Australian Journal of Basic and Applied Sciences, 6(12): 269-285, 2012
ISSN 1991-8178

Investigation Of Pore Geometry And Flow Unit Concepts In Reservoir Characterization And Prediction Of Performance

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Abstract: Petrophysical flow unit concept can be used to resolve some of the key challenge faced in characterization of hydrocarbon reservoir. The aim of this study, after evaluation of porosity and permeability, these flow unit types were used to reveal that one key to understand the relationship between porosity and permeability and so predict the performance of reservoir in spite of the present lithology type by represent them as combinations of different flow units, each with uniform pore throat size distribution and similar performance. Also Winland's approach of using multiple regression analysis to develop an empirical equation for calculating pore throat that corresponds to the 35th percentile was examined. In this study, the relationships between porosity and permeability of certain pore throat flow unit types were established on a data base of sandstone and limestone samples from 21 different stratigraphic units, which range in age between Cretaceous and Pliocene. These formations are varying in composition and texture. A statistical method was used to establish a correlation between porosity, permeability properties and pore throat R35. Empirically derived equations of good correlation coefficients were obtained using this technique of grouping the samples. The established technique of pore throat cutoff improve the relationships of porosity and permeability at certain flow unit type in sand, carbonate and sand and carbonate rock samples all together, and construct empirically derived equations of good correlation coefficients. A three empirically derived multiple regression equations for sandstone, limestone and all samples together are found, and indicate close correlation among pore aperture radius corresponding to mercury saturation value of 35 %. these developed multiple regression models able to predict R35 using porosity and permeability from routine core analysis. If the relationships exist between petrophysical properties and flow units, one can develop a common geological and engineering zonation. Then these relationships of these flow units with the interpreted sequence stratigraphy of the area provide a useful tool for mapping reservoir performance and predict the location of stratigraphic traps.

Key words: petrophysical flow unit, porosity, permeability, pore throat R35, multiple regression.

INTRODUCTION

There are many applications for pore geometry in reservoir quality and characterization. In many developed oil fields capillary pressure test is not available and only porosity and permeability are available. In this application, it is important to predict, either empirically or theoretically, the needed pore throat radii at certain mercury saturation values from available petrophysical properties. Pittman 1992, presented empirical relationships among porosity, permeability and the pore aperture size that crossponds to the displacement pressure and the apex of mercury injection plot.

In rock physics and its application, three methods are used normally to study the petrophysical properties of rocks; theoretical and model studies, laboratory measurements and investigations, and statistical and empirical correlations.

During the past years, many studies have been done on the pore aperture corresponding to 35th percentile of cumulative mercury saturation curve which was developed by H.D. Winland, Amoco Production Company, it focused on predicting of R35 from other data such as porosity and permeability.

The R35 of a given rock sample type reflects its depositional and digenetic fabric and influences fluid flow and reservoir performance (Hartmann and Coalson, 1990). Consequently, estimating R35 from logs, using the Winland's model (Kolodzie, 1980), or directly from capillary pressure core data (when available) provides the basis for a common zonation that can be used by both geologists and reservoir engineers. Four petrophysical flow units with different reservoir performances are distinguished by ranges of R35 (J. Hartmann, 1997).

In this study, separating technique based on range of R35 flow unit type values was utilized to create a better correlation among effective petrophysical properties in all studied rock samples in spite of their type of lithology. This indicates that, pore throat parameter is the only controlling parameter of the relationship between porosity and permeability.

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Flow units can be identified from the calculation of pore throat radii at the 35 % pore volume (R35), using Winland's model and from laboratory measured mercury saturation curves.

Identifying and quantitatively characterizing flow unit types is the key step in this study because it subdivide the data samples into units having similar and predictable flow characteristics.

The approach presented in this paper differs in that our procedure is based on assembling our data with different R35 and, hence potential reservoir performance. This approach enable facies and rock types to be quantitatively represented in terms of petrophysical flow unit types with distinctive ranges of petrophysical characteristics. Flow unit distribution scaled up to create new relationships between porosity and permeability and improve permeability prediction using empirically derived model of high correlation coefficients.

MATERIAL AND METHODS

A data set of laboratory measurements porosity, permeability and R35 in 179 sandstone core samples and 101 limestone core samples were used. The petrophysical properties of the sandstone core samples cover a wide range for exploration interest with porosity from 2.3 % to 39.9 %, permeability from .003 md to 5341 md, and measured R35 from 0.01 ηm to 52 ηm. While the petrophysical properties of the limestone core samples have porosity from 1.8 % to 34.6 %, permeability from 0.004 md to 2286 md, and measured R35 from 0.008 ηm to 29.5 ηm.

The size of the sample suite coupled with the wide range in porosity and permeability, the diverse composition and variable texture of the studied samples suggests this should be a representative sample set for reservoir sandstone and limestone.

The pore aperture radii were determined graphically from the mercury injection curves corresponding to the 35^{th} percentiles of mercury saturation and calculated theoretically from Winland's equation.

A statistical analysis system (SPSS) multiple regression program was used to establish various empirical relationships. Multiple regressions are an extension of the regression analysis that incorporates additional independents variables in the predictive equations (Balan *et al*, 1995).

Results:

In This study porosity, permeability and R35 have been measured for all samples. In order to resolve the performance of the different studied reservoir formations, we study the effect of petrophysical flow unit types on the relationship between porosity and permeability for all studied core samples and their influence will be distinguished from crossplots and obtained statistical equations and regression coefficients.

Grouping of studied core samples is made according to the values of pore throat radius at 35 % of our studied core samples which distinguish each flow unit types and are directly related to the permeability (figure 1 to 16).

In this study, we didn't have enough data samples to make relationships neither at mega flow unit type of limestone samples nor micro flow unit type of sandstone.

Figure 1 illustrates the weak relationship between the porosity and permeability for all the studied sandstone samples. The regression equation and correlation coefficient value are shown in the figure.

Figure 2 shows that there is no relationship exists between porosity and permeability for the studied sandstone samples at the nano flow unit type. This is plausible, because at this ranges of pore throat radius, R35 smaller than 0.1 ηm, permeability is too low and no fluid flow exist.

The relationship between porosity and permeability for the studied sandstone samples of meso flow unit types is presented in figure 3. The sample data points distribution present a strong relationship of high correlation coefficient. The regression equation and correlation coefficient are shown in figure. The relation between the porosity and permeability is improved, that indicates these range of R35 values affect on the permeability of our studied sandstone samples.

Figure 4 depicts the relationship between porosity and permeability for studied sandstone samples of macro flow unit type. The figure presents a good relationship with a high correlation coefficient. Improvement of the porosity permeability relationship is clearly appears on the figure at this range of values of pore throat radii R35 of this flow unit type. The permeability values increase with increasing lab estimated R35 values which controlling the permeability and directly related to fluid flow.

Figure 5 illustrates the relationship between porosity and permeability for studied sandstone samples of mega flow unit type. The samples data points of larger values of R35 and so permeability and fluid flow values. At this reservoir flow unit type data samples the relation is strong. The statistical equation and correlation coefficient are shown in the graph.

