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A New Approach of Reservoir Description of Carbonate Reservoirs

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ABSTRACT

This study is conducted to test and evaluate the use of current methods of reservoir characterization, namely the permeability-porosity correlation, the J-function, and the Reservoir Quality Index (RQI) concepts, for reservoir description of heterogeneous carbonate formations. These approaches were compared with a new technique developed in this paper for improved reservoir description of carbonate reservoirs. This technique is called the Characterization Number (CN) technique and it is based upon considering fluid, rock, rock-fluid properties and flow mechanics of oil reservoirs.

To compare these reservoir characterization techniques, measurements of porosity, absolute permeability, oil and water relative permeability and irreducible water saturation for 83 actual core samples extracted from eight different wells for a new oil reservoir in the U.A.E. are obtained. These experimental data are used first to develop a permeability-porosity correlation. Then, the J-function and the RQI concepts along with the newly developed CN approach are applied and evaluated for reservoir description of the UAE carbonate reservoir under investigation. The results show that the Reservoir Quality Index concept is capable of identifying the flow units while the J-function concept is quiet poor. Also, a more refined identification of flow units is obtained by using the newly-developed Characterization Number. This improved description for the Characterization Number approach may be attributed to the consideration of rock/fluid properties of flowing fluid(s) and flow dynamic conditions of its containing formation.

INTRODUCTION AND REVIEW

Reservoir characterization techniques are quite valuable as they provide a better description of the storage and flow properties of a petroleum reservoir and thus provide the basis for developing its simulation model. Also, carbonate reservoirs, in particular, present a tougher challenge to engineers and geologists to characterize because of their tendency to be tight and heterogeneous.

Permeability and porosity of the reservoir rock have always been considered as two of the most important parameters for formation evaluation, reservoir description, and characterization. Beyond evaluating permeability and porosity, one can also use combinations of two or more rock properties to gain insight into the character of flow through porous media. The J-function and the Reservoir Quality Index (RQI) concepts are two of the ways that the oil industry has used to characterize the reservoir media. They incorporate parameters such as porosity and permeability into a single quantity that describes/characterizes the formation. The application of the J-function and/or the Reservoir Quality Index (RQI) concepts, however, may or may not determine whether a formation can be considered to have a single flow unit or multiple ones[1-4].

It is well recognized that an improved and effective reservoir description is a prerequisite for efficient development of oil reservoirs. The following is a brief review of the most common techniques available for reservoir description:

1.1. Permeability-Porosity Correlation Technique

The effective porosity[1] of a rock is defined as the ratio of its interconnected pore volume to its bulk volume. The permeability of the reservoir rock is defined as the ability of that rock to allow fluids to flow through its interconnected pores. The permeability-porosity relationship has always been considered as a very valuable tool for interpreting petrophysical properties of the rock, providing better reservoir description and/or enhanced reservoir characterization. A number of investigators[5-8] showed that rock permeability depends mainly upon the effective porosity. For this reason, permeability is mainly affected by grain size, grain shape, grain packing, sorting, and degree of cementation.

Wyllie-Rose[1,5,6], Timur[1,5,7], and Morris-Biggs[1,5,8] developed similar empirical correlations to calculate the permeability using porosity and irreducible water saturation for sandstone reservoirs. If one is to apply these correlations in general, he has to take into consideration the following limitations:
(1) they are not applicable to carbonate reservoirs,
(2) they were developed for local fields/formations,
(3) they apply only to irreducible water saturation condition (which may vary with oil production), and
(4) they can not be applied to wells drilled in water zones.

Recently, Saner *et al.*[11] used 75 core plugs from a Saudi Arabian carbonate reservoir to develop an experimental relationship capable of calculating permeability using porosity data. It is one of the few available correlations for carbonate rocks. The proposed correlation (which has a correlation coefficient = 0.81) can also be applied for sandstone reservoirs as well and was given as follows:

$$K = 0.0078726 * 10^{(0.16602*\varphi)} \qquad (1)$$

Since carbonate reservoirs data show severe scattering due to their heterogeneous nature, one has to be cautious in using the permeability-porosity correlation for calculating permeability unless a good correlation coefficient is available. In addition, a permeability-porosity correlation technique is not enough by itself since simulation studies also require more accurate tools for reservoir description and diagnosis of flow and non-flow units.

