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Permeability Estimation from Stoneley Waves in Carbonate Reservoirs

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Abstract: Permeability is one of the petrophysical properties of oil and gas reservoirs and is defined as the ability of rock to transmit fluids through the porous media. After exploration of any reservoir, permeability information is necessary to optimize the well completion method, oil and gas production and field development. Permeability is determined by both direct and indirect methods. Direct methods are core analysis, well testing, and modular dynamic tester (MDT) and the indirect method is using well logging data such as nuclear magnetic resonance (NMR) and porosity. Determination of permeability from the Stoneley slowness is one of the indirect and continuous methods in the whole well-bore and has been chosen as the goal of this study. The result of this correlation has been plotted against other well logging data and there is a very good match between this result and other petrophysical properties. Due to the complex nature of permeability in carbonate reservoirs, most of the time there is not a good match between this parameter and other petrophysical properties. This study has been conducted on the data of a single well and correlation has been determined. The results show that in calculation of permeability from Stoneley waves, the effective parameters are porosity, lithology, Stoneley slowness and accuracy of the MDT tool. For more precise correlation in a reservoir or a specific geological area, more data from other wells or reservoirs are necessary.

Keywords: Carbonate reservoirs, Dipole Shear Sonic imager, permeability, stoneley waves.

INTRODUCTION

Knowledge of permeability and its distribution is critical in many aspects, such as planning and implementing completion strategies for successful water flooding programs and constructing a representative simulation model for effective reservoir management. Nowadays in industry, core analysis is considered as the most representative permeability tool for micro scale characterization, and well test acquisition is considered as the most representative method to measure permeability for entire reservoir modeling (Burchette, 2012). Core analysis is not possible unless coring a representative sample during or after the drilling operation. In addition, if there is large scale heterogeneity, like in carbonate reservoirs, then a core sample might represent the only local variation. In a carbonate reservoir, high permeability thin streaks might exist, which will be masked by the overall permeability seen through the testing operation. In addition, both coring and testing wells are not performed in every well in a field.

Since logs are generally performed in every well, several empirical attempts were made to utilize the available log data to estimate

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permeability. In 1927, Kozeny proposed an equation which related measurable rock properties to permeability that was modified by Carman (Ren et al., 2016). In 1968, based on laboratory studies of 155 sandstone cores from different US oil fields, Timur (1968) proposed a slightly different relationship that was used by the entire oil industry. Neasham (1977) studied the impact of clay on the porosity-permeability relationship in sandstones. In order to measure rock permeability by acoustic logs, the relation between permeability and borehole acoustic waves has been studied both theoretically and experimentally over the past several decades. Rosenbaum (1974) simulated acoustic logs in a porous formation by applying Biot's poroelastic wave theory (Biot, 1962) and found a relationship between permeability and the borehole Stoneley wave (Guan, et al., 2013). This model is therefore termed as the Biot-Rosenbaum model (Tang & Cheng, 1996). From acoustic logging data, Williams et al. (1984) also recognized that the velocity and the attenuation of the Stoneley wave are related to formation permeability (Zemanek et al., 1984). Then Tang and Cheng (1996) proposed a fast inversion method to determine formation permeability from Stoneley wave logs (Tang & Cheng, 1996). Brie et al. (2000) proposed an equation that the Stoneley slowness in a nonpermeable zone can be calculated (Abbott et al., 2000). Al-Adani & Barati (2003) studied the effect of permeability on Stoneley slowness. They presented Stoneley slowness around the borehole divided into Stoneley slowness in nonpermeable and permeable zones. Hadavandand and Moradzadeh (2007) used Al-Adani's method in sandstone reservoirs and showed that this method is useable in carbonate and sandstone reservoirs (Al-Adani & Al-Khatib, 2008). Mosalman-Nejad (2008) compared the permeability obtained from Stoneley waves with permeability obtained from NMR (nuclear magnetic resonance) and showed that the result of Stoneley waves has more similarities with core analysis (Jafari et al., 2012). Sun et al. in 2012 studied the full spectrum of sonic waves and examined permeability associated with each type of sonic waves (Sun & Han, 2012). They found that the variation in speed and the extent of slowness in a Stoneley wave is more related to permeability. Guan et al. (2013) investigated Stoneley waves in water saturated pores and obtained a continuous log that showed the permeability changes around a borehole (Guan et al., 2013; Shirazy et al., 2020a & b). Permeability is one of the indicators that can be checked using remote sensing (Shirazi et al., 2018a, b, c, d, & e). It can also be used to study mineral processing (Doodran et al., 2020; Khakmardan et al., 2020; Shirazy et al., 2020a &b; Shirazy et al., 2021a & b).