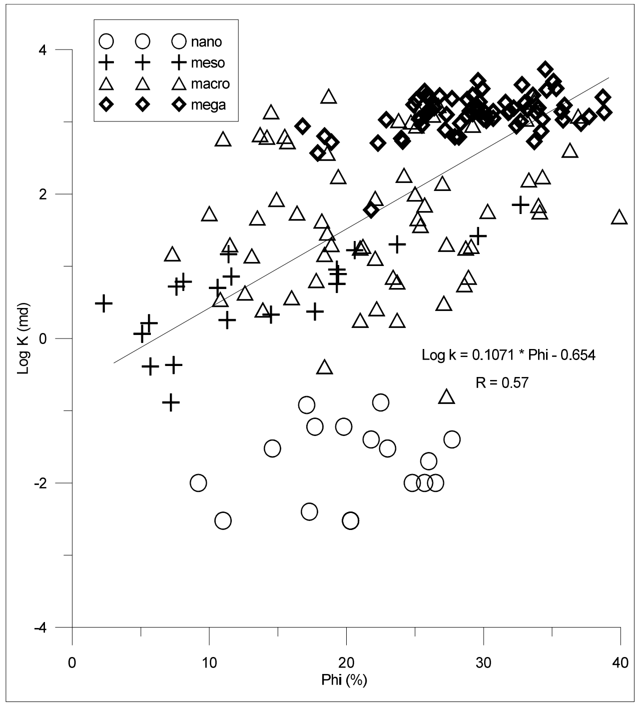


Fig. 1: The reationship bewteen Log K and Phi for the all studied sandstons sampies.

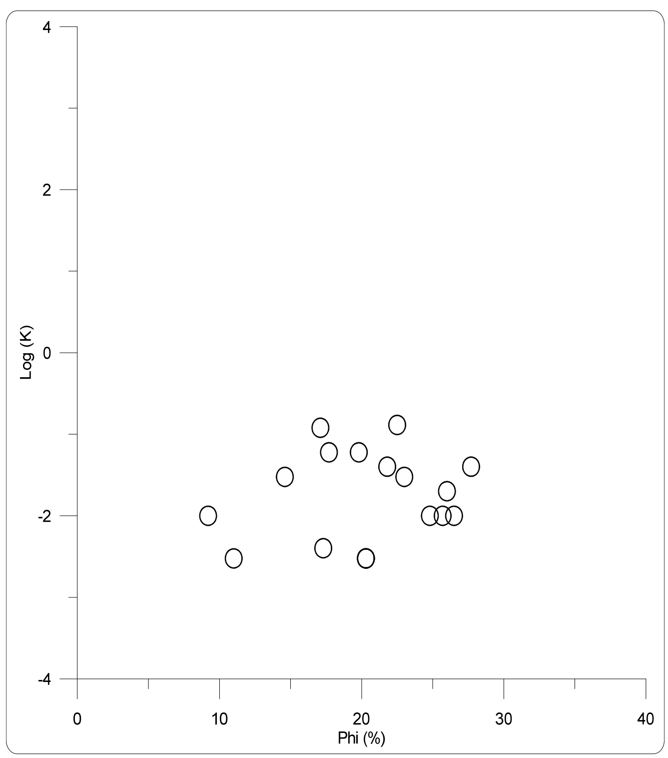


Fig. 2: The reationship bewteen Log K and Phi for the sandstons sampies, R35 (less than 0.1 micron).

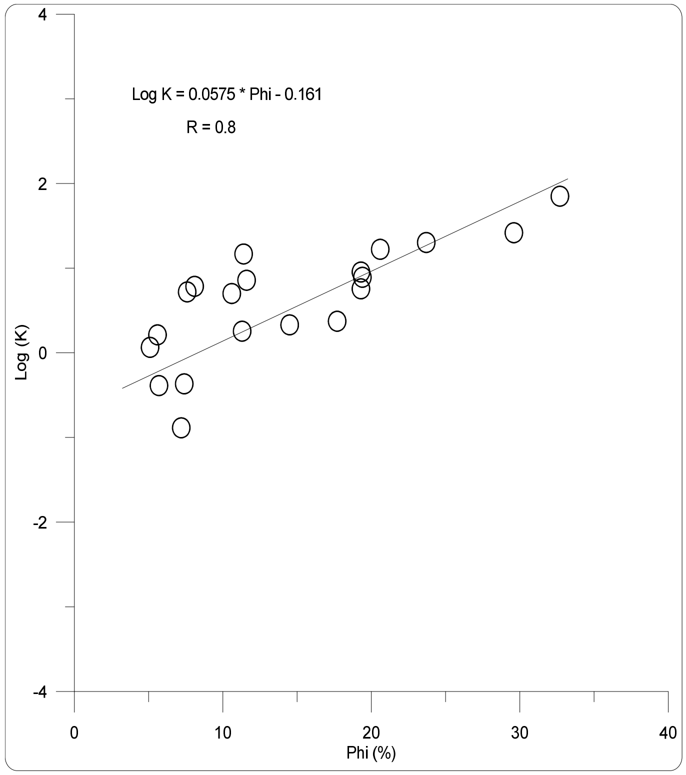


Fig. 3: The reationship bewteen Log K and Phi for the sandstons sampies, R35 (0.5: 2 micron).

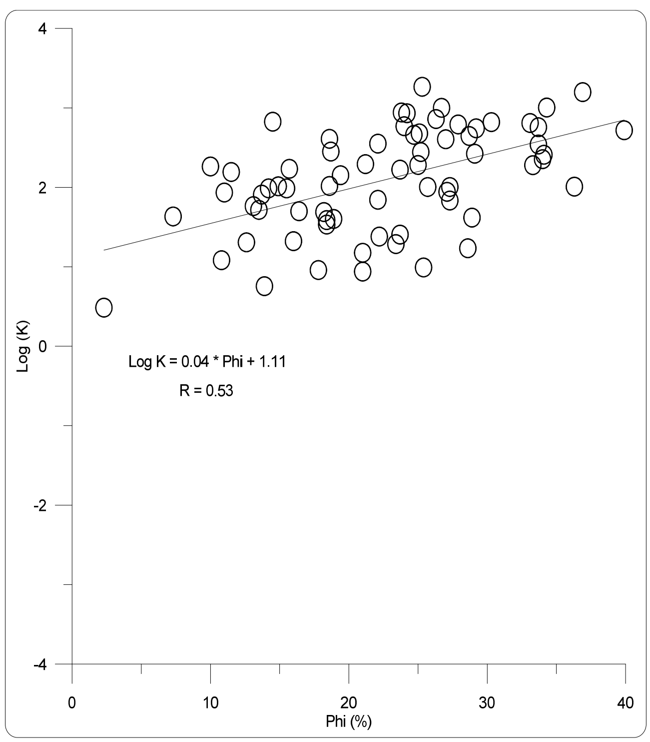


Fig. 4: The reationship bewteen Log K and Phi for the sandstons sampies, R35 (2: 10 micron).

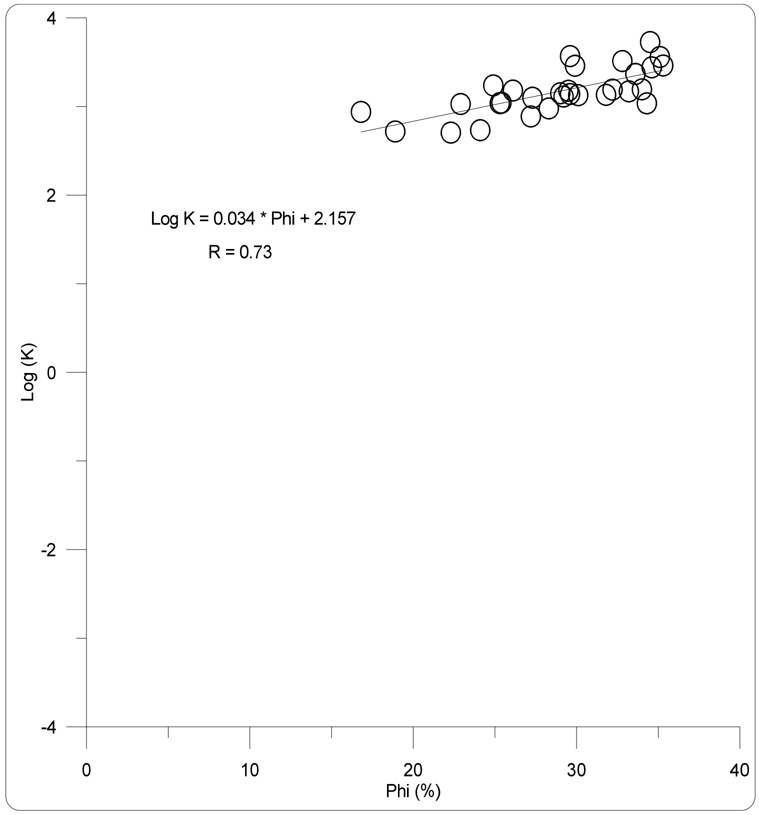


Fig. 5: The reationship bewteen Log K and Phi for the sandstons sampies, R35 (more than 10 micron).

