A NMR PERMEABILITY MODEL BASED ON PARTIAL LEAST SQUARE (PLS) REGRESSION ANALYSIS FOR A LOW PERMEABILITY GAS SAND IN SANTOS BASIN

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ABSTRACT

This study explores the benefits of PLS (Partial Least Squares) regression in the permeability prediction from NMR relaxation data over the classical SDR (Schlumberger Doll Research) and Timur-Coates models based on the T_{2LM} and FFI/BVI ratio, respectively. To pursue this case study, the transversal relaxation times (T_2) of 13 Santos Basin low permeability gas sand samples, with absolute permeability ranging from 0.01 to 15 mD, were measured at two different saturation states, completely saturated (Sw=100%) and irreducible saturation (Swi), at 2 MHz. From the relaxation measurements a new empirical model by PLS regression was derived, additionally the coefficients of SDR and modified Timur-Coates were reestimated. Both prediction models were applied to entire log length and the results compared to 600 absolute permeability results from basic core analysis. As expected, the PLS model response presented far better match to the core permeability values when compared with the optimized SDR and modified Timur-Coates.

INTRODUCTION

The decrease in oil discoveries and the consequent rise of barrel prices have been progressively increasing the importance of the tight sandstones as a viable hydrocarbon resource. Considering the fact that most of commercial tight-sand reservoirs are saturated with gas, permeability is one of the most important petrophysical properties in this adverse kind of rock formation.

In Santos Basin, located off-shore in the eastern margin of Brazil, santonian siliciclastic reservoirs, related to the drift phase of the Atlantic Ocean open, were a result of high density hyperpycnals flow associated with a fluvial system under catastrophic floods, Souza et al (2007). In these reservoirs, composed of a poor selected fine sandstone, the presence of dispersed clay (chlorite) may difficult the petrophysical analysis using conventional tools in order to predict porosity and permeability.

In this scenario NMR Logging has been increasingly used by petroleum companies worldwide to predict rock formations and its native fluids proprieties. Total and effective porosity, producible fluid volumes, fluid typing and permeability estimations are some of the principals NMR deliverables, Freedman (2006). There are two primary approaches for predicting permeability from NMR data, one based on the estimation of an average pore size and other on the irreducible water saturation.

The SDR (Schlumberger-Doll Research), Kenyon et al (1986), or average pore size approach, relays 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_{2LM}), as a representation of the average pore size, and the porosity to predict the permeability:

$$K = aT_{2LM}^{b}\phi^{c} \tag{1}$$

where, K is the permeability (mD) and ϕ the porosity (%).

The second approach is based on the studies that shown that permeability is related to the irreducible brine saturations. The Timur-Coates, Coates (1991), model uses the free fluid to the bound fluid ratio, determined from the T_2 distribution, and the porosity to predict the permeability:

$$K = \left(\frac{FFI}{BVI}\right)^{a} \times \left(\frac{\phi}{c}\right)^{b} \tag{2}$$

where, K is the permeability (mD) and ϕ the porosity (%).

Despite of some efforts to avoid the inaccuracy of FFI/BVI ratio determination proposed by Kleinberg et al (1997), tapered cutoffs, and Coates et al (1997), spectral BVI, one of the drawbacks of the above permeability models is that they summarize all the information contained in the T_2 distribution spectra in a single variable, FFI/BVI ratio or T_{2LM}, ignoring that each bin may have a complex and singular contribution in the plug permeability prediction.

Therefore, our purpose in the present study is to explore the benefits of multivariate data analysis, more specifically the PLS (Partial Least Squares) regression, in the permeability prediction from NMR data over these two classical models, largely used in the NMR well logging interpretations. PLS is explained in detail in literature, Martens et al (1993), and only a summary of the PLS method is presented.

