

Calculating absolute permeability using nuclear magnetic resonance models

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Abstract 1D transverse relaxation measurements were made on fully cylindrical cores of sandstone sediments with varying values of porosity, pore size and magnetic susceptibility. Porosity calculated from amplitudes of transverse relaxation measurements agrees well with porosity determined by independent method. Transverse relaxation measurements within the homogeneous magnetic field can be used for permeability prediction. In the case of sandstone samples with high porosity, a standard calculation scheme from NMR logging in the oil industry yields good results. However, standard SDR (Schlumberger Doll Research) model based on the T_{2LM} cannot be applied for an accurate permeability prediction for samples with low porosity, small pore sizes, clay filling pores, and presence of iron minerals and associated with high internal magnetic field gradients. Therefore, a model theory was developed physically based on Kozeny-Carman equation, which describes the pore radius dependence of the surface relaxivity ρ as both an analytical and a more practicable empirical equation was applied. Regarding corrected ρ values, permeability can be predicted more accurately from the physically based Kozeny-Carman equation than from the logarithmic mean of the T_2 distribution. From the relaxation measurements new empirical models with high coefficient of correlation by MLS regression were derived, additionally the coefficients of SDR and Kozeny were reestimated. The prediction models were applied, and the results compared to absolute permeability results from basic core analysis. As expected, the Kozeny model response presented better match to the core permeability values when compared with the optimized SDR.

Keywords Porosity · Transverse relaxation measurements · NMR logging · Schlumberger Doll Research model · Surface relaxivity · Kozeny-Carman equation

One-dimensional transverse relaxation measurements were made on fully cylindrical cores of sandstone sediments with varying values of porosity, pore size, and magnetic susceptibility. Porosity calculated from amplitudes of transverse relaxation measurements agrees well with porosity determined by independent method. Transverse relaxation measurements within the homogeneous magnetic field can be used for permeability prediction. In the case of sandstone samples with high porosity, a standard calculation scheme from NMR logging in the oil industry yields good results.

However, standard Schlumberger Doll Research (SDR) model based on the T_{2LM} cannot be applied for an accurate permeability prediction for samples with low porosity, small pore sizes, clay filling pores, and presence of iron minerals and associated with high internal magnetic field gradients. Therefore, a model theory was developed physically based on Kozeny-Carman equation, which describes the pore radius dependence of the surface relaxivity ρ , as both an analytical and a more practicable empirical equation was applied. Regarding corrected ρ values, permeability can be predicted more accurately from the physically based Kozeny-Carman equation than from the logarithmic mean of the T_2 distribution.

From the relaxation measurements, new empirical models with high coefficient of correlation by multivariate least squares (MLS) regression were derived; additionally, the coefficients of SDR and Kozeny were reestimated. The prediction models were applied, and the results were compared to absolute permeability results from basic core analysis. As expected, the Kozeny model response presented better match to the core permeability values when compared with the optimized SDR.

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Introduction

Laboratory nuclear magnetic resonance (NMR) measurements can be used to obtain porosity, permeability, free fluid volume (free fluid index (FFI)), capillary-bound irreducible fluid (bound volume index (BVI)), clay-bound water (CBW), oil saturation, etc., from core plugs from transverse relaxation time (T_2) distribution (Paul and Tiller 2005). Numerous authors have explored the link between NMR measurements and petrophysical properties, e.g., the wettability investigation by NMR measurements by Al-Mahrooqi et al. (2003, 2006). Fleury and Deflandre (2003) propose a new method to determine wettability indices from NMR relaxometry. Vevle (2011) showed that wettability state of the rock may affect the NMR signal to a degree where it is detectable and that the use of NMR in core analysis could give valuable information, complementing other investigation methods.

Porosity is one of the key parameters for hydrocarbon reservoir evaluation, and NMR is an effective tool to determine the porosity. However, several authors reported that there exist significant differences between NMR porosity and core analysis porosity (Xie et al. 2008). Additionally, iron and other paramagnetic minerals affect the surface relaxivity and produce a shift of the relaxation distribution to shorter times (Dodge et al. 1995).

