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Derivation of Regression Models forFlow Zone Indictor (FZI) which usingin Permeability Prediction

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ABSTRACT

Knowledge of permeability values and its variations within a pay zone is an important and significant criterion in developing an effective reservoir description and evaluation. 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 will focus on the evaluation of formation permeability for a Carbonate reservoir in one Iraqi field from well log data using the concept of Flow Units (FU). A statistical model was developed by the regression method using correlations between the Flow Zone Indicator (FZI) from core data and well logs data for each reservoir unitin this Formation in this study. The validity of the proposed model was tested for each reservoir unit, and it was used together with the (FZI) values to estimate the permeability in the un-cored sections of the wells.

Keywords: Carbonate reservoir, Flow Zone Indicator (FZI), Hydraulic Flow Unit (HFU), Permeability

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INTRODUCTION

Permeabilityis the measurement of a rock’s abilityto transmit fluidswhich may be subdivided into absolute and effective (Kumar N.and Frailey,2003) [1].

Permeability is a function of effective porosity and irreducible water saturation. Thus, in many cases, estimates of permeability are obtained from porosity values.The most reliable local permeability values may be obtained fromcore analysis. However, core samples are usually not available for all the layers either because of borehole conditions or due to the high cost of coring (thus, it is usually carried out in limited cases of drilling operations),(Lacentre E. and Carrica M.,2008) [2].

Statistical models, which are based on multiple regression approach, were used to develop a relationship for permeability predictions in cored and un-cored intervals of the wells. The multiple regression technique was applied to develop a relationship between log responses with Flow Zone Indictor (FZI) to predict the permeability of the reservoir units for all the wells under this study.

THEORETICAL BACKGROUND OF FLOW UNIT CONCEPT

Amaefule et al. (1993) [3,4,5]considered the role of the mean hydraulic radius in defining hydraulic flow units and correlating permeability from core data. Their approach was essentially based on a modified Kozeny-Carmen equation (Wyllie, 1958) [6]:

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

S_{gv}: may also be define as the surface area of grains exposed to fluid per unit volume of soild material.
The Amaefule et al. (1993) approach was essentially based on a modified Kozeny-Carmen equation (Wyllie, 1958) coupled with the concept of mean hydraulic radius:

$$r_{mh}=\frac{\text{Cross Section Area}}{\text{Wetted surface area}}=\frac{r}{2}\text{……………………………………………………….. (2)}$$

The concept of sub-grouping reservoir volume into flow units, suggests that the term $2\tau^2$ in Eq. (1), which is classically referred to as Kozeny constant, is actually "variable constant". This means that Kozeny constant may vary for different hydraulic units, but is constant for a specific unit. Based on that, Taib (2004) [7] introduced the "variable constant" k_τ referred to as the effective zoning factor:

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

k_τ: it is a function of pore-pore throat size and geometries, tortuosity and cementation.
Taib (2004) proposed to estimate the effective zoning factor:

$$k_\tau=F_s\tau^2\text{ ……………………………………………….. (4)}$$

F_s: is the effective pore throat shape factor.

Kozeny and Carmen simulated a porous medium as a bundle of capillary tubes. They combined Darcy's law for flow in a porous medium and Poiseuille's law for flow in tubes. A tortuosity factor was also included, because for a realistic model of porous media the connected pore structure is not straight capillary tubes. The following relationship between porosity and permeability was suggested:

$$k=\frac{r^2\varphi_e}{8\tau^2}=\frac{\varphi_e}{2\,\tau^2}\left(\frac{r}{2}\right)^2=\frac{r_{mh}{}^2\varphi_e}{2\tau^2}\text{…………………………………….(5)}$$

The mean hydraulic radius can be related to the specific surface area per unit grain volume, S_{gv}, and the effective porosity, φ_e, by the following equation:

$$S_{gv}=\frac{1}{r_{mh}}\left[\frac{\varphi_e}{1-\varphi_e}\right]\text{………………………………………… (6)}$$

Combining Eqs. (5) and (6), gives the generalized Kozeny –Carmen equation:

$$k=\left[\frac{\varphi_e{}^3}{(1-\varphi_e)^2}\right]\frac{1}{F_s\tau^2 S_{gv}{}^2}\text{…………………………………..(7)}$$

The term $F_s\tau^2$ is known as the Kozeny constant, which is usuallybetween 5 and 100 in most reservoir rocks. The term$F_s\tau^2S_{gv}{}^2$is a function of geological characteristics ofporous media and varies with changes in poregeometry. The determination ofthe $F_s\tau^2S_{gv}{}^2$group is the focal point of theHydraulic Flow Unit (HFU) classification technique.

