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Hydraulic flow units and permeability prediction in a carbonate reservoir, Southern Iraq from well log data using non-parametric correlation

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Abstract: The determination of permeability in heterogeneous and anisotropic reservoirs is a complex problem, because core samples and well test data are usually only available for limited number of wells. This paper presents hydraulic flow units and flow zone indicator for predicting permeability of rock mass from core and well log-data. The concept is applied to some uncored wells/intervals to predict their permeability. Flow zone indicator depends on geological characteristics of the material and various pore geometry of rock mass; hence it is a good parameter for determining hydraulic flow units (HFU). Flow zone indicator is a function of reservoir quality index and void ratio. We are determined flow zone indicator from well log and core data and divided the reservoir into various hydraulic flow units using K-means. Then will be develop a correlation (The Alternating Conditional Expectation (ACE) technique will be used and tested in this study) between hydraulic flow units from the core and the well log data which can be used to estimate permeability in un-cored wells, these correlations enable to estimate reservoir permeability at the "flow unit" scale. Finally, having effective porosity and flow zone indicator, permeability was calculated in each hydraulic flow unit. Results of permeability prediction based on HFU were examined for a number of wells and were compared with the measured permeability value of cores. Then will be evaluate a good correlation between the predicted and measured permeability.

Introduction

A hydraulic flow unit is a section of reservoir which is different from other parts by means of hydraulic characteristics or characters controlling fluid flow in reservoir.[1] Thus, if we divide the reservoir into various flow units, permeability can be estimated with sufficient accuracy. Hydraulic flow units, HFU which is a function of flow zone indicator, FZI. FZI is also dependent upon Reservoir Quality Index, RQI and void ratio, φz.[2] A knowledge of these two properties is essential before questions concerning types of fluids, amount of fluids, rates of fluid flow, and fluid recovery estimates can be answered. Methods for measuring porosity and permeability have comprised much of the technical literature of the oil industry. Permeability is one of the essential parameters in reservoir calculation, modeling, and production estimation. It is determined in different methods such as well test data, log data, and core analysis. In some intervals/wells core is not available to be tested, thus estimation of permeability should be carry out based on other types of data. Several authors have tried to estimate permeability of rock mass from well logs.[3] Predicting permeability with low cost and sufficient accuracy is an important issue. Flow zone indicator can be calculated using ACE to represent mathematical model between input and output data is used in this study to determine flow zone indicator in uncored wells.

Theory of Flow Units

The Hydraulic Unit concept (Amaefule et al., 1993)[1] was selected for subdividing the reservoir into distinct petrophysical types. Each distinct reservoir type has a unique Flow Zone Indicator (FZI) value.
According to Tiab (2000)[4], a hydraulic flow unit is 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.
This technique is based on a modified Kozeny-Carman (1927)[5] (cited in Jude O. Amaefule 1993)[1] and the concept of mean hydraulic radius:

$$k = \left\{\frac{1}{2\tau^2 S_{gv}^2}\right\}\left(\frac{\varphi_e{}^3}{(1-\varphi_e)^2}\right) \text{……………..(1)}$$

S_{gv}: may also be define as the surface area of grains exposed to fluid per unit volume of soild material.
Flow zone indicator depends on geological characteristics of the material and various pore geometry of a rock mass; hence, it is a good parameter for determining hydraulic flow units (HFU). Flow zone indicator is a function of reservoir quality index and void ratio.[18]

Amaefule et al. (1993)[1] addressed the variability of Kozeny's constant by dividing Eq. (1) by the effective porosity, φ_e and taking the logarithm:

Defining the flow zone indictor FZI (μm) as: [2]

$$FZI = \frac{1}{S_{gv}\,\tau\sqrt{F_s}} \qquad \text{………….…….(2)}$$

Reservoir quality index RQI (μm) as: [2]

$$RQI = 0.0314\sqrt{\frac{k}{\varphi_e}} \qquad \text{…………….(3)}$$

Normalized porosity φ_z (fraction) as: [2]

$$\varphi_z = \left(\frac{\varphi_e}{1-\varphi_e}\right) \qquad \text{…………………(4)}$$

Eq. (1) becomes:

$$RQI = FZI \times \varphi_z \qquad \text{……………… (5)}$$

Taking the logarithm of both sides of Eq. (5) yields:

$$\text{Log } RQI = \text{Log } FZI + \text{Log } \varphi_z \qquad \text{……(6)}$$