1.2 The J-Function Technique

The J-function[1,9,10] has been extensively used to describe and characterize porous media through evaluating capillary pressure data and plotting these together using the concept of J-function. The J-function[9] is defined as:

$$J(S_W) = \frac{P_C}{\sigma_{o-w} Cos\theta} \sqrt{\frac{K}{\varphi}} \qquad (2)$$

Important information about the pore structure may be obtained by studying the fine structure of capillary pressure curves that result from capillary instabilities at the single and multi-pore level. This J-function technique[1,9, 13] is, however, limited in practice because of lack of accurate instrumentation, data gathering, and interpretation requirements.

1.3. The Reservoir Quality Index Technique

A hydraulic flow unit is defined[2-4] as "the representative elementary volume (REV) of total reservoir rock within which geological and petrophysical properties that affect fluid flow are internally consistent and predictably different from properties of other rock volumes. Amaefule *et al.*[4] developed a practical and theoretically correct methodology to identify the flow unit(s) constituting the reservoir of interest. Amaefule *et al.*[4] developed the reservoir quality index (RQI) which is given as follows:

$$RQI(\mu m) = 0.0324 \sqrt{\frac{K}{\varphi_e}} \qquad (3)$$

This method uses core data to describe the variations in pore geometry within different lithofacies. This variation defines similar fluid-flow characteristics (flow units). The application of this technique requires a log-log plot of reservoir quality index (RQI) versus pore volume-to-grain volume ratio (φ_z).

2. Development of New Technique for Reservoir Description

Description and/or characterization of heterogeneous porous media have to consider all types of fluid and rock properties. A new correlation is developed here that considers variable characteristics of porous media and its contained fluids. These variables include rock properties (porosity, permeability, and pore diameter), fluid properties (oil density, and viscosity of both oil and water), rock-fluid properties (interfacial tension and wettability), and dynamic conditions (oil and water flow velocities). The detailed derivation of this correlation is shown in Appendix A. This correlation is obtained by using the dimensional analysis technique. This technique shows that these variables can be reduced to a dimensionless combination called here the Characterization Number (CN). It is given by equation (A-8) as follows:

$$\mathrm{CN} = 1.0067 \times \left(\frac{\rho_o \sigma_{o-W}}{\mu_o^2 \mathrm{Cos}\theta}\right)\left(\frac{K_{ro}}{K_{rw}}\right)\sqrt{\frac{K}{\varphi}} \qquad (A\text{-}8)$$

It is important to point out that K_{rw} and K_{ro} (at intersection point of the two curves) are relative permeability of water and oil, respectively. K_{rw} is generally less than 30 % for water-wet reservoirs and greater than 50 % for oil-wet reservoirs[13]. The corresponding S_w for the selected K_{ro} point is less than 50 % for oil-wet reservoir and S_w > for water-wet reservoirs. Where the oil density is expressed in Kg/m^3, viscosity in centipoise, IFT in N/cm, and permeability in darcy.

3. APPLICATIONS AND EVALUATIONS

3. 1. Description of Field Data Used

Analysis of Eighty-three actual carbonate core samples from one of the United Arab Emirates (UAE) reservoirs was obtained[12]. These core samples were cleaned, dried, and vacuumed for almost 24 hours. Then, samples were saturated with actual water formation. Porosity was measured volumetrically while water absolute permeability was estimated using Darcy's law after a steady-state condition is well established (using constant flow rate = 1.00 cc/min). The core was flooded with actual crude oil (viscosity = 6.2 cp and

API gravity is 37^o) until condition of irreducible water saturation is gained. These flood tests were used to calculate the relative permeability of oil and water. Oil water interfacial tension of the used actual liquids was measured using capillary pressure apparatus for oil-water system (Core Lab. Inc, Catalog No. 118) at room temperature (29.3 ^{o}C). Capillary pressure for four core samples (from Well A) was measured.

The obtained porosity and absolute permeability data are used next to develop a permeability-porosity correlation for this carbonate UAE reservoir, and also in calculating the J-function and the RQI. In addition, these along with all other measured data are used to investigate the validity of the newly developed Characterization Number (CN).

3.2. Application of the Permeability-Porosity Correlation Technique

All available data for permeability versus porosity are plotted as shown in Fig. 1. A mathematical expression was developed relating the two variables with a correlation coefficient R^2 of 0.87 is obtained. It is given as follows:

$$K= 0.2722*EXP (0.5351*\varphi) \qquad (4)$$

Equation 4 can be used generally throughout the reservoir to predict permeability using porosity data for this reservoir. Additionally, for each single well, a separate correlation is developed so that permeability around wells can be better estimated. Table 1 shows all developed permeability equations for the eight wells in this carbonate reservoir. The developed permeability correlations have the following advantages: (1) they have very good correlation coefficient (the range is between 0.83 and 0.95), which makes them a good and representative tool for predicting permeability, and (2) they are capable of predicting permeability in the water zone, the transition zone, and the oil zone.