Permeability is a difficult property to determine from logging data, yet it is essential for reservoir characterization. Laboratory measurements provide absolute permeability at core scale which could be different from reservoir permeability. NMR is the only tool that attempts to estimate in situ formation permeability (Hidajat et al. 2002; Glover et al. 2006). Weller et al. (2010) studied NMR of iron-rich sandstone from the Western Desert, Egypt, and found a detrimental effect of iron-bearing minerals on permeability estimation by NMR T_2 .

Therefore, our purpose in the present study is to explore the benefits of multivariate data analysis, more specifically the multivariate least squares (MLS) regression, in the permeability prediction from NMR data over these classical Schlumberger Doll Research (SDR) models, largely used in the NMR well logging interpretations, and the modified one based on the Kozeny equation. The permeability obtained by using the two different methods was compared for the studied sandstone samples. The potential use of surface area data is also described and illustrated.

Method

We studied 38 samples with 2.5-cm diameter and an average length of 4-cm horizontal and vertical core plugs from the three sand formations (10 samples from Szolnok Formation

from Hungary, 14 samples from Bahariya Formation (8 horizontal and 6 vertical), and 14 samples from Abu Madi Formation from Egypt). The samples had already been used for routine core and NMR analysis.

Routine laboratory core analysis

Helium porosity (φ_H) of the samples was measured by the gas expansion method by the Frank Jones helium porosimeter, and applying Boyle's law, the void volume is then can be calculated. Helium porosity is a good measure of total porosity, including porosity in clay minerals, as no pores are so small that helium cannot enter.

The Ruska gas permeameter (cat. no. 6121) is used for measuring the permeability of the studied samples using nitrogen gas. The clean and dry core samples are pushed into a rubber stopper of the corresponding hole size.

The effective bulk specific surface (S) was obtained from permeability (k) and macroporosity (φ) by using the Kozeny equation (Rabbani et al. 2014) as follows:

$$K = C^*(\varphi^3/S^2) \dots \dots \dots (1)$$

where C is the Kozeny factor which can be estimated from porosity via a simple model of linear 3-D interpenetrating tubes (Mortensen et al. 1998):

$$C = [4\cos\{1/3\arccos[\varphi 8^2/\pi^2 - 1] + 4/3\pi\} + 4]^{-1} \dots \dots (2)$$

According to Eq. (7), C increases from 0.15 to 0.25 as porosity increases from 0.05 to 0.5. Specific surface of pores from the Kozeny equation (S_p (Kozeny)) can then be calculated:

$$S_p(\text{Kozeny}) = S/\varphi \dots \dots \dots (3)$$

While

$$1/T_2 = \rho^*S_p \dots \dots \dots (4)$$

where ρ is the surface relaxivity.

NMR measurements

2-D T_1 – T_2 relaxation correlation experiments can be performed to test the influence of diffusion on the shape of the T_2 distribution function (Anferova et al. 2007). The echo spacing in our investigations was fixed at 600 μ s. The NMR experiments to determine the transversal relaxation time distribution of our studied sandstone samples were performed

with the Maran Ultra 8 Resonance Instruments equipment operating at a Larmor frequency of 7 MHz. The instrument operates at 35 °C. NMR porosity of the fully saturated samples was determined by using the total signal amplitude of each sample and known standard of similar diameter. NMR porosity is then calculated using the total signal amplitude, the bulk volume, hydrogen index of both plug and reference, and the equivalent porosity of the reference.

For determining the macroporosity (free water) and microporosity, we need a cutoff value from the T_2 distribution. A single T_2 cutoff value was used for all samples of each formation. The cumulative porosity over the range $T_2 > T_{2\text{cutoff}}$ was the macroporosity (free water) and below the range $T_2 < T_{2\text{cutoff}}$ was the microporosity or capillary-bound water and irreducible water saturation (CBW).