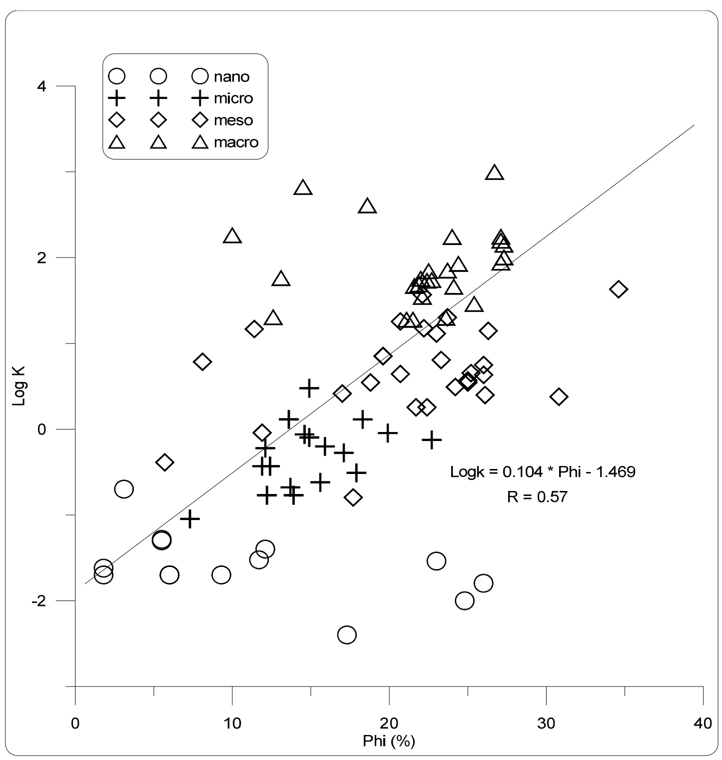


Fig. 6: The reationship bewteen Log K vs Phi for the studied limestone samples.

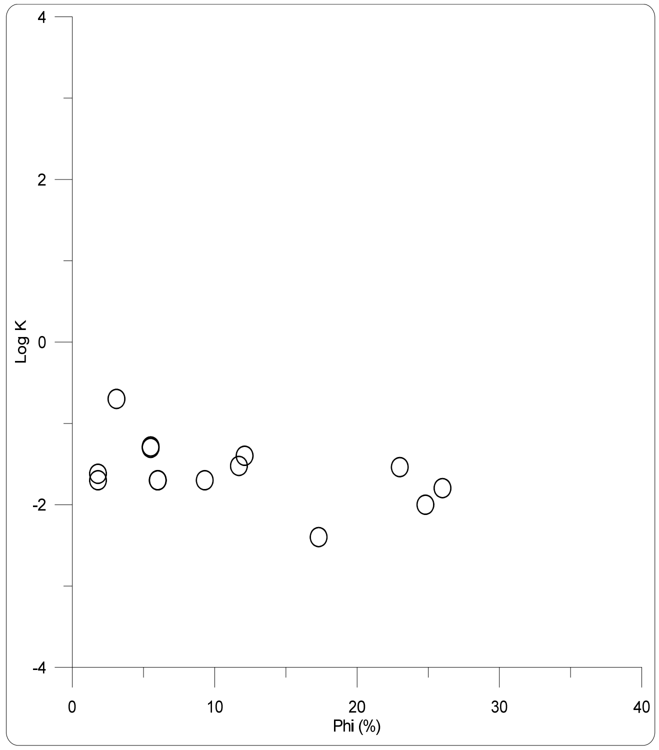


Fig. 7: The reationship bewteen Log K5 vs Phi for the studied limestone samples, meas R35 (less than 0.1 micrometer)

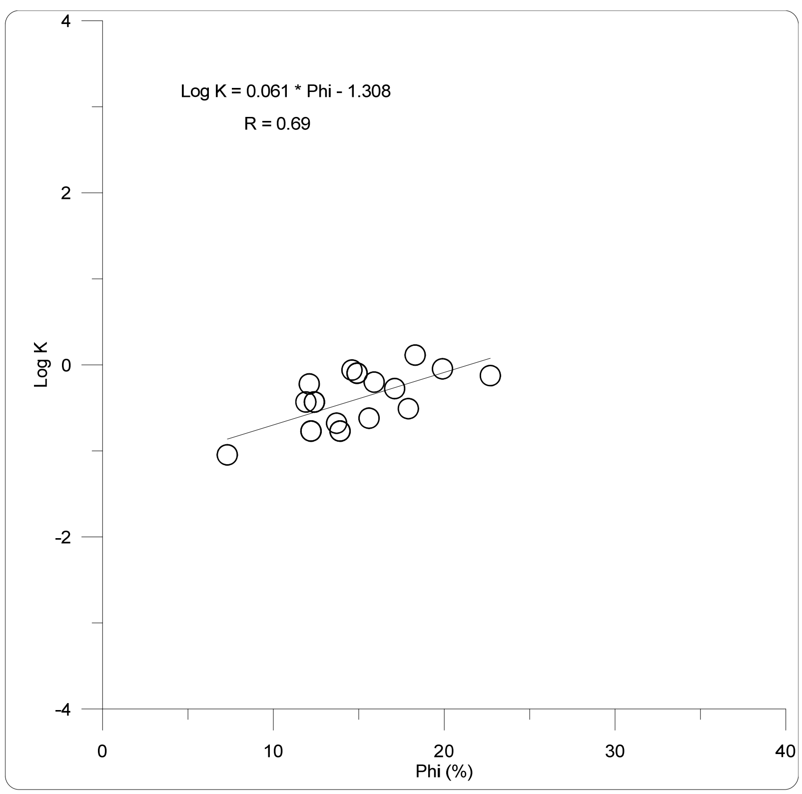


Fig. 8: The reationship bewteen Log K5 vs Phi for the studied limestone samples, meas R35 (0.1:0:5)

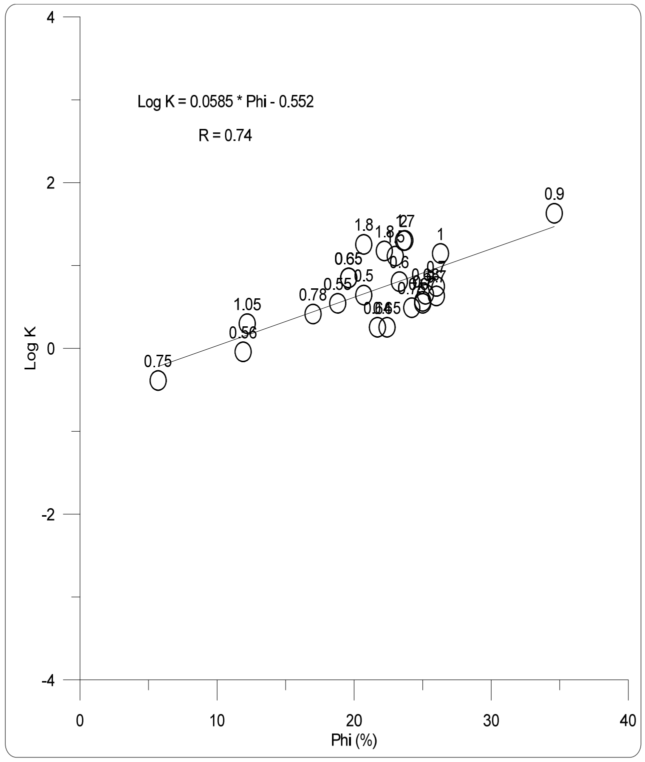


Fig. 9: The reationship bewteen Log K5 vs Phi for the studied limestone samples, meas R35 (0.5:2)

