Comparison between Stoneley and NMR permeability of a post-salt carbonate reservoir in the Campos Basin

Alexandre Campi and Abel Carrasquilla

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Abstract

The characterization and management of an oilfield requires knowledge about petrophysical properties of hydrocarbon reservoirs, which they are extreme important. Among several properties stands out permeability. This paper evaluated a post-salt carbonate reservoir located in the Campos Basin and has purpose to compare permeabilities estimated from full wave acoustic logs (Stoneley wave) and NMR logs. The NMR permeability has been estimated from Timur-Coates empirical model. In the case of the full wave acoustic log, Stoneley permeability is obtained from Stoneley wave travel-time and attenuation that are directly related to formation permeability. The Stoneley and NMR permeabilities was compared and, the permeability results have been shown very good correlation for these two different methods.

Introduction

Permeability can be estimated from full wave acoustic and nuclear magnetic resonance (NMR) logging data.

There have been many attempts at evaluating permeability from Stoneley wave. Rosenbaum (1974) was the first to propose a method to estimate permeability using Stoneley wave, who used the Biot (1962) theory to established the connection between permeability, Stoneley wave attenuation, and travel time delay. In 1984, Williams et al. published the first field examples of effects on Stoneley wave data. The simplified based on Biot's poroelastic theory were developed by Schmitt et al. (1988). By combining laboratory measurements and petrophysical models, Winkler et al. (1989) demonstrated the connection between formation permeability and Stoneley wave properties. Based on the Biot-Rosenbaum model, Tang et al. (1991) developed a simplified model to invert Stoneley wave amplitude to permeability. A fast algorithm to estimate using the Stoneley wave data have been described by Tang et al., (1996). Stoneley permeability has been estimated through the attenuation and travel time delay. NMR permeability was evaluated using the Free Fluid empirical developed by Timur (TIMUR, 1969).

The main objective on the present study is to estimate Stoneley and NMR permeability from logging data, in specially Stoneley permeability. The NMR permeability will be used as a benchmark to verification Stoneley permeability model efficacy. As these measurements are based on different physical principles, the agreement of the results increases confidence in the validity of the permeability results (TANG and CHENG, 2004).

Method

The approach to compare permeability estimation from Stoneley waves and NMR consist, basically, on the main processes:

1. Stoneley permeability – Determine the wavenumber of an elastic equivalent formation (ke); calculate the wavenumber (k) of the Stoneley wave measured; determine the Stoneley wave attenuation as it propagating on perforation fluid/borehole wall interface; estimate Stoneley permeability through Stoneley wave attenuation.
2. NMR Permeability – Estimating NMR permeability using the Timur-Coates model.
3. Comparison between permeability – Make a comparison between Stoneley and NMR permeability to evaluate the potential of using Stoneley waves estimating permeability.

Stoneley Permeability

Stoneley wave is a surface wave, which travels along the interface between the borehole fluid and formation. When a Stoneley wave travels along the borehole, this axially symmetric pressure pulse deforms the borehole wall. If the formation is hard, the deformation is small and the propagation velocity is close to the acoustic velocity of the borehole fluid. In a soft formation the deformation is larger resulting in a slower velocity. When the Stoneley wave travels trough a permeable formation, it not only deforms the rock matrix but also pushes the pore fluid away from the borehole wall into the formation. As a result, the Stoneley wave velocity decreases and the attenuation increases in a permeable interval (CHEN, 1999). These interaction between Stoneley waves and formation permeability, accordingly Tang and Cheng (2004) can be characterized by their wavenumber, whose equation is described as:

$$k = \sqrt{k_e^2 + \frac{2i\rho_f\omega\kappa R}{\eta(R^2-a^2)}\sqrt{\frac{-i\omega}{D}+k_e^2}\,\frac{K_1\left(R\sqrt{\frac{-i\omega}{D}+k_e^2}\right)}{K_0\left(R\sqrt{\frac{-i\omega}{D}+k_e^2}\right)}} \quad (1)$$

Where K_0 and K_1 is the zero and first order modified Bessel function, respectively. ρ_f is pore fluid density e η is viscosity. R is the borehole radius, a is the tool radius. The pore fluid diffusivity (D), the Stoneley wave propagation in the equivalent elastic formation (k_e) can be found from Tang and Cheng (1993a). κ is the static Darcy permeability. From wavenumber separation real and imaginary components, it is possible to calculate the Stoneley wave velocity and attenuation trough following expressions (TANG e CHENG, 2004).

$$V_{st} = \frac{\omega}{Re\,(k)} \tag{2}$$

$$Q^{-1} = 2\frac{Im\,(k)}{Re\,(k)} \tag{3}$$

At low frequencies, estimate permeability related to Stoneley wave attributes, such as attenuation, which is roughly controlled by following combination (TANG e CHENG, 2004).

$$\kappa_{st} = Q^{-1}\eta\sqrt{K_f} \tag{4}$$

Where $K_f = \rho_f V_f^2$ is formation pore-fluid modulus or incompressibility, η is formation fluid viscosity, Q^{-1} is the Stoneley wave attenuation and κ_{st} is the Stoneley derived permeability.