Approaches for predicting permeability from NMR

There are two primary approaches for predicting permeability from NMR data used in this work, one based on the estimation of an average pore size and other on the surface relaxivity.

The SDR, Wang et al. (2014), or average pore size approach relies on the T_2 distribution, measured by the NMR tool, as being a pseudo-pore size distribution of the formation. Short T_2 values are associated with small pores and long T_2 with the larger ones. Therefore, the SDR model uses the logarithmic mean, the T_2 distribution ($T_{2,LM}$), as a representation of the average pore size, and the porosity to predict the permeability:

$$K = aT_{2,LM}^b \varphi^c \dots \dots \dots (5)$$

where K is the permeability (mD); φ is the porosity (%); and a , b , and c are the coefficients that depend on the formation type.

The second approach is based on studies that have shown that permeability is related to the mean T_2 relaxation time and the T_2 time was converted into permeability using the relaxivity equation of Kozeny (Pape et al. 2006; Lala 2013; Rabbani et al. 2014). The Kozeny model uses the effective surface relaxivity, determined from the specific surface of pores (S_p Kozeny), and the porosity to predict the permeability from the Kozeny equation:

$$K = C * \varphi * (T_2, LM * \rho)^2 \dots \dots \dots (6)$$

where K is the permeability (mD), C is the Kozeny factor, ρ is the surface relaxivity (which measured the rock surface’s ability to enhance relaxation), and φ is the porosity (%).

SDR and Kozeny equations were used for NMR permeability prediction. The assumption of the Kozeny model is that (1) the pore structure controlling the T_2 distribution is a bundle

of capillary tubes and the drainage is controlled by the hierarchy of pore sizes, (2) the surface relaxivity is constant overall the sample, and (3) diffusion relaxation is negligible.

Results and discussion

The samples had already been used for routine core analysis and were chosen so as to cover the range of variation in porosity (3.6–32.27 %) with mean value of 16.8 % and air permeability (0.01–3474 md) with mean value of 455.86 md, calculated specific surface area (0.02–18.6 μm^{-1}) with mean value of 2.7 μm^{-1} and NMR computed geometric mean $T_{2,LM}$ of variation range (1.00–135.44 msec) with mean value of (29.6 msec), and calculated porosity from NMR (4.67–32.99 %) with a mean value of 16.97 %.

Correlation between measured and NMR-derived petrophysical parameters

Routine core analysis of our studied sandstone core samples thus shows an excellent relationship between porosity and permeability (Fig. 1).

Helium porosity and NMR porosity are compared in Fig. 2. Helium porosity is associated with the total porosity of the sample including microporosity in clay, and it shows excellent correlation with the NMR porosity values. Thus, NMR porosity also, in principle, represents the total porosity of a sample but could be lower if water saturation is below 100 %. NMR porosity tends to be closely approximated to helium porosity. However, NMR porosity gives lower correlation of regression when correlated against the measured permeability compared

