IMPROVING LAB NMR PETROPHYSICAL ESTIMATIONS BY INCORPORATING THE SURFACE RELAXIVITY PARAMETER

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ABSTRACT

Nuclear Magnetic Resonance (NMR) relaxation time measurements are used routinely to evaluate the permeability (k) of porous media. For this application, the Timur-Coates (k_{TC}) equation is one of the most widely used k estimators. It takes into account the ratio of porosity associated with large and small pores, based on the interpretation of the transversal relaxation time (T_2) distribution as a pore size distribution. A key parameter is the value of $T_{2\mathrm{cutoff}}$ that separates the free and bound fluids. It is related to a characteristic pore size by the transversal surface relaxivity (ρ_2). However, ρ_2 is not routinely measured in petrophysical NMR laboratory studies of sedimentary rock cores. In current practice, a default value of $T_{2\mathrm{cutoff}}$ is used. We have recently introduced a new technique to measure ρ_2 directly in a given core. This allows us to calibrate the T_2 distribution in terms of a distribution of V/S (the volume-to-surface area ratio) and introduce a V/S_{cutoff} to separate free and bound fluids. We demonstrate that this approach results in an improvement of over a factor of 2 in the permeability estimates based on the modified k_{TC} equation. Additionally, a correlation of ρ_2 with Swi is proposed, making possible the estimation of this parameter as well.

INTRODUCTION

The NMR technique is routinely used to evaluate important petrophysical properties of porous media, in particular reservoir rock cores [1]. The main application relies on the measurement of T_2, and the interpretation of the resulting T_2 distribution as a pseudo pore body size distribution, given by:

$$T_2 = \frac{1}{\rho_2} . \left(\frac{V}{S}\right)_{pore} \tag{1}$$

Here we neglect diffusion in internal magnetic field gradients and bulk relaxation. This is a resonable assumption for most of sedimentary rock cores when the measurement is done with proper acquisition parameters and when vuggy porosity is absent. As seen, Equation (1) depends on the pore body-to-surface area ratio (V/S), a term proportional to pore radius and pore geometric features, and also on the surface relaxivity. ρ_2 describes how efficiently the pore walls can relax the polarized saturating fluids [1], and so it is the key parameter to relate T_2 to pore size. However, in most of the routine petrophysical applications of Equation (1), it is usually assumed that ρ_2 is a constant (for a given lithology). This is a common practice when estimating permeability based on T_2 distributions [2,3]. Furthermore, measuring ρ_2 is not simple and most of the developed methods rely on *a priori* knowledge, as pore geometry or V/S determination [1].

Recently, Souza et al. [4] have shown a significant improvement on the accuracy of permeability estimation using the classical k_{SDR} equation, when ρ_2 is determined and is used together with the mean T_2. The equation is defined as $k_{SDR} = a_{SDR}.\phi^4.(T_{2LM})^2$, being a_{SDR} a constant that depends on the lithology, ϕ the porosity and T_{2LM} the logarithmic mean of the T_2 distribution. The authors show an impressive gain in k_{SDR} accuracy (more than a factor of 2) when the term $(T_{2LM})^2$ is replaced by the $(\rho_2.T_{2LM})^2$. The determination of ρ_2 presented in that work is based on the restricted diffusion phenomena. When a fluid is diffusing in a confined geometry, its diffusion coefficient (*D*) is reduced by a amount that is proportional to the pore´s S/V ratio [4]. Since T_2 is also dependent on this parameter (Equation 1), the correlation of *D* with T_2, acquired by the two dimensional *D*-T_2 experiments, allows the determination of ρ_2 through a linear fitting of the measured *D* versus T_2. This method eliminates the need of a model for the porous system under investigation, since it does not depend on the pore´s size and geometry, giving a more reliable effective ρ_2 when compared to the ones given by correlations between NMR relaxation times with different techniques, like MICP derived pore throat size distribution, surface area by BET, image analysis, among others. Another problem with these methods is that each one probes different length scales of the porous system, resulting in correlations that are not reliable enough to be used in routine studies.

