ROCK TYPING AND PERMEABILITY PREDICTION FOR WATER-WET AND OIL-WET ROCKS

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ABSTRACT
This paper addresses a link between engineering principles and geological characteristics of rocks in developing a method of rock typing and a general procedure for generating permeability correlations. A capillary tube model is the basis used to develop relationship between pore geometry and the structure. These two pore attributes are quantified from the two fundamental physical properties of rocks, permeability and porosity, and used to derive rock type equation.

Two types of rocks, carbonate and sandstone, with different wettability are used in this study. It is found that there is a strong correlation between the similarity in microscopic geological features and the similarity in both pore geometry and the structure. These similarities are found to be the foundation for rock typing. It is also found that each rock type established tends to have a specific relationship between irreducible water saturation and permeability. The permeability correlations derived showed that rock wettability has the effect on the irreducible water saturation exponent.

INTRODUCTION
Rock typing is a process of subdividing a reservoir into groups, each has specific characteristics, geologically as well as petrophysically [1]. Some of many investigators have proposed techniques for flow unit and rock typing [2,3] and permeability prediction [4,5]. However, they did not explicitly account for pore geometry-pore structure relationship and rock wettability. The objectives of this study are to investigate these pore attributes relationship in developing a method of rock typing and permeability correlations for rocks of different wettability.

METHODS DEVELOPMENT
Rock Typing.

A well known classical approach of the study of fluid flow through porous media is the use of circular capillary tube model. The model equation can take the form [6]:

$$k = C\phi^3 \quad \text{or} \quad C = k/\phi^3 \qquad (1)$$

where k is permeability, ϕ is porosity, and C is a function of both tortuosity τ and specific surface area S. Here C is thus a representation of pore structure. Eq.(1) can be re-arranged in the following form:

$$\sqrt{(k/\phi)} = \phi\sqrt{C} \qquad (2)$$

The term $\sqrt{(k/\phi)}$ is well recognized as pore geometry representation. Eq.(2) says that plotting $\sqrt{(k/\phi)}$ against $C = k/\phi^3$ on a log-log graph produces a straight line. This plot is so called as pore geometry-pore structure cross-plot (or PGS plot). This implies that samples with data points falling on and around the straight line should all have similarity in pore geometry and pore structure. The equation given by this straight line denoted here as rock type equation is:

$$\sqrt{(k/\phi)} = a(k/\phi^3)^b \quad (3)$$

where a and b are constant and exponent, respectively, that vary with rock type.

Permeability Prediction.

Among petrophysical properties that are strongly controlled by both pore geometry and pore structure are permeability, capillary pressure curve, and irreducible water saturation. It is therefore expected that a given rock type has a specific correlation between S_{wirr} and k. Suppose that the specific relationship would be in the following form:

$$S_{wirr} = ck^{-d} \quad (4)$$

where c and d are constant and exponent, respectively, that also vary with rock type. Then, combining Eq.(3) with Eq.(4) will result in the following equation:

$$k = \text{constant}\times[\phi^p/(S_{wirr})^q] \quad (5)$$

One can find that $p = [3\text{-}(0.5/b)]$ and $q = [0.5/(bd)]$ which both are used to make plotting k versus $[\phi^p/(S_{wirr})^q]$. For a given data set, the best fitting line will establish the final values of p and q. Eq.(5) above is very similar to the well known Timur equation [4]. The present study has found that the p and q exponents are both rock type dependent.

APPLICATIONS

Water-wet Carbonate

The wetting condition is usually indicated by the oil-water relative permeability curves (see Figure 1). Core data of the carbonate plugs were first sorted on the basis of similarity in the micro-geological features such as types and sizes of dominant grains, hardness, pore types, *etc*. The summary of sorting is given in Table 1, showing the four distinguishable groups. PGS plot (see Figure 2) was then made using the related permeability and porosity data. The open-circle data points shown in the figure represent samples having S_{wirr} data. One can see clearly that the data points establish four clusters each separates from the others and yields a fitting line with a slope of lower than 0.5. When k-ϕ cross-plot is used (see Figure 3), it is found that there is clear separation of the data point distribution among the rock types.

