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A New Algorithm for Foot-By-Foot Permeability and Irreducible water Saturation Estimation in Iraqi Limestone Reservoirs

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Abstract. This paper discusses the methodology developed for petrophysical modeling and its application to the main limestone formations in the Mid-region of Iraq. The systematic approach presented in this study evaluates not only combination of porosity, permeability and irreducible water saturation at each depth, but also free-water level and capillary pressure curve, such that water-cut of flow tests is closely reproduced in numerical simulation. It is one of the major achievements in this study. The algorithm matched to several sets of core samples: 2,903 porosity, 2,767 permeability, and 95 Irreducible water saturation samples that give the algorithm the robustness for future properties prediction. To develop the prediction Algorithm, it was employed multiple regression analysis (MRA) which mathematically requires independence between explanatory variables. Since possible explanatory variables (porosity, permeability and facies) indicate interdependency, it was investigated when necessary to transform the variables into independent axes. It was found that logarithm of permeability has correlations positive to porosity and FZI and negative to irreducible water saturation. Therefore, foot-by-foot evaluation shall meet the following conditions, (S_w) along wells shall be explained by single free-water level (FWL) for each pressure compartment and Water-cut observed on production test shall also be closely simulated with the FWL, For modeling purposes, Sw is split into irreducible water saturation (S_{wir}) and transitional (mobile) water saturation (S_{wm}) as water-cut is a function of only the latter.

1. Introduction

The determination of the Petrophysical properties in the specific geographical location is a challenging matter since it depends on the geological and rock properties, reservoir characteristics and as well as on the economic parameters. Hence, reservoir characteristics correlation is recognized as one of the most reliable tools for defining the optimum strategy for petrophysical properties prediction in uncored intervals the method proposed could be one of the useful tool to assist the progress in the decision making for the field development and strike towards the optimal and effective hydrocarbon Evaluation.

2. Conventional Core Analysis

This section presents the petrophysical analyses on conventional core measurements. From 28 Khasib and 20 Tanuma wells, 2,903 porosity and 2,767 permeability data are available. But water saturation information is somewhat limited (see Table.1). We conducted the following works using those data in this study.

- Core data classification by Hydraulic Unit concept

- Construction of property prediction mode

Table 1. Available Data sets for Property modelling.

Formation	Porosity	Permeability	S_{wir}
Tanuma	990 samples	990 samples	38 samples
Khasib	1879 samples	1777 samples	57 samples

3. Hydraulic Unit concept

This concept of rock type classification focuses on pore-structure geometry. Resulted rock type is denoted "hydraulic unit" and is characterized by a value called "flow zone indicator (FZI)", Based on Kozeny-Carman equation:

$$k = \frac{\emptyset^3}{(1-\emptyset)^2}\frac{1}{k_z S_{gv}^2} \quad (1)$$

Where,
K: Permeability (cm^2),
$\emptyset$: Effective porosity,
K_z: Kozeny's constant
S_{gv}: Surface area per unit grain volume
Eq. (1) can be transformed into the following expression using field unit:

$$0.0314\sqrt{\frac{k}{\emptyset}} = \frac{\emptyset}{(1-\emptyset)}\frac{1}{k_z S_{gv}} \quad (2)$$

Rock matrix's quality comprises two properties, i.e. storage capacity (porosity) and flow capacity (permeability). An index called "reservoir quality index (RQI)" relates pore scale attributes to macroscopic reservoir parameters as follows:

$$RQI = 0.0314\sqrt{\frac{k}{\emptyset}} \quad (3)$$

RQI distinguishes between reservoir intervals with different hydraulic characters. Parameters called "flow zone indicator (FZI)" and "normalized porosity ratio ($\emptyset_z$)" are defined as follows:

$$FZI = \frac{1}{\sqrt{k_z S_{gv}}} \quad , \emptyset_z = \frac{\emptyset}{1-\emptyset} \quad (4)$$