NMR Permeability

NMR permeability has been estimated using the Timur-Coates equation, in which uses the ratio of the moveable to bound fluid saturation derived from the T_2 distributions:

$$K_{TIM} = \left(\frac{\emptyset}{C}\right)^m \left(\frac{FFI}{BVI}\right)^n \tag{5}$$

Where, Φis the porosity in percent, FFI is the free fluid index that is related to the moveable fluid in large pores, while BVI is the bulk volume irreducible that is associated to the volume of capillary bound fluid contained in small pores (SKALR, 1997) and KTIM is the permeability in millidarcy.

Results

Stoneley permeability is obtained from Stoneley wave travel time and attenuation (Eq. (3)) that are directly related to formation permeability, while NMR permeability is derived from NMT T2 relaxation data that are related to pore size distributions (TANG and GHENG, 2004). Both Stoneley and NMR permeability were obtained without calibrating on other sources. NMR permeability was estimated from the Timur-Coates model (Eq. (5)) using the theorical default values for m, n e C (m=4, n=2 e C=10) while Stoneley permeability was obtained by using **a**, $\boldsymbol{\eta}$, $\boldsymbol{\rho_f}$ e $\boldsymbol{V_f}$ from the dataset (a=0.0461m, η =0. 0517Pa.s, ρ_f =1150.33 kg/m³ e V_f=1496 m/s).

Figure 1 shows the result of comparing Stoneley derived permeability (Eq. (4)) with NMR permeability for a carbonate formation. Track 2 shows gamma-ray log. Track 3 shows effective porosity along the well. Track 4 shows attenuation of Stoneley wave and the slowness difference measured Stoneley wave and Stoneley wave of simulated equivalent elastic formation. The correspondence between the attenuation and slowness difference gives a good indication of permeability effects, as is expected by theorical relation. Therefore, the correspondence between these two curves is used as the quality control for Stoneley wave permeability estimation (TANG and CHENG, 2004). Track 5 shows the Stoneley and NMR permeability results.

From the results in Figure 1 it is remarkable to see that the permeability from Stoneley wave and NMR correlate very well. However, in the section between 320 m and 375 m, where the gamma-ray log shows considerably high values, we can see difference between the Stoneley and NMR permeability, probably because of the presence clay-sized matter, which have very low permeability values.

In the section 375 m and 445 m, along the reservoir, it can be seen that both permeabilities curves are nearly coincident, that is, they overlap over this interval. Figure 2 shows a crossplot of the permeability estimates from NMR log versus Stoneley wave log, where an adjustment was made using linear regression. The equation of the linear regression is given by:

$$\log(PERM_{ST}) = -0{,}170 + 1{,}236\log(PERM\_TC\_NMR) \tag{6}$$

The adjusted curve presented a correlation factor R^2 = 0.756, which represents a very good match between the curves, even though there are some variations between them.

Conclusions

Logging data from a carbonate formation of a post-salt Campos Basin reservoir was used to compare permeability estimates from NMR and full wave acoustic log. From analyzes in this work it was possible to verify that the permeability estimated by Stoneley wave correlates very well with the permeability estimated by the NMR method, whereas it has shown a correlation factor R^2 = 0.756. Since the two permeability profiles are based on fundamentally different physical concepts and derived from different measurements, the agreement gives confidence that the derived permeability profiles are correct.