Figure 4 shows S_{wirr}-k cross plot for the carbonate. Swirr are derived from capillary pressure (SCAL) data for rock types 1, 2 and 3, and, due to limited SCAL data, from routine core analysis data for rock type 4. The regression is constructed for each rock type data except rock types 2 and 3 because rock type 3 has only one data point. Combining each rock type equation established with the corresponding S_{wirr}-k correlation results in equations in the form of Eq.(5). Plotting k against $\phi^p/(S_{wirr})^q$ is typically shown in Figure 5 for the rock type 1. The summary of permeability correlations obtained for all the rock types is presented in Table 2 showing that the values of $p < 2.0$. Also, the table indicates that the poorer the rock type quality (i.e. both the lower porosity and permeability) the lower the exponent values for both porosity and irreducible water saturation.

Oil-wet sandstone

Based on the core observation, description, and biostratigraphy from palynology analysis, the sandstone was deposited in supralitoral environment. Figure 6 shows an indication of oil-wet behavior of the sandstone. Table 3 presents the summary of grouping the core samples on the basis of the microscopic features and indicates that each group is clearly distinguishable from the others in terms of specific types of fragments or grains composing the rocks, grain size, and hardness.

Figure 7 is the PGS plot for the sandstone core samples. The data points of each rock type are clearly separated from those of the other rock types. All the fitting lines established also have the slope value less than 0.5. The conventional k-ϕ crossplot for all the rock types data (see Figure 8) demonstrates that no data point of two rock types is overlapping and thus a borderline may be drawn in between two closest rock types.

The SCAL data for this sandstone were limited. The data available represent only for rock types 1 and 3. The S_{wirr} versus k for all the data points are shown in Figure 9. It is assumed that this correlation holds for all the rock types established for this oil-wet sandstone. The correlation is used to estimate S_{wirr} for all the sandstone core plugs.

Integration of the rock type equations established with the S_{wirr}-k equation results in permeability correlations for the three rock types. The typical plot k against $[\phi^p/(S_{wirr})^q]$ for the sandstone's rock type 1 is shown in Figure 10. The summary of permeability equations is presented in Table 4, showing that the exponent p for porosity decreases with rock type quality and values of the exponent $p < 2.0$. Contrary to the water-wet carbonate case, the exponent for S_{wirr} increases as the rock type quality decreases.

COMPARISONS OF PERMEABILITY PREDICTION

Permeability predictions are made using the developed method and some previous correlations that appear in the most recent publication [5]. The predictions are compared in Figure 11 for the carbonate and Figure 12 for the sandstone. Also, comparisons of the correlation coefficient r^2, average relative error *ARE*, and average deviation from 1:1 line are presented in Table 5. This table shows that the correlation developed in this study outperforms the previous correlations for the two types of rocks used.

CONCLUSIONS

1. A general methodology for reservoir rock typing and for more accurate permeability estimation has been developed in this study.
2. There is a strong correlation between geological features of core samples at microscopic scale and physical meaning of the pores system at macroscopic scale.

3. The two types of rocks used demonstrate that the effect of porosity on permeability decreases with rock type quality. Unlike the water-wet carbonate, the effect of S_{wirr} on permeability for the oil-wet rock increases as rock type quality decreases.

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Table 1. Summary of rocks grouping for the carbonate.

Group	Microscopic features
1	Fine-medium grain, xls, moldic/biomoldic, vugs, chalky.
2	Micritic-very fine grain, vf-f grain, crystalized & re-cryst., some stylolite, abd/ sli moldic/ biomoldic, abandoned vugs.
3	Micritic-vf grain, vf-f grain, crystalized & re-cryst., stylolite.
4	Very fine-fine grain, re-crystalized, stylolite.

Table 2. Summary of permeability correlations for the carbonate.

Rock Type	Permeability Correlation
1	$k = 4.10^{-5} \times \phi^{1.4}/(S_{wirr})^{13.821}$
2	$k = 0.072 \times \phi^{1.183}/(S_{wirr})^{8.363}$
3	$k = 0.091 \times \phi^{0.913}/(S_{wirr})^{7.912}$
4	$k = 0.072 \times \phi^{0.032}/(S_{wirr})^{4.942}$

Table 3. Summary of rocks grouping for the sandstone.

