Petroleum & Coal
ISSN 1337-7027

Available online at www.vurup.sk/petroleum-coal
Petroleum & Coal 54 (1) 52-58, 2012

PERMEABILITY ESTIMATION AND HYDRAULIC ZONE PORE STRUCTURES IDENTIFICATION USING CORE AND WELL LOGS DATA

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Received November 24, 2011, Accepted January 15, 2012

Abstract

An improved methodology to accurately estimate permeability from well log devices, with commonly available core log data is presented. Core permeability and porosity data were used to identify three different hydraulic zones namely: micro, meso and macro pores respectively with unique pore structures. Selected logging tools showed different responses for each hydraulic zone. Multi-dimensional data base that relate four logging values to core permeability in order to provide relationship for permeability predictions from log where core is not available was constructed. The obtained predictions are more accurate than ones with other methods due to the fact that permeability transforms are provided for each pore type and however, pore throat size is considered. Well log permeability estimations using this method are used to map permeability for improved reservoir simulation models, well test, and permeability estimation and more importantly, well completion optimization operations.

Keywords: Permeability; Core; Well log; Hydraulic; Pore structure.

1. Introduction

Permeability (a measure of fluid conductivity in porous medium) is a critical parameter in models for reservoir characterization, reservoir estimation and production forecast. Estimation of permeability in a reservoir is a complex task and a poorly estimated permeability will make the model inaccurate and unreliable thus, affecting the degree of success of many oil and gas operations based on such model. However, knowing permeability is significant for developing an effective reservoir description and quality. Formation permeability controls the requirements involving such operations such as well completion, stimulation and reservoir managements.

Accurate well log permeability is desirable because logs exist for all wells and because permeability is one of the most important parameters used to define reservoir performance, standard methods of estimating permeability from well logs are not accurate enough to provide reliable values and are not widely used. Typically, empirical transforms are developed between porosity, irreducible water saturation (SW_{irr}) and permeability with the understanding that reflects internal pore surface roughness. However, It is possible to predict permeability within a single reservoir without diagenetic alteration or complex pore types, but a dependable permeability estimation technique, to the best of my knowledge, not available in literature.

2. Developed methodology

2.1 Modeling methodology

Permeability has been measured as an indicator of fluid transmissibility in rock or soil since the concept was introduced by Darcy [6]. The Darcy is the standard unit of permeability representing the ability of a rock to deliver one cm^3 of fluid across an area of one cm^2 in a time of one second with an imposed pressure differential of one atmosphere for each centimeter of sample length. Permeability is affected by: fluid flow path length per unit sample length as defined by tortuosity; by the internal pore surface roughness and shape as defined by specific surface area per unit pore volume; and by the mean hydraulic radius of pore throats in fluid conduits. The rock properties above are adequate for defining a permeability relationship within a reservoir.

A widely used equation linking porosity and permeability was proposed in 1927 by Kozeny in a model which represents fluid flow in capillary tubes. Kozeny derived his model equation by algebraically combining Darcy and Poiseuille's equation to yield

$$k = \frac{\varphi^3}{5(1-\varphi)^2 S_{pv}^2} \tag{1}$$

Carman [9], developed a more closely representative reservoir conditions using the geometry of a spherical bead pack, altered the constants from five to two. A large deficiency with these equations is the specific surface area and pore volume which have direct link with permeability in clean sandstones well sorted grains were not considered.

Coates and Dumanoir [3] developed a permeability relationship to ensure zero permeability at zero porosity and at 100 % water saturation. However, Timur [2] developed equation which is widely used in porosity to permeability transform was used here to compare empirical permeability estimations to those made with statistical methods.

$$k = \frac{0.136(\phi * 100)^4 * 0.4}{(S_{wir})^2} \tag{2}$$

Empirical permeability relationships do not directly include pore throat size. This is a problem because pore throats have more influence over permeability than other pore attributes. With consideration for pore throat size, Tiab [7] developed the following permeability relationship given in equation 3 where H_c (hydraulic character) is a variable.

$$k = \frac{\phi^3}{H_c(1-\phi)^2} \tag{3}$$

Hydraulic character is a variable that includes the "lumped" effect of mean pore throat/ hydraulic radius; pore surface area per volume (S_{pv}^2); and tortuosity (T). This essential variable can be approximated by porosity - permeability relationships; or measured by Petrographic Image Analyses (PIA), capillary pressure data or surface adsorption measurements.

