



New Empirical Models for Estimating Permeability in One of Southern Iranian Carbonate Fields using NMR-Derived Features

Shahin Parchekhari^a, Ali Nakhaee^{a,b,*}, Ali Kadkhodaie^c

a. Department of Petroleum Engineering, Kish International Campus, University of Tehran, Kish, Iran

b. Institute of Petroleum Engineering, School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran

c. Earth Sciences Department, University of Tabriz, Tabriz, Iran

Received: 4 October 2019, Revised: 17 May 2020, Accepted: 20 May 20

© University of Tehran 2020

Abstract

Permeability is arguably the most important property in evaluating fluid flow in the reservoir. It is also one of the most difficult parameters to measure in field. One of the main techniques for determining permeability is the application of Nuclear Magnetic Resonance (NMR) logging across the borehole. However, available correlations in literature for estimating permeability from NMR data do not usually give acceptable accuracy in carbonate rocks. In this research, two new empirical models are introduced for quantifying NMR extracted permeability in carbonate formations. These models are validated for three carbonate formations, namely, Yamama, Gadvan, and Daryan in one of Iranian offshore reservoirs in the Persian Gulf. The first empirical model applies the pore-related NMR data such as free and bound fluid parameters. The second model, however, is a novel approach that uses the geometric features of the occurring humps in T2 distribution. For assessing the performance of the proposed models, statistical parameters as well as graphical tools are utilized. It is found that the for the examined case studies, geometric approach gives more accurate and reliable estimates compared to the available models in the literature including Timur-Coates and SDR methods.

Keywords:

Carbonate Reservoir, Empirical Model, Logging Data, Nuclear Magnetic Resonance (NMR), Permeability, T2 Distribution

Introduction

Measuring the permeability is a great challenge for petroleum engineers and petrophysicists dealing with hydrocarbon reservoirs. Numerous techniques of permeability measurement have been developed so far, including core analysis, pressure-transient analysis, in-situ measurements (i.e., formation testers) and well logging. Coring operation is in the need of a rig and special equipment, which makes it very costly and time-consuming. The pressure-transient analysis gives only an average value for the permeability of the reservoir. Furthermore, some in-situ tests such as modular dynamic testers (MDT) are restricted to a few points along the wellbore. Well logs, on the other hand, could provide continuous profiles of permeability along the boreholes using the frequently available log data [1].

Applying Nuclear magnetic resonance (NMR) as a petrophysical tool has recently gained a lot of attention in petroleum industry [2,3]. NMR has several applications in determining rock and fluid properties including distribution of pore size for porosity characterization, absolute permeability, fluid types existing in porous media, diffusivity and viscosity of the fluids in the

* Corresponding author:

Email: anakhaee@ut.ac.ir (A. Nakhaee)

pore spaces, and capillary pressure [4-9]. NMR is an indirect permeability measurement, which can be estimated by establishing reasonable correlations between the well-log data and rock permeability [1]. In NMR logging, the primary natural magnetic field of the earth has been used for measuring reservoir properties, however, artificial magnetic fields have been employed lately for the establishment of these measurements [10-12]. In sandstone reservoirs, NMR tools can be simply used for evaluating the formations, even though a considerable challenge is in front of NMR measurement and interpretation in carbonate formations [1,13]. In other words, despite sandstone reservoirs, in which porosity is a dominant variable influencing petrophysical parameters such as irreducible water saturation and permeability, a simple relation is not existing between porosity with permeability in carbonate formations [14-16]. These additional dependencies include a number of paradigms namely, heterogeneous pore connectivity, pore distribution, pore type, and size of the grains. Thereby, heterogeneity in porosity imposes a fundamental limitation on permeability estimation with respect to the NMR-derived porosity model. The main reason for this phenomenon is the large variations in micro-geometry of primary porosity in the carbonate rocks than that of the sandstone one [17-21]. Additionally, many geological processes termed as diagenesis, create secondary porosity in the carbonate rock. These are known as dissolution, repeated cementation, fracturing, and dolomitization. Forecast of permeability is largely dependent upon the alteration in the different types of pore connectivity [2,22].