A comparison of permeability of the UAE and the Saudi Arabian (SA) carbonate reservoirs is carried out using equations 1 and 4, respectively. Table 2 presents the used porosity values and the permeability predicted by both equations. It is clear that the UAE carbonate reservoir has higher permeability than that of the Saudi Arabian one, when both have the same porosity values of the carbonate rock. The significance of this comparison is that its confirmation to the severe nature of heterogeneity of carbonate reservoirs. Although both correlations are developed for carbonate reservoirs in the same region of Gulf area, a drastic difference of the obtained permeability is proven.

3.3. Application of the J-Function Technique

Reservoir description and/or characterization has been considered as a critical component of any reservoir development because of its ability in distinguishing the essential features of petrophysical and geological parameters influencing the fluid flow in the pay zones. The J-function[9] is used to correlate many variables of rock/fluid systems. The obtained values of porosity and permeability for well A are used in conjunction with capillary pressure, shown in Table 3, oil-water interfacial tension of 32 dyne/cm, and contact angle (assumed 70 degree) to calculate the J-function. The obtained J-function versus water saturation for the well A is presented graphically in Fig. 2.

It is clear, as can be seen from Fig. 2, that the application of this concept provides an identification of two overlapping flow units constituting the pay zone. This result is more accurate than that obtained using permeability-porosity technique since two flow units are identified. The obtained results using the J-function may be considered inaccurate characterization since the obtained flow units are overlapped and showing very close values for the J-function. The reasons for the J-function inaccuracy may be attributed to the existence of capillary pressure in the J-function, which is restricted to only the transition zones and lower values of applied capillary pressure measurements. In addition, the J-function inability to identify the flow units is due to the functional form of the J-function combining porosity, permeability, capillary pressure, and contact angle does not allow for reservoir flow-unit characterization.

3.4. Application of the Reservoir Quality Index Technique

Based on the flow unit concept, equation 2, the obtained permeability values of the UAE carbonate reservoir are used with their corresponding porosity values to calculate the RQI. The obtained RQI is plotted versus pore volume-to-grain volume ratio (φ_z), as shown in Fig. 3. This figure indicates that two flow units can be identified when all data points covering 8 wells are used. Data of RQI and φ_z for the single well A are also plotted in Fig. 4 to test the existence of flow units on the single well scale. The same two flow units also show up in Well A as in the data for all wells in this carbonate reservoir. Fig. 4 shows a high scattering degree. This may be attributed to the heterogeneous nature of carbonate reservoir(s) and/or the non-suitability of the RQI concept for this situation.

3. 5. Application of the Characterization Number Technique

Although the use of reservoir quality index (RQI) for reservoir description has proven effective. A number of other available properties can still be added to improve the application of the concept. Three such improvements have been identified in this work. These are including (1) the density of reservoir flowing fluids (oil and water), (2) the rock-fluid properties, such as interfacial tension and relative permeability of oil and water system, and (3) the variation in dynamic flow conditions. The addition of these properties provides a more robust reservoir description/characterization considering fluid, rock and rock/fluid properties. This variation of fluid properties (density, viscosity, and IFT) from well to another is expected to have more impact to differentiate between different oil flow units because of expected variations of temperature and pressure conditions.

The Characterization Number (CN) is plotted versus $\{\sqrt{K/\varphi}\}$ using all data points for the UAE carbonate reservoir under investigation in Fig. 5. Inspection of Fig. 5 shows that the producing formation of this reservoir consists of four distinct flow units. This result is very interesting and means that one may be able to produce a more refined reservoir description over the description provided using the concepts of J-function and RQI, as obtained in this study in Figs. 2 and 3, respectively. The reasons for this more refined reservoir description are that the Characterization Number (CN) considers almost all the important variables of the reservoir rock (porosity and permeability), its contained fluid (viscosity and density of oil), and oil-rock properties (relative permeability of oil and water, wettability, and oil-water interfacial tension). Data for Well A is again used to plot the Characterization Number (CN) versus $\sqrt{K/\varphi}$ for this well, shown in Fig. 6. This figure shows the existence of only two flow units. This means that the reservoir shows four flow units when all wells are considered but only two of them cross through Well A.