In this study, reservoirs are subdivided into layers and described as computer models for predicting reservoir performance. The major challenge was in the model development was the integration of the engineering flow model with the geological faces model. However, this revealed that reservoirs can either be layered with geological knowledge or mathematically with knowledge of hydraulic character. Each face was considered to have unique hydraulic character with similar log response and fluid flow characteristics.

Equation (3) was then modified algebraically to yield a mathematical explanation for a methodology to use porosity and permeability measurements to group reservoirs into hydraulic zones. Both sides of Eq. (3) are divided by porosity to yield Eq. (4).

$$\frac{k}{\phi} = \frac{\phi^2}{(1-\phi)^2 H_c} \tag{4}$$

The square root of each side of the equation 4 was then taken to yield Eq. (5).

It should be noted that the square root of k/φ is Leverett's mean hydraulic radius and is an approximation of the mean pore throat size in the core plug on which permeability was measured.

$$\sqrt{\frac{k}{\phi}} = \frac{\phi}{(1-\phi)} * \frac{1}{H_c^{0.5}} \tag{5}$$

Taking the logarithm of each term above yields Eq. (6) in the form of a straight line, where y=mx + c. Core porosity and permeability data are plotted with log – log coordinates into hydraulic zone groupings with boundaries of slope one. Notice that intercept b is defined by hydraulic character.

Inspection of Eq. (6) shows that y position is controlled by pore throat size (square root k/φ) and that x position is controlled by pore volume divided by to bulk volume (φ/(l -φ)).

$$\log\sqrt{\frac{k}{\phi}} = 1\ \log\frac{\phi}{(1-\phi)} + \log\frac{1}{H_c^{0.5}} \qquad (6)$$

This grouping of hydraulic zones is important because it places constraints on how the hydraulic zones are selected and determines how much permeability databases would be needed to be constructed. Hydraulic zones so selected from core permeability and porosity data must agree with core geologic descriptions. With this mathematical expression, It is possible to describe many different hydraulic layers - depending on the scale of the reservoir description. It is however, not practical to consider resolving hydraulic layers which are too small to be measured by well logs.

Well log measured hydraulic zones are themselves scaled up for reservoir simulation. There are rarely more than four hydraulic zones discernible with logs. Macro, meso, micro pores, and non-flow layers are considered.

2.2 Method of Application

Permeability estimations are used to determine where wells should be completed; to determine productive intervals and heights for well test permeability estimations; and to calculate layer average permeability for reservoir simulation. Permeability estimation from logs, even though they agree well with core permeability must be placed in context. Log-measurements are taken from wellbores which are very far between and permeability estimations must ultimately be determined between wells. Log derived permeability are integrated with well test permeability, history matched simulator permeability or with permeability model in three dimensions with geologic modeling software to achieve the distribution of permeability in a reservoir. Log permeability provides an excellent starting point for building the most physically correct reservoir models.

However, correct permeability estimation can be achieved by well logs with proper selection and calibration of logs by core data. Core porosity and permeability are used to recognize different hydraulic zones. Well logs are selected that respond differently to each hydraulic zone and databases are constructed for each hydraulic zone with core permeability and log responses in “key” wells. Permeability predictions are made with logs at depths without core in key or offset wells with standard log suites. Two porosity devices, a gamma ray log and resistivity logs are the normal logs required.

2.3 Simulation Approach

Laboratory permeability and porosity data are used to determine the number of hydraulic zones and are linked to log responses so that permeability can be estimated directly from well logs. This methodology is employed to scale up laboratory permeability (measured on samples of approximately 20 ml volume) to log permeability (measured on samples of approximately 20 liters or more volume). It is important to recognize that not all core data and not all log data are correct and that bad data must not be included in predictive databases. Databases must have data from each hydraulic zone or rock type to be encountered in the reservoir. The entire range of permeability to be encountered must also reside in the database; permeability values will not be predicted that are greater or smaller than those stored in the database. Approximately 20 to 30 permeability values are required for each hydraulic zone, thus typically providing 120 permeability transforms for a reservoir with four hydraulic zones. Obviously, if a database contains only 120 permeability values, many more permeability exist in a reservoir and a method was therefore developed to estimate permeability that are different from those in the database. Kriging approach was employed for this purpose.