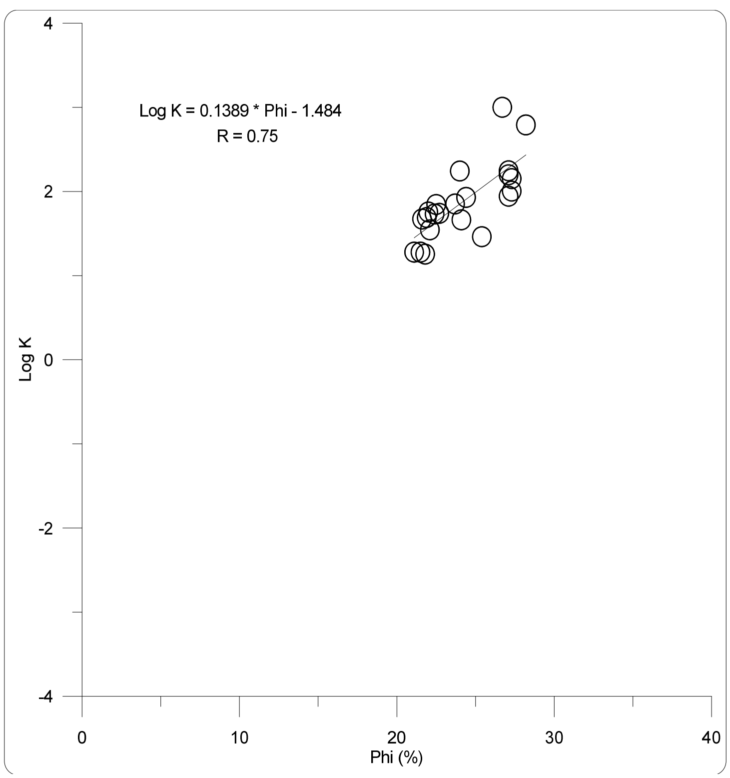


Fig. 10: The reationship bewteen Log K5 vs Phi for the studied limestone samples, meas R35 (2:10)

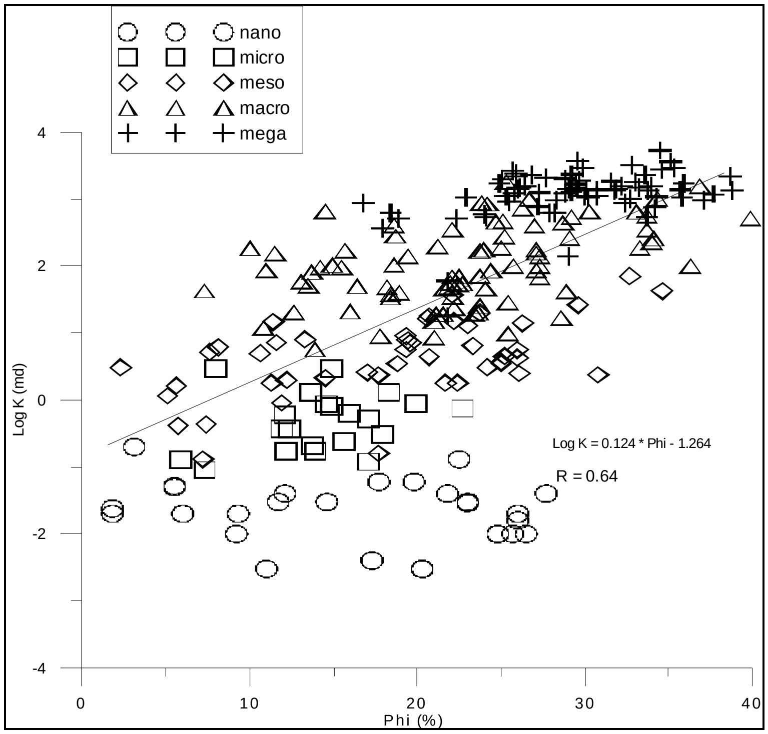


Fig. 11: The reationship bewteen Log K and Phi for the all studied samples.

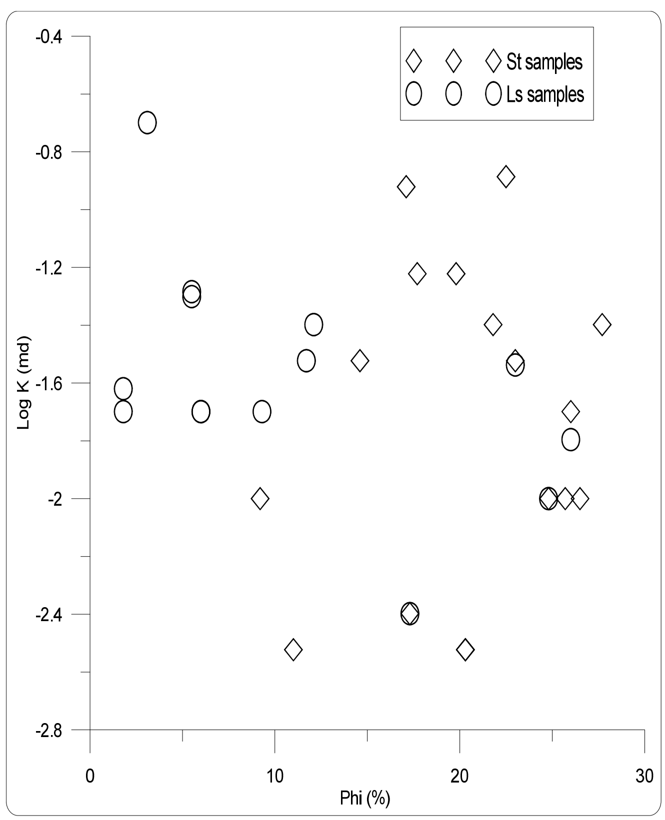


Fig. 12: The reationship bewteen Log K and Phi for the studied limestone samples, R35 (less than 0.1).

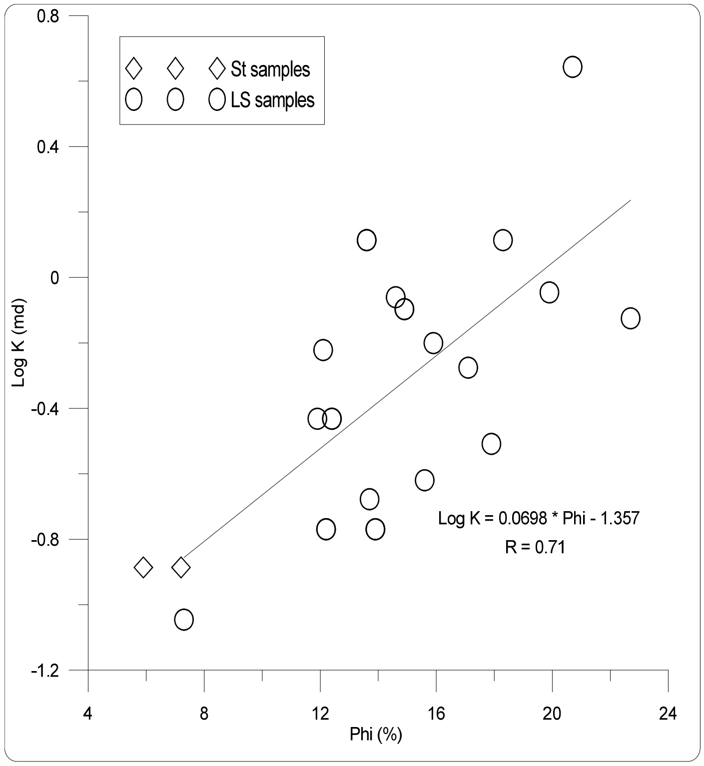


Fig. 13: The reationship bewteen Log K and Phi for the all studied samples, R35 (0.1:0.5)