Using Eqs. (3) And (4), Eq. (2) can be rewritten as

$$RQI = \emptyset_z FZI \quad (5)$$

Or,

$$Log(RQI) = \log\emptyset_z + \log(FZI) \quad (6)$$

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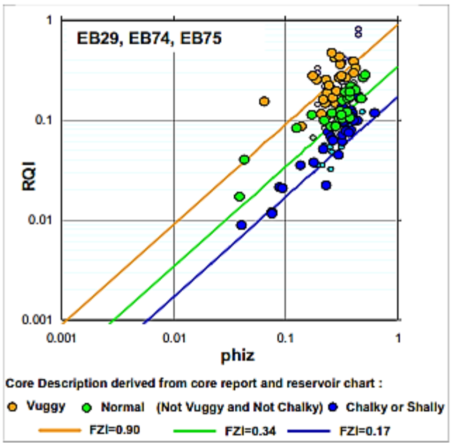

Figure 1. Cross-plots of core Calculated RQI and porosity

As Kz and Sgv stay constant so long as pore structure is similar, relation between RQI and "normalized porosity ratio ($\emptyset_z$)" should form a unit slope in log-log plot. Its y- intercept at x=1 is log (FZI). Samples with similar pore-space attributes are plotted Log (FZI) around same line and thus, RQI and FZI are powerful tools to correlate between different rock properties. Fig. 1 shows a cross plot of RQI against $\emptyset_z$ on some cores. Facies classification is copied from core description. Fig. 2 shows histograms of Log (FZI) by facies. Strong relationship can be observed between facies and FZI in Khasib formation. Strong relationship can be observed between facies and FZI in Khasib formation. Fig.3 and Fig.4 show histograms of porosity and permeability in each hydraulic unit. FZI technique was proved to be robust and was found to be valuable to supplement core data in the prediction of log-permeability in the reservoir modelling in the Middle East[1][2][3].

If FZI value in uncored sections is estimated, corresponding permeability can be computed using the following relation