In 2002, Richard Sigal [5] studied the k_{TC} and k_{SDR} equations, aiming to clarify their inter-correlations. He proposes that k_{TC} can be interpreted exactly as the k_{SDR} one through the definition of a "Coates time" (T_{Coates}), which is the product of $T_{2cutoff}$ and the (FFI/BVI) term, if applied on fully brine saturated samples. Its general form can be written as:

$$k_{TC} = a_{TC}.\phi^4.\left(T_{2cutoff}\right)^2.\left(\frac{FFI}{BVI}\right)^2 \qquad (2)$$

where a_{TC} is a constant that depends on lithology, FFI and BVI are defined by integrating the T_2 distribution: FFI by the signal above a pre-defined T_2 cutoff and the BVI, below. When ρ_2 deviates from its default value, the pore size associated with the T_2 cutoff value changes and will make Equation (2) less reliable. This effect was already observed for k_{SDR} as well [4]. Furthermore, the lack of unit consistency is another problem [5]. In the seminal works about permeability estimation by NMR [2-4], the authors have implicitly assumed a constant value for ρ_2 for each lithology and rock type that was reflected in the values of a_{TC} *and* a_{SDR}. So, the explicit inclusion of ρ_2 on those equations must also lead to a re-definition of those constants. This corrects the dependency of permeability (squared length) by NMR measurement, clarifying and keeping the required consistency.
The general assumption when core lab calibration is not available, is to use for the $T_{2cutoff}$ values 33 ms for sandstones and 100 ms for carbonates [1]. However, using these values

can give erroneous permeability estimates, especially in carbonates where the heterogeneity and complexity can be high. In such cases, a specific calibration procedure is often used to determine a more appropriate value of $T_{2cutoff}$ [1].

Following Souza et al. work [4], the aim of this work is to propose a methodology that incorporates the ρ_2 parameter to routine petrophysical analysis by NMR, with focus on the k_{TC} equation, cutoff definition and Swi estimation. All those quantities are very important and crucial parameters for best routine oil-field decisions and operations [1].

PROCEDURES

16 sandstones and 10 carbonate cylinders outcrop rock cores with 1.5” diameter and 2” length were studied. Helium gas porosity (ϕ_{He}) and permeability (k_{He}) were measured applying a confining pressure of 500 psi. Cores were saturated with 20,000 ppm NaCl brine and NMR T_2 relaxation times were measured using the CPMG pulse sequence, on a low-field GeoSpec spectrometer (2 MHz frequency for ^1H) from Oxford Instruments (UK). Details of the 2D *D*-T_2 experiment acquisition and signal processing can be found in [4]. Table 1 shows the basic petrophysical data (ϕ_{He} and k_{He}) and ρ_2 obtained.

RESULTS

The purpose of this work is to present a methodology that applies ρ_2, measured by the *D*-T_2 experiment, to re-define the cutoff concept widely applied in the petrophysical estimations of permeability and irreducible water saturation. As already stated, ρ_2 is the parameter that provides the relationship between relaxation time and pore size distributions, so having itself a strong physical meaning.

Therefore, a cutoff on the (V/S) dimension, instead of the regular T_2 dimension, is proposed. In this new approach, we have a fixed $(V/S)_{cutoff}$ that corresponds to a variable $T_{2cutoff}$ that depends on ρ_2 (as shown in Equation 1), given by:

$$T_{2cutoff} = \frac{1}{\rho_2} . \left(\frac{V}{S}\right)_{cutoff} \tag{3}$$

Figure 1 compares the error in permeability prediction (σ_k) based on k_{TC} as a function of the cutoff value for the two approaches. When a traditional $T_{2cutoff}$ is used (Figure 1a), the minimum σ_k for sandstones is 3.6 and occurs for $T_{2cutoff}$ at around 50 ms, while for carbonates the minimum σ_k is 5.4 for a $T_{2cutoff}$ = 150 ms. This has to be compared with the new approach where the $(V/S)_{cutoff}$ is used instead (Figure 1b). The minima in σ_k are significantly smaller, i.e. 2.3 for sandstone with $(V/S)_{cutoff}$ = 0.4 μm and 2.6 for carbonates with $(V/S)_{cutoff}$ = 1.8 μm. Figure 2(a) shows the results of k_{TC} using the optimized $T_{2cutoff}$’s, and Figure 2(b) shows the estimations using the corresponding $(V/S)_{cutoff}$´s. The accuracy, analysed via σ_k and considering both lithologies, shows a significant improvement of more than a factor of 2. To test the proposed estimator, 10 additional twin plugs chosen from the available samples described in Table 1 were measured and plotted on Figure 2, using the same $T_{2cutoff}$ and $(V/S)_{cutoff}$ values. The correlation of their estimated k_{TC} versus k_{He} was as good as the one found for the other cores. It is notable that the new method proves to be applicable for a permeability range that spans over almost 5 orders of magnitude.