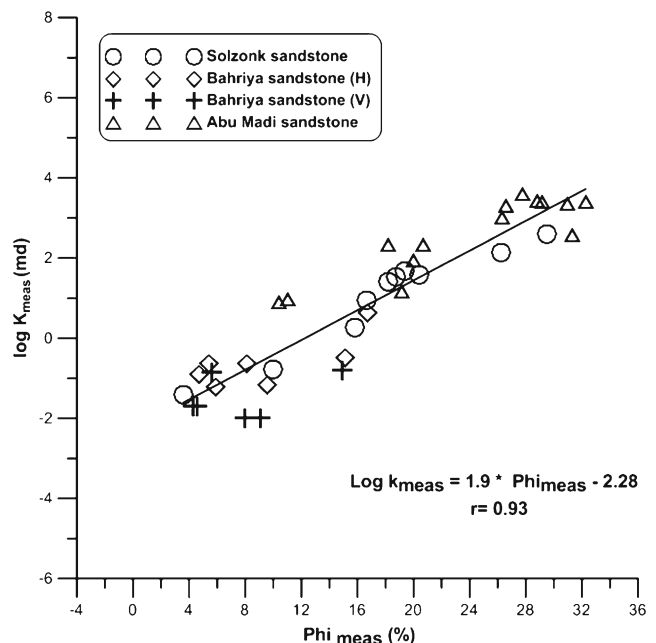


Fig. 1 Relationship between lab-measured porosity and permeability

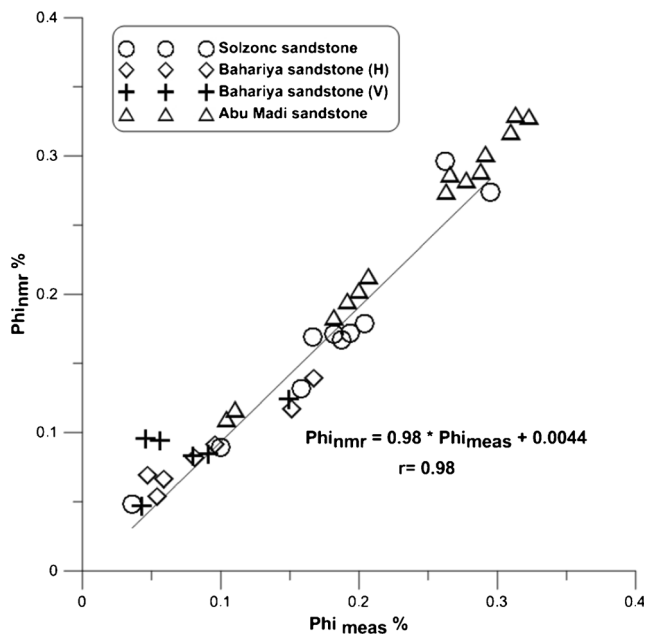


Fig. 2 Relationship between NMR porosity versus helium porosity

with laboratory-measured porosity (Fig. 1). This is due to that both macroporosity and microporosity are underestimated by the NMR measurements. The discrepancy between helium porosity and NMR porosity could be due to several factors. First, NMR and helium porosity depend on saturation condition of the sample. So, we can rule out that during NMR measurement, the saturation condition was lower than that at the helium measurements. Second, paramagnetic iron-bearing minerals in reservoir rock may be an important factor influencing T_2 measurements as shown by Dodge et al. (1995). The presence of paramagnetic ions increases the rate of relaxation of the hydrogen proton. The decreases of T_2 relaxation time are expected especially for horizontal Bahariya sandstone samples that are characterized by flaser bedding structure, because it is iron-bearing formation. These clay minerals have large surface area and high magnetic susceptibilities leading to large internal gradients and short T_2 (Straley et al. 1997). Third, here, the influence of diffusion due to internal magnetic field gradients caused by paramagnetic centers at the pore walls can be neglected in large-radius pores. However, in the case of the horizontal Bahariya sandstone samples with low porosity and permeability, this calculation scheme yields errors. These errors are caused by diffusion in the internal magnetic field gradients which are associated with small pore radii of the rocks.

The NMR T_2 cutoff value >33 msec from the T_2 distribution was used for determining the free water, while T_2 cutoff range value 4–33 msec for capillary-bound water and T_2 cutoff value <4 msec for CBW.