Group	Microscopic features
1	Tuff & little andesitic sand, very fine-coarse & medium.-coarse grain, hard, poor sorted, ash matrix, large mica
2	Metamorphic tuff, tuff, andesitic sand, vf-c grain, f-m grain, m-c grain, hard-very hard, p-srtd, ash mtrx & argilaceous, slightly carbonaceous & slight fossil, ash mica
3	Mudstone, tuff & little andesitic sand, vf-f grain, veryfine silty grain, hard-very hard, p srtd, m- well sorted, very argilaceous & ash mtrx, volcanic ash, mica

Table 4. Summary of permeability correlations for the sandstone.

Rock Type	Permeability Correlation
1	$k = 8.829 \times \phi^{1.265}/(S_{wirr})^{3.846}$
2	$k = 0.143 \times \phi^{1.169}/(S_{wirr})^{5.025}$
3	$k = 0.032 / \phi^{0.256} \times (S_{wirr})^{5.818}$

Table 5. Comparisons of r^2, *ARE*, and average deviation. (k= 0.02 to 1875md for the carbonate and 0.10 to 488md for the sandstone; average k= 116.5md for the carbonate and 43.2md for the sandstone).

Method	Correlation. Coefficient, r^2		Average Relative Error		Avg. Deviation from 1:1 line	
	Carbonate	Sandstone	Carbonate	Sandstone	Carbonate	Sandstone
This study	0.99	0.96	0.16	0.13	21.64	10.30
Tixier	0.90	0.69	0.65	1.33	57.78	41.04
Timur	0.90	0.72	0.70	1.31	57.86	36.23
Coates	0.89	0.87	3.80	1.41	542.73	66.35
Torskaya	0.89	0.64	6.13	10.16	626.72	61.89

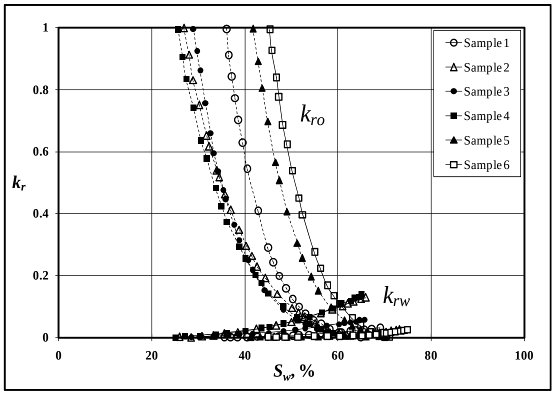

Figure 1. Water-wet behavior of the carbonate.

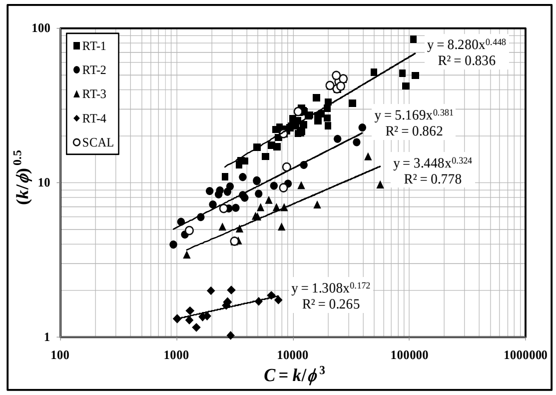

Figure 2. PGS plot for the carbonate.