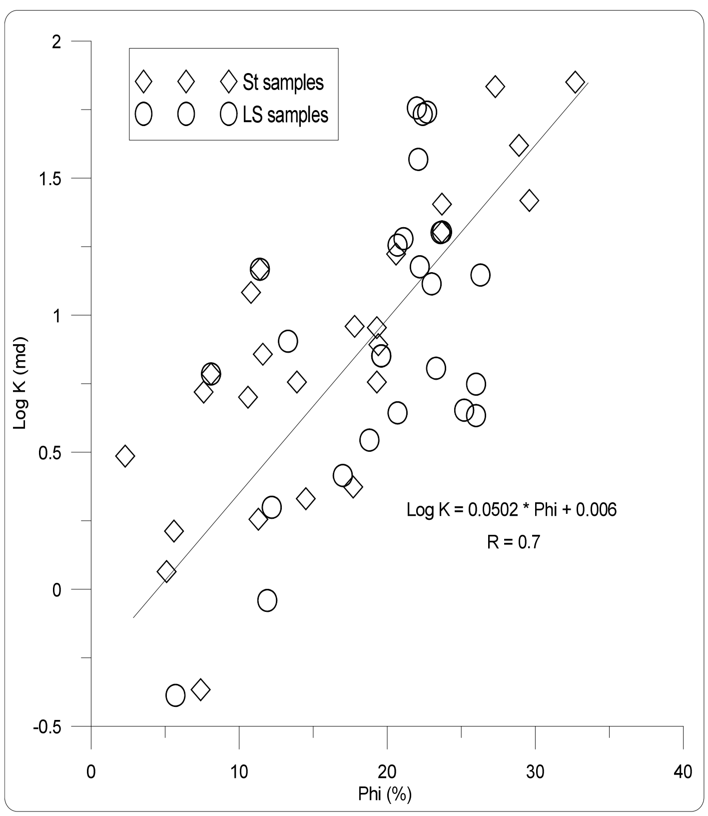


Fig. 14: The reationship bewteen Log K and Phi for the all studied samples, R35 (0.5:2)

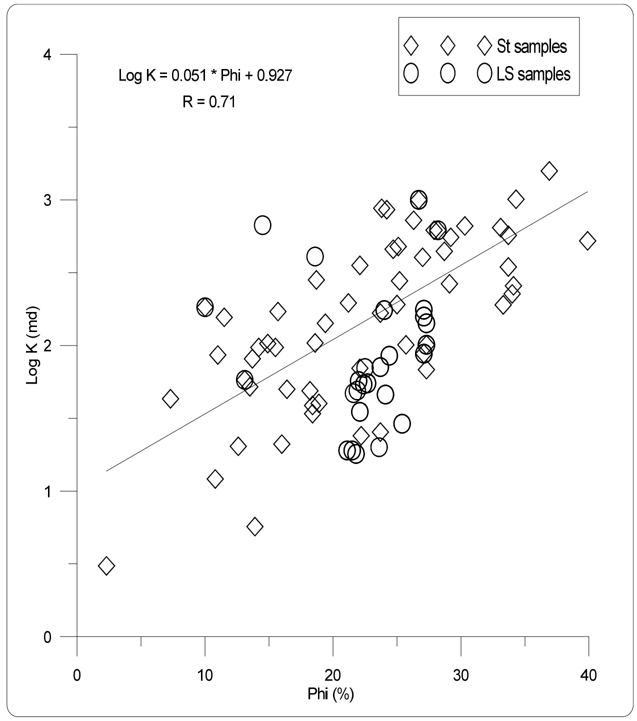


Fig. 15: The reationship bewteen Log K and Phi for the all studied samples, R35 (2:10)

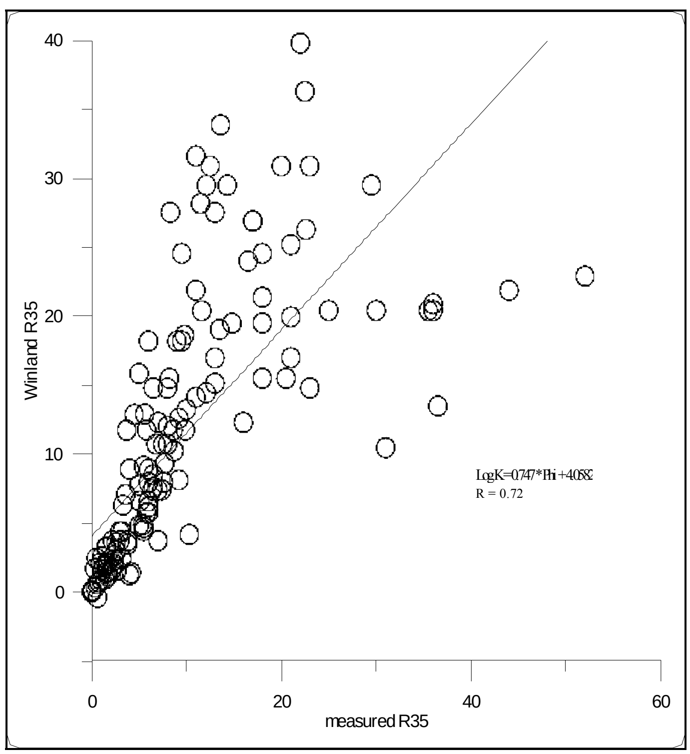


Fig. 16: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples.

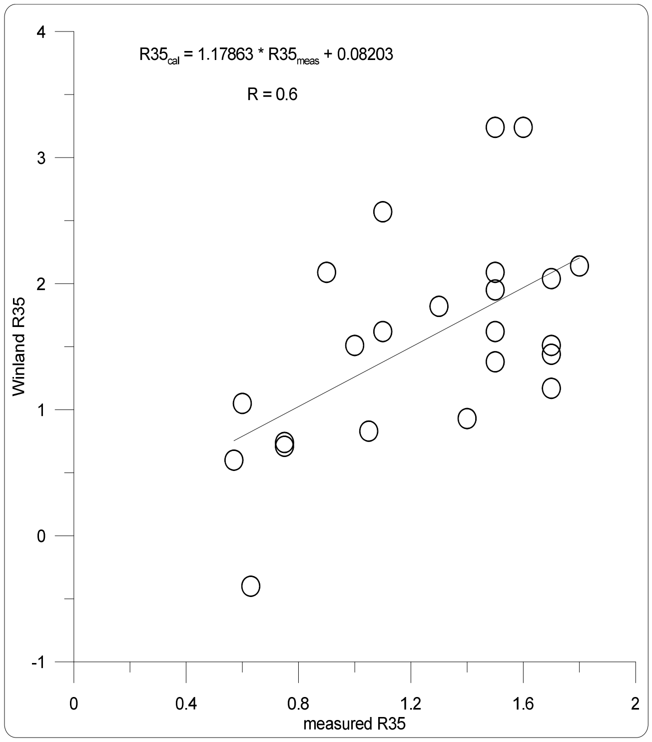


Fig. 17: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples, R35 (0.5:2)