Amaefule et al. (1993) addressed the variability of Kozeny's constant by dividing Eq. (7) by the effective porosity, φ_e and taking the logarithm:

$$0.0314\sqrt{\frac{k}{\varphi_e}}=\left[\frac{\varphi_e}{(1-\varphi_e)}\right]\frac{1}{\sqrt{F_s}S_{gv}\,\tau}\text{……………………………… (8)}$$

Where, the constant 0.0314 is the permeability conversion factor from μm^2 to md.
Defining the flow zone indictor FZI (μm) as:

$$FZI=\frac{1}{S_{gv}\,\tau\sqrt{F_s}}\text{………………………………………………(9)}$$

Reservoir quality index RQI (μm) as:

$$RQI=0.0314\sqrt{\frac{k}{\varphi_e}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(10)$$

and normalized porosity φ_z (fraction) as:

$$\varphi_z=\left(\frac{\varphi_e}{1-\varphi_e}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Eq. (8) becomes:

$$RQI=FZI\times\varphi_z\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

Taking the logarithm of both sides of Eq. (12) yields:

$$LogRQI=LogFZI+Log\varphi_z\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(13)$$

RESULTS AND DISCUSSIONS

A-Identifying Flow Zone Indictor

Ideally, in a Log-Log plot of RQI versus$\varphi_z$all the samples with similar FZI values lie on a straight line with a slope of one (that is, having similar flow characteristics)and data samples with the same FZI values, but significantly different from the preceding one, will lie on another, parallel, unit-slope lines; and so on. Samples that lie on the same straight line have similar pore throat attributes, and thereby constitute a unique hydraulic flow unit. Each line represents a Hydraulic Flow Unit **(**HFU) and the intercept of this line with φ_z= 1 is the mean FZI value for that Hydraulic Flow Unit**(**HFU) each flow unit is characterized by a Flow Zone Indicator (FZI)

Figs.(1-a, 1-band 1-c) show a cross plot of the logarithm of the reservoir quality index (RQI) versus the logarithm of the normalized porosity (φ_Z) for various values of the Flow Zone Indicator (FZI). All the data points that fall on the same (FZI) straight line can be considered to have similar pore throat attributes (i.e., they represent the same hydraulic unit). **Fig.** (1-b) shows the existences of five distinct hydraulic subunits within the cored interval of xx-2 unit in the study field. **Figs.** (1-a and 1-c) show the existences of three distinct hydraulic subunits within the cored interval for each of the xx-1and xxx units in the study field.

B-Flow Zone Indicator (FZI) Correlation with Well Logs

The Flow Zone Indicator (FZI) is then correlated to certain combinations of logging tool responses to develop regression models for permeability predictions in cored and un-cored intervals of the wells. The use of several types of well logs will improve the overall behavior of a correlation and establish a more consistent statistical model. Such well log types may comprise:

- The gamma ray log response, which provides evidence of shale content, has an impact on permeability and Flow Zone Indictor (FZI); it also provides information about the lithology of the formation.
- The bulk density, sonic, and neutron logs whichare functions of porosity, and help to differentiate between hydrocarbons.
- The resistivity log response provides information about the presence of hydrocarbons and the relative mobility of the fluid in the formation.

The depth correlation between logs and core data are performed by comparing log-derived porosity (effective porosity) with core porosity data after the reported core data depth has been adjusted to match the well log depth.