The predicted clay-bound water (CBW), capillary-bound water (BVI), and free water distribution (FFI) obtained by using T_2 cutoff value are shown in Figs. 3, 4, and 5 against

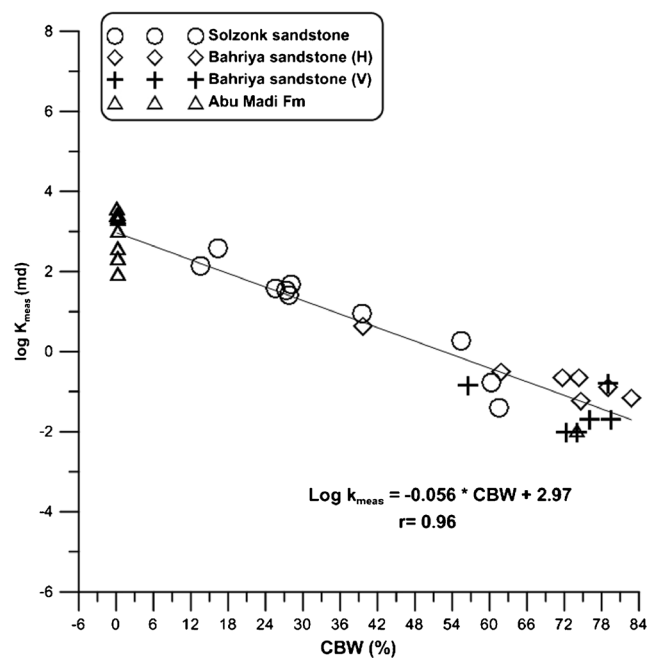


Fig. 3 Relationship between lab-measured permeability and clay-bound water

laboratory-measured permeability, respectively. Below cutoff time, the amplitude of permeability is zero which means that microporosity does not contribute to fluid flow and give inverse relationship. From cutoff time to 33 ms (capillary-bound water), the amplitude of coefficient of regression of the relationship is small but, above 33 ms (free water), the contribution only of macroporosity which means that permeability and fluid flow increase and so the coefficient of regression.

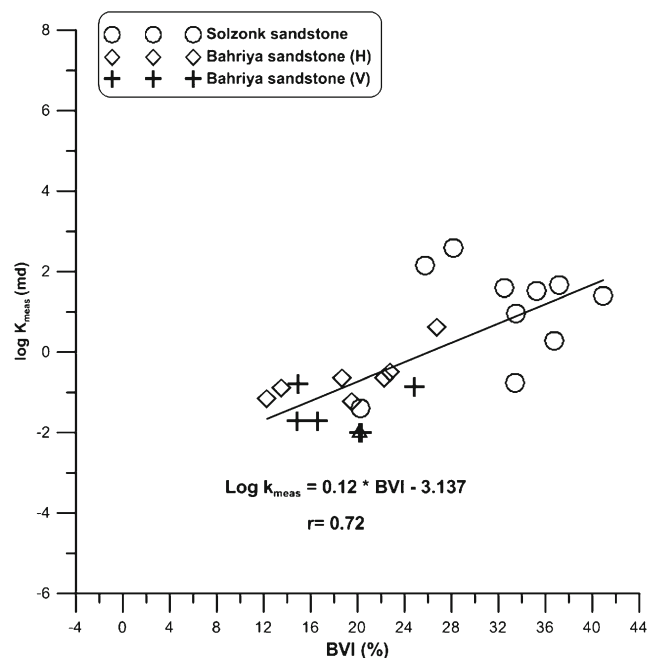


Fig. 4 Relationship between laboratory-measured permeability and capillary-bound water