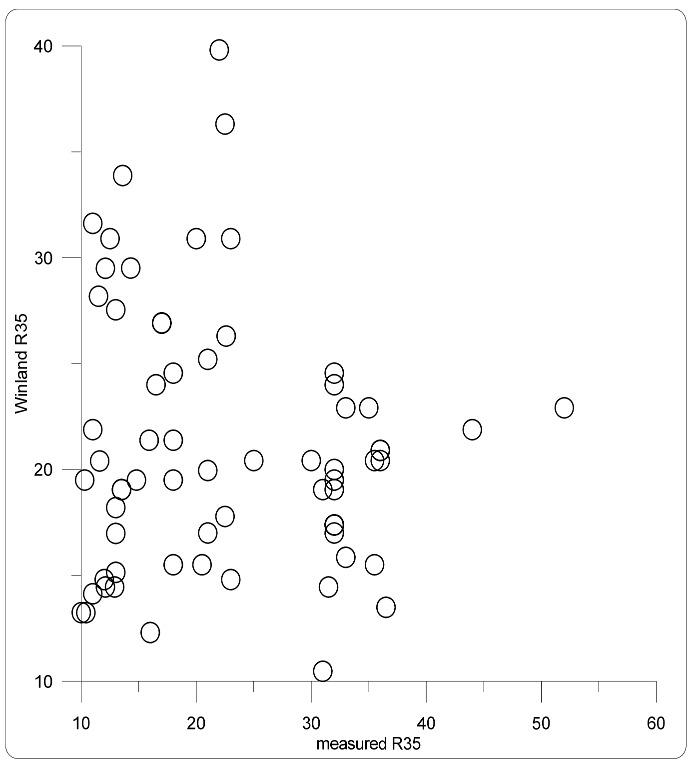


Fig. 18: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (more than 10)

The relationship between the porosity and permeability for all studied limestone samples is shown in figure 6. The figure shows weak relationship with small value of correlation coefficient. The graph contains reservoir and non reservoir sample data points.

Figure 7 depicts the relationship the relationship between porosity and permeability for studied limestone samples of nano flow unit type. No relationship is exist between the two petrophysical properties.

Figures 8, 9 and 10 illustrate the relationship between porosity and permeability for studied limestone samples of micro, meso and macro flow unit types respectively. All the figures show improvement of the relationship between the two petrophysical variables. The linear regression equation and correlation coefficient are shown on the figures. The relationship between the porosity and permeability for all studied samples is shown in figure 11. There is a weak relationship as indicated by small value of regression correlation coefficient.

The sample data points of nano flow unit type shows scatter distribution between porosity and permeability for all studied samples, (figure 12).

Figures 13, 14 and 15 depict the relationship between porosity and permeability for all studied samples of micro, meso and macro flow unit types. The figures show strong relationship between the two studied petrophysical variables. The regression equations and correlation coefficients are shown in the graphs.

In this study, also the relationships between measured and theoretically calculated R35 were studied at different flow unit types to Verify Winland's approach (figure 16 to 30).

Figure 16 illustrates the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the all studied sandstone samples. The linear regression equation and correlation coefficient are shown in the graph. The data shows that, the relation is good till R35 value equal to 10 ηm. Larger than the predetermined value the Winland's approach results are not matching with the empirical R35 results. So, Winland's equation is not applicable at these ranges of pore throat radii values.

Figures 17 & 18 shows the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the studied sandstone samples at meso and mega flow unit types respectively. It appears that, the studied sample data points are scattered and weak relationships are exist at these scales of pore throat range values.

Figures 19 & 20 depict the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the studied sandstone samples at nano and macro flow unit types. The studied samples give the strong relationship between the two studied variables. The calculated R35 values using Winland's equation are closely approximated from the measured pore throat values at these flow unit types. The correlation coefficients are shown in the figures.

The relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the all studied limestone samples is presented in figure 21.

Figure 22, 23 and 24 depict the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the studied limestone samples at nano, meso and macro flow unit types respectively.

Figure 25 illustrates the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the limestone samples at micro flow unit type. The data samples show scattering and weak relationship between the two variables.

Figure 26 illustrates the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the all studied samples show a strong relationship between the two variables. As shown before the deviation between the two variables is realized at calculated Winland's R35 greater than 10 ηm.

Figure 27, 28 and 29 show the relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the all studied samples at micro, meso and macro flow unit types respectively. These figures indicate strong relationship and high correlation coefficients as shown. The strong relation illustrates the availability of Winland's equation results at these ranges of pore throat radii of different flow unit types.

Figure 30 illustrates weak relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the all studied samples at nano flow unit type. Our results suggest that Winland's approach is verified only at certain flow unit type in non reservoir pore throat ranges, while a weak relationship is found at the reservoir pore throat radii ranges between the theoretically calculated Winland's R35 and lab measured R35 for the sandstone, limestone and all studied samples altogether. Multiple regressions statistical analysis was done. In general these relationships give good results and high correlation coefficients as following. Using the radius of the pore aperture corresponding to the mercury saturation at 35 %(R35 in ηm) as the dependent variable in the multiple regression involving permeability (K in md) and porosity (φ in %) yielded:

$R35_{meas} = -0.172+0.071\varphi +0.017\,k+ 0.0005\,K^2$ limestone samples (1),

$R35_{meas} = 3.078 -0.255\varphi +0.01\varphi^2+0.016\,k+ 0.0004\,K^2$ sandstone samples (2),

$R35_{meas} = 2.113 -0.21\varphi +0.009\varphi^2+0.017\,k+ 0.0005\,K^2$ all studied samples(3).

The equations have a correlation coefficient of 0.91, 0.79, and 0.83 respectively. Predictions of R35 with lab measurements show that prediction using porosity and permeability is reliable especially in carbonate rocks.

The weight of the input variables to predict R35 is given by their degree of contribution to the R35, which is determined by the multiple regressions.

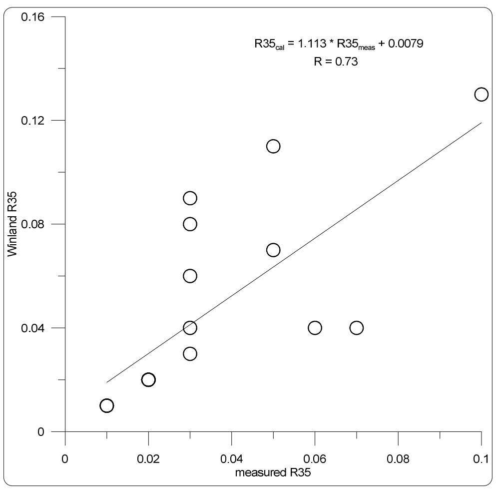
4.Discussion

For the studied sandstone and limestone samples at the nano flow unit type. There is no relationship exist between the porosity and permeability. This is plausible, because at this ranges of pore throat radius, R35 smaller than 0.1 ηm, permeability is too low and no fluid flow exist.

The relationships between the porosity and permeability for our studied sandstone samples are improved in the meso, macro and mega flow unit type, indicates that these ranges of R35 values affect on the permeability of our studied sandstone samples.

Using permeability cutoff at certain value of R35 will improve the relation between the porosity and permeability for all studied limestone samples by separate the limestone samples of no fluid flow from the other reservoir samples.

