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Permeability Prediction for Sandstone Reservoir Rock Utilizing Laboratory NMR Measurements

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Abstract. One of very important parameters is reservoir permeability in the researches of hydrocarbons and/or producing aquifers realizing the production index. Numerous realistic methods with geophysical well logging data have been utilized to approximate ultimately. The Timur model is included in the methods, and conventional logs and nuclear magnetic resonance log is used. The present study aims to correlate core porosity with NMR-porosity. The regression line equations are calculated with a consistently very high coefficient of correlations for 25 sandstone core samples (R2 = 0.93 and 0.71) obtained from the Szolnok (Hungary) and the Baharyia (Egypt) formations, respectively. In addition, the Timur-Coates model was used to predict permeability for sandstone core samples obtained from different drilled wells in hydrocarbon reservoir intervals. Only 11 core samples belonged to the Szolnok Formation (Hungary), while the rest belonged to the Baharyia Formation (Egypt). An innovative model was suggested and approved to be more effective than the Coates model for permeability prediction for sandstone reservoir rocks. It produces a reliable solution with constant parameters and gives an accurate permeability estimation.

Keywords: Sandstone reservoir; porosity; permeability; Szolnok Formation; Baharyia Formation.

INTRODUCTION

Rock density, porosity, permeability, and water saturation to be petrophysical properties, influence the reservoir rocks' storage capacity and productivity index in either hydrocarbon or water-bearing aquifers. Permeability prediction is of great implication for various subsurface fluids studies. Core analysis is one of the most valuable and essential rock evaluation tools for assessing these reservoir properties. This procedure enables well-logging data corrections. The formation depths are to be correlated with nearby wells, and interpretations of the quantity and quality of the petroleum present are to be evaluated. A reservoir rock must be porous and permit fluid flow through the interconnected pore spaces or fractures to be commercially viable. One of the critical parameters that must be estimated in the characterization of an oil reservoir is permeability, which is the ability to conduct fluids [1]. It is a critical variable for comprehending fluid movement behavior, and in the oil and gas sector, predicting it accurately is a facing task and a key component of reservoir characterization. The accurate permeability estimation aids in reservoir development and production strategy optimization. Due to the influence of various geological factors that regulate fluid circulation, this prediction is defiance [2& 3].

Empirical models developed by [4;5;6;7&8] have been used in several attempts to establish permeability from logs over time. Therefore, log-based permeability predictions may have drawbacks because of presumptions and uncertainties in empirical relationships, although they are relatively quicker and less expensive.

According to [9], most petrophysical parameters are typically correlated with well-logged data. However, no evident and significant correlation exists between reservoir permeability and logged data. Multiple linear regression [10], multivariate analysis [11], and polynomial regression [12], among others, used logs as input to perform this estimation.

Theoretical-mathematical models like Kozeny-Carman [13; 14; 15] have all been used to estimate permeability. AI-methods and neural networks are very helpful [16], while genetic algorithm techniques are effective, too [17]. They have also been used recently in the prediction of the reservoir rocks' permeability.

Since 1940, mathematical and physical problems have been solved using Monte Carlo methods, which are most valuable when it is challenging to use other strategies.

They comprise a large group of computational algorithms that rely on repeated random sampling to produce numbers. The underlying idea is to use randomness to find solutions to issues that, theoretically, could be deterministic. These techniques are typically used to generate sketches from probability distribution, integrate numerically, and solve optimization problems.

The experimental technique has been used in many fields to estimate permeability [18]. Numerous studies have been conducted in the petroleum field, including those by [19;20 21& 22]. Using well-logging data to determine reservoir permeability is a deadly needed as a common task due to the very high budget of coring and core analysis reasons [23]. Even so, permeability prediction from logs is complicated, but numerous additional attempts will be made in the future [24].

In the present work, the Coates model-predicted permeability is used for sandstone core samples obtained from hydrocarbon reservoir intervals. Only 11 core samples belonged to the Szolnok Formation (Hungary), while the rest belonged to the Baharyia Formation (Egypt). The geologic age and environment of deposition of both the Szolnok and Bahariya formations were outlined by [1].