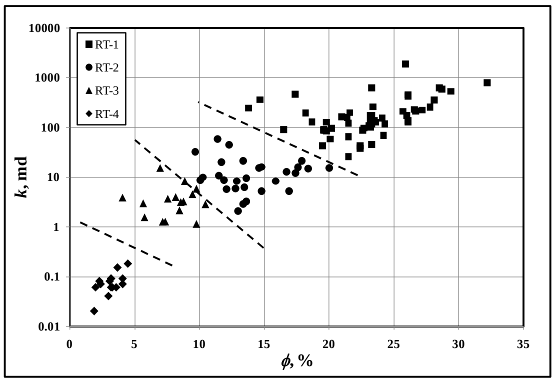

Figure 3. ***k*-ϕ crossplot for the carbonate .**

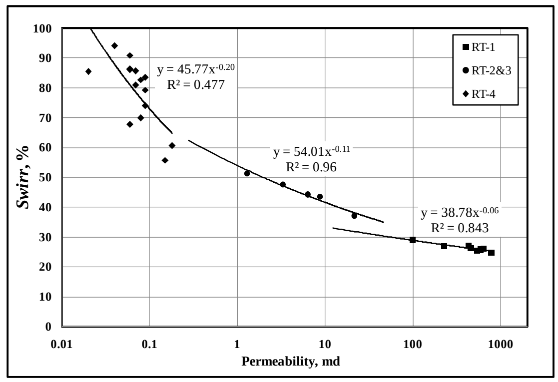

Figure 4. **S_{wirr}-*k* correlations for the carbonate.**

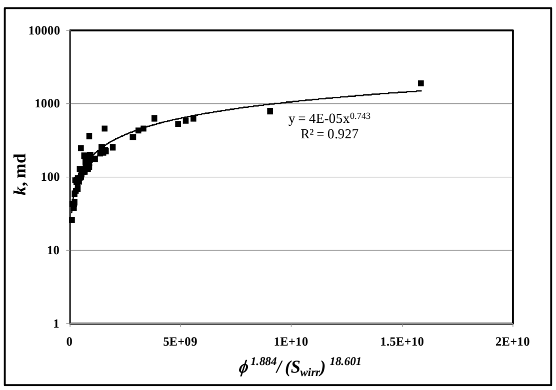

Figure 5. A typical plot of *k* vs. $[\phi^p/(S_{wirr})^q]$ for the carbonate – Rock Type 1.

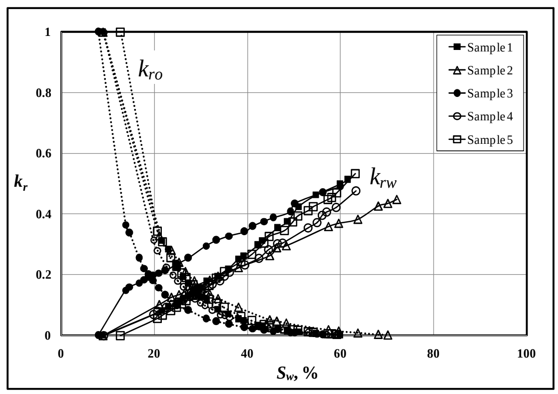

Figure 6. Oil-wet behavior of the sandstone.

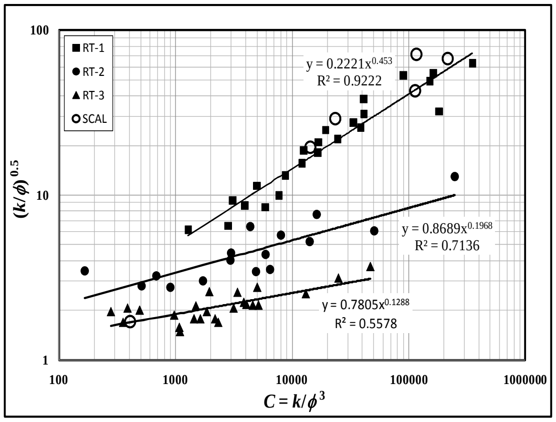

Figure 7. PGS plot for the sandstone.

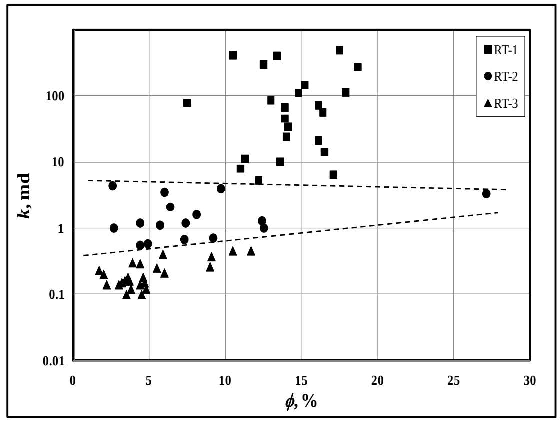

Figure 8. k-ϕ crossplot for the sandstone.

