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Reducing predictive uncertainty in log-derived water saturation models in a giant tight shaly sandstones – A case study from Mesaverde tight gas reservoir

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ABSTRACT

A log-derived calibration coefficient is introduced to calibrate conventional water saturation models in tight shaly sandstone reservoirs in the Rocky Mountains, western United States, in this study.

It is implemented for calibration of eight traditional saturation models in this giant gas field to prove its validity. The application of this calibration coefficient indicates that it is a simple and strong tool for improving of water saturation estimation in tight shaly sandstones, particularly for zones with high GR and/or low true resistivity. The proposed calibration coefficient is based upon an expression which depends on true resistivity log, neutron and density logs to take total porosity and gamma ray log. It has a significant advantage i.e. independency from electrical rock properties (Archie's parameters): **m** (cementation factor), **n** (saturation exponent) and **a** (tortuosity factor). It means that the variety of them cannot affect the operation of the introduced calibration coefficient.

In this study, the calibration results of the eight traditional water saturation models are compared with core results for 2579 data points that are taken from fourteen wells (39 different zones) from Mesaverde in five western USA basins. This study shows that the new approach that is introduced is more efficient as it reduces the uncertainty associated with water saturation estimation in zones with high GR and/or low true resistivity than zones with low GR and/or high true resistivity in tight shaly sandstones.

1. Introduction

Tight gas reservoirs are decidedly "non-Archie" in their behavior (Miller and Shanley, 2010). For this reason, the current log-derived water saturation models cannot be used in these types of reservoirs. However, in the absence of an alternate approach, the petrophysical community has to use these types of models.

One of techniques in order to dominate this problem is introducing a calibration coefficient to calibrate traditional water saturation models with tight sandstones in low porosity and low permeability system. In previous work (Amiri et al., 2012a), a calibration coefficient was introduced to calibrate Indonesian water saturation model with tight shaly sandstones that is:

$$MA^{*} = \frac{GR/(N-(((100{*}\phi_t)+R_t)/2))}{\sqrt[3]{\left(\sqrt[3]{((\phi_t/C_o)+(R_t/F))/2}+(R_o/R_t)\right)/2}} \tag{1}$$

where GR is response of gamma ray tools, N is GR corrector that should be '70' or '100' that depends on especial conditions, ϕ_t is the total porosity, R_t is the true resistivity that is response to deep resistivity tools, C_o is the conductivity of the shale free formation 100% saturated with water, F is the formation resistivity factor, R_o is the resistivity of the shale free formation 100% saturated with water.

To improve Indonesian model, the introduced calibration coefficient (MA^{*}) should be multiplied by Indonesian model. However, this expression has three disadvantages.

1) It calibrates especially Indonesian model in tight system.
2) Its denominator does not have scientific justification and it was gained by a trial and error process.

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3) It does not show good performance to calibrate the other traditional log derived models because it depends upon formation resistivity factor.

The method that was used for determination of formation resistivity factor is:

$$F = \frac{a}{\phi_t^m} \tag{2}$$

where $\boldsymbol{a}$ is the tortuosity factor that was considered 1, ϕ_t is the total porosity and $\boldsymbol{m}$ is cementation factor. Therefore, the introduced calibration coefficient is highly dependent on cementation factor. For this reason it cannot show good performance in different rocks with different physical properties.

The major aim of this study is solving these problems in order to reduce the uncertainty associated with the prediction of water saturation by the other saturation models in tight shaly sandstones.

2. Calibration coefficient

The calibration coefficient is introduced by using “Finding true position” technique based on porosity–resistivity cross plot (Amiri et al., 2012b) to improve prediction of water saturation by conventional models in tight shaly sandstones.

Firstly, it must be found out what is happening in tight formations. Normally, the bulk porosity decreases in tight sandstones formations due to compaction and cementation. Hence, with decreasing porosity value, the bulk density will increase therefore the amount of water saturation decreases and subsequently it can be understood that true resistivity formation will increase.

Thus, there are two attributes in tight formation that differ from conventional reservoir:

1) Lower porosity
2) Higher resistivity

Therefore, calibration coefficient can be assumed with regard to these two properties.