On a log-log plot of RQ1 versus φ_z, all samples with similar FZl values will lie on a straight line with unit slope, Figure (1). Samples with different FZ1 values will lie on other parallel lines, Figure (2). The value of the FZ1constant can be determined from the intercept of the unit slope straight line at $\varphi_z = 1$. Samples that lie on the same straight line have similar pore throat attributes and, thereby, constitute hydraulic unit. The permeability of a sample point is then calculated from a pertinent HFU using the mean FZI value and the corresponding sample porosity using the following equation: [1]

$$k = 1014\, FZI^2 \frac{\varphi_e}{(1-\varphi_e)^2} \qquad \text{…………….(7)}$$

Results and Discussion

Determining the number of Hydraulic Flow Units from core data

We determined the number of hydraulic flow units in three different ways by using Statistica v.5 program and compared the results obtained:

Histogram Analysis

When we plot the data of flow zone indicator in the form of histogram, normal distribution will be obtained which represent n hydraulic flow units.[6]
Since FZI distribution is a superposition of multiple log-normal distributions, a histogram of log FZI should show n number of normal distributions for n number of HFU's. However, it is often difficult to separate the overlapped individual distributions from a histogram plot, Figure (3). We distinguished 4 HFU based on histogram analysis.

Normal Probability Analysis

If we analyze the flow zone indicator with normal probability, n linear distributions are obtained which show n HFU. The probability plot (the cumulative distribution function) is the integral of the probability density function (histogram).

A normal distribution forms a distinct straight line on a probability plot. Therefore, the number of straight lines in the probability plot may be used to indicate the number of hydraulic flow units in the reservoir. Figure (4) shows a probability plot of the logarithm of FZI for Well 27. A total of 4 HFU were distinguished for the reservoir in question.
After determine 4 HFU from Histogram and probability plot we can be predict permeability with a good accuracy of correlation coefficient ($R^2 = 0.813$). Figure (5) shows calculated permeability versus measured core permeability using the 4 hydraulic flow units.

Using least-squares regression

The basic concept of this method is that a log-log plot of RQI versus ϕz will produce a straight line with a unit slope and an intercept that represent the mean FZI value for each HFU using the following steps:

1- Compute the reservoir quality index (RQI) and normalized porosity (ϕz) from core data using Eqs. 3 and 4.
2- Plot RQI versus ϕz in logarithmic space.
3- Use a reasonable initial guess of the intercept of each straight-line equation, the mean FZI value of each HFU.
4- Assign core sample data to the nearest straight line.
5- Recalculate the intercept of each HFU using least-squares regression equations.

Figure (2) shows Plot RQI versus ϕz in logarithmic scale and we identified 5 HFU, using to predict permeability in high accuracy of correlation coefficient ($R^2 = 0.863$) as shown in Figure (6)

FZI Correlation with Well Logs Using ACE

The next major task is to extend the concept of hydraulic flow units in wells where only well log measurements are available. Correlations were developed between well log measurements and FZI values from core data. The well logs used to develop the correlation were gamma ray, deep resistivity to shallow resistivity, effective porosity, and sonic travel time. A technique of optimal non parameteric transformation of variables regression was used. Specifically, we used GRACE software[7], which is based on an algorithm called Alternating Conditional Expectation (ACE). The ACE algorithm was used because of its ability to derive optimal dependent and independent variable transformations that improve correlation. The GRACE program generates an optimal correlation between a dependent variable (say, y) and multiple independent variables (say, x1, x2, x3 .....up to x30). This is accomplished through non-parametric transformations of the dependent and independent variables. Non-parametric implies that no functional form is assumed between the dependent and independent variables and the transformations are derived solely based on the data set.

FZI is predicted from the well log data using the following equations derived by ACE:

$DT\text{-}Tr = 0.0009166\times DT^2 - 0.16668\times DT + 7.3337$ ………………………..(8)

$GR\text{-}Tr = 0.0034305\times GR^2 - 0.063024\times GR + 0.2486$ ………………………(9)

$PHIT\text{-}Tr = 49.077\times PHIT^2 - .4602\times PHIT - 1.7923$…………………………...…..(10)

$RTO\text{-}Tr = -1.227\times RTO^2 + 2.7726\times RTO - 1.098$ …………………………..…….(11)

$SUMTr = DT\text{-}Tr + GR\text{-}Tr + PHIT\text{-}Tr + RTO\text{-}Tr$………………………………….(12)

$FZI = 0.2706\times SUMTr^2 + 0.7659\times SUMTr + 0.838$ ……………………………(13)

The optimal transformation for FZI from relationships above using well log data with Good correlation coefficient ($R^2 = 0.812$), which indicates a good level of correlation, Figure (7).