Step 1: Perform quality control on permeability and porosity data to generate a standard porosity - permeability plot mainly to recognize bad core data. Besides, to identify any fractured core plugs that exhibit high permeability with low porosity. Observe any obvious rock type groupings that are easily identified to give some indications of the number of potential hydraulic zones.

Step 2: Use Eq. (6) to group permeability and porosity data into hydraulic zones and choose hydraulic zones that represent macro pores (hydraulic zone 1); meso-pores (hydraulic zone 2); and micro pores (hydraulic zone 3).

Step 3: Display the log responses with log estimated hydraulic zones to as-certain that logs are responding to differences in pore type. Compare the log displayed and proportion of each hydraulic zone with core descriptions. The log representation of hydraulic zones should match geologic descriptions from "core when core is available. The hydraulic zone log shows the pore type distribution found in the reservoir volume sampled by well logs. The relative proportions of micro, meso and macro pores can be used to determine which relative permeability and capillary pressure curves best represent each reservoir layer.

Step 4: Constrict a predictive permeability database with unique log responses for each core plug permeability. The database will have three or four log values for each depth level and one laboratory measured permeability. The goal is to find unique log responses for a 20 liter volume which can be linked to a 20 milliliter core plug for which permeability is reported. The entire range of permeability in the reservoir must be included in this database.

Step 5: Predict permeability from log values by comparing to log values stored in the database. There should be a match between log and core permeability at all permeability ranges. When there is a match between all log values at a particular depth level and those found in the database, permeability is estimated.

3. Case Studies

Permeability estimation data presented for sandstone reservoirs was used for the study. The permeability estimations by Kriging and Timur's porosity - permeability transform (Eq.2) are compared. Additionally, foot by foot permeability estimates from well logs are compared to layer average permeability from core.

4. Results and Discussions

Results are presented for a single sandstone reservoir to allow for comparability between various permeability estimation techniques. Many different sandstone reservoirs have been studied with this method and results are consistent with the observation reported in this study. Figure 1 is from a sandstone reservoir with both Aeolian and fluvial faces. More than eight different faces were identified. The log permeability versus porosity plot shows an apparent strong dependency of permeability on porosity with a correlation coefficient r2 equals 0.91.

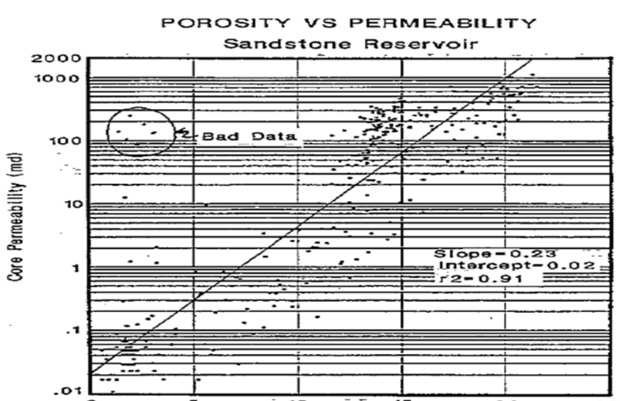

Figure 1 Porosity –Permeability Plot

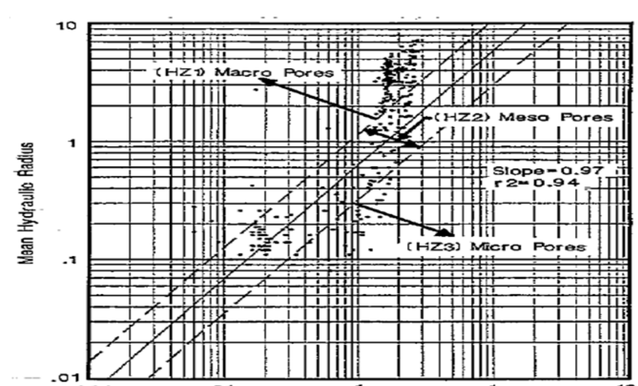

Figure 2 Hydraulic Zone Plot

This data suggests that it would be possible to estimate permeability directly from porosity with linear regression or a single Timur equation. It turns out that there are three different hydraulic zones in this reservoir, each requiring different permeability transforms.