The impact of the knowledge of ρ_2 that generates the achieved gain on k_{TC}, is illustrated in Figure 3 on three carbonate samples. In Figure 3(a), the regular T_2 distributions for a very high ρ_2 (Indiana 70, high k_{He}), a high ρ_2 rock (Austin Chalk, low k_{He}) and a low ρ_2 (Indiana 2-4, low k_{He}), are shown. It is clear that assuming identical scaling factors for converting T_2 distributions into pore size distributions is not appropriate to explain the permeability range for these samples. However, when (V/S) is plotted (Figure 3(b)), the two low k_{TC} cores lined almost perfectly at small (V/S) values, and the high one is shifted to longer values. The plots show also the cutoffs of 150 ms for T_2 and 1.8 μm for (V/S). Clearly, the (FFI/BVI) calculated in Figure 3(b) based on (V/S) correctly reflects their permeabilities. These analyses demonstrate the improved pore size representation based on the (V/S) dimension. The gain for carbonates was greater than for sandstones, corroborating the well described high complexity of that lithology.

As a check of consistency and following Sigal's work [5], the suggestion that Swi can be estimated from the NMR T_2 on fully saturated cores, with the *a priori* knowledge of the $(V/S)_{cutoff}$, was studied. Substituting Equation (3) in (2), $k_{SDR} \approx k_{TC}$ gives:

$$a_{SDR}.\phi^4.(\rho_2.T_{2LM})^2 \approx a_{TC}.\phi^4.\left(\frac{V}{S}\right)^2_{cutoff}.\left(\frac{FFI}{BVI}\right)^2 \qquad (4)$$

Figure 4(a) shows the plot of T_{2LM} versus $T_{2cutoff}$.(FFI/BVI) (as described by k_{SDR} equals to Equation 2) and Figure 4(b) shows $\rho_2.T_{2LM}$ versus $(V/S)_{cutoff}$.(FFI/BVI) (as described by Equation 4). The correlation in Figure 4(a) is reasonably good for sandstones, with a Pearson's coefficient (R^2) of 0.80, but very poor for carbonates, with a R^2 of only 0.26. Figure 4(b) shows the notable gain in linearity for the carbonate lithology when ρ_2 information is included to improve the pore size estimation, with a R^2 of 0.88. Sandstones have shown an increase of only 7% (R^2 of 0.87), due to its low complexity.

In conclusion, if T_2 distribution, ρ_2 and $(V/S)_{cutoff}$ are measured, Equation (4) can be used to estimate (FFI/BVI), that in turn can be used to estimate Swi (if total porosity, ϕ_T is known). Laboratory Swi measurements are being conducted, in order to be compared with the estimating method of Swi proposed in this work.

CONCLUSION

The methodology presented, based on the definition of a new NMR cutoff value on the (V/S) dimension (instead of the regular $T_{2cutoff}$ widely used on petrophysical estimations), proved to be very efficient to improve: (a) by more than 2 times the permeability estimation by Timur-Coates equation, (b) the cutoff concept itself and (c) the estimation of Swi. ρ_2 parameter can be robustly and accurately measured by the 2D *D*-T_2 experiment, a well established technique available in most of the lab NMR machines used by the oil production and exploration industry. For this reason and considering all the deliverables that this parameter can improve, the main proposition is that ρ_2 should be thought and considered when lab NMR investigations are being planned.

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Table 1. Porosity (ϕ_{He}), permeability (k_{He}) and effective surface relaxivity (ρ_2), of the samples studied.

	Sample	**ϕ_{He} (p.u.)**	**k_{He} (mD)**	**ρ_2 (μm/s)**
Sandstone	Bandeira Brown	20.8	1.2	8.6
	Bandera Gray	21.7	22.6	10.0
	Bentheimer	23.2	2490.0	7.6
	Berea	20.2	149.0	11.4
	Berea Stripe	21.2	415.0	12.1
	Boise Idaho Brown	27.5	1510.0	8.3
	Boise Idaho Gray	29.3	4310.0	12.0
	Briarhill	24.3	3900.0	16.5
	Buff Berea	24.4	698.0	13.0
	Carbon Tan	17.1	38.0	15.9
	Castlegate	26.3	1080.0	20.0
	Crab Orchad	6.5	0.1	19.6
	Leapord	20.5	1610.0	55.1
	Kirby	21.8	17.3	19.4
	Nugget	10.8	8.6	24.7
	Sister Gray Berea	20.8	149.0	12.5