A comparison of Figs. 3 and 5 shows that the application of the CN concept is capable to identify four flow units while the RQI application provides only two flow units. This means that addition of fluid, rock-fluid properties (which may be almost constant for the same well but it is different from well to another) into the CN technique improves the performance for reservoir description although the same data set is used. In addition, a comparison of Figs. 4 and 6 indicates that although the RQI and CN concepts confirm the existence of two flow units through well A, the CN provides accurate and more harmonious identification than the RQI concept does. This is well shown in Fig. 6 where the scattering degree of used data points is much more lower than that shown in Fig. 4 for the RQI. It is important to emphasize that although the application of the RQI concept requires a log-log plot (which usually accumulates data points and reduces its scattering degree) to obtain a straight line (characterizing single flow unit), its final result still shows high scattering degree of data points. On the other side, the CN concept uses a Cartesian plot and provides lower scattering degree. The CN technique also has another advantage of plotting more rock/fluid variables involved in the CN versus dual parameter of $\sqrt{K/\varphi}$.

4. CONCLUSIONS

1. A permeability correlation is developed for the UAE carbonate reservoir. This correlation is capable of predicting the permeability using porosity data. A comparison between it and the permeability correlation for Saudi Arabia shows that the UAE carbonate reservoir has higher permeability than that of the Saudi Arabian reservoir, when both have the same porosity values.

2. Application the concepts of J-function and reservoir quality index on an actual carbonate reservoir show that the RQI provides better identification of the flow units constituting this formation than the J-function does.

3. A new technique is developed to provide more detailed information on the flow units of the reservoir. This technique is based on using the dimensionless analysis technique to develop the Characterization Number. It was successfully applied for the UAE carbonate reservoir for which data was available.

4. The improvement in definition of flow units for the Characterization Number is attributed to its consideration of the dynamic flow conditions in conjunction with properties of the rock and its contained fluids.

NOMENCLATURE

CN	Characterization Number, dimensionless
D_P	Pore diameter, cm
$J(S_W)$	J-function, dimensionless
K	Absolute rock permeability, md
K_{ro}, K_{rw}	Oil and water relative permeability, respectively, at intersection point of oil and water relative permeability curves.
IFT	Interfacial tension, N/cm.
N_C	Capillary Number, dimensionless
P_C	Capillary pressure, psia
RQI	Reservoir Quality Index, μ m
S_W	Water Saturation, fraction PV
V_o ,V_w	Velocity of oil and water, respectively, m/sec

Symbols

φ	porosity, fraction
φ_z	pore volume-to-grain volume ratio
μ_O , μ_W	viscosity of oil and water, respectively, cp
ρ_O , ρ_W	density of oil and water, respectively, Kg/m^3
θ	contact angle, degree
σ_{O-W}	oil-water interfacial tension, N/m

Subscripts

c capillary

o oil

p pore

r relative

w water

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Appendix A: Derivation of the Characterization Number

The characterization number combines the comprehensive set of variables that are considered the most relevant and representative of porous media and its contained fluids. These are the rock data K, φ , and D_P, the dynamic flow data V_O, V_W, the fluid properties data μ_O, μ_W, ρ_O, σ_{O-W}, and the rock-fluid data $Cos\theta$. Mathematically, this can be expressed as:

Characterization function = f (K, φ , V_O, V_W, μ_O, μ_W, ρ_O, σ_{O-W}, $Cos\theta$, D_P) (A-1)

Dimensions of these variables are expressed as follows:

$K = [L^2]$; $V_O = [L/T]$; $V_W = [L/T]$;
$\mu_O = [M/LT]$; $\mu_W = [M/LT]$; $\rho_O = [M/L^3]$;
$\sigma_{O-W} = [M/T^2]$; $Cos\theta$ = [dimensionless];
$D_P = [L]$; and φ = [dimensionless] (A-2)