C-Data Correlation

A multiple regression technique was applied to develop a model for the parametric correlation of Flow Zone Indictor (FZI) with well log responses, for each reservoir unit in all the wellsin this study. The statistical program "**Statistica Software**" was used for this purpose. The model was applied to each reservoir unit (about 70% of the core samples data was used for model development and 30% for model validation) within x-formationof the study field. Several trial were attempted, in each of which the anomalous log or FZI data were omitted in order to get a better average absolute error(AAE) and improve the correlation coefficient R^2. The trials were terminated when it has been found that any further omission of anomalous values would not improve the (AAE) and (R^2) values.

It was found that omission of 9 to 13 values out of values, which were used to formulate the model from each unit that was sufficient to get the final parametric correlation model whose coefficients are given in **Table 1**

The parametric correlation equation for determining the Flow Zone Indicator (FZI) for each unit is given by:

$FZI=e^{(C0+C1+C2+C3+C4+C5+C6+C7)}$………………………………. (14)

Where,
C0= B0,
C1= B1*ln(GRC),
C2= B2*ln(GRC)*ln(φ_e),
C3= B3*ln(GRC)*ln(φ_e)*ln(R_t/R_{xo}),
C4= B4*ln(φ_e),
C5= B5*ln(φ_e)*ln(R_t/R_{xo}),
C6= B6*ln(R_t/R_{xo}), and,
C7= B7*ln(GRC)*ln(R_t/R_{xo}).

D-Validation

The validity of the proposed Eq. (14) was tested for each reservoir unit in all the wellsin this study. It is to be noted that, the data that were used for model verification are those representing the unused 30%, which was kept for this purpose. The verification is a necessary step prior to development of a general model for each reservoir unit of all the wells. Acceptable agreement, between the predicted and observed Flow Zone Indicator (FZI) values, may be noticed from **Figs.** (2-a, 2-b, and 2-c) for most intervals.

The permeability can be computed for those points on the same straight line (with same FZI) using the equation (Amaefule et al. (1993)[3,4,5]:

$k=1014FZI^2\frac{\varphi_e^3}{(1-\varphi_e)^2}$………………………………….(15)

Thus, Eq. (15) was used for permeability prediction using the average values of Flow Zone Indicator (FZI) which were computed by the parametric correlation equation Eq. (14). This process was carried out for each reservoir unit in the study field. Figs. (3-a,3-b and3-c) show the profile of measured permeability vs. predicted permeability by multiple regression. A good agreement between the k-predicted and k-core values along most depth intervals of the three units may be noticed from the figures.

CONCLUSION

- Reservoir porosity permeability relationship is best achieved if rocks with similar fluid-flow conductivity are identified and grouped together. Each group is referred to as a flow unit.
- The analyses that were based on the Flow zone indicator (FZI) showed the existence of five distinct hydraulic subunits within the cored interval of the lithological unit xx-1. It also showed that, only three hydraulic subunits were indicated in the cored interval of each of the two-lithological units xx-2 and xxx.
- Permeability estimation using the FZI method was extended to uncored wells by statistical regression model and may be noticed a good agreement between the k-predicted and k-core values along most depth intervals of the three units in this study.

NOMENCLATURE

τ: is the tortuosity
φ_e:is the effective porosity
$F_s\tau^2$= Kozeny constant
S_{gv}: is specific surface area per unit grain volume
k: is the permeability
r: is the pore throat radius
r_{mh}: is the mean hydraulic radius
R_t: is the Deep Resistivity
R_{xo}: is the Shallow Resistivity
FZI : is the flow zone indictor
GRC : is the Corrected gamma ray
HFU: is the Hydraulic Flow Unit
RQI : is the Reservoir quality index

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Table 1: The coefficients of the parametric correlation of FZI model

Unit Name	The coefficient of parametric correlation								Number of core samples	Correlation Coefficient	Average Absolute Error
Unit	B0	B1	B2	B3	B4	B5	B6	B7	N	R^2	AAE
Xxx	-2.6	-1.3	-0.5	1.3	-0.3	-0.3	-0.5	1.6	167	0.68	0.23
xx-1	-2.8	-1.2	-0.3	1.8	-0.2	-0.5	-0.4	2.3	382	0.54	0.28
xx-2	-1.8	-1.2	-0.6	1.3	-0.8	-0.9	-0.6	2.1	117	0.69	0.21