The studied graphs between porosity and permeability for studied limestone samples of micro, meso and macro flow unit types indicate that, by increasing the values of R35 the connectivity between



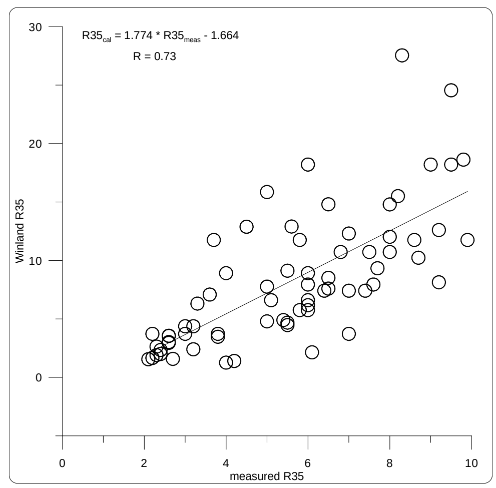
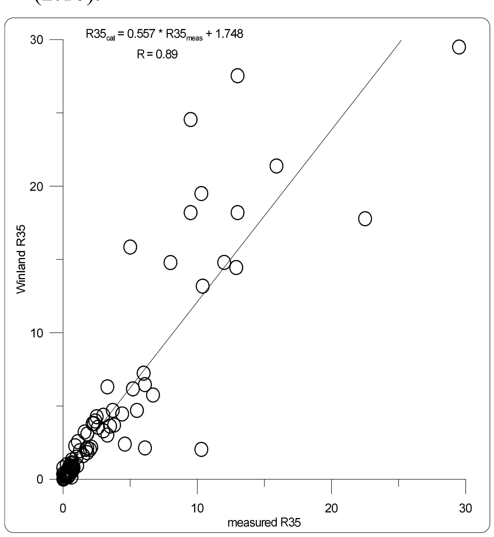


Fig. 19: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (less than 0.1).

Fig. 20: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (2:10).



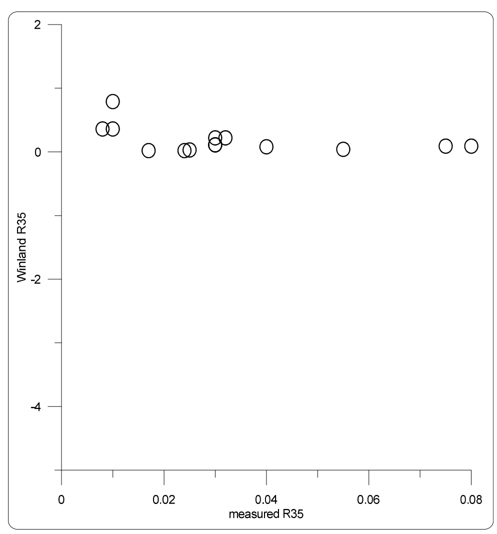
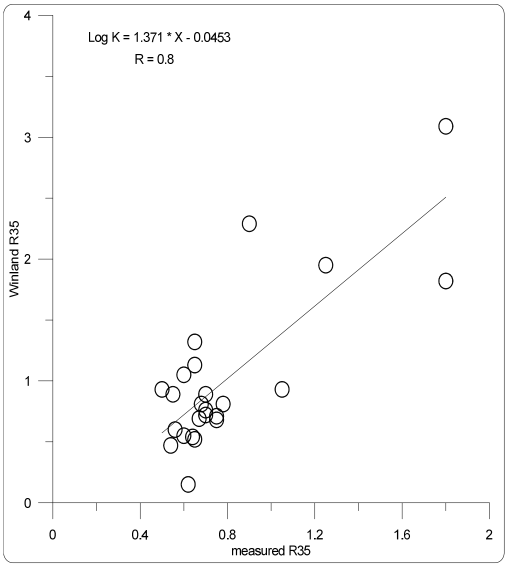


Fig. 21: The reationship bewteen Calcuated winand R35 versus measured R35 for all the limestone samples.

Fig. 22: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (less than 10)



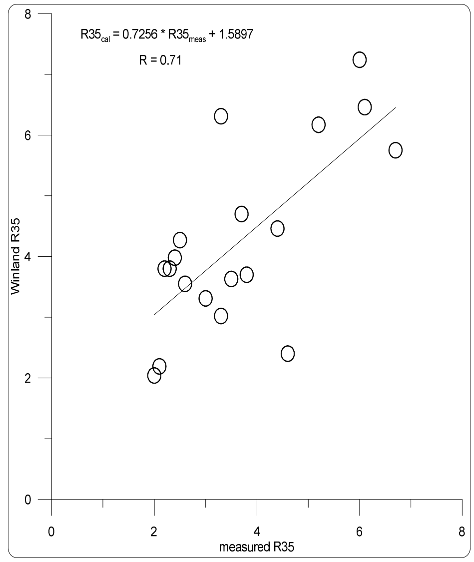
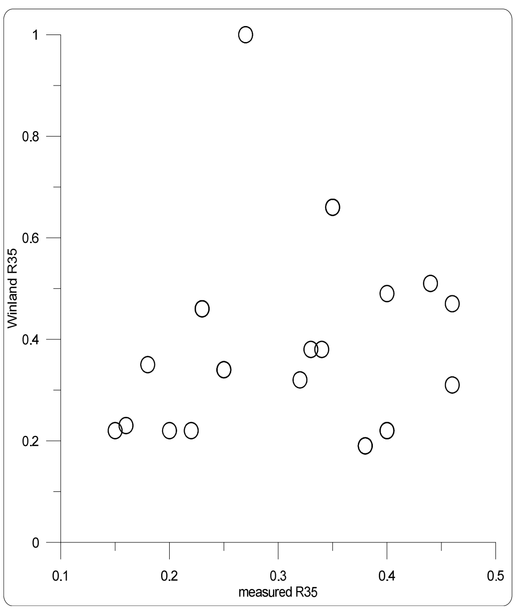


Fig. 23: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (0.5:2) micron.

Fig. 24: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (2:10).



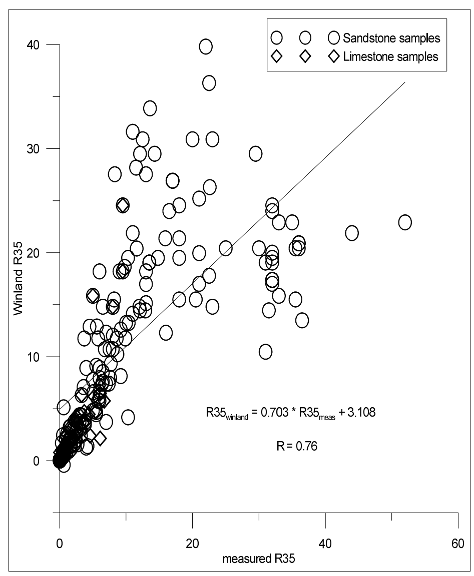
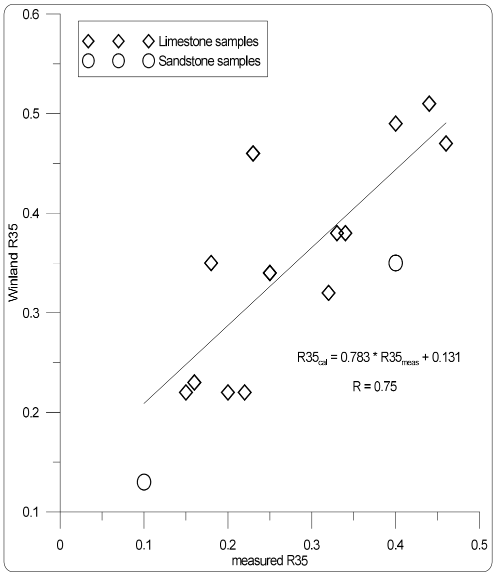


Fig. 25: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (0.1: 0.5)

Fig. 26: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples.