Application of the dimensional analysis yields the following three groups:

$$\pi_1 = \left(\frac{\rho_O V_O D_P}{\mu_O Cos\theta} \right) \tag{A-3-a}$$

$$\pi_2 = \left(\frac{\sigma_{O-W}}{V_W \mu_W} \right) \tag{A-3-b}$$

$$\pi_3 = \left(\frac{\sqrt{K/\varphi}}{D_p} \right) \tag{A-3-c}$$

One can characterize the first group (A-3-a) as the Reynold's Number , Re, (divided by contact angle), the second group (A-3-b) as the inverse of Capillary Number, Nc, (without porosity), and the third one (A-3-c) as the Reservoir Quality Index, RQI, divided by pore diameter. Multiplication of the above three dimensionless groups together yields the characterizing function, denoted here as the characterization number (CN), combing the type of flow regime (Reynold's Number), the ratio of viscous to interfacial tension forces (Capillary Number) and the reservoir description of porous rock (Reservoir Quality Index). The result of the multiplication is expressed as follows:

$$CN = \left(\frac{\rho_o \sigma_{o-W}}{\mu_o Cos\,\theta}\right)\left(\frac{V_o}{\mu_w V_w}\right)\sqrt{\frac{K}{\varphi}} \qquad \text{(A-4)}$$

By definition using Darcy's law for steady-state flow, oil and water velocities can be expressed as follows:

$$V_o = \frac{2\pi K_o h(P_e - P_{wf})}{\mu_o Ln(r_e / r_w)} \text{,and } V_w = \frac{2\pi K_w h(P_e - P_{wf})}{\mu_w \; Ln(r_e / r_w)} \qquad \text{(A-5)}$$

Divide V_o by V_w from equation (A-5) yields

$$\frac{V_o}{V_w} = \left(\frac{K_o}{K_w}\right)\left(\frac{\mu_w}{\mu_o}\right) = \left(\frac{KK_{ro}}{KK_{rw}}\right)\left(\frac{\mu_w}{\mu_o}\right) = \frac{K_{ro}}{K_{rw}}\left(\frac{\mu_w}{\mu_o}\right) \qquad \text{(A-6)}$$

Substitution of equation (A-6) into equation (A-4) provides the characterization number as follows:

$$\mathrm{CN} = \left(\frac{\rho_o \sigma_{o-W}}{\mu_o^2 \mathrm{Cos}\theta}\right)\left(\frac{K_{ro}}{K_{rw}}\right)\sqrt{\frac{K}{\varphi}} \qquad \text{(A-7)}$$

Where ρ_O , μ_O , σ_{O-W} , and K are expressed, respectively, in Kg/m^3, Kg/m × s, N/m (N/m = 1000 dyne/cm), and m^2. In practice, the viscosity is expressed as centipoise (Kg/m × s = 1000 cp), oil density as Kg/ m^3, IFT as N/cm, permeability in darcy (m^2 = 1.013248 x 10^{13} darcy). For filed units then, the characterization number will be:

$$\mathrm{CN} = 1.0067 \times \left(\frac{\rho_o \sigma_{o-W}}{\mu_o^2 \mathrm{Cos}\,\theta}\right) \times \left(\frac{K_{ro}}{K_{rw}}\right) \times \sqrt{\frac{K}{\varphi}} \qquad \text{(A-8)}$$

Where K_{rw} is the water relative permeability at maximum water saturation (K_{rw} < 30 % for water wet reservoirs and K_{rw} is generally greater than 50 % and sometimes approaches 100 % for oil-wet reservoirs, as shown by Craig (1971)), The K_{ro} is the oil relative permeability at the point of intersection of the oil and water relative permeability curves. The intersection point of oil and water relative permeability is considered also as a good indication for reservoir wettability[13].

TABLE 1 Developed permeability correlations for some UAE producing wells.

Well Number	Developed Permeability-porosity Correlation	Correlation Coefficient (R^2)
A	$K = 0.2112 * EXP(0.4505\ \varphi)$	0.8455
B	$K = 0.0743 * EXP(0.5376\ \varphi)$	0.8617
C	$K = 0.1528 * EXP(0.4761\ \varphi)$	0.9056
D	$K = 0.0916 * EXP(0.6006\ \varphi)$	0.8097
E	$K = 0.0592 * EXP(0.5647\varphi)$	0.9416
F	$K = 0.0486 * EXP(0.5851\varphi)$	0.9501
G	$K = 0.0503 * EXP(0.5851\varphi)$	0.9258
H	$K = 0.0413 * EXP(0.6426\varphi)$	0.8337

TABLE 2 Comparison of the Computed Permeability of the UAE and Saudi Arabian (SA) Carbonate Reservoirs.

Porosity (%)	K (UAE) (md) using equation (3)	K (Saudi Arabian) (md) using equation (4)
1	0.47	0.01
3	1.35	0.03
5	3.94	0.06
7	11.46	0.12
9	33.35	0.25
11	97.09	0.53

TABLE 3 Data of capillary pressure versus water saturation for Well A.