	Sample	**ϕ_{He} (p.u.)**	**k_{He} (mD)**	**ρ_2 (μm/s)**
Carbonate	Austin Chalk	23.0	10.0	23.3
	Desert Pink	30.5	95.5	18.8
	Edwards Yellow	22.9	165.0	16.5
	Guelph Dolomite	7.9	4.3	12.4
	Indiana 8-10 mD	9.1	0.4	2.9
	Indiana 2-4 mD	13.8	1.9	3.3
	Indiana 70 mD	18.9	301.0	35.8
	Leuders	16.2	1.0	10.5
	Sillurian Dolomite	12.4	18.3	9.5
	Winsconsin	5.6	0.8	8.6

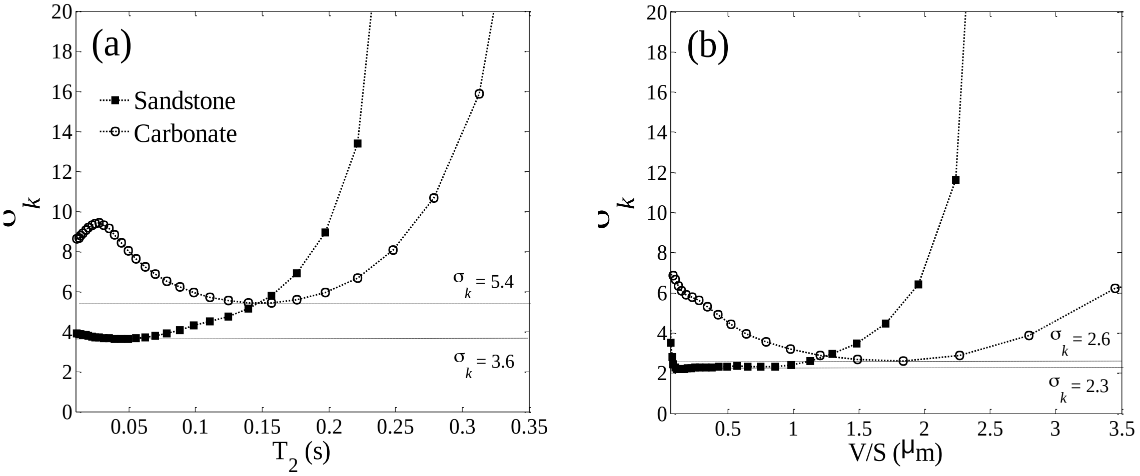

Figure 1. Error of Timur-Coates model considering the cutoffs: (a) from each T_2 bin; and (b) each (V/S) (ρ_2.T_2) bin. The minima of σ_k represent the best predictions for each lithology.

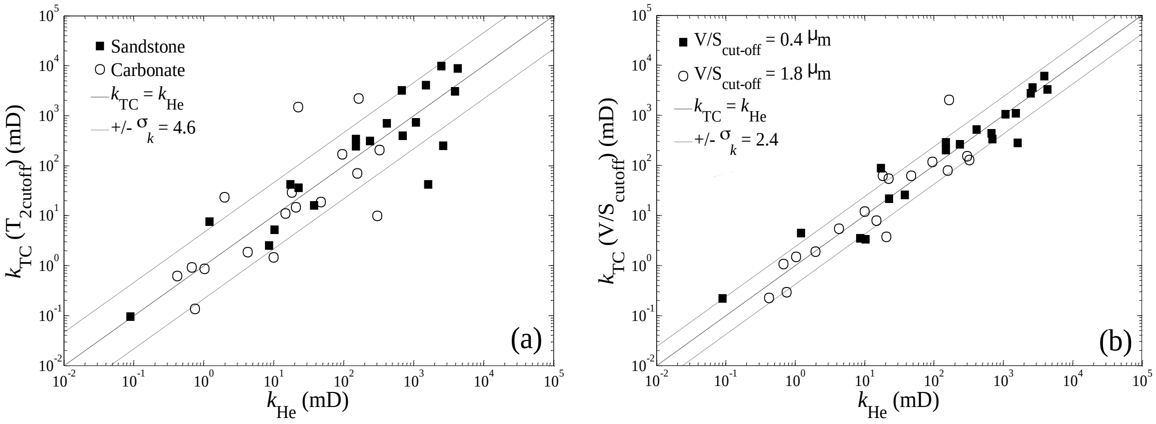

Figure 2. Timur-Coates permeability estimations considering: (a) $T_{2cutoff}$ of 50 ms for sandstones (black squares) and 150 ms for carbonates (open circles); and (b) V/S$_{cut-off}$ of 0.4 μm for sandstones and 1.8 μm for carbonates. The gain in accuracy is notable, with a reduction in σ_k from 4.6 to 2.4 (in log scale).