There are numerous investigations in literature focusing on predicting permeability by NMR techniques in which Timur-Coates [23] and Schlumberger-Doll-Research (SDR) [24] correlations are the most commonly used models [25,26]. Recently, several investigations have been conducted through the literature to explore this parameter by different methods in various reservoir types, including the work of Zayed et al. [27] in Egyptian gas reservoirs, Di and Jensen [28] in tight reservoirs, Zhu et al. [29] in tight sandstone reservoir using artificial intelligence, and Zhang et al. [30] by applying digital rock modeling and NMR measurements.

The aforementioned models have proper performance in sandstone reservoirs; however, their default constants should be tuned when they will be applied in carbonate rocks. Despite the prementioned tuning, applications of SDR [24] and Timur-Coates [23] models beyond their development range may lead to large deviations when predicting permeability. Therefore, there is a great requisite for developing a generalized model for fast and efficient permeability estimation in carbonate reservoirs.

The main objective of this study is to extend a generalized model using advanced regression tool for estimating permeability in a carbonate reservoir. For this purpose, a bulk of petrophysical data including conventional logs and NMR data was utilized in one of the offshore Iranian oil wells. The main focus of this study is characterizing permeability using advanced regression tool in three Iranian carbonate formations including Yamama, Gadvan, and Daryan. For the first time in literature, two generalized and new types equations based on the geometrical and pore-derived features are developed for permeability estimations in carbonate formations. The pre mentioned models for permeability are mainly developed on the basis of limited database, or special sandstone cases; thereby, the literature models need to be improved by establishing universal models. The abovementioned features can be easily extracted from NMR measurements. In the first step, the data was separated into the two groups of test and train sets. Using the train set, the empirical model was extended, and then, checking the prediction potential was implemented via the test set. It is worthwhile mentioning that the proposed models here were developed considering various input variables. Afterward, the proposed equations here were evaluated with respect to the core analysis and existing conventional permeability models, Timur-Coates [23] and SDR [24]. The main benchmarks used for the pre mentioned comparison are visual tools and statistical quality parameters.

Finally, a sensitivity analysis was carried out to show the impact of each parameter on permeability estimation in this study.

Data Gathering

In this research, a set of petrophysical data as well as core measurements along three carbonate formations of an offshore well is used. A MATLAB code is developed to extract TCMR (PHI), BVF, CMFF, T2LM and CLF parameters from a CMR-type NMR log. Geometric features of T2 distribution curve, including the number of humps, their representative amplitude and corresponding time are also calculated. A total of 461 permeability measurements of core samples were also used to calibrate and validate the models. Roughly 80% of the data are used for model construction and the remaining 20% are utilized for testing and validation.

Modeling

In order to calculate permeability from NMR data, we developed two models using regression analysis. The first model correlates permeability with pore-related parameters extracted from NMR data. It should be noted that SDR and Timur–Coates models are also pore-related models. Four different types of pore-related permeability equations are proposed and compared (Eqs. 5 to 8). In the second model, however, the geometric features of T2 distribution curve are used. This is a new approach that, to the best of our knowledge, is introduced for the first time in literature. We examined five different forms of geometric equations to find the best fit to experimental data points (Eqs. 10 to 14).

The proposed models are calibrated and validated for NMR data of three carbonate formations, namely, Yamama, Gadvan, and Daryan in one of Iranian offshore reservoirs in the Persian Gulf. Apart from statistical parameters such as root mean square error (RMSE) and coefficient of determination (R^2), several pore volume plots are sketched to graphically examine the accuracy of the developed models. Eq. 1 presents the function for RMSE, in which, superscripts *Pred.* and *Meas.* denote predicted (model) and measured (core) permeability values, respectively.

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^n (K_i^{\text{Pred.}} - K_i^{\text{Meas.}})^2} \quad (1)$$

Pore-related Model

In this model we used the key parameters related to NMR porosity that have the most significant impact on permeability estimation based on previous studies [25]. Eq. 2 represents the general format of pore-related equation.

$$K = f(\text{PHI}, \text{T2LM}, \text{BVF}, \text{CMFF}, \text{CLF}) \quad (2)$$

where PHI is NMR porosity, T2LM is the logarithmic mean of T2 distribution, BVF is bound volume fluid, CMFF is free fluid, and CLF (curve length factor) is defined as follows:

$$\text{CLF} = (\text{CL} - 4.3) \times 10^4 \quad (3)$$

$$\text{CL} = \sum_{n=1}^{N_a} \sqrt{(\text{Amp}_n - \text{Amp}_{n-1})^2 + (\log T2_n - \log T2_{n-1})^2} \quad (4)$$