Water Saturation (%)	P_c for core sample 1 (psia)	P_c for core sample 2 (psia)	P_c for core sample 3 (psia)	P_c for core sample 4 (psia)
16	50	47	41	48
26	25	27	32	29
40	15	14.5	18	12
49	12	10.5	13	9.5
70	5	4.5	6	5
84	3	2	3	2
90	2	1	2	1.5

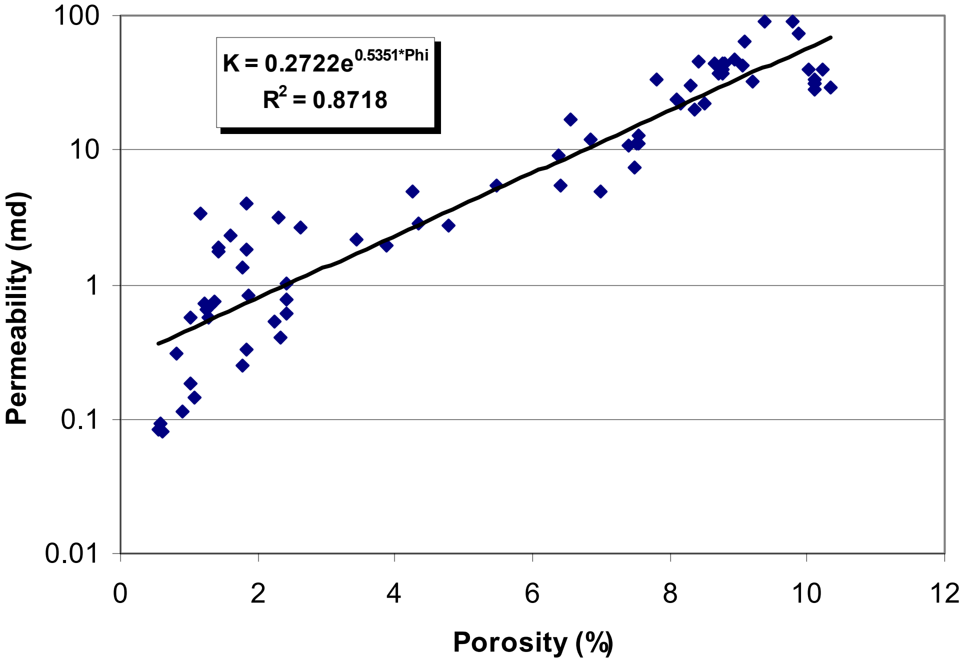

Fig. 1 Permeability-porosity correlation for UAE carbonate reservoir.

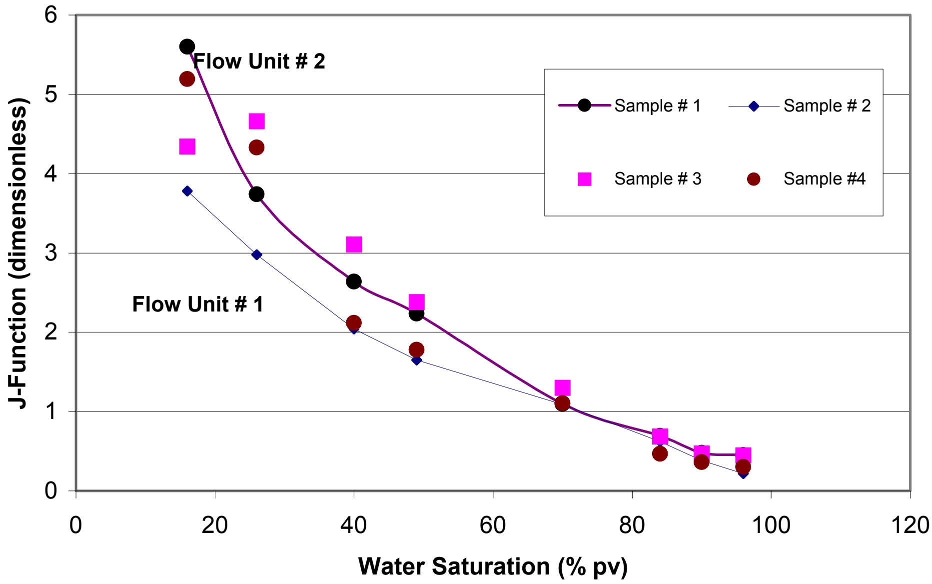

Fig. 2 J-Function of the producing formation for well A.