$$K = 1014\,FZI^2 \frac{\emptyset^3}{(1-\emptyset)^2} \qquad (7)$$

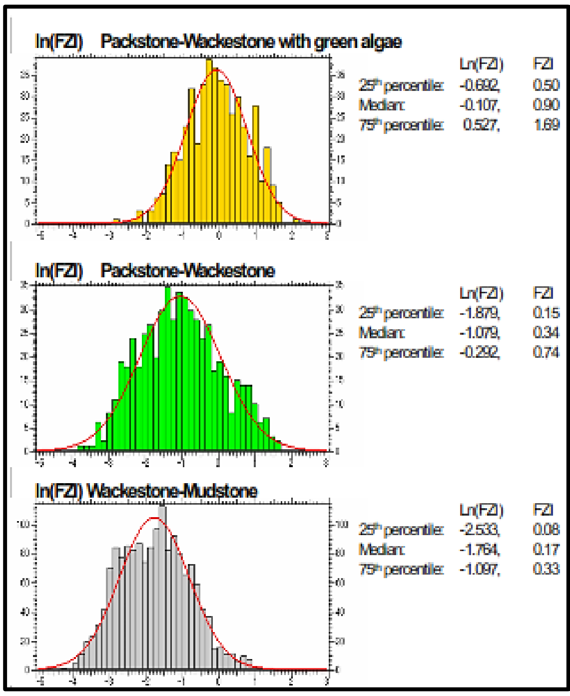

Figure 2. Histogram of Log (FZI) by facies

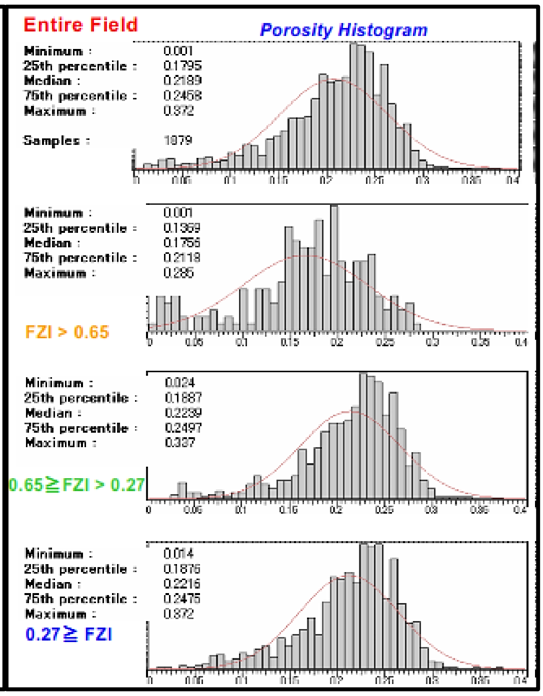

Figure 3. Histogram of Porosity in each hydraulic unit

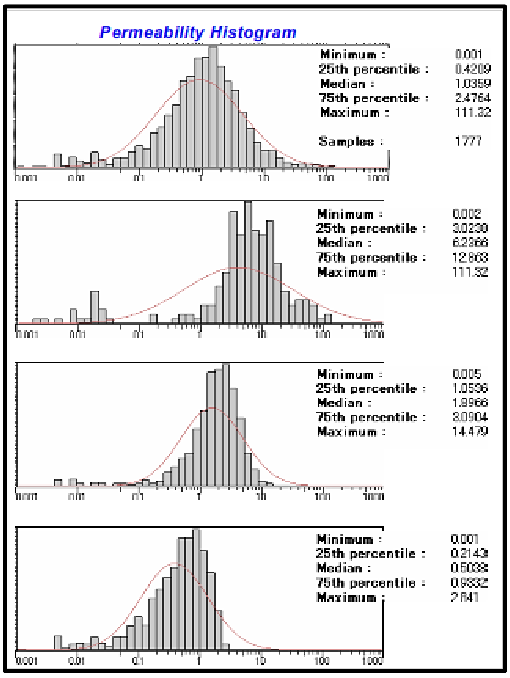

Figure 4. Histogram of Permeability in each hydraulic unit

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4. Construction of property prediction model

In order to predict permeability and irreducible water saturation from log data for uncored sections, we constructed a property prediction model. Scatter plots between porosity, permeability and irreducible water saturation on cores are shown in Figs (5, 6) which indicate notable interdependency among those properties. The prediction model was constructed in a way that the correlations are kept.

Permeability, Porosity, and S_{wir} data are derived from Core Flooding test & Capillary Pressure measurements. The correlation between these properties does not honour the facies or rock type therefore the predicted property estimated from these correlation will be tested for facies and production test result to get the more reasonable value.

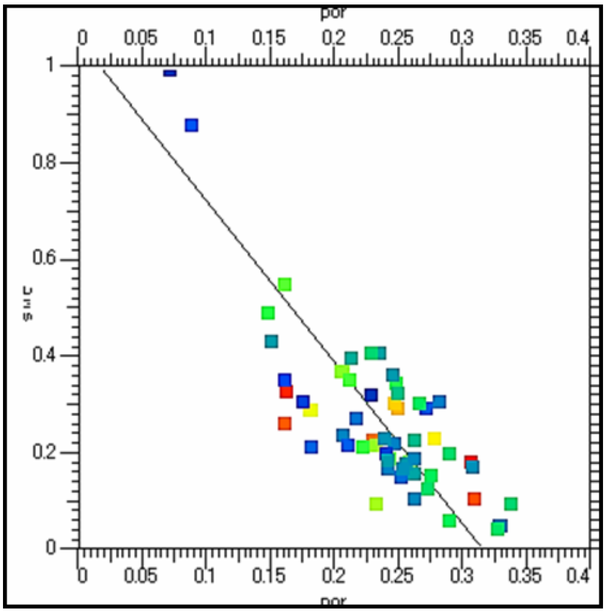

Figure 5. The scatter plot between porosity and Irreducible water saturation

Comprehensive analysis confirmed results that are different from well log for oil and gas, in case of oil and gas are produced from reservoir interval that has a high water saturation but does not produce water during test the interpretation for this phenomena is the existence of irreducible water saturation therefore in many cases the simulator fails to predict the actual water cut due to unrealistic value of S_{wir} ,even though that there are many methods for s_{wir} estimation[5] of Swir , we have used Crude oil displacement method by displacing rock samples of water by crude until the rock samples water content has not changed.