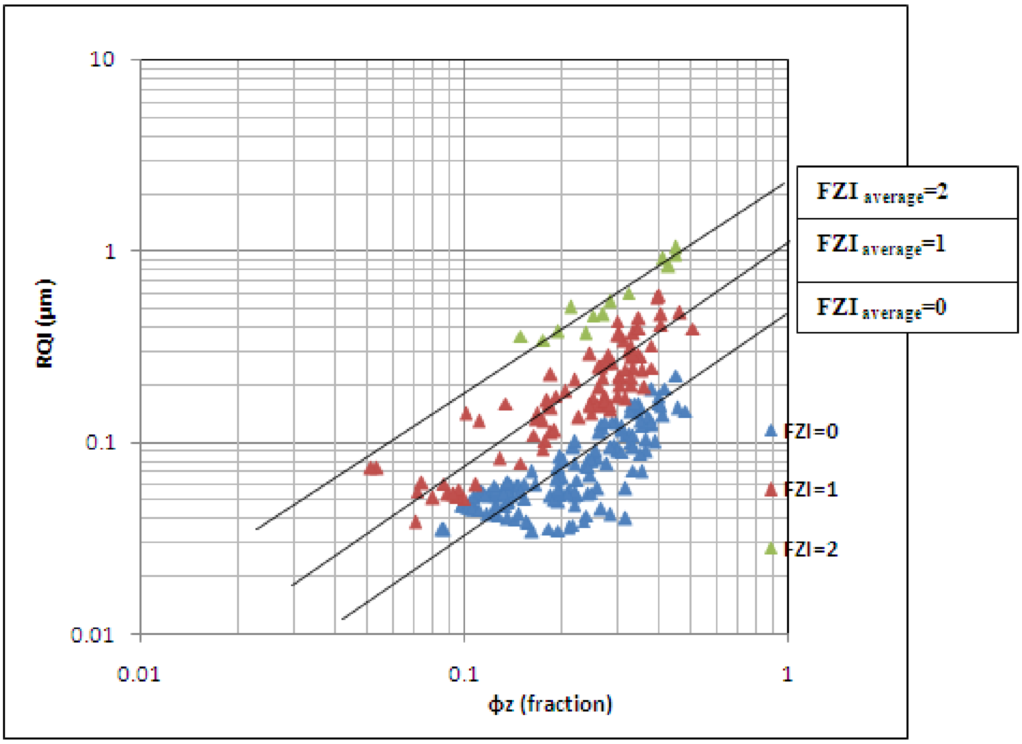

Fig. (1- a): xxx unit

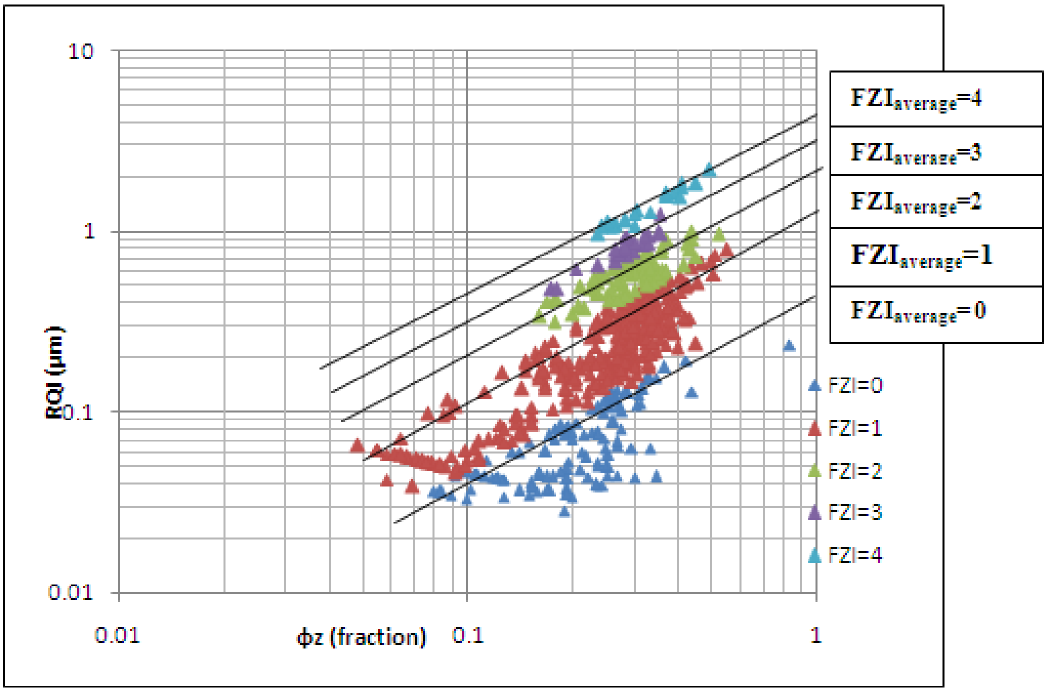

Fig. (1- b): xx-1 unit

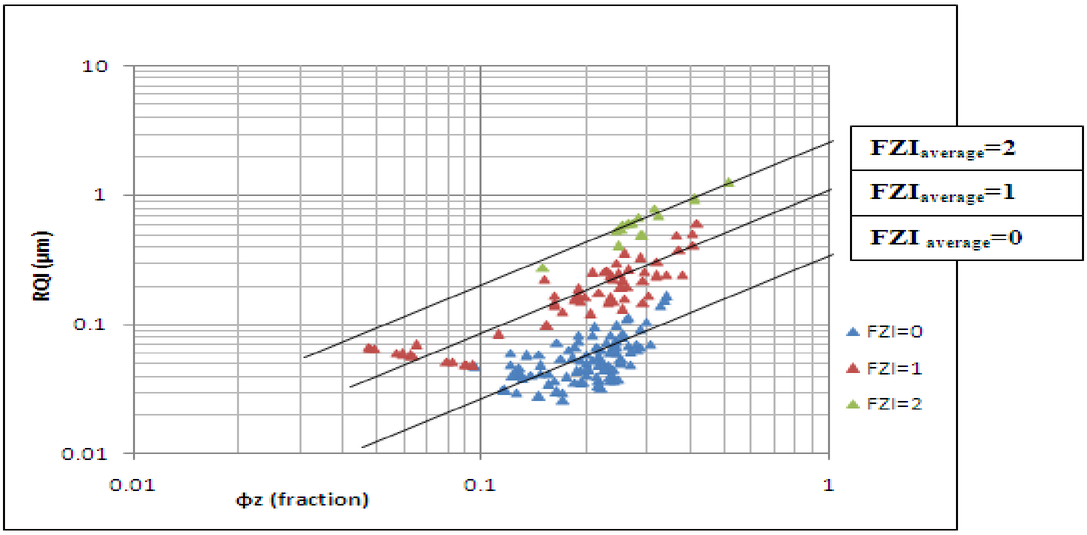

Fig. (1- c): xx-2 unit

Fig. 1: Cross plot of logarithm RQI versus logarithmφZ with Flow Zone Indicator (FZI) for (a) xxx unit, (b) xx-1 unit and (c) xx-2 unit