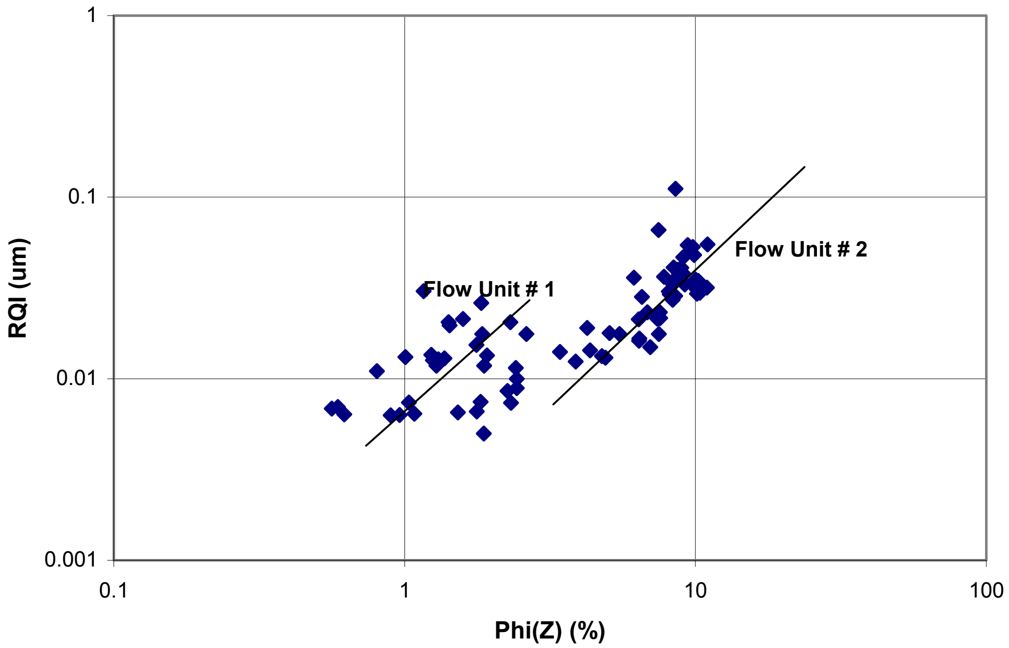

Fig. 3 Reservoir Quality Index versus phi (Z) for UAE carbonate reservoir.

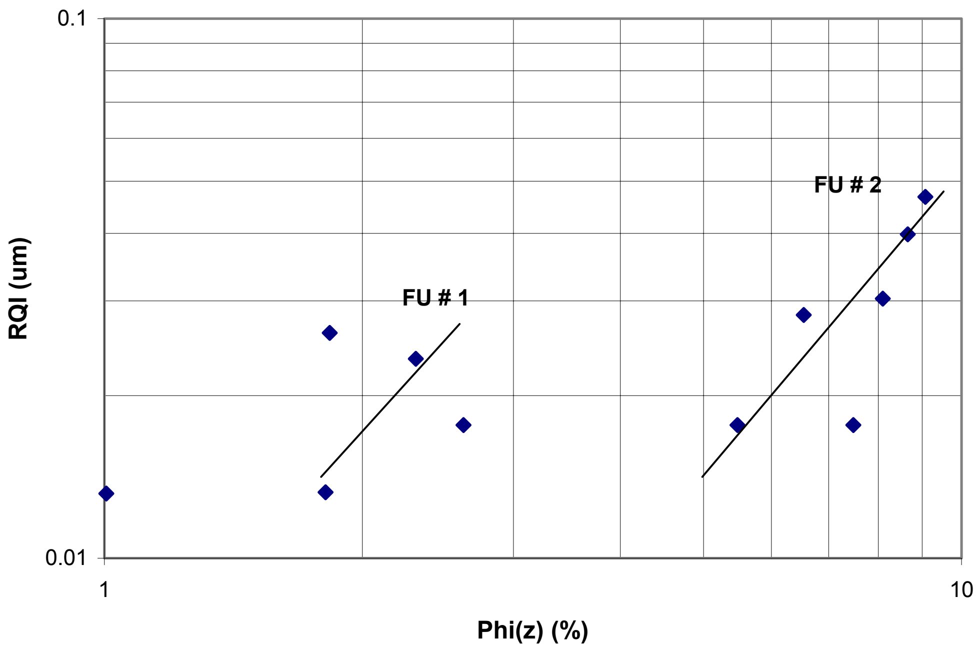

Fig 4. RQI versus phi (z) for Well-A.