The aim of this study is to obtain a continuous graph of permeability changes throughout the reservoir formation. For this purpose, using acetone waves and mathematical relations, the permeability value was calculated continuously throughout the formation. The values obtained were also compared with the values measured by the MDT tool.

METHODOLOGY

The subject of the study is wave-based permeability in carbonate reservoirs. When boreholes are drilled in permeable areas, the movement of liquids in that area increases, which slows down and dampens the wave. In fact, what reflects the wave in the rock is the strong impedance contrasts that appear as Chevron patterns in the variable density log (VDL) display (Ahmed et al., 1991; Brie et al., 2000).

As mentioned above, because the slowness of Stoneley waves is affected by dynamic processes between the borehole and formations, this factor is a qualitative indicator of permeability variation in the whole well-bore. After plotting Stoneley slowness against permeability (MDT permeability) data, and calibration of this data with available permeability, this qualitative indicator is converted to a quantitative relationship between permeability and Stoneley slowness (Equation1):

$$K=\frac{DT_{st}-DT_{st\ none-permeable}}{\sum_{i=1}^{n} m_i v_i} \quad \textbf{(1)}$$

where DT_{st} is total Stoneley slowness time, $DT_{st\ non\text{-}permeable}$ is Stoneley slowness time in a non-permeable zone, and n is the porosity factor necessary to be determined in each reservoir or single well individually. M is $\sum m_i v_i$ where is the fraction volume of different lithologies (from petrophysical analysis) and m_i is determined by solving a system of two equations that are represented in Equation 2. This equation can determine the accordance factor between Stoneley slowness and the variation of lithology in the formation. (In Equation 2, two types of lithology are assumed, illite and calcite.):

$$\begin{cases} V_{ill}m_{ill} + V_{clc}m_{clc} = M_{oil\ zone} \\ V_{ill}m_{ill} + V_{clc}m_{clc} = M_{water\ zone} \end{cases} \quad \textbf{(2)}$$

where m_{ill} is the accordance factor between Stoneley slowness and illite, m_{clc} is the accordance factor between Stoneley slowness and calcite, V_{ill} is the average volume of illite in each zone, V_{clc} is the average volume of calcite in each zone, and $M_{oil\ zone}$ and $M_{waterzone}$ are the accordance factors in the oil zone and water zone, respectively.

Stoneley slowness in a non-permeable zone is calculated by using the expression in Equation 3:

$$Dt^2_{st\ non-permeable} = \frac{\rho_m}{\rho_b}(Dt_{sh})^2 + Dt^2_{bf} \quad \textbf{(3)}$$

$Dt_{st\ non-permeable}$ is the slowness in a non-permeable zone.

ρ_b is the bulk density of the rock.

Dt_{bf} is the borehole fluid (mud) slowness.

ρ_m is the density mud.

Dt_{sh} is the shear slowness of the rock.