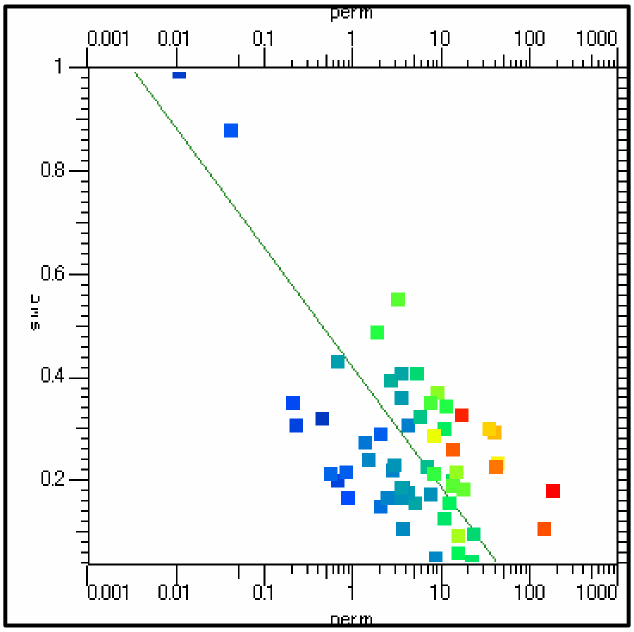

Figure 6. The scatter plot between permeability and Irreducible water saturation

5. Extraction of correlation from core data

To develop the prediction model, we employed multiple regression analysis (MRA) which mathematically requires independence between explanatory variables. Since the possible explanatory variables (porosity, permeability and facies) indicate interdependency (Fig.7), it was investigated when necessary the transform of the variables into independent axes. (Fig. 8 and Fig. 9) Compare Two prediction models using MRA with:

1. “Raw” variables (case MRA)
   and
2. Principal components of those variables, (case PCA+MRA).

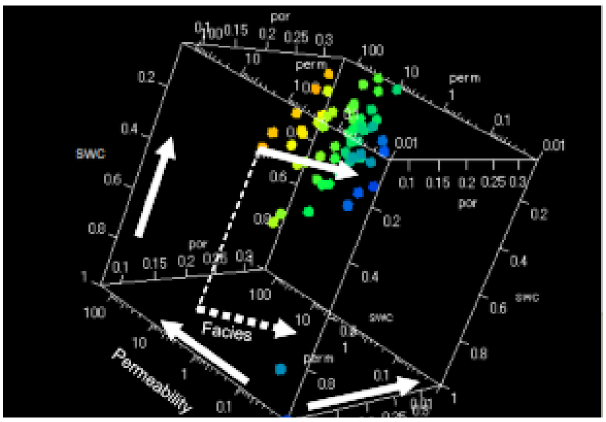

Figure 7. 3-D plots of properties

Correlation coefficients on Swir between the prediction and core measurement were 0.88 and 0.87, respectively for the two models. Both achieve good property Reproduction. However, Swir values predicted by PCA+MRA were too high in low permeability range (compare in Fig. 8 and Fig 9 solid lines). We therefore chose MRA with raw variables for Khasib property prediction with the following expression for Swir hereafter

$$s_{wir} = \exp[-0.1263\ \ln(k) - 4.62762\emptyset + 0.1224] \qquad (8)$$

Where,
K: permeability. (md),
φ: effective porosity,
Swir: irreducible Water saturation.