In Eq. 4, N_a is the number of amplitudes in T2 distribution curve which is equal to 30 for the CMR tool employed in this study. The following equations represent different forms of pore-related permeability estimation:

$$K = a \times CLF^b \times PHI^c \quad (5)$$

$$K = a \times CLF^b \times TL2M^c \quad (6)$$

$$K = a \times CLF^b \times PHI^c \quad (7)$$

$$K = a \times CLF^b \times PHI^c \times TL2M^d \times BVF^e \times CMFF^f \quad (8)$$

The goodness-of-fit of these functions are discussed in section 4.

Geometric Model

As mentioned earlier, we developed a model for permeability estimation that directly utilizes some features of T2 distribution humps. The general geometric equation could be written as:

$$K = g (AMP1, AMP2, AMP3, T1, T2, T3, T2LM, PHI) \quad (9)$$

In Eq. 9, the symbols Amp1, Amp2, Amp3, T1, T2, T3, T2LM and PHI denote the amplitude of first hump, the amplitude of second hump, the amplitude of third hump, the corresponding time of Amp1, the corresponding time of Amp2, the corresponding time of Amp3, logarithmic mean of T2 time distribution, and NMR porosity, respectively. The following five different forms of equations are used to estimate permeability:

$$K = [a. AMP1^b + c. AMP2^d + e. AMP3^f] \times PHI^g \quad (10)$$

$$K = [a. AMP1^b + c. AMP2^d + e. AMP3^f] \times T2LM^g \times PHI^h \quad (11)$$

$$K = [a. AMP1^b \cdot T1 + c. AMP2^d \cdot T2 + e. AMP3^f \cdot T3] \times PHI^g \quad (12)$$

$$K = [(a. AMP1 + b. AMP2)/(c. AMP3)]^d \times PHI^e \quad (13)$$

$$K = [(a. AMP1^b + c. AMP2^d)/(e. AMP3^f)] \times PHI^g \quad (14)$$

In the following, the statistical evaluation of these estimations is presented.

Results and Discussions

It is of great interest of reservoir engineers to estimate permeability from porosity data. Carbonate rocks typically present complex diagenesis and could have several porosity types [31]. As a result, permeability in carbonate reservoirs could not easily and accurately be estimated by indirect method like using petrophysical logs. Therefore, other petrophysical parameters have to be considered to represent the heterogeneity of the rock.

In this study, we presented two models for predicting permeability in carbonate rocks from NMR data. The first model uses pore-related parameters while the second model employs geometric parameters of T2 distribution curve. Table 1 presents the tuned coefficients of the pore-related model (Eqs. 5 to 8) as well as the tuned coefficients for geometric model (Eqs. 10 to 14). The corresponding RMSE and R^2 of the correlations are also reported.

In Fig. 1 a cross-plot of the predicted values of models (Eqs. 5 to 8 and Eqs. 11 to 14) against measured values (core permeability) is depicted. Among pore-related correlations, Eq. 6 (RMSE=28.56, $R^2=28.26\%$) and Eq. 7 (RMSE=21.93, $R^2=26.55\%$) offer most accurate estimates of permeability. On the other hand, among geometric correlations, Eq. 11 (RMSE=27.9, $R^2=43.6\%$) and Eq. 12 (RMSE=21.9, $R^2=36.44\%$) deliver the most accurate predictions.