Permeability in uncored wells

Many of the Petrophysical models used for simulation studies are based on the classical approach of cross plotting the logarithms of permeability versus porosity (Figure. 8). and then, by fitting a regression line on this plot, predicting the permeability through the reservoir rock with correlation coefficient ($R^2 = 0.446$) (Figure 9). This approach is critical when used to model permeable rocks, as it implies two misleading concepts. First, it considers the relationship between the logarithms of core permeability versus core porosity as linear,. Secondly, using log porosities on this plot to predict the permeabilities would imply a scaling agreement between the macroscopic level (core plug) and the megascopic level (log data). Discretizing the reservoir into units such as layers and blocks, and assigning values of all pertinent physical properties to these blocks will give a better agreement with the reservoir heterogeneity.[9]
We have identified 5 flow units in Well 27 and The permeability porosity relationship constructed for the different HFU's is illustrated in Figure 10. The samples in the scatterplot are grouped by HFU's

After calculating FZI in uncored well using equations (8 to 13) from well log data, permeability can be determined for each HFU(mean FZI value) using equation (7).

A result of calculated permeability versus core permeability with depth is shown in Figure 11. It is observed in the Figure (11) good correlation between the calculated permeability and core permeability.
These predicted permeability profiles were obtained by assuming that this well had been logged only and did not have core data, while in reality core data were available at well. This was done only to check how accurately the HFU method would predict permeability in these well if they had not been cored. As shown, the permeability profiles of the log-derived HFU agree with core data.

Conclusions

1- Flow zone indicator is a suitable parameter for determining hydraulic flow units because it based on pore throat radius and geometry of porous medium that related to Petrophysical rock types
2- Correlations were developed between well log measurements and FZI values from core data using the ACE algorithm in uncored well which gives good results to predict FZI and using these values to predict good result of permeability.
3- Using least-squares regression for determining the number of hydraulic flow units, visual and personal errors which are common in histogram and normal probability errors would be minimized.
4- Good correlation coefficient (R^2 = 0.86) was obtained between permeability calculated based on HFU and permeability of cores which is an index for accuracy of this method.
5- Determining permeability using regression analysis of porosity –permeability gives weak results and usually causes errors with correlation coefficient (R^2 = 0.446).

Symbols

τ: is the tortuosity,
S_{gv}: is specific surface area per unit grain volume (cm^2/cm^3),
k: is the permeability (μm^2), and

φ_e: is the effective porosity (fraction).

FZI: is the Flow Zone Indicator (μm).
ACE: Alternating Conditional Expectation
DT: Sonic travel time (Delta Time, μsec/ft)
Tr: Transformation
GR: Gamma Ray, API
PHIT: Total Effective Porosity
RTO: Deep Resistivity to Shallow Resistivity
SUM: Summation

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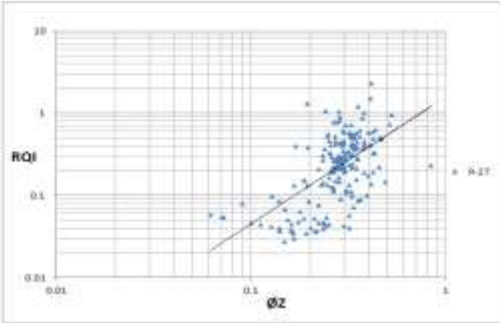

Figure (1): Scatter plot of log RQI versus log ϕ_z when one HFU is used to fit the whole data.