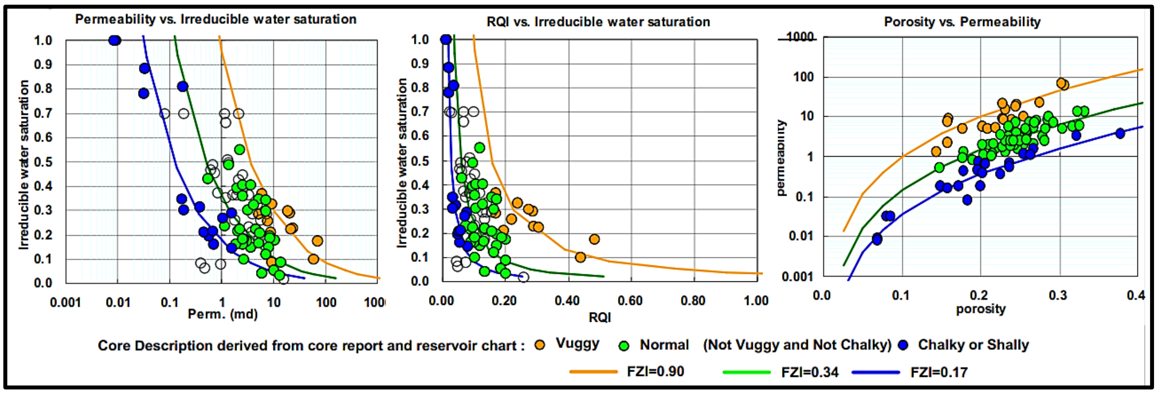

Figure 8 . Prediction model using MRA with “raw” properties (MRA)

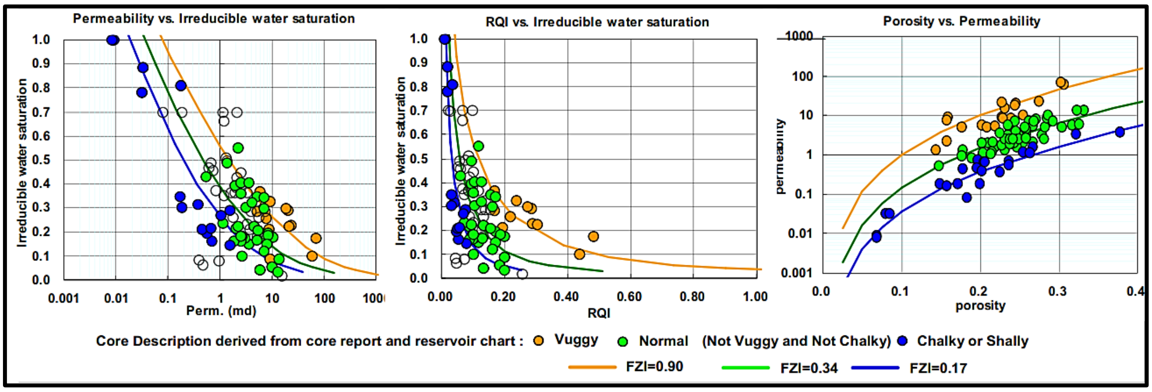

Figure 9. Prediction model using MRA with principal components of properties (MRA+PCA)

6. Capillary Pressure Curves

Capillary pressure data from oil-water system of drain cycle from special core analysis were used. The core data were modeled and averaged for each rock type with the capillary pressure function then, these curves were converted to values of "J" and these were related with water saturation from capillary pressure curves, We took the following J-function approach to extract representative capillary pressure Curves from a number of core measurements.

$$P_c = J(s) \times ST \times \left(\frac{\varphi}{k}\right)^2 \times U_{const} \qquad (9)$$

Where:

J(S): J-function, ST: Surface tension, φ: Porosity, K: Permeability,
U_{const}: Constant depending on the unit system =4.61678 (FIELD units, pressure in PSIA, perm in MD)
Derived J-functions for Tanuma and Khasib are shown in Fig.10 and Fig.11 for each facies. Table 2 present the proposed constant input data to J-function equation

$$J(s) = A\,(sw+0.49)^{B} \times U_{const} \quad (10)$$

Uconst=0.216601,see Table 2. for J-Function equation constants.

