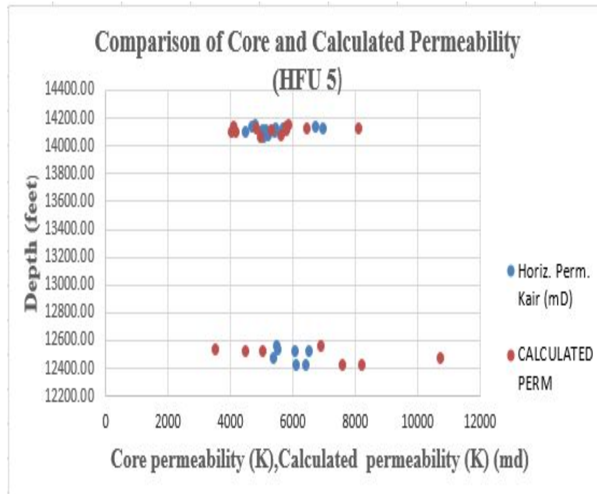

Figure 4 Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 5

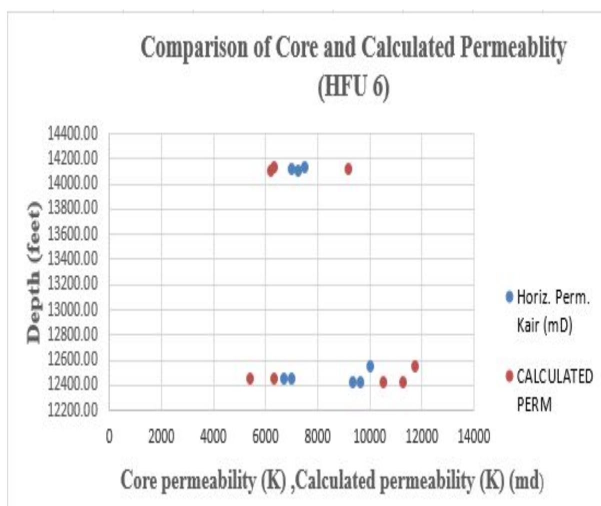

Figure 5 Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 6

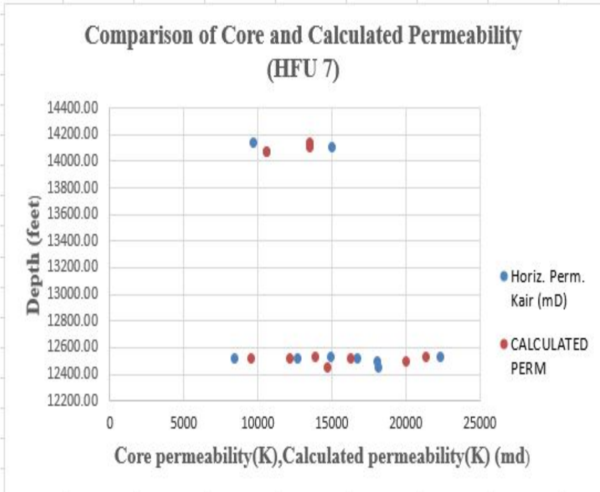

Figure 6 Chart showing a comparison of the core permeability and the predicted permeability for the uncored zone/interval using hydraulic flow unit 7

Conclusion

The theoretically based technique appears to be the most complete technique for analysis/correlation of the core and wireline log data in the prediction of permeability in uncored wells/interval. Good agreement was obtained between the core permeability and the predicted/calculated using the hydraulic flow zone indicator because it takes into consideration the geologic attributes of the formation such as the type of rock, flow capacity, storage capacity and flow unit. The integrated approach produces enables better decision making in the prediction perforation zones, well placement and enhanced recovery methods as against the traditional method of permeability estimation.

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