An innovative model was suggested and approved as more effective than the Coates model in predicting permeability for sandstone reservoir rocks. Therefore, this work focuses on assessing permeability from NMR laboratory measurements.

The present work aims to introduce a modified Timur-Coates equation to estimate NMR permeability from either well logging or laboratory measurements.

METHODOLOGY

The vacuum-pressure which is saturated with NaCl brine was applied to the samples [25], where the concentration values were adjusted to be almost equal to the salinity of water of the Bahariya Formation penetrated in the Bed-1 field (0.56 g/l). Proton NMR of all samples at brine saturation of 100% was measured. By using the CPMG method with phase alteration and having the interecho spacing TE = 0.5 ms T2, measurements were done in the homogeneous magnetic field. In order to achieve a minimum signal- to – noise ratio of 200:1 (300:1 type), adequate echo trains were measured and stacked.

The (BVM⁄BVI) ratio is associated with each *T*2 spectrum for each sample. The exponents' values of the SDR equation and the Timur–Coates model's multipliers were earlier subject to modification [26 & 29].

As the last stage, the modified Timur–Coates model (Eq.3) make possible to estimate the permeability by using using the previously estimated (BVM⁄BVI) ratio and an available laboratory-measured sample porosity value. The core porosity for all studied samples, collected from different boreholes penetrating both the Szolnok Formation (Hungary) and the Bahariya Formation (Egypt), was measured by the saturation method [1,25&27].

RESULTS AND DISCUSSIONS

T_2 Spectrum for Szolnok and Bahariya Samples

The laboratory NMR measurements of sandstone samples are shown in Figures 1 and 2. The T_2 spectrum of both Szolnok and Bahariya samples are ranged from 10 up to 10^6 ms, while the maximum relative amplitude is 830 and 1800 for Szolnok and Bahariya, respectively. The areas under curve are different, while the BVM of most of the Szolnok samples was higher than that of the Bahariya samples (Figures 1&2).