The $R_t - \phi_t$ cross-plot is used with regard to these properties. The points from 100% water bearing formations were laid on the line for $S_w = 1$ drawn from the pivot point ($\phi = 0$, $R_t = \infty$) through the most northwesterly plotted points (right line in Fig. 1). According to Eq. (3) and if a = 1 and n = m = 2, then it can be observed that water saturation is inversely related to true resistivity. Furthermore, true resistivity and porosity have inverse proportional relationship too.

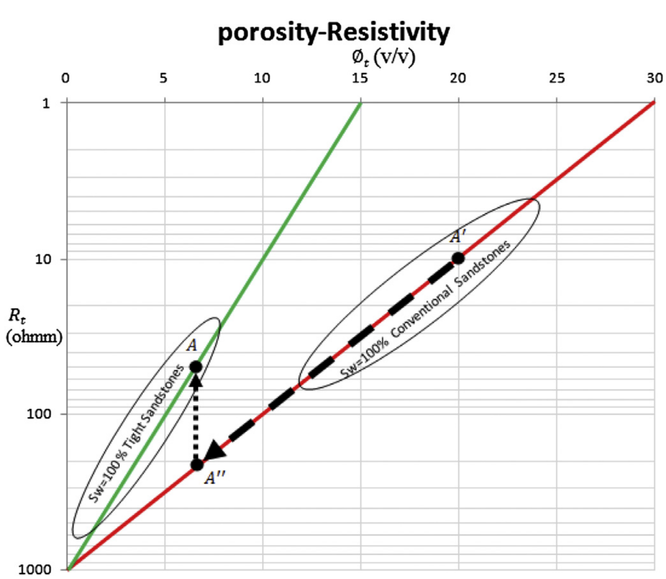

Fig. 1. Transformation in resistivity–porosity cross-plot.

$$S_w^n = \frac{F \cdot R_w}{R_t} = \frac{a \cdot R_w}{\phi^m \cdot R_t} \tag{3}$$

$$\phi \propto \frac{1}{\sqrt{R_t}} \rightarrow {\phi_t}^2 \propto \frac{1}{R_t} \tag{4}$$

Because of decreasing porosity and increasing resistivity in tight sandstones, it can be seen that the slope of $S_w = 100\%$ line for tight sandstones formations increases and moves to the left side of $S_w = 100\%$ line for conventional sandstones (left line in Fig. 1) and the center of data aggregation (peak frequency) in conventional sandstones, shown by black ellipse, will be shifted to beneath the resistivity–porosity cross-plot on green line (left line in Fig. 1).

All previous water saturation models were fundamentally derived from Archie's classic work in the Gulf Coast, where he was working with high-porosity and high-permeability systems. Thereby, previous models were calibrated for high-porosity and high-permeability conditions. Consequently, the points with $S_w = 100\%$ in tight sandstones were laid on red line apparently and these models cannot determine the actual position (green line) of these points. To improve them for tight sandstone formations, a calibration coefficient should be determined in order to move the points with $S_w = 100\%$ from apparent position to actual position. It is important to know that the determined calibration coefficient shall be based on (or depend on) variation rate of resistivity and porosity.

2.1. Transformation from apparent position to true position

All along for simplification of theory, it was assumed that there are two zones with water saturation 100% one of which is conventional sandstone and the other one is tight sandstone (Fig. 1). Because conventional models were fundamentally derived from Archie's model in high porosity and permeability, they were therefore calibrated by these conditions. As a result, point A that represents water saturation values on tight sandstones formations is incorrectly located on A' representative of water saturation values on conventional sandstones formations. The proposed calibration coefficient should return point A' to A.

To do so, first a relationship (calibration coefficient (CC)) must be assigned to shift points induced by traditional models (A') to left hand along red line (toward increasing resistivity and decreasing porosity – point A''). In order to shift points from A' to A'', the value of water saturation is reduced. Therefore, a fraction less than one needs to be proposed. Following analyses, the expression 5 was found that is related to porosity and resistivity. Porosity values were multiplied by 100 for unit conversion to percentage.

$$CC = \frac{1}{\left(\frac{(100*\phi_t)+R_t}{2}\right)} \tag{5}$$

where R_t is true resistivity obtained from resistivity log, ϕ_t is total porosity.

Now, transform from A' to A'' can be done via multiplying the expression 5 by the traditional water saturation model to shift data set to left hand. Then, it should be tried to change the value of expression 5 in order to shift point A'' near the point A because the