PLS tries to find a relationship between the latent structures in predictor, X, and response variables, Y. It is carried out projecting the predictor variables (in the present case, each bin of T_2 relaxation spectra) and response variables (in the present case, the permeability) onto a new set of axis, the so-called latent variables. The PLS model has the form:

$$X = TP' + E \qquad Y = UQ' + F \tag{3,4}$$

where, T = X-scores, U = Y-scores, P = X-loadings, Q = Y-loadings, E = X-residuals, and F = Y-residuals.

Loadings give information about the relationship between the original variables directions and the latent variables directions in data space. Scores are the projections of the samples on the latent variables directions. PLS algorithms choose successive orthogonal factors that explain most of the variation in both predictors and response, maximizing the covariance between each X-scores and the corresponding Y-scores.

PROCEDURES

Sample preparation

To pursue this case study, a set of 13 plugs were selected from one well of Santos Basin. The plugs choice was guided to cover representative lithologies and sedimentary structures as well as the more frequent absolute permeability and porosity ranges 0.01mD to 15.5mD and 8.1% to 21.3%, respectively, Figure 1. The plugs with 1 in. x 1.5 in. were routine core analyzed after cleaned of residual hydrocarbons and salts. Before the first NMR analysis, the samples were completely saturated (Sw = 100%) with NaCl brine 225,000ppm, after that they were taken to the irreducible saturation (Swi), Figure 2, by air ultracentrifugation at a capillary pressure of 600 PSI (11,000 RPM for 6 h) and NMR reanalyzed.

NMR analysis

^{1}H transversal relaxation time measurements (T_2) were performed at 35°C and 5,000 PSI confining pressure in a Maran Ultra 2 MHz (Oxford Instruments, UK) bench top analyzer, equipped with a NMR compatible holder (TEMCO, USA) and a 52 mm probe. The samples were analyzed at two different states, completely saturated (Sw=100%) and at Swi. The pulse sequence used was the CPMG (Carr Purcell Meiboom Gill), with time between echoes of 200μs. 8192 echoes were summed with a recycle delay of 10 seconds, until to reach a signal-to-noise ratio of 100. The FFI/BFI ratio and $T_{2cutoff}$ were calculated such as Ohen et al (1996) using the T_2 spectra at Sw=100% and Swi.

Data processing and PLS modeling

Each CPMG relaxation curve was phase adjusted and the odd echoes removed before the Inverse Laplace Transformation (ILT). The T_2 relaxation spectra were generated using the WinDXP ver.1.8.1.0 (Oxford Instruments, UK) software, with 28 points (bins) distributed on the 0.3536 - 4096 ms interval. The PLS model was constructed from X_{13x28} and Y_{28x1} matrices containing the relaxation spectra and absolute permeability of the calibration plugs, respectively. The input data were preprocessed by mean-centering X_{13x28} and auto-scaling Y_{28x1} (logarithmic transformation). The model stability verification was performed using the full cross validation scheme, Martens et al (1993). The PLS regression was performed by the The Unscrambler ver.9.7 (Camo, Norway) software.

RESULTS AND DISCUSSION

SDR and modified Timur-Coates

From the experimental measured $T_{2cutoff}$, FFI/BFI, T_{2LM} and ϕ the modified Timur-Coates and SDR equation coefficients (a, b and c) were adjusted to match the 13 plugs absolute permeability measurements by a multiple linear regression (MLR), Table 1. In both cases the permeability predicted by the new calibrated equations presented good accordance with the 13 samples as shown in Figure 3.

In the modified Timur-Coates example, the $T_{2cutoff}$ used to calculate the FFI/BFI ratio in the field log was an average measurement for the 13 calibration plugs ($T_{2cutoff}^{average} = 32ms$). In this case, local lithology heterogeneities of the formation may cause the real $T_{2cutoff}$ to drift too much from the average value, consequently taking the FFI/BFI and the permeability to disagree from the core values.

Despite its good accordance to the plugs, when applied to the entire log length and comparing its response to 600 absolute permeability results from basic core analysis, the new calibrated equations did not present a satisfactory match, Figure 4a and 4b. The Timur-Coates and SDR show a clear trend to overestimate the permeability by several orders of magnitude. As can be observed, this effect is much more pronounced in the SDR case.