Also, three hydraulic zones are shown in Figure 2. The result showed that Hydraulic zone,*HZ1* is dominated by macro pores; *HZ2* by meso pores; and *HZ3* micro pores. The values of H_C used to differentiate zones are selected based on experience as to which pore throat radii most commonly provide correct flow zones. The selection of hydraulic zones is somewhat an iterative process where log hydraulic zones shown in Figure 3 are based on Figure 2 core groupings and compared to cores descriptions. However, the identified Hydraulic zones shown in Figure 3 are used to characterize the larger reservoir volumes sampled by well logs to predict the proportions of each pore type. This figure shows that log responses are indeed different for each hydraulic zone and suggests that different log transform is required for permeability estimation in each hydraulic zone.

Figure 4 presents core permeability values as plotted against log permeability values, with a near perfect one to one correlation. The r^2 correlation between core and log predicted permeability value is 0.99. This plot is evidence that for each permeability value measured on a core plug, there is a unique, set of log responses for a larger sample volume. What has been achieved is a scaling up where core plug volumes have been uniquely tied to log volumes. The software that performs this exercise is a very powerful tool. Linkage of core and log measurements in this manner has now been performed in tens of reservoirs in more than one hundred wells.

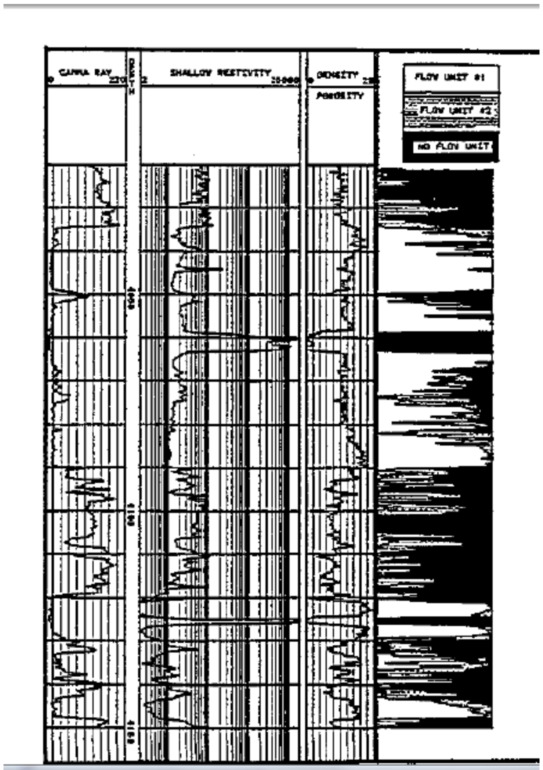

Figure 3 Hydraulic zone

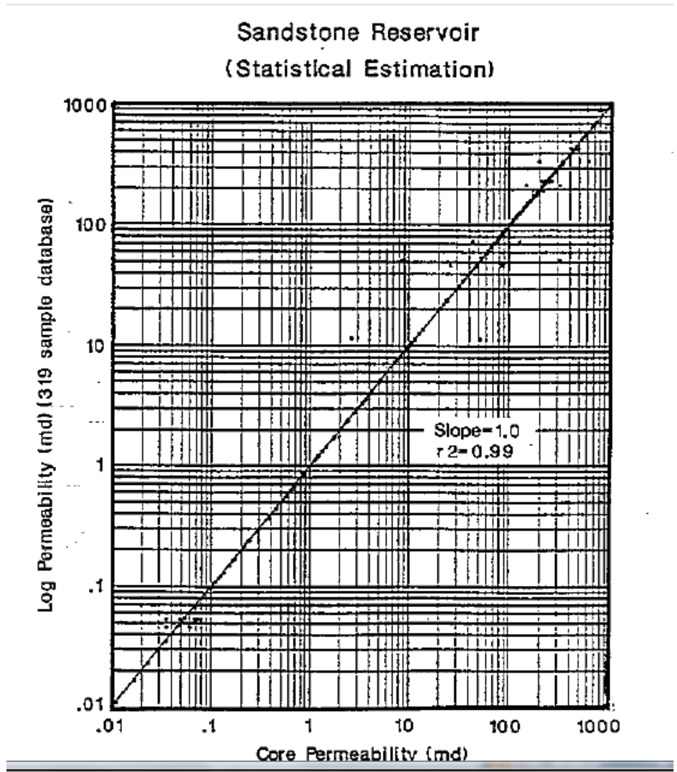

Figure 4 log vs. core permeability

A combination of gamma ray, shallow resistivity, and density logs was used to provide unique log "fingerprints" for each permeability from 0.01 md through 1000 md. In simplistic terms, the gamma ray tool tends to measure pore throat properties; the density log measures matrix properties; and the shallow resistivity log measures pore attributes. The key to instructing these databases is to represent the full range of permeability values, with associated log values, without having conflicting information in the database. The permeability predictive database from Figure 4 provides permeability logs as shown in Figure 5. There are accurate permeability predictions for the full range of values found in the reservoir. Figure 5 was generated using 319 core measurements of permeability. Because of the excellent agreement between core and log predictions with the full database, it confirms that the log curve presented in Figure 5 is accurate. This curve can be used for comparisons, in this well, to Timur permeability estimations and to statistical permeability with fewer core samples.