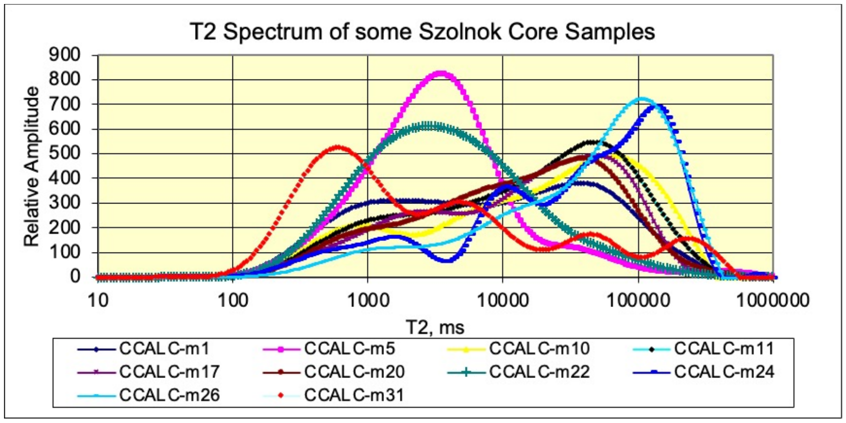

FIGURE 1. T2 Spectrum of some Szolnok Sandstone samples

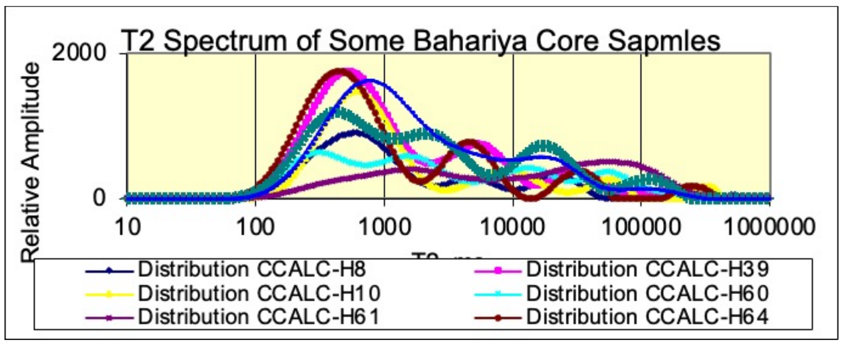

FIGURE 2. T2 Spectrum of some Bahariya Sandstone samples

Core Porosity vs NMR Porosity

Most of the Baharyia samples studied are laminated sandstones, while the Szolnok sandstone samples are non-laminated [28&1]. The core porosity for all samples of both the Szolnok Formation (Hungary) and the Bahariya Formation (Egypt) were plotted versus its NMR porosity (Fig.3). It exhibits a very close relationship (R^2 = 0.708&0.930) for both Szolnok and Bahariya samples. It means that one of them ($Ø_{nmr}$ can be predicted from the other ($Ø_c$).

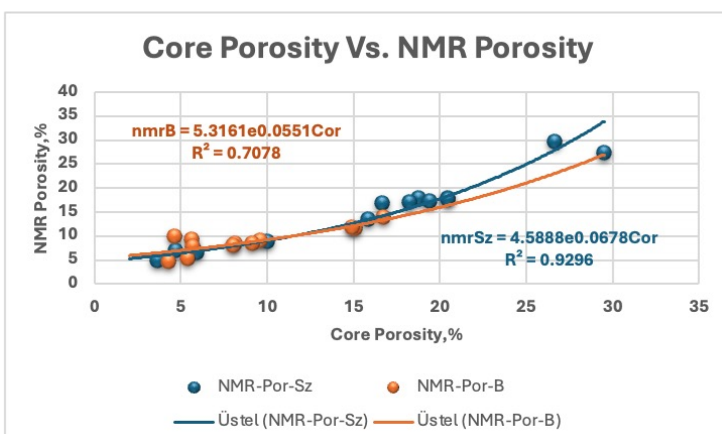

FIGURE 3. Core porosity versus NMR porosity for the Szolnok and Bahariya formations

The calculated coefficient of correlation (R^2) for the Szolnok samples is greater than that for the Bahariya samples due to the pore architecture characterizing their storage capacity network.

Permeability

Processes to predict core permeability are classified as direct methods based on Darcy's law, pore-scale model, and indirect computation [29;30;31;25&32]. In the present work, all core sample permeability belongs to core measurements. The modified Timur–Coates model and core data results were compared for verification and validation.

Permeability reflects the capabilities of porous rocks, and it enables the transmition of the fluids through the network of pores. For the estimation of rock permeability there are numerous permeability models developed. Still, the Timur–Coates model [33&7] and the Schlumberger-Doll-Research model [34] are the main two models based on NMR data in oil and gas industry, and they are given below respectively:

$$KT\ C\ = \left(\frac{Ø}{C}\right)^4 * \left(\frac{BVM}{BVI}\right)^2 \tag{1}$$

$$KSDR\ =\ a * \phi^4 * T^2\ 2gm \tag{2}$$

where k reflects permeability (millidarcy-md), φ corresponds porosity (%), BVM is the value of generable part of the porosity, while BVI reflecting the non-generable part of porosity, herein this equation the formation dependent is C, the geometric mean of the T2 distribution (ms) is given to be T^2 2gm, and the formation-dependent correction is a. However, these models (eq. 1 & 2) are usually inaccurate in either carbonate or sandstone formations [26;29&35].

In this study, comparing core and NMR permeability using Eq-1, it was found that NMR permeability assessment cannot be applicable with the commonly used coefficients (C =10, m = 4, n = 2). Figure 4 exhibits the NMR permeability versus core permeability. It shows a very poor coefficient of correlation (R^2 = 0.0828) and, therefore, Eq.1 is regulated for the Szolnok and Bahariya sandstone reservoir samples to be more reliable and applicable to permeability prediction using trial and error with the iteration technique as,

$$KTC\ = 0.9 * \{ \left(\frac{Ø}{5.5}\right)^{3.9} * \left(\frac{BVM}{BVI}\right)^{0.51} \} \tag{3}$$