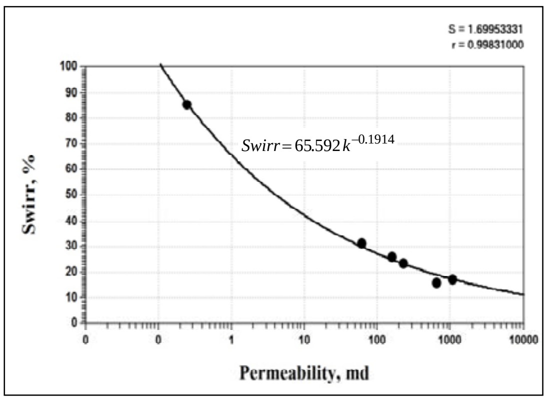

Figure 9. S_{wirr}-k correlation for the sandstone.

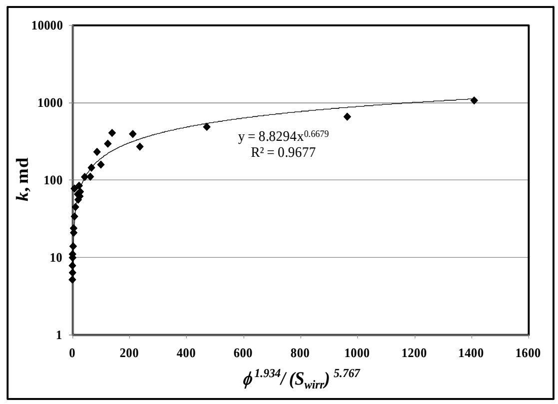

Figure 10. A typical plot of k versus $[\phi^p/(S_{wirr})^q]$ for the sandstone – Rock Type 1.

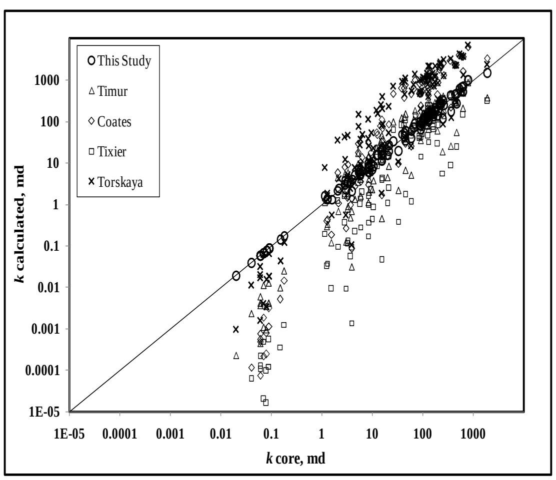

Figure 11. Comparison of permeability prediction for the carbonate.

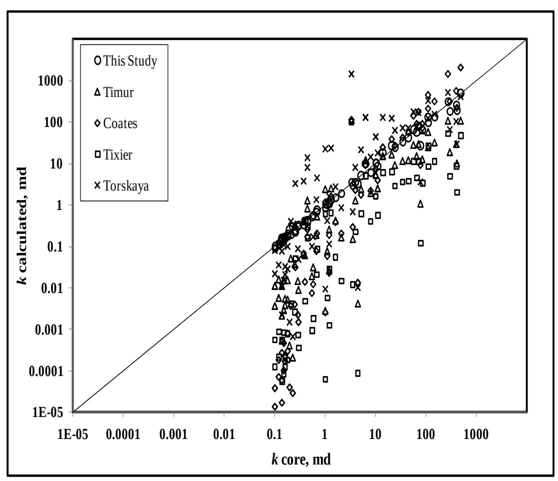

Figure 12. Comparison of permeability prediction for the sandstone.