The difference between $Dt_{st\ non-permeable}$ and Dt_{st} indicates the fluid mobility indicator. By cross plotting $Dt_{st\ non-permeable}$ versus $\frac{Dt_{sh}}{\rho_b}$ across non-permeable zones, the slope of the straight line is and the y-intercept is Dt^2_{bf}. There is one condition in such a linear fit; that all data on the cross plot should be above or on the fit line. According to Equation 4, by determining Dt^2_{bf}, then $Dt_{st\ non-permeable}$ can be calculated around the borehole:

$$Dt_{st} = Dt_{st\ non\text{-}permeable} + Dt_p \quad \textbf{(4)}$$

DATA

In this study, the aim is to determine the permeability by Stoneley waves in one of the carbonate reservoirs in the south of Iran. The Fahlian formation is the main reservoir rock of this field, having about 500 meters of carbonate deposits, a gradual boundary over the Garou formation, and a discontinuous boundary under the Gadvan formation. In this study, the Resistivity, SGR, NPHI, Sonic logs and MDT test were acquired. Firstly, the petrophysical analysis was carried out using IP software (Interactive Petrophysics). The petrophysical parameters were determined and are shown in Figure 1. The clay mineral type could not be identified accurately due to the very low concentration of clay in the study zone. Illite was assumed as the main clay mineral in this formation.

RESULTS and DISCUSSION

First, the calibration factor was determined in each oil and water zone by cross plotting MDT permeability versus DT_{st}. The slope of the straight line represents the calibration factor. Figures 2 and 3 show these cross plots in the oil and water zone, respectively.

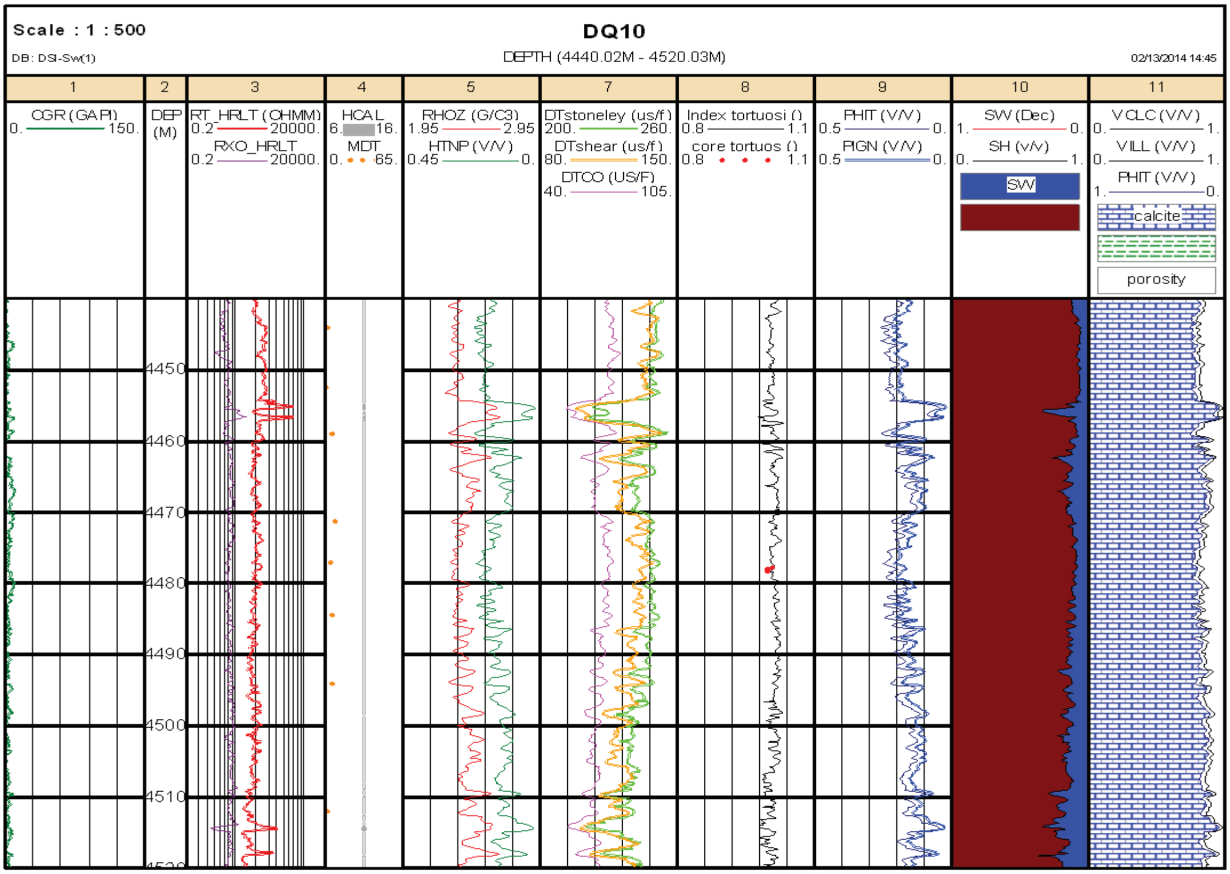

Figure 1. Petrophysical logs in studied well.