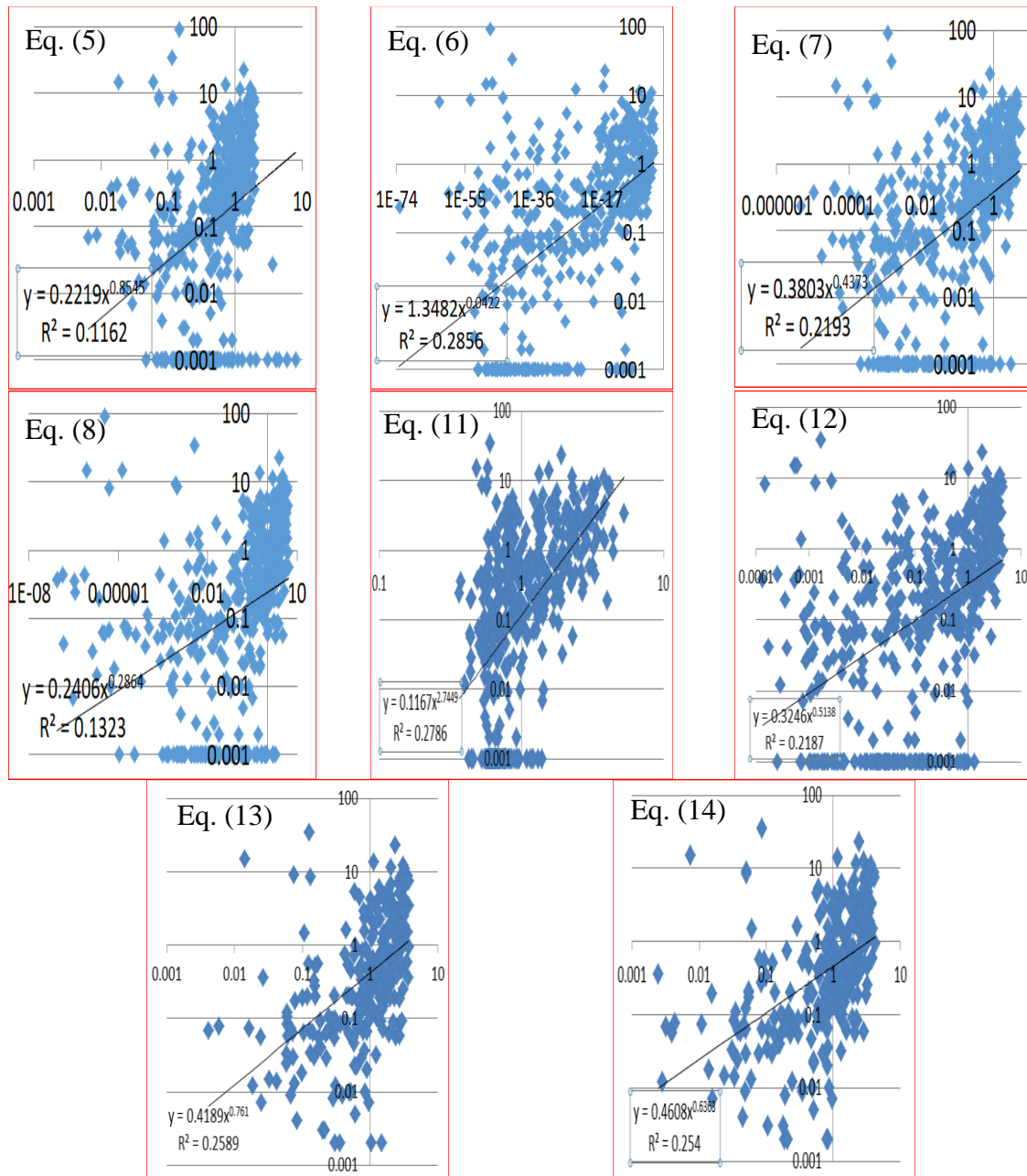


Fig. 1. Cross plot of predicted data (proposed permeability models) and measured data (core)

To further evaluate the performance of these models, predicted values of model are plotted against core data in Darian, Gadvan, and Yamama formations separately. Figs. S1 to S3, and Figs. S4 to S6 depict pore-related and geometric correlations, respectively (presented in the supplementary information). These plots indicate that in general Eqs. 11 and 12 are more capable in accurately predicting permeability. The novel geometric model is therefore, arguably, a good alternative to well-established pore-related models. In Fig. 2, a comparison is made between well-known SDR and Timur-Coates models and proposed models by this study in Darian formation. This figure shows that Eq. 12 performs much better than SDR and Timur-Coates models in estimating permeability. It should be noted that Eq. 12 is the only equation incorporating the corresponding time of amplitude, which is an indicator of pore sizes.