The J-function plot shows Moderate initial stage and relative long middle stage indicates the good sorting and seepage conditions. The calculated Sw from the J-function equation for each rock type is calculatred as mobile water saturation (Swm) then compared with swi estimated from wireline log .In

Table 2. for J-Function equation

	Constant A	Constant B
K>100 md	3.1758	-4.4300
Vuggy Limestone	2.4925	-3.8251
Normal Limestone	1.9661	-3.2326
Chalky Limestone	1.5269	-2.6011

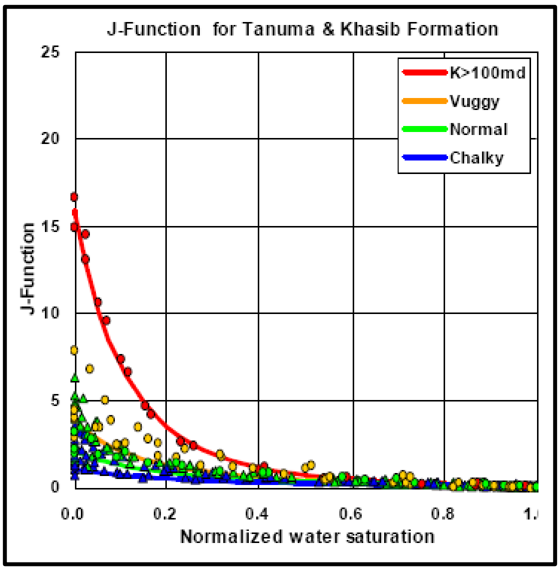

Figure 10. Derived J-functions for Tanuma and Khasib

case the values are identical the value is considered for fractional flow calculation to match the production test result at the specified depth, however if the estimated value mismatched the log sw then according to the proposed algorthim the FZI is revised to start inner itration of calculating new Swi and K properties. reasonable agreement between predicted and measured water saturation is relying on appropriate estimations permeability and flow unit indicator FZI of the specified depth.

The proposed formula for water saturation covers the most avaiable limestone formations in the middle region of Iraq and can be utilized for any carbonate formation with rock type similar to our mode in the same area.

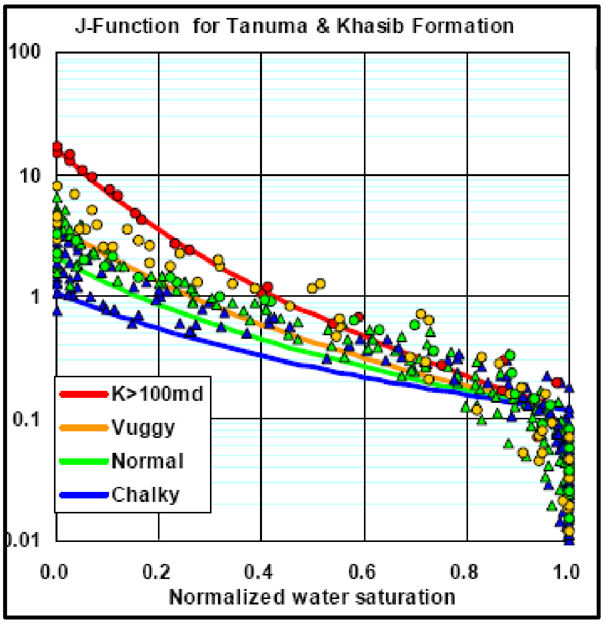

Figure 11. Derived J-functions for T&K Formation in semi-log

7. Foot-by-foot estimation of permeability and irreducible water saturation

Next, it was estimated the permeability and irreducible water saturation foot-by-foot along wells for uncored sections. Three parameters (Porosity , Sw and facies classification) are available from log analyses. Representative J-function curves are also available for each facies (see section 6 for details). It was found that logarithm of permeability has correlations positive to porosity and FZI and negative to irreducible water saturation. Now foot-by-foot evaluation shall meet the following two conditions.

Sw along wells shall be explained by single free-water level (FWL) for each pressure compartment.

Water-cut observed on production test shall also be closely simulated with the FWL.

For modeling purposes, Sw is split into irreducible water saturation (Swir) and transitional (mobile) water saturation (Swm). As water-cut is a function of only the latter,

$$Sw = Swir\,(FZI) + Swm\,(FZI, FWL, J\text{-function})$$

$$WC = function\,(Swm, Kr, Vis)$$

Where, FZI: flow zone indicator, FWL: free water level, Kr: relative permeability, Swir: irreducible water saturation and Vis: fluid viscosity. FZI and FWL are unknowns while the others are known.