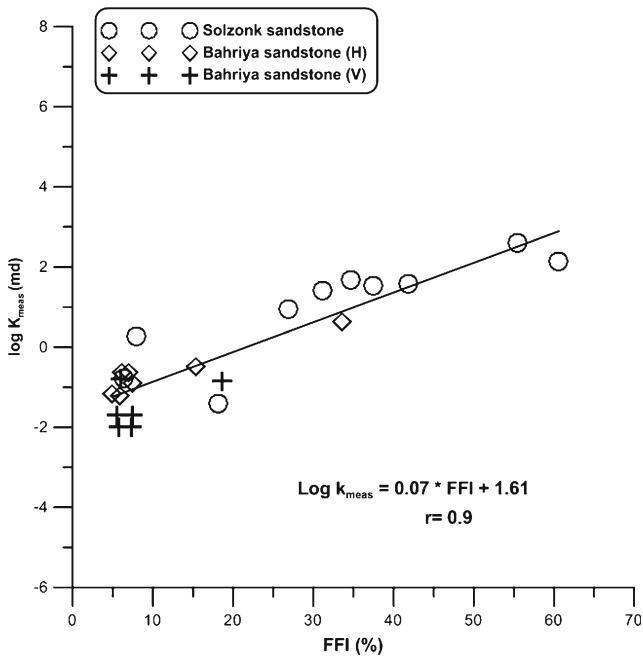


Fig. 5 Relationship between lab-measured permeability and free water

Reevaluation of SDR and Kozeny equation coefficients

From the experimentally measured $T_{2,LM}$ and φ , the SDR and Kozeny equation coefficients (a , b , and c) were adjusted to match the 38-plug absolute permeability measurements by a multiple linear regression (MLR) (Eqs. 7 and 8). In both cases, the permeability predicted by the two new calibrated equations distinguished with high coefficient of determination presented good accordance with the 38 samples as shown by the following formulas:

$$\log K_{NMR} = -1.5 + 17.56(\varphi) - 0.0005(T_{2,LM}) \quad (SDR) \quad R = 0.9... \quad (7)$$

$$\begin{aligned} \log K_{NMR} &= -5.16 + 30.91(\varphi) + 0.008(T_{2,LM}) \\ &+ .031(\rho)(Kozeny)R \\ &= 0.94..... \quad (8) \end{aligned}$$

with $T_{2,LM}$ given in milliseconds, φ as a fraction, ρ surface relaxivity in meters per second, and $\log K_{NMR}$ in millidarcy.

In the SDR example, the $T_{2,LM}$ used to calculate the permeability was an average measurement for each one of the 38 calibration plugs. In this case, local lithology heterogeneities of the formation may cause the real $T_{2,LM}$ to deviate from the average value, consequently taking the permeability to disagree from the core values by small value of magnitude (Fig. 6).

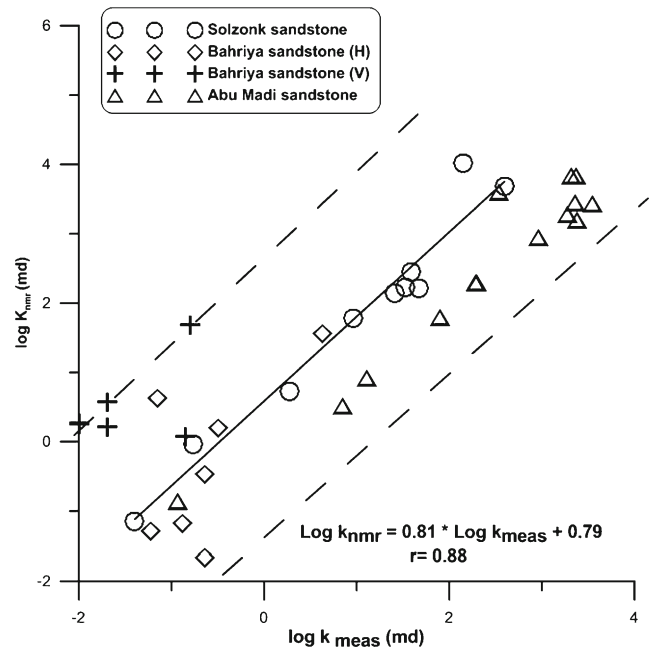


Fig. 6 Relationship between NMR permeability from SDR model versus lab-measured permeability

The Kozeny equation which incorporated the surface relaxivity also presented a satisfactory match and gives good accordance to the permeability results from basic core analysis. However, the permeability prediction showed a far better response, when compared with the SDR model (Fig. 7). Most of the predicted permeability values that fall into two dashed lines to both sides of the diagonal indicate a deviation between measured and NMR predicted permeability values of the range $0.25 < k_{nmr}/k_m < 4$, where k_{nmr}