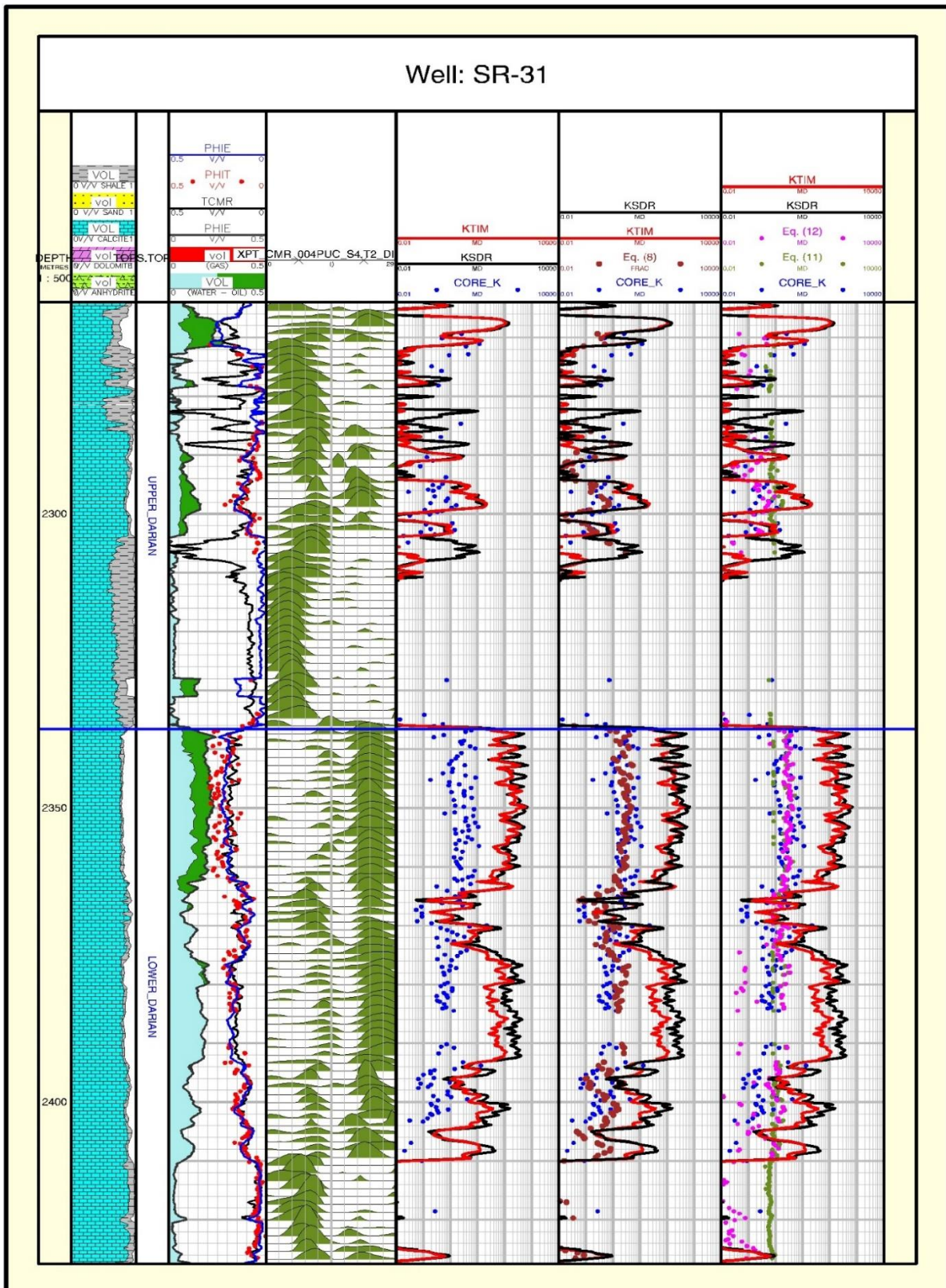


Fig. 2. Performance comparison between proposed models and conventional NMR-derived permeability models in Darian formation