Figure 5 compares the average T_2 field log spectra of 15 different measurements, ranging from 4,933.95 to 4,935.02 m, with one calibration core sample (100% brine saturated) with an intermediate depth of 4,934.45 m. It is possible to observe that the average log spectra presents two well defined regions. The first one, at lower relaxation times, is attributed predominantly to bound water surface relaxation and the second, at higher relaxation times, to the light-hydrocarbons bulk relaxation and, in the case of gas, diffusion relaxation.

The severe overestimation produced by the SDR model can be clearly understood when considering the huge difference observed in both T_{2LM}, from calibration plug and equivalent field log. The relaxation time of the non-wetting fluids pushes the T_{2LM} to values almost eight times superior that the calibration core (248.8 against 32.7 ms). Therefore the T_{2LM}^{a} term of the SDR equation overestimate the permeability by approximately 4 orders of magnitude, considering an adjusted value of a=4.56.

PLS regression

After several preliminary processing rounds (data not shown), the best combination of pre-processing parameters found were the exclusion of bins above $T_{2cutoff}^{average}$ and the normalization by unitary area. The final PLS model (equation 5), with only one latent variable and excluding one outlier, explained more than 80% of variance for both X and Y:

$$K = b_0 + b_1 X_{T_{21}} + b_2 X_{T_{22}} + ... + b_n X_{T_{2cutoff}^{average}} \qquad (5)$$

where, b_n= regression coefficients and $X_{T_{2n}}$ = bins of the T_2 spectra.

As can be observed in the Figure 3, the PLS regression also presented good accordance with the 13 samples. However, when the final PLS regression model was applied to the entire log length and compared to the response of 600 absolute permeability results from basic core analysis, the permeability prediction showed a far better response, when compared with the other models, Figure 4c. Part of the success of the PLS regression was due the exclusion of the bins above the $T_{2cutoff}^{average}$, removing the influence of the light-hydrocarbons on the NMR log data. In addition, the T_2 spectra normalization by unit area turned the PLS model insensible to porosity inaccuracies, an important feature when compared with both SDR and Timur-Coates models. This approach allowed to a close match between the laboratory measurements to the NMR log data, without demanding a sample preparation with the same fluids found in subsurface, a task extremely difficult, when considering the gas as one of them.

CONCLUSION

In this paper we presented the benefits of multivariate data analysis, PLS (Partial Least Squares), in the permeability prediction from NMR relaxation data. This approach can be useful mainly when evaluating low permeability gas sands reservoirs, resulting in a more realistic production development plan. We also demonstrated that classical models like SDR, and the modified Timur-Coates, even with reestimated coefficients, suffered from a strong dependence of hydrocarbon occurrence, local lithology heterogeneities and porosities inaccuracies. Its worth to mention that an important feature of PLS regression demands a fewer number of calibration samples when compared with other multivariate techniques as ANN (Artificial Neural Networking). Despite the presented benefits, it is necessary to extend this research to verify the applicability of the PLS to other cases.

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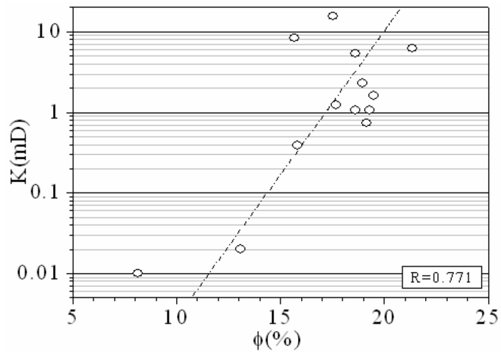

Figure 1. Porosity(ϕ) x absolute permeability(K), Klinkenberg corrected.