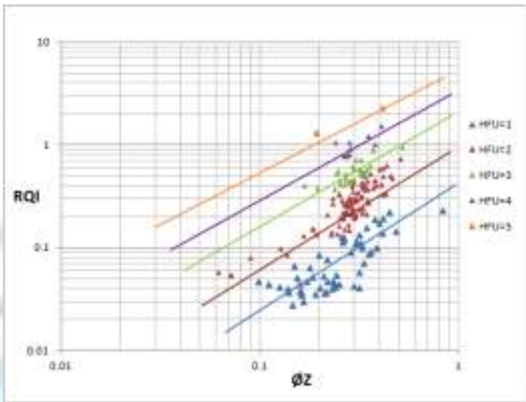

Figure (2): Clustering core data into the optimal number of HFU's using least-squares regression

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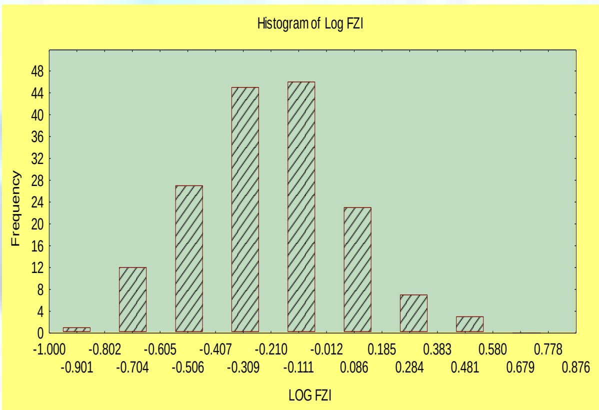

Figure (3): Histogram of the logarithm of FZI for Well 27.

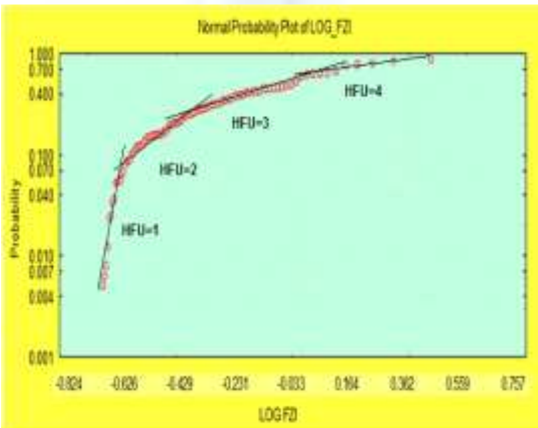

Figure (4): Probability plot of logarithm of FZI for Well 27.

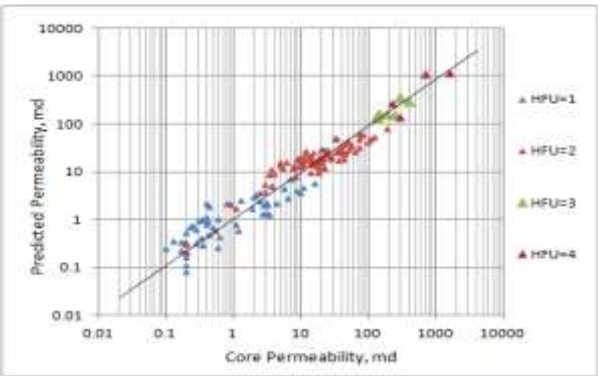

Figure (5): Permeability determined when considering 4 hydraulic flow units versus core permeability.

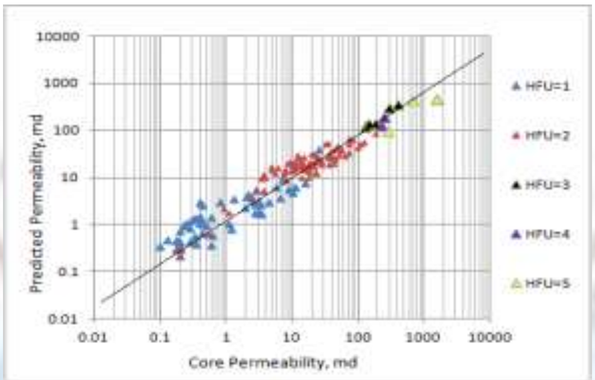

Figure (6): Permeability determined when considering 5 hydraulic flow units versus core permeability.

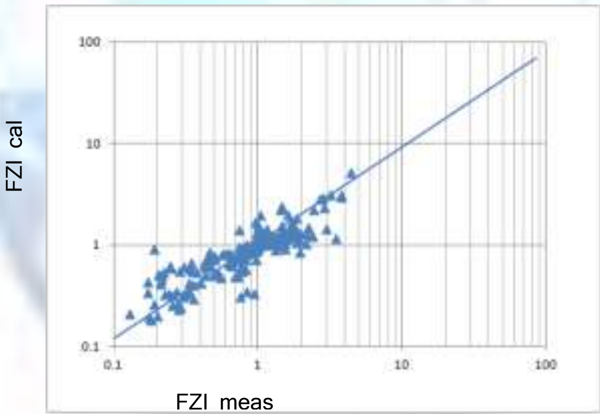

Figure (7): FZI values predicted from well logs using ACE versus core FZI.