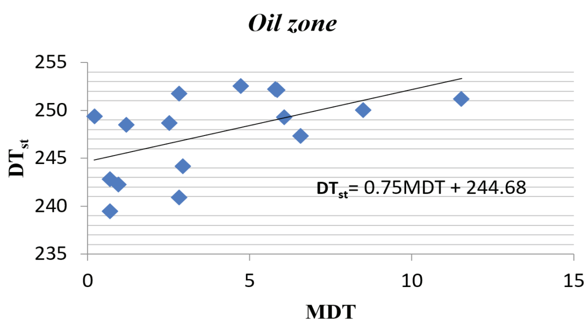

Figure 2. Cross plot of MDT versus DT_{st} in oil zone.

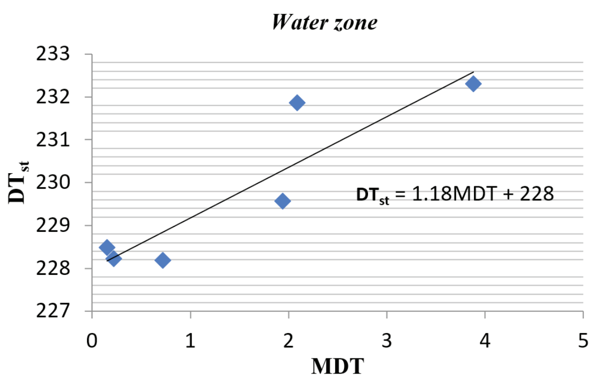

Figure 3. Cross plot of MDT versus DT_{st} in water zone.

As shown in the figures, the calibration factor in the oil zone is equal to 0.75 and in water zone it is equal to 1.18.

From Equation 2 the m_{ill} equals 85.213, and m_{clc} equals 0.347 from Equation 5.

$$\begin{cases} 0.00525m_{ill} + 0.8746m_{clc} = 0.75 \\ 0.01m_{ill} + 0.9325m_{clc} = 1.18 \end{cases} \qquad \textbf{(5)}$$

Now the Stoneley slowness in non-permeable zone has been calculated by Equation 3 and 4, then by using Equation 1, the continuous quantitative permeability along the bore-hole can be calculated. The generated permeability log with Stoneley slowness measured by the DSI tool is shown in column 9 of Figure 4. The red point on the log refers to MDT permeability. There is a good fit between the generated log and MDT permeability (Figure 5), equal to 89%.

