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Comparison and sensitivity analysis of water saturation models in shaly sandstone reservoirs using well logging data

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ABSTRACT

Shaly sandstone reservoirs have complex pore systems with ultra-low to low interparticle permeability and low to moderate porosity. This has leaded to development of several models to calculate water saturation in shaly sandstone reservoirs using different approaches, assumptions and certain range of conditions for application.

This practical study has used actual well logging data from two different fields of South Texas and North Sea to evaluate and compare the most popular five shaly sandstone models for calculating water saturation. A systematic approach is presented for identification of shale distribution for selection of suitable model. Furthermore, sensitivity analysis of tortuosity coefficient (a), cementation exponent (m) and water saturation exponent (n) is achieved to investigate their effects on computed values of water saturations using different models.

The results indicated that identification of shale distribution is necessary and improper utilization of shaly sandstone models results in drastically erroneous values of water saturation. Therefore, shale distribution in the South Texas field is identified to be mainly laminated with few of structural ones while distribution is dispersed in the North Sea field. The results also showed that the increase of shale volume decreases water saturation calculated for all popular models. In addition, the increase of tortuosity coefficient and/or cementation exponent (m) causes overestimation of water saturation while the increase of saturation exponent (n) results in an underestimation values.

The application of the attained results of this study will have real improvement in selection and application of the appropriate shaly model. This provides more accuracy and real improvement in formation evaluation, reserve estimation, reservoir characterization, and consequently in reservoir simulation.

1. Introduction and literature review

Development of shaly reservoirs represents a real challenge in the oil industry due to their severe heterogeneity and complex nature.

The calculation of irreducible water saturation (S_{wi}) is essential to calculate the oil saturation ($S_o = 1- S_{wi}$), which is imperative in calculating hydrocarbon volumes. The existence of clay minerals in oil and gas reservoirs complicates the calculation of water saturation using Archie's equation (1942). This is because the behavior of the clay particles depends mainly on shale type and its distribution in the pore space which contributes to the electrical conductivity of the formation.

The effective use of well logging data is essential is different areas of the oil industry such as formation evaluation (Shedid et al., 1998), reservoir characterization (Shedid et al., 1998; Shedid-Elgaghah et al., 2001) and enhanced oil recovery applications (Nian et al., 2015). Nian et al. (2015) presented an effective inversion method for estimating the flow rate from temperature log data. They also applied a sensitivity analysis to investigation of the correlation between the flow rate and fluid temperature log data. Nian and Cheng (2017) indicated that predictions of the field behavior under thermal enhanced oil recovery requires accurate formation and reservoir evaluation to improve efficiency of oil recovery.

Many models have been developed to calculate the water saturation in shaly sandstone formation depending on the shale type and its distribution. Applying different approach of each water saturation model has leaded to different values of water saturation are calculated. This may cause drastic erroneous values of calculated hydrocarbon volumes.

1.1. Water saturation model for clean-sand reservoirs

Archie (1942) proposed the most popular and widely used model to determine water saturation in clean sand zones. This model was mainly

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developed using a theoretical approach for clean sandstone and carbonates having zero shale volume. Therefore, application of Archie's model requires special consideration for the resistivity data used. Archie's model is given by the following equation:

$$S_w = \left(\frac{aR_w}{\phi^m R_t}\right)^n \quad (1)$$

where a is the tortuosity factor, m is the Archie cementation constant, n is the Archie saturation exponent, R_w is the brine water resistivity at formation temperature (ohm-m), R_t is true resistivity of uninvaded deep formation (ohm-m), and φ is the total porosity (%).

Shale is defined as a clay-rich heterogeneous rock which contains variable content of clay minerals (mostly illite, kaolinite, chlorite, and montmorillonite) and organic matter (Brock, 1986; Mehana and El-Monier, 2016). The absence of shale characteristics in the above-Archie's equation, equation (1), reveals that Archie's equation wasn't designed and cannot be used for shaly sand formations. The presence of clay in the formation complicates the interpretation and may give misleading