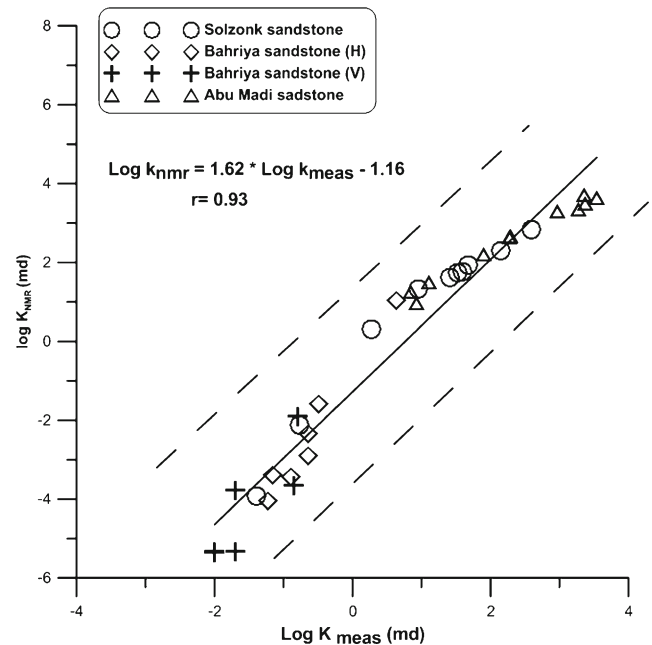


Fig. 7 Relationship between NMR permeability from Kozeny model versus lab-measured permeability

and k_m are NMR calculated and measured permeabilities, respectively. This range is considered acceptable as discussed in Weller et al. (2010).

The overestimation produced by the SDR model can be clearly understood, where the relaxation time of the pore filling clay pushes the $T_{2,LM}$ to values almost two times superior. Therefore, the $T_{2,LM}$ term of the SDR equation overestimates the permeability by approximately two orders of magnitude.

Part of the success of the Kozeny equation was due the inclusion of the effective surface relaxivity, removing the influence of the pore filling clays on the NMR log data. This approach allowed to a close match between the laboratory measurements to the NMR log data. However, the difference between the predicted permeability and lab measured values may be caused by the presence of high iron concentrations in the core samples which increases the effective surface relaxivity (ρ) values of the studied core samples especially for horizontal Bahariya Formation.

Where iron is highly concentrated along the pore perimeter which interferes with NMR measurements by increasing T_2 relaxation times, the pore volumes calculated from T_2 relaxation times were too low in all instances. NMR-derived pore sizes were perhaps too low in the studied core samples. Exact corrections for the iron are beyond the scope of this study. Pores that exhibited rare iron and paramagnetic minerals that are generally located away from pore walls do not significantly affect the NMR pore size calculation.

Conclusion

- This study shows the ability of new empirical models to predict permeability from NMR T_2 distributions using multivariate data analysis.
- Good agreement is found between Helium porosity and NMR porosity with high correlation of regression. However, the small discrepancy between them may be due to a combination of several factors, including the presence of clay and iron minerals in the studied sandstone samples.
- The effective surface area as calculated by the Kozeny equation and the estimated effective surface relaxivity is more associated with macropores.
- We found that predicted permeability from NMR by using average T_2 equation works well. However, by using the Kozeny-Carman equation, predicting permeability agrees better when surface relaxivity is known. In spite of different type locality of our studied sandstone samples, empirical equations which are calibrated for T_2 distributions measured on our studied sandstone samples can be used to calculate better accurate permeability values.
- The deviation between the NMR permeability by SDR model and the Kozeny equation and laboratory-measured permeability for the studied samples is due to the contrasting relaxivity on the surface of quartz, pore filling clay, and iron concentration.

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