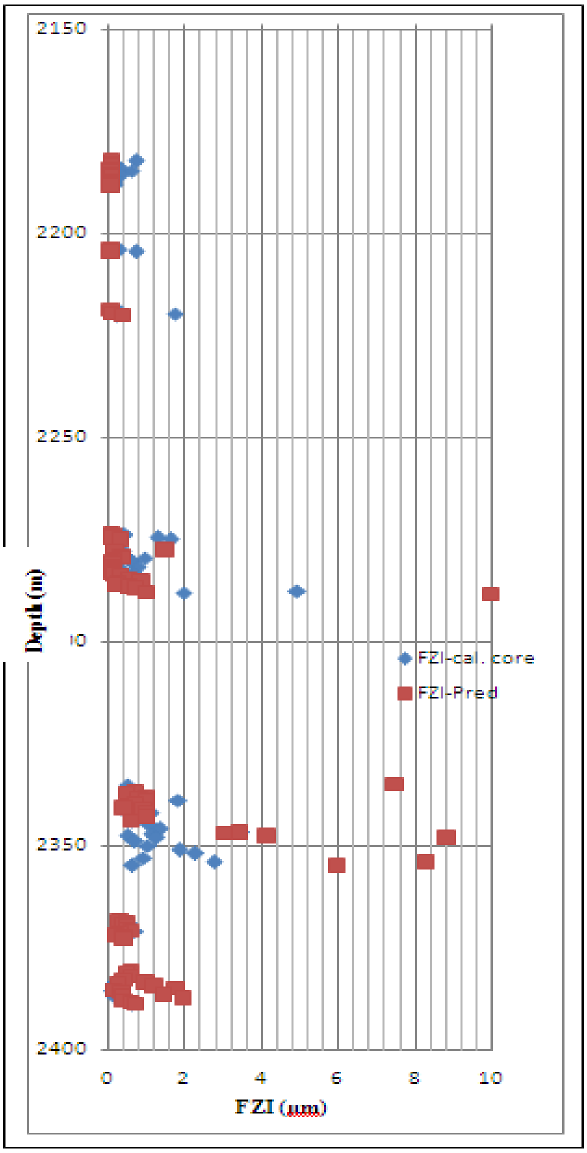

Fig. (2-a): xxx unit

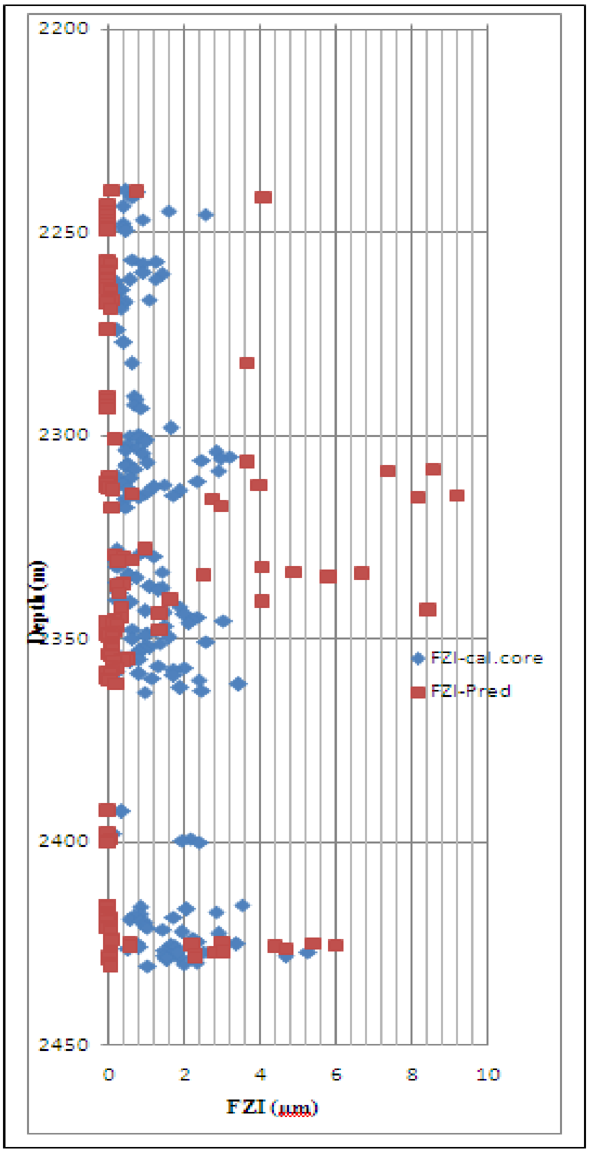

Fig. (2- b): xx-1 unit

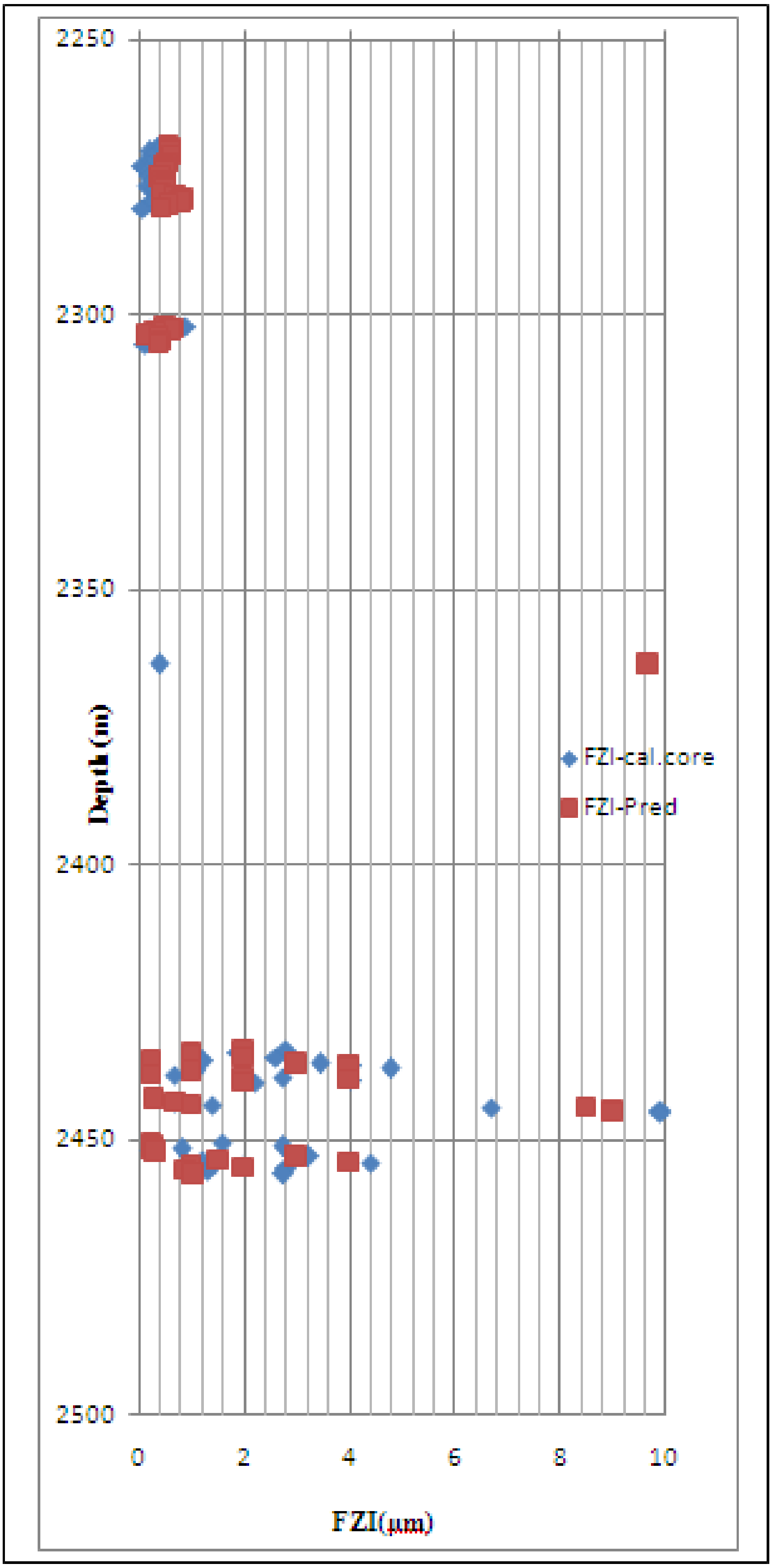

Fig. (2- c): xx-2 unit

Fig. 2: Cross plot of measured vs. predicted Flow Zone Indicator (FZI) for (a)xxx unit, (b) xx-1 unit and (c) xx-2 unit.