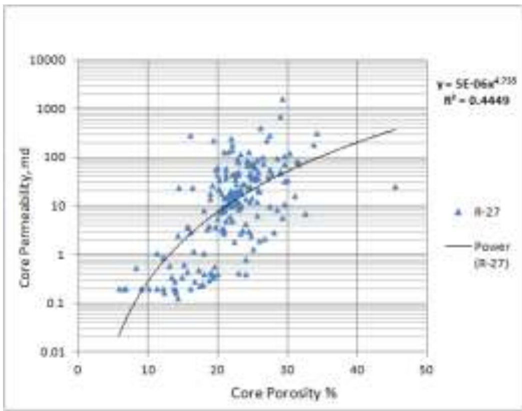

Figure (8): Scatterplot of core permeability vs. core porosity for the study well.

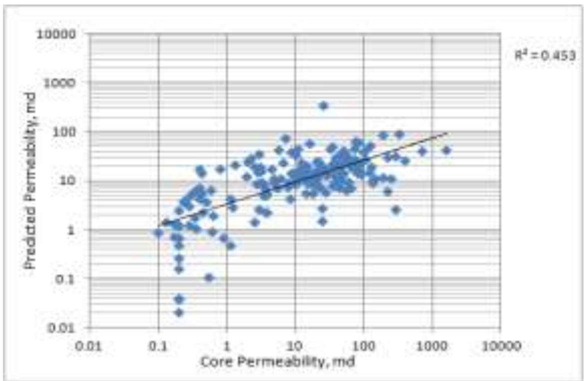

Figure (9): Permeability determined through regression analysis versus core permeability.

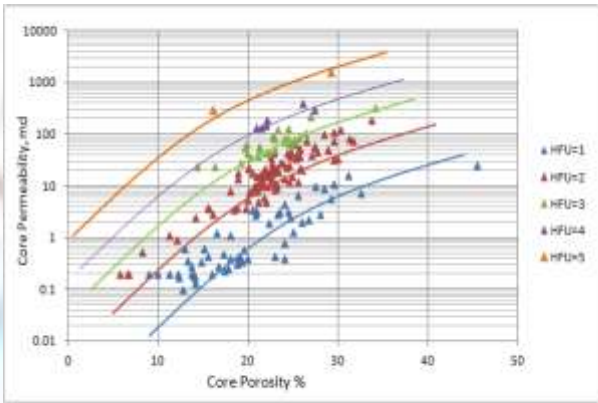

Figure (10): Porosity permeability relationship derived by HFU's method.

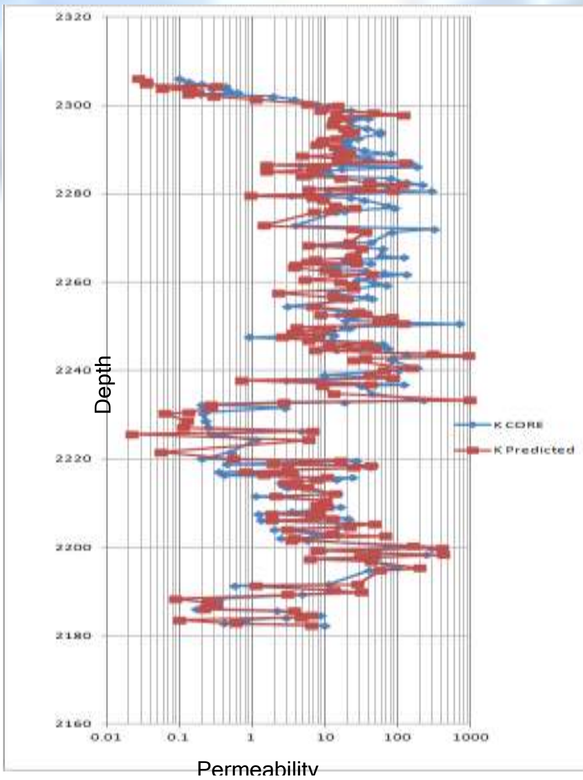

Figure (11):Permeability profile derived using HFU's method for Well 27.