The general form of equation (3) is

$$KTC\ =\ A * \{(X)\text{^}3.9\ * (Y)\text{^}0.51\} \tag{4}$$

where: A = 0.9, X = $(Ø/5.5)^{3.9}$ and Y = $(BVM/BVI)^{0.51}$

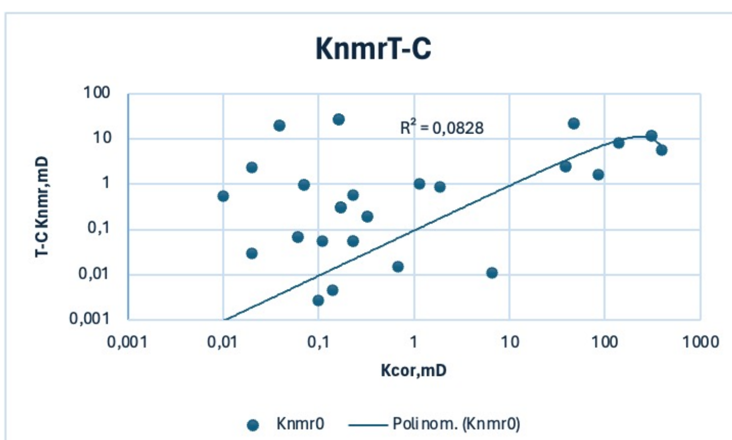

FIGURE 4. Predicted Versus Core Permeability Using TC Equation-1

Equations (3 & 4) were used to calculate NMR permeability from the measured transverse relaxation time (T_2, ms) and cut-off values of CBW, BVI, and BVM at the standard and recommended T_2 for clastic deposits.

It is plotted against the core permeability (Figure 5) and represented by a very close linear relationship depicted by a robust and reliable coefficient of correlation (R^2= 0.842). That means the rock parameters listed in Eq.1 (C, m, and n) are subject to modifications depending on the rock's physical properties and the depositional environment.

The absolute error is calculated between the core permeability of both Szolnok and Bahariya formations and the predicted NMR permeability and plotted (Figure 6). It shows that most of the samples studied (29 out of a total 37) have negligible absolute error percentages (0.08%). That means our proposed equation (3) is effective and reliable for permeability prediction from NMR data acquisition either from borehole logging or laboratory measurements.

The model verification is required for other samples with the same lithology, depositional environment, and another geographic location and geologic age to indicate that the proposed equation works well everywhere and for different geologic ages. However, the same lithology is required.