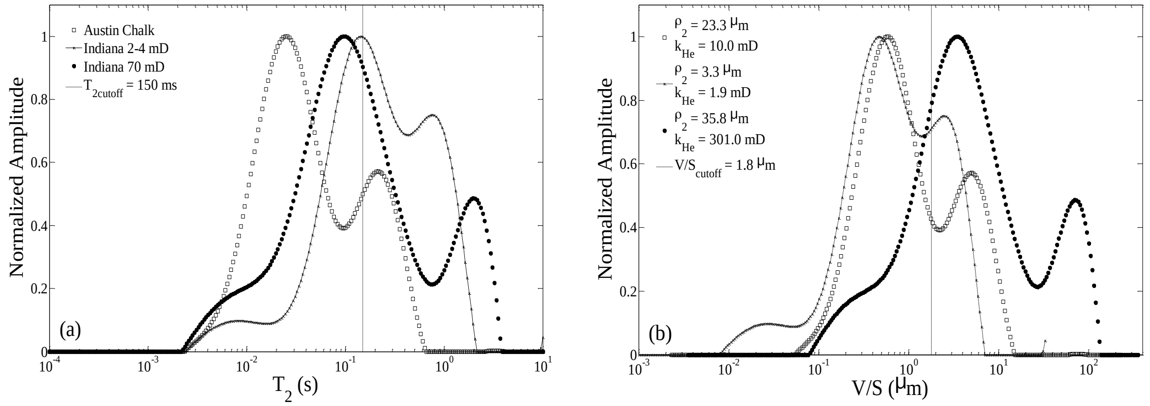

Figure 3. T_2 (a) and V/S (b) distributions and respective cuttoffs, for 3 carbonate samples with very high to low ρ_2. When ρ_2 is applied, a dramatic shift properly correlates pore sizes with permeabilities.

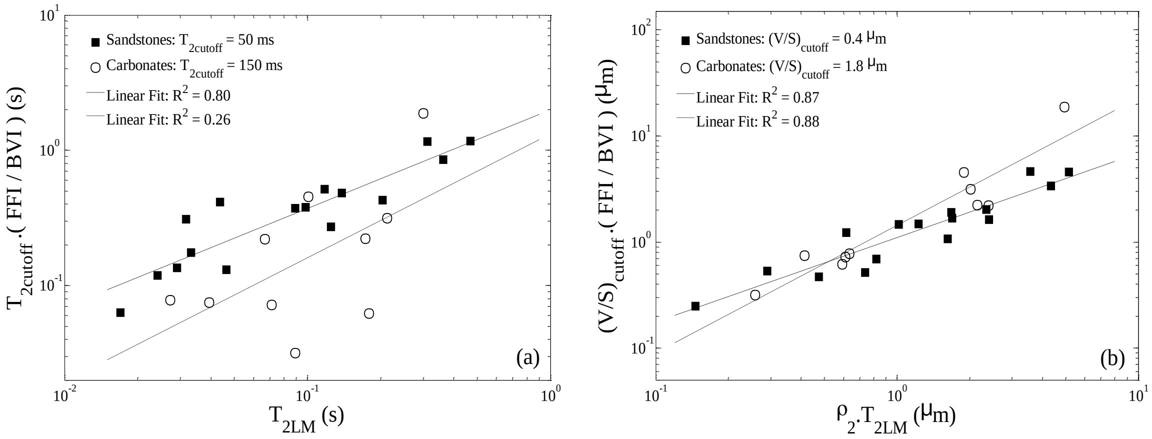

Figure 4. Correlation of (FFI/BVI) with: (a) T_{2LM}; and (b) ρ_2.T_{2LM}. The *y* axis is multiplied by each cutoff, in order to keep the consistency. The analysis of R^2 clearly indicates the gain in linearity in (b).