We developed a new algorithm that honors available all information and conditions. Fig.12 and Fig. 13 are its flow chart and computation process for foot-by-foot permeability and irreducible water saturation. Via using this procedure, we built permeability and irreducible water saturation “logs” calibrated to production test results. Moreover, free water level, estimated in try-and-error basis, is now endorsed by dynamic data. discussions on pressure compartments are based on the free water levels established in this way.

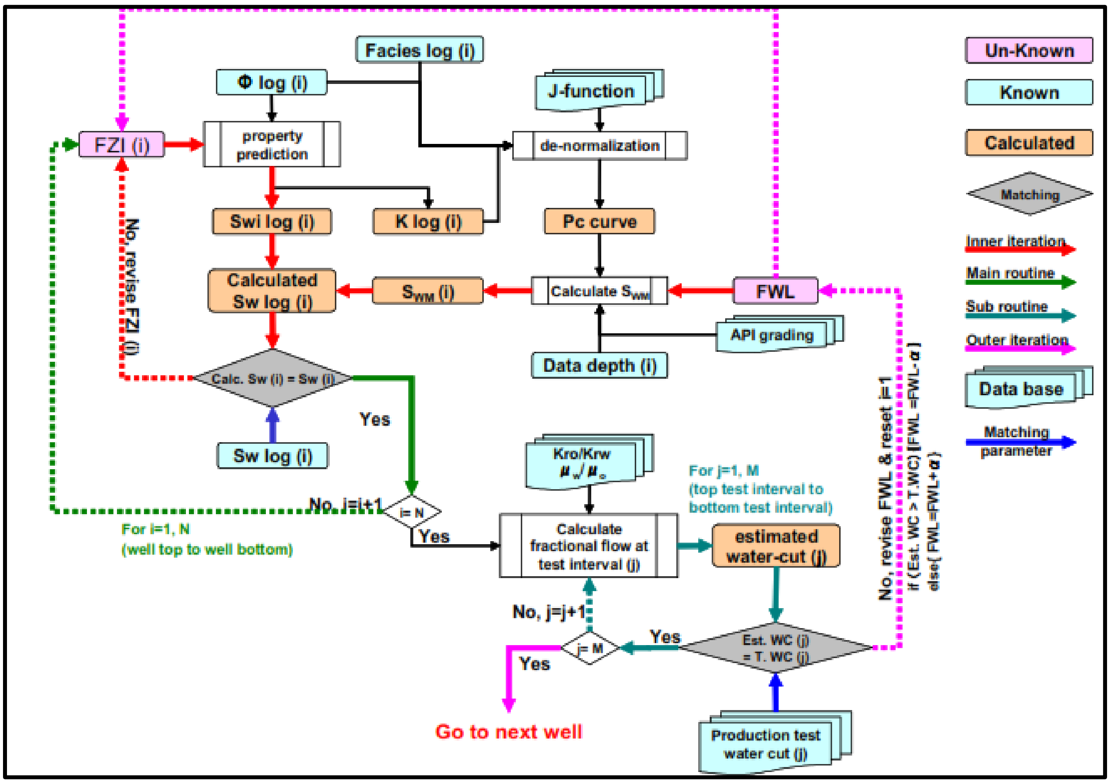

Figure 12. The new Algorithm Calculation flow chart of foot-by-foot permeability and irreducible water saturation