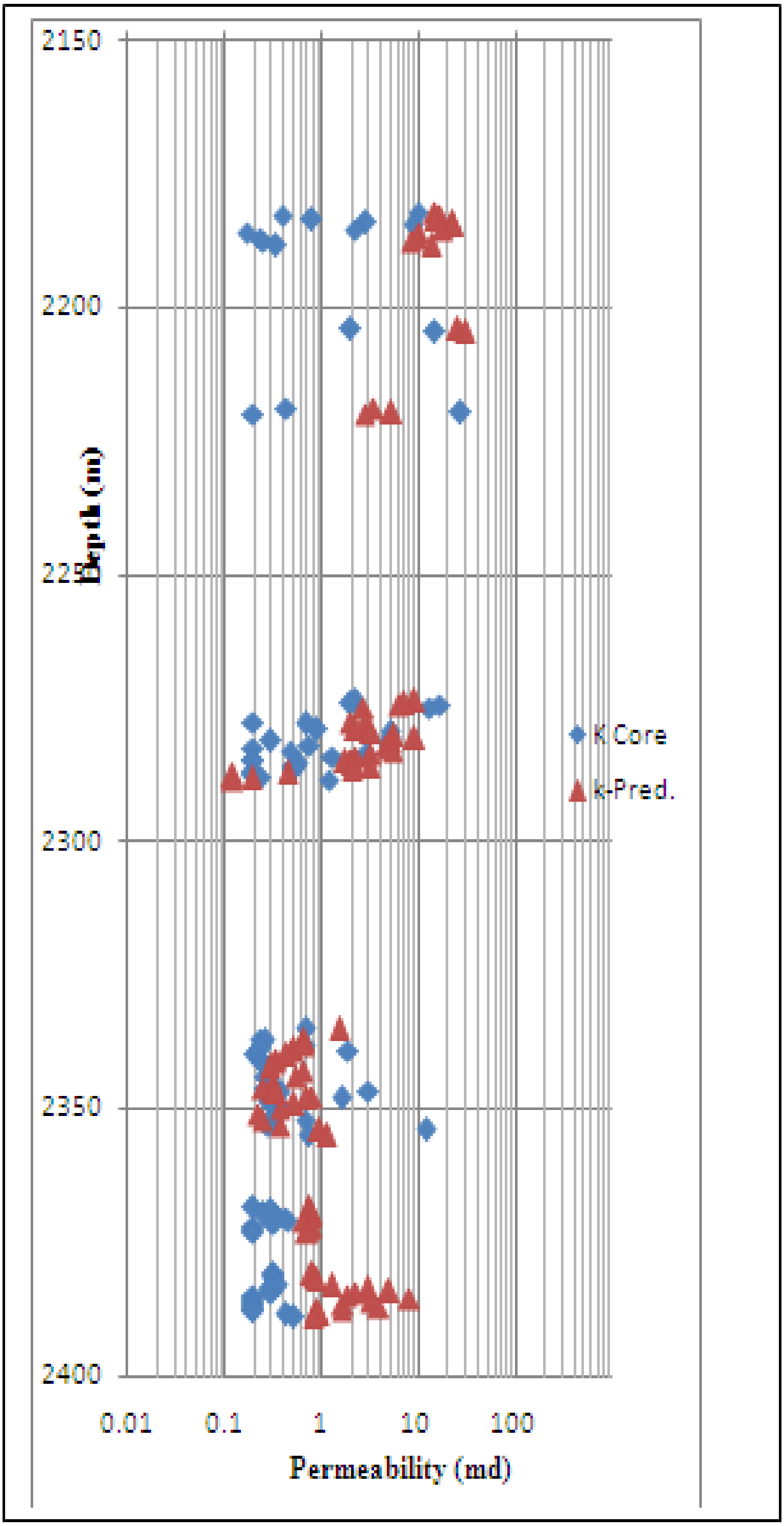

Fig. (3- a): xxx unit

Fig. (3- b): xx-1 unit **Fig. (3- c): xx-2 unit**

Fig. 3: Cross plot of core permeability vs. predicted permeability values by multiple regressions for (a) xxx unit, (b) xx-1 unit and (c) xx-2.

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