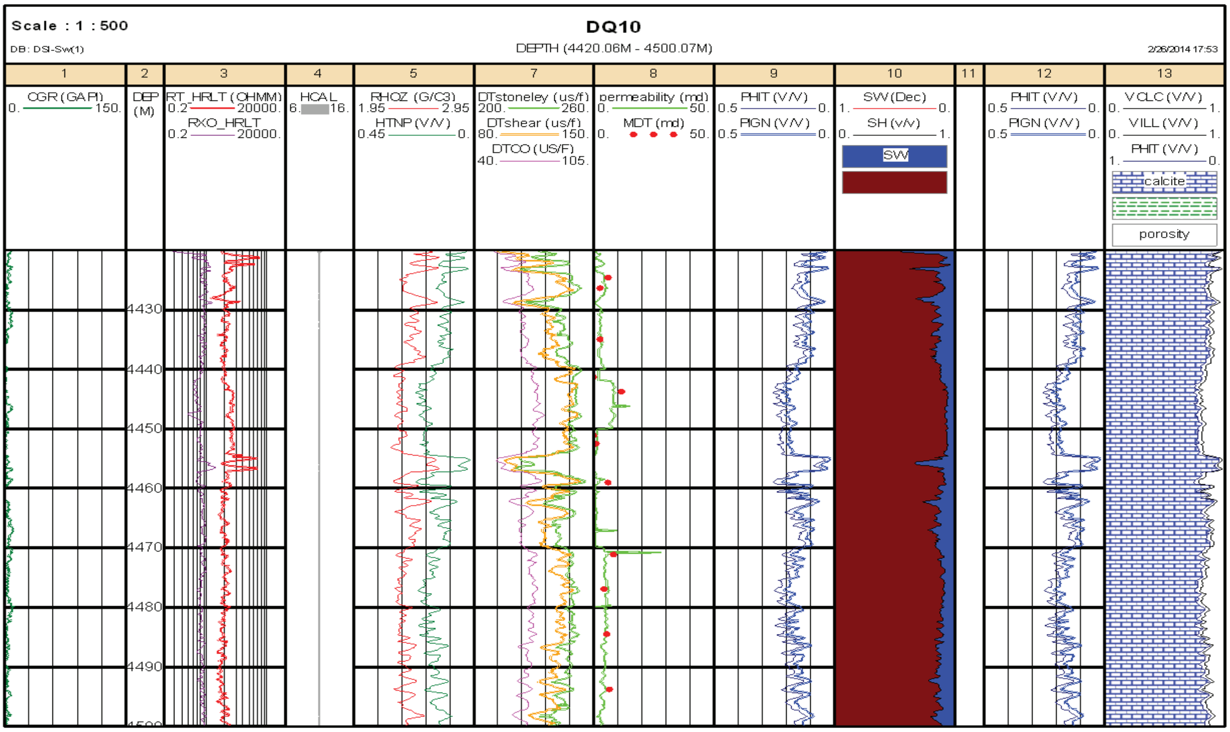

Figure 4. Generated permeability log by Stoneley slowness in column 7. The red points are MDT permeability.

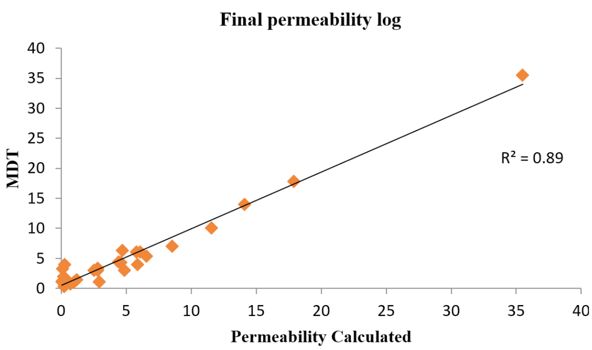

Figure 5. Good match between calculated values and MDT (mD).

CONCLUSION

The main advantage of using Stoneley waves in estimating permeability is by providing a continuous log of permeability changes through the borehole without using core data, which are obtained by recording the intrinsic properties of Stoneley waves influenced by permeability and by quantifying the relation between these waves and permeability. In order to calculate an accurate value of permeability by this method, it is necessary to consider all parameters which affect permeability.

Results show that one of the effective parameters in this method is the slowness of Stoneley waves in a rock matrix. If the values of this parameter are not accurate enough, the values of the calculated permeability cannot be sufficiently precise. In this study, we used advanced sonic technology to determine permeability in a prolific oil reservoir in one of the carbonate reservoirs in southern Iran. The advanced sonic technology method uses Stoneley wave analysis, in which the input parameters are calibrated with the MDT data. Accordingly, the result of this correlation was plotted against other well logging data and there is a very good match between this result and other petrophysical properties. Due to complex nature of permeability in carbonate reservoirs, there is generally not a good match among the parameters of the cementation coefficient and the porosity and tortuosity coefficients in comparison with other permeability calculation methods, such as artificial neural networks.

This study has been conducted on the data of a single well and a certain correlation has been determined. For more precise correlation in a reservoir or specific geological area, more data is required, such as more wells from which the DSI chart is prepared, or the FMI log.

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