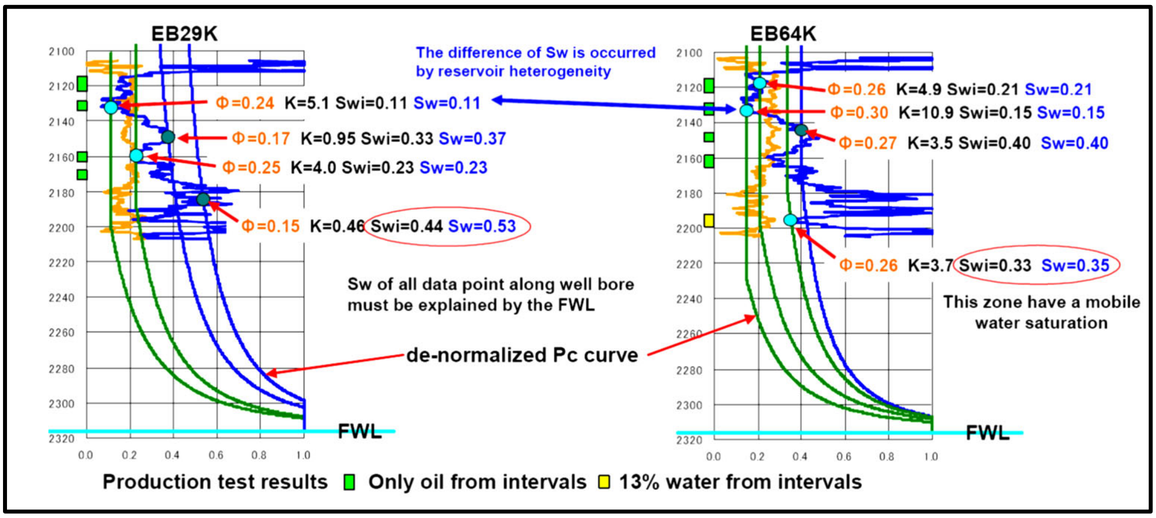

Figure 13. Example calculations: Sw profile along a well is explained by single FWL for each pressure

The computed permeability and irreducible water saturation "logs" are used later in geostatistical reservoir modeling, to characterize reservoir heterogeneity. The implementation of the new algorithm shows the good match between the actual and the predicted petrophysical indices as seen in Fig.13.

Results of this paper contribute to further understanding of the dynamic reservoir characters of Late Cretaceous Formation in Middle of Iraq, and benefit for favorable reservoir predicting and oil producing in this oilfield.

This study algorithm consistently produced correlation superior to the existing models that were compared against and extremely sensitive to possible changed in flow zone indicators within the area of interest

8. Conclusions

The new algorithm honors all available information and conditions such as free-water level (FWL) for each pressure compartment and the production test at each production interval through the fractional flow calculation at each depth.

This study is not exceptional, comparable work has been conducted and is accessible in the literature. What is noteworthy about this study is that this method delivered a significantly improved irreducible water saturation and permeability estimation in limestone reservoirs compared to the standard correlation models, moreover the uniqueness of this study is that it overcomes the data limitation constraint when conducting reservoir studies because it includes large amount of genuine data collected from two main carbonate formations in the middle region of Iraq (total core samples =2903).

The calculated results of porosity and permeability are in accord with the core analysis data, the algorithm model is reliable in petrophysics properties prediction for simulation purposes.

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References

[1] Kharrat R, Mahdavi R, Bagherpour M, and Hejri S, 2009 Manama Rock Type And Permeability Prediction Of A Heterogeneous Carbonate Reservoir Using Artificial Neural Networks Based On Flow Zone Index Approach *Society of Petroleum Engineers* 10.2118/120166-MS,

[2] Shenawi. S, White J, Elrafie E and AL-Kilany K 2007 Permeability and Water Saturation Distribution by Lithologic Facies and Hydraulic Units: A Reservoir Simulation Case Study Manama *Society of Petroleum Engineers*

[3] Pourafshary A Mirzaei-Paiaman Hadi Saboorian-Jooybari, and Peyman 2015 Improved Method to Identify Hydraulic Flow Units for Reservoir Characterization *Energy Technology* **3** 726-733

[4] Cui Y and Kuan Jie Y 2015 The measure of irreducible water saturation of low permeability reservoir and its influencing factors is analysed **42** 17 20-21

[5] Wang Fengqi and Daqing Heilongjiang 2016 China Discussion on the Irreducible Water Saturation and Ultra-Low water saturation *IOSR Journal of Engineering (IOSRJEN*) **06** 2278-8719