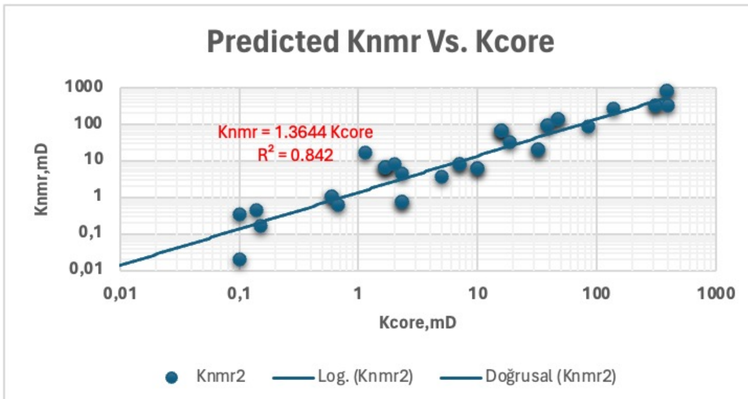

FIGURE 5. Core Versus Predicted Permeability using Equation-3

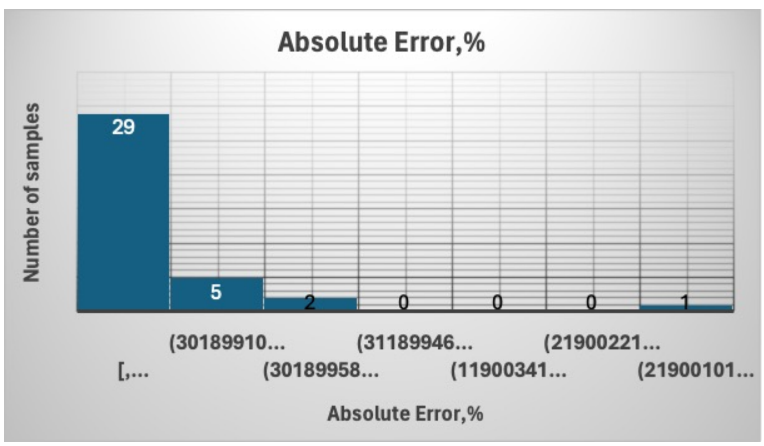

FIGURE 6. Absolute Error Between Bahariya and Szolnok Core and Predicted Permeability

Model Verification

Equation (3) was used to estimate NMR permeability from core permeability for 59 core samples attained from three boreholes (Baltim-East-1,3 and N-2 wells, level III main) drilled and penetrating the Abu Madi Formation in the Baltim gas field, Nile Delta, Egypt. The Abu Madi Formation is composed mainly of sandstones and shaly-sandstones, while the environment of deposition is mostly marine -fluvio-marine deposits (El Sayed et al., 2020). The relationship between core and predicted NMR permeability (Figure 6) reveals a linear absolute and complete connection with a unity correlation of coefficient.

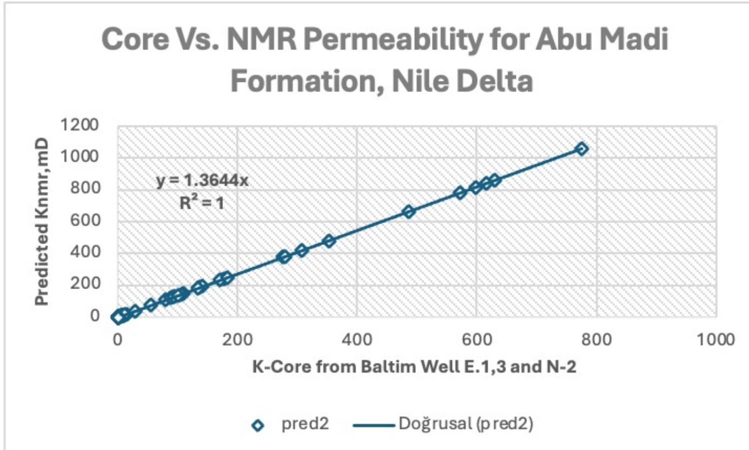

FIGURE 6. Core Vs. NMR Permeability for Abu Madi Formation, Nile Delta

The calculated absolute error (Figure 7) exhibits a very low value for almost 80% of Baltim gas field sandstone samples (A.E.= 0.000182). These results give positive signs that the present model is suitable for NMR logging tools and/or laboratory measurements and their applications.

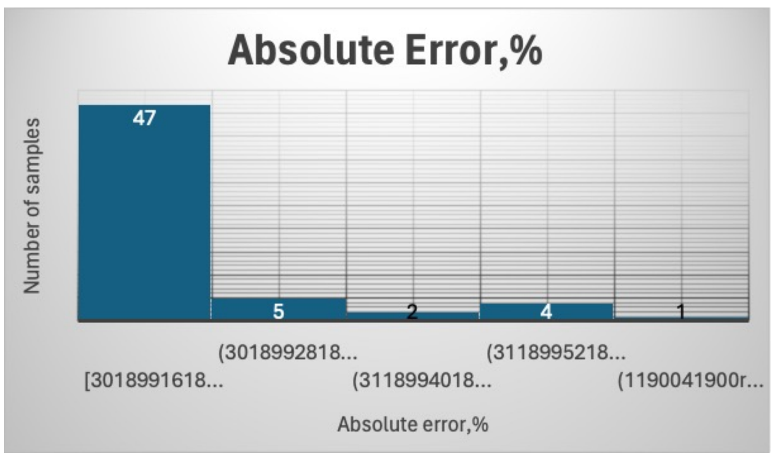

FIGURE 7. Absolute Error Between Baltim E-1,3 and N-2 Core and Predicted NMR Permeability

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