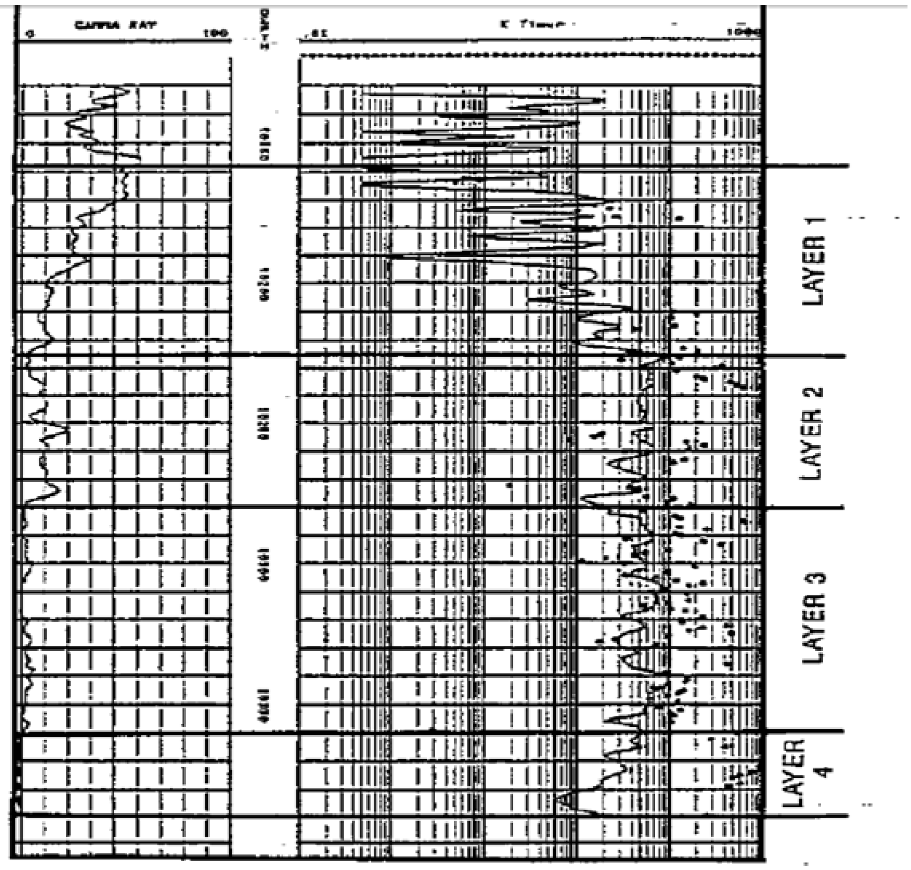

Figure 5 Core log vs. log permeability in Sandstone Reservoir

5. Conclusions

1. A method has been found to link core plug permeability to well log measurements in relational databases. Core plugs of approximately 20ml volume have a permeability value which can be uniquely linked to log measurements.
2. Well logs respond differently in different hydraulic zones.
3. If the entire range of permeability from all hydraulic zones is included in a core - log database, it is possible to predict permeability accurately enough to represent changes in permeability across a reservoir. Databases constructed at "key" wells can be used to predict permeability at offset wells.
4. Permeability predictions are good in sandstone reservoirs if permeability is predicted by Kriging with a multi-dimensional database calibrated for each hydraulic zone. Permeability predictions from porosity-permeability transforms were of little value case study presented.
5. Standard gamma ray, density, and resistivity log suites and routine core analyses provide enough data to predict permeability from well logs.

Nomenclature:

S_{wir} = irreducible water saturation, %
H_c = hydraulic character, dimensionless
HZ = hydraulic zone
k = permeability, (md)
φ = porosity, fraction
r^2 = goodness of fit correlation
S_{pv}^2 = specific surface area per unit pore *volume,* 1/cm

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