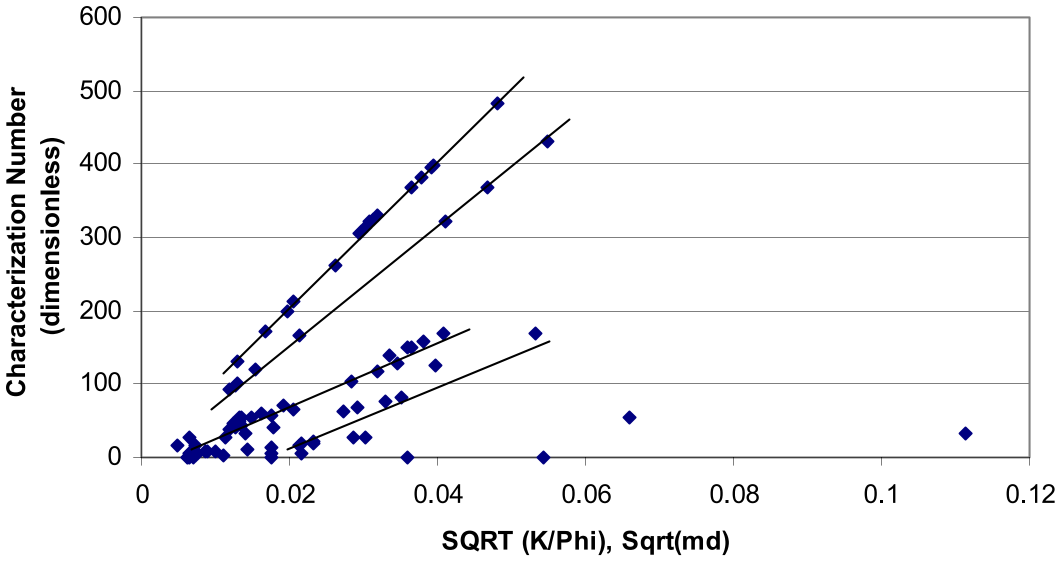

Fig. 5 Characterization Number versus SQRT (K/Phi) for UAE Carbonate Reservoir.

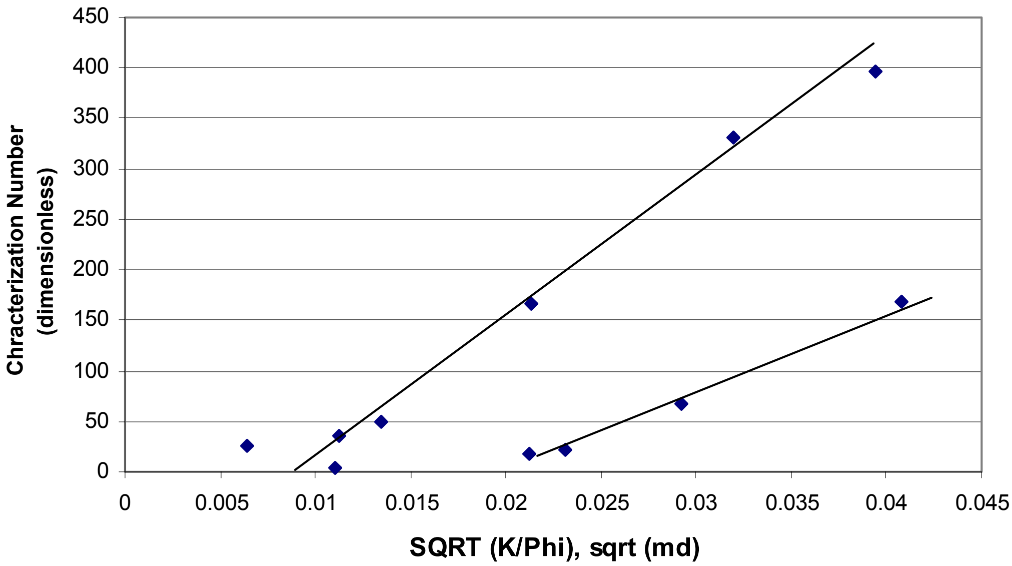

Fig. 6 Characterization Number (CN) versus sqrt (K/Phi) for well-A.