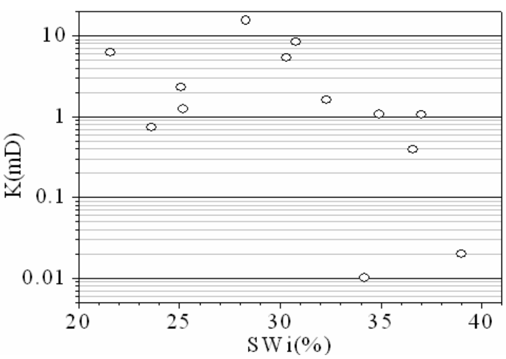

Figure 2. Irreducible water saturation (Swi) x absolute permeability (K).

Table 1. Optimized coefficients to the SDR and modified Timur-Coates equations.

Equation	Reestimated Coefficients		
	a	b	c
SDR	7.28×10^{-11}	4.56	2.68
Timur-Coates	3.85	1.74	109.64

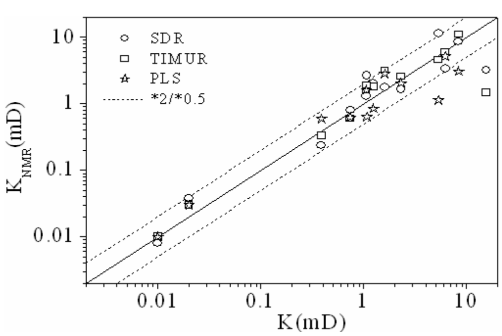

Figure 3. Absolute permeability (K) x core NMR-derived permeability (K_{NMR}), showing a good agreement between the SDR, Timur-Coates and PLS regression.

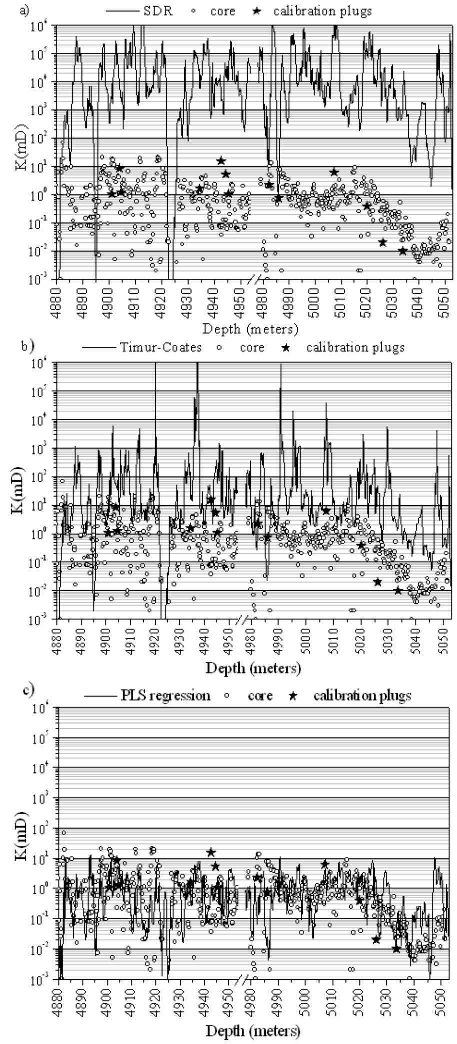

Figure 4. Application of calibrated SDR (a), modified Timur-Coates (b) and PLS model (c) to the NMR field log.

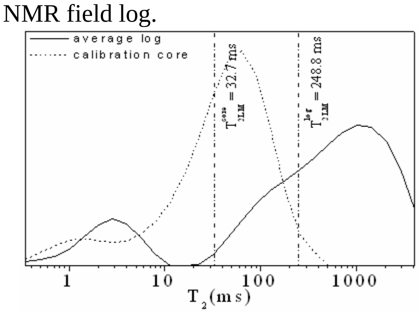

Figure 5. Normalized average T_2 log spectra of 15 different depths (4,933.95 to 4,935.02 m) and a 100% brine saturated calibration sample of 1.60mD.