Table 1. Tuned coefficients of proposed permeability models

Eq. No.	a	b	c	d	e	f	g	h	R ²	MSE
5	0.0002	1.443	19.0106	-	-	-	-	-	11.62	26.89
6	288.8369	-12.827	19.145	-	-	-	-	-	28.56	28.26
7	2.487049	0.0764	0.8334	3.00	-	-	-	-	21.93	26.55
8	468.0663	0.3122	0.0996	2.00	1.0000	1.00	-	-	13.23	26.33
10	-280.93	200.38	277.36	36.65	350.29	56.820	54.35	-	-	-
11	1.0630	4.48E-2	600.93	2.11	1811.46	2.75	0.116	0.0217	27.9	43.60
12	0.0099	1.89E-10	0.0453	0.494	0.0325	0.5056	0.209	1.4450	21.90	36.44
13	71.5500	5.675E-11	1.855	-	-	-	-	-	25.90	28.92
14	14.4400	422.4	153.11	2.086E05	0.1285	1.74	-	-	25.40	15.38

Conclusions

In the current study, NMR logging is utilized to construct new empirical model for estimating absolute rock permeability. For this goal, NMR data from one offshore well in the Persian Gulf are used. Two different approaches are used for model development. In the first approach, the pore-related NMR parameters are used. In the second approach, geometric features of the humps occurring in T2 distribution curves are used. The results show that the geometric model gives slightly better estimates of rock permeability compared to the pore-related model. Notably, the presented geometric model provides reasonable reliability and accuracy (e.g., RMSE=21.9 and R²=36.44%) in comparison to available models in the literature. The developed models in this study could assist petrophysicists and reservoir engineers to better estimate the permeability of complex carbonate reservoirs.

References

- [1] Babadagli T, Al-Salmi S. A review of permeability-prediction methods for carbonate reservoirs using well-log data. *SPE Reservoir Evaluation & Engineering*. 2004 Apr 1;7(02):75-88.
- [2] Westphal H, Surholt I, Kiesl C, Thern HF, Kruspe T. NMR measurements in carbonate rocks: problems and an approach to a solution. *Pure and Applied Geophysics*. 2005 Mar 1;162(3):549-70.
- [3] Hamada GM, Al-Blehed MS, Al-Awad MN. NMR logs find reserves by-passed by conventional analysis. *Oil & Gas Journal*. 1999;97(39):75-80.
- [4] Kleinberg RL, Vinegar HJ. NMR properties of reservoir fluids. *The log analyst*. 1996 Nov 1;37(06):20-32.
- [5] Kenyon WE. Petrophysical principles of applications of NMR logging. *The Log Analyst*. 1997 Mar 1;38(02).
- [6] R. Freedman, M. Johnston, C. Morriss, C. Straley, P. Tutunjian, H.J.T.L.A. Vinegar, Hydrocarbon saturation and viscosity estimation from NMR logging in the Belridge Diatomite, 38 (1997).
- [7] Chen S, Olima O, Gamin H, Georgi DT, Minetto JC. Estimation of Hydrocarbon Viscosity with Multiple TE Dual Wait-Time MRIL Logs. InSPE Annual Technical Conference and Exhibition 1998 Jan 1. Society of Petroleum Engineers.
- [8] Coates GR, Xiao L, Prammer MG. NMR logging: principles and applications. Houston: Haliburton Energy Services; 1999.
- [9] Allen DF, Boyd A, Massey J, Fordham EJ, Amabeoku MO, Kenyon WE, Ward WB. The practical application of NMR logging in carbonates: 3 case studies. InSPWLA 42nd Annual Logging Symposium 2001 Jan 1. Society of Petrophysicists and Well-Log Analysts.
- [10] Krajewski P, de Groot P, Kruspe T, Thern H, Kiesl C, Wulff A, Martens H, van Riel P, Henke C, Krieger M. Deutsche Geophysikalische Gesellschaft eV. 2002.
- [11] Appel M, Radcliffe NJ, Prabhakar A, Bonnie RJ, Ridvan A. Nuclear magnetic resonance while drilling in the UK Southern North Sea. InSPE Annual Technical Conference and Exhibition 2002 Jan 1. Society of Petroleum Engineers.
- [12] Prammer MG, Goodman GD, Menger SK, Morys M, Zannoni S, Dudley JH. Field test of an experimental NMR LWD device. InSPWLA 41st Annual Logging Symposium 2000 Jan 1. Society of Petrophysicists and Well-Log Analysts.