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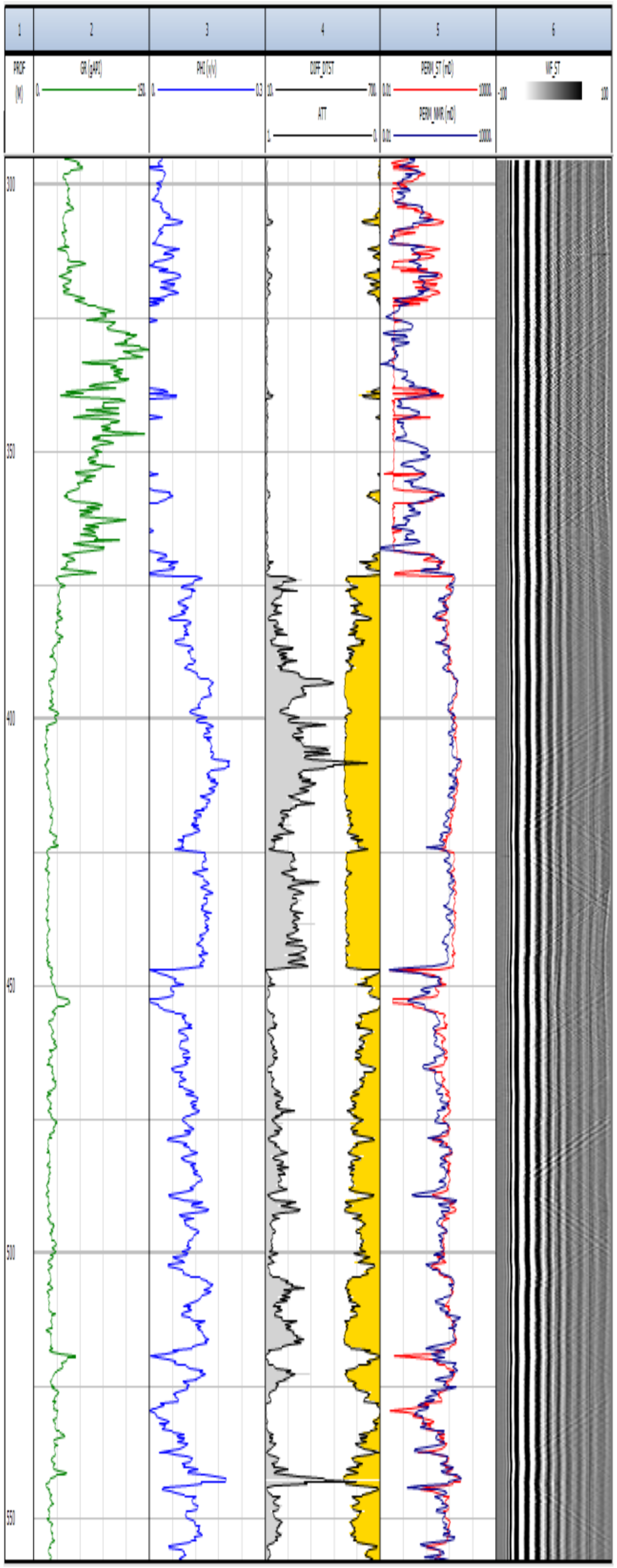

Figure 1 – Permeability results along the well. Good correlation is observed from the interval 375 – 445m.

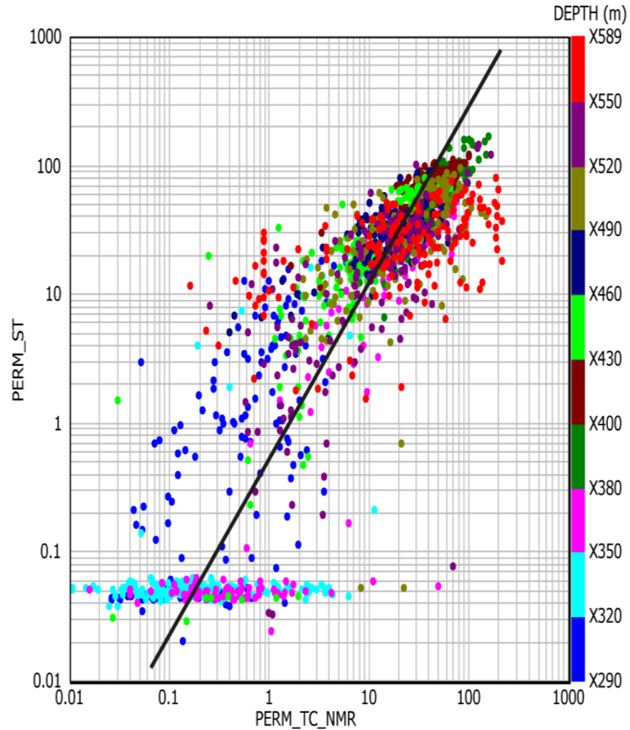

Figure 2 - Stoneley permeability vs NMR Permeability