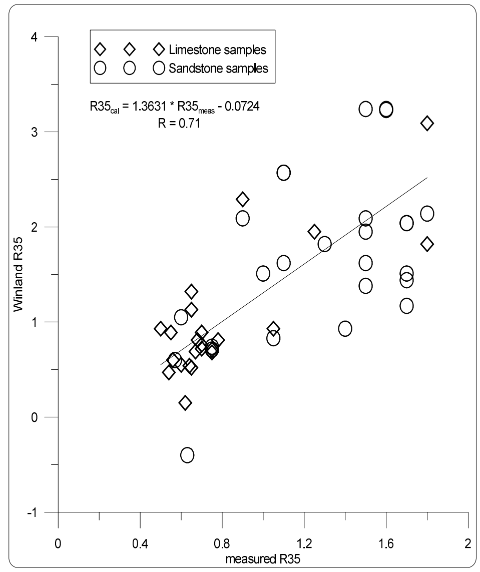
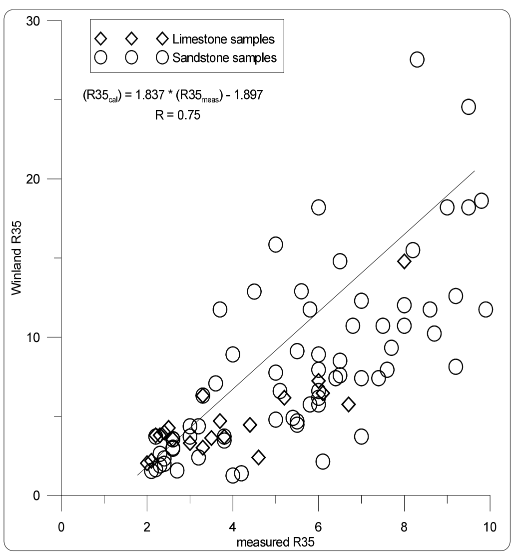


Fig. 27: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (0.1:0.5)

Fig. 28: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (0.5:2)



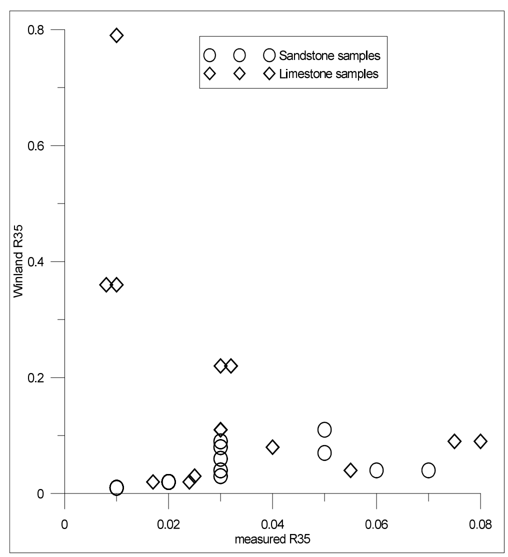


Fig. 29: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (2:10)

Fig. 30: The reationship bewteen Calcuated winand R35 versus measured R35 for the sandstone samples. R35 (less than 0.1).

the pores increases and so fluid flow increase and permeability will be the major controlling factor.

For all studied sandstone and limestone samples the porosity and permeability relationship is very weak at the scale of nano flow unit type because pore throat radii are too small and impede the fluid flow. However, at the micro, meso and macro flow unit types, the improvement of the relationship is caused by increasing the pore throat size and so the permeability and amount of fluid flow. So by using of the graphically predicted R35 we able to get real discrimination between reservoir and non reservoir zones which improve the porosity permeability relationship. This is due to the pore throat radii at 35% are directly related to permeability and reservoir performance. In spite of, some zones have high porosity greater than porosity cutoff (8 to 10%) it have low value of R35 of nano or micro flow unit type and so considered as non reservoir.

These zones considered as contain bad connected small or large pores. Hence we can't use the porosity cutoff concept to differentiate between reservoir and non reservoir zones instead Permeability cutoff according to the R35 make this discrimination more realistic and accepted.

In this study, also the relationships between measured and theoretically calculated Winland's R35 for the all studied sandstone samples, the data shows that, the relation is good till R35 value equal to 10 ηm. Larger than the predetermined value the Winland's approach results are not matching with the empirical R35 results. So, Winland's equation is not applicable at these ranges of pore throat radii values.

The relationship between graphically estimated R35 and theoretically calculated Winland's R35 for the studied sandstone samples indicates that winland's equation either over or under estimate the pore throat radii at meso and mega flow unit types ranges of pore throat values. However, the calculated R35 values using Winland's equation are closely approximated from the measured pore throat values at nano and macro flow unit types.

For the all studied limestone samples, the study indicates that, Winland's equation can't be used for the samples have measured R35 greater than 10 ηm. However, for the studied limestone samples at nano, meso and macro flow unit types, Winland's equation is success in calculating R35 closely related to lab estimated R35 values for our studied limestone samples at these flow unit types. Also, Winland's output is not valid for the limestone samples at micro flow unit type.

Our studied relationships show that theoretically calculated Winland's equation results are available for the all studied samples at micro, meso and macro flow unit types but the Winland's equation results are not valid at nano flow unit type. Our results suggest that Winland's approach is verified only at certain flow unit type in non reservoir pore throat ranges, while a weak relationship is found at the reservoir pore throat radii ranges between the theoretically calculated Winland's R35 and lab measured R35 for the sandstone, limestone and all studied samples altogether.

Multiple regressions statistical analysis was done. In general these relationships give good results and high correlation coefficients Predictions of R35 with lab measurements show that prediction using porosity and permeability is reliable especially in carbonate rocks. Contribution factors (2.113, 0.21 and 0.017 respectively for a_0, φ and k) indicate that the most important variable in this regression is φ.

Conclusion:

Application of petrophysical flow unit types approach on the empirical relationships give good results even in different formations and depositional environment. The calibration constructed in our study indicates their reliability for different rock lithologic types. The R35 characteristics of a certain flow unit reflect both its depositional environment and digenetic fabric and influence its flow performance. Pore throat radii at the 35 % pore volume provide the best basis for defining reservoir flow units.

The relationship between porosity and permeability usually faces problems, such problem can be avoided with flow unit types assembling technique, and then the regression method gave good results during the application phase.

In this study a statistical method was utilized to create a correlation among effective petrophysical properties and R35 in different lithologic rocks. The introduced multiple regression method can estimate R35 with high correlation coefficients for the studied core samples.

A multiple regression presented a robust correlation to predict R35 from porosity and permeability measured values.

Increasing the regression coefficients of the studied relationships between porosity and permeability indicate that the flow unit approach was done successfully, especially with reservoir formation of macro and mega flow unit types.

This petrophysical studies has investigated the use of petrophysical flow unit types approach on core samples for improving prediction of permeability. In this study, linear regression was applied to core samples data to predict k. The results show that this approach performs better for predict permeability by represent reservoirs as combination of different flow units, each with uniform pore throat size distribution. Permeability is directly related to effective pore throat size R35 which assist in identification and quantitative characterization of flow unit types. Reservoir performance can then be characterized in term of each flow unit type.

The flow unit types seem to be an ideal tool, if used properly, and enough data is available for k prediction. We observed that the most important flow unit types for this inversion are the macro and mega that play significant role in the statistical model. The introduced equations can predict k with R of about 0.72 for established groups of data samples. It seems that the approach causes the data samples to correlate and converge as better as possible and minimize the relationship individual weaknesses.

By combining the porosity, permeability and flow unit type relationships with the interpreted sequence stratigraphy of the area we can predict the location of hydrocarbon productive stratigraphic traps.

The petrophysical flow unit model is an excellent tool to explain the porosity permeability relationship and appear to serve well for distinguishing nonproductive from productive core samples.

Pattern recognition from petrophysical crossplots used to identify flow units from core and log data is the key to flow unit characterization in the absence of core.

Flow units can be characterized in both sandstone and limestone as it depend on their principle pore systems and interpreted using a similar procedure in spite of different lithology type and so help identify higher resolution sequence stratigraphy.

Estimated R35 using Winland's model shows a good match with our lab measured R35 till a certain cutoff value of pore throat radius at 35% mercury saturation equal. The results show that, at pore throat radii greater than 10 ηm the Winland's approaches not perform well.

It seems that petrophysical flow unit types concept, with their ability to discover porosity –permeability relationships will increasingly be used in engineering application, especially those in petroleum engineering usually associated with a high inherent complexity.

The flow unit types gave good results during the application phase, and can be applied to new wells.

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