- [13] Ehrlich R, Crabtree SJ, Horkowitz KO, Horkowitz JP. Petrography and reservoir physics I: Objective classification of reservoir porosity (1). *AAPG bulletin*. 1991;75(10):1547-62.
- [14] Chang D, Vinegar HJ, Morriss C, Straley C. Effective porosity, producible fluid and permeability in carbonates from NMR logging. In *SPWLA 35th Annual Logging Symposium 1994 Jan 1*. Society of Petrophysicists and Well-Log Analysts.
- [15] Kenyon B, Kleinberg R, Straley C, Gubelin G, Morriss C. Nuclear magnetic resonance imaging—technology for the 21st century. *Oilfield Review*. 1995 Dec 31;7(3):19-33.
- [16] Kaufman J. Numerical models of fluid flow in carbonate platforms; implications for dolomitization. *Journal of Sedimentary Research*. 1994 Jan 1;64(1a):128-39.
- [17] Enos P, Sawatsky LH. Pore networks in Holocene carbonate sediments. *Journal of Sedimentary Research*. 1981 Sep 1;51(3):961-85.
- [18] Lucia FJ. Petrophysical parameters estimated from visual descriptions of carbonate rocks: a field classification of carbonate pore space. *Journal of petroleum technology*. 1983 Mar 1;35(03):629-37.
- [19] Lucia FJ. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *AAPG bulletin*. 1995 Sep 1;79(9):1275-300.
- [20] Anselmetti FS, Eberli GP. Controls on sonic velocity in carbonates. *Pure and Applied geophysics*. 1993 Jun 1;141(2-4):287-323.
- [21] Melim LA, Anselmetti FS, Eberli GP. The importance of pore type on permeability of Neogene carbonates, Great Bahama Bank.
- [22] Choquette PW, Pray LC. Geologic nomenclature and classification of porosity in sedimentary carbonates. *AAPG bulletin*. 1970 Feb 1;54(2):207-50.
- [23] Timur A. Pulsed nuclear magnetic resonance studies of porosity, movable fluid, and permeability of sandstones. *Journal of Petroleum Technology*. 1969 Jun 1;21(06):775-86.
- [24] Kenyon WE, Day PI, Straley C, Willemsen JF. A three-part study of NMR longitudinal relaxation properties of water-saturated sandstones. *SPE formation evaluation*. 1988 Sep 1;3(03):622-36.
- [25] Coates GR, Miller M, Gillen M, Henderson C. The MRIL In Conoco 33-1 an investigation of a new magnetic resonance imaging log. In *SPWLA 32nd Annual Logging Symposium 1991 Jan 1*. Society of Petrophysicists and Well-Log Analysts.
- [26] Amabeoku MO, Funk JJ, Al-Dossary SM, Al-Ali HA. Calibration of permeability derived from NMR logs in carbonate reservoirs. In *SPE Middle East Oil Show 2001 Jan 1*. Society of Petroleum Engineers.
- [27] Zayed S, Leone A, El Sayed AM, Lala A, Salah A. Permeability Prediction using Nmr Measurements for Some Gas Reservoirs-Nile Delta, Egypt. In *Offshore Mediterranean Conference and Exhibition 2019 May 6*. Offshore Mediterranean Conference.
- [28] Di J, Jensen JL. A new approach for permeability prediction with NMR measurements in tight formations. *SPE Reservoir Evaluation & Engineering*. 2016 Jul 1;19(03):481-93.
- [29] Zhu LQ, Zhang C, Wei Y, Zhang CM. Permeability prediction of the tight sandstone reservoirs using hybrid intelligent algorithm and nuclear magnetic resonance logging data. *Arabian Journal for Science and Engineering*. 2017 Apr 1;42(4):1643-54.
- [30] Zhang H, Yuan P, Wu J, Mezzatesta A, Jin G, Satti R, Koliha N, Bautista J, Crouse B, Freed D. Using digital rock modeling to estimate permeability and capillary pressure from NMR and geochemical logs. In *SPE Middle East Oil & Gas Show and Conference 2017 Mar 6*. Society of Petroleum Engineers.
- [31] Lucia FJ. Carbonate reservoir characterization: An integrated approach. Springer Science & Business Media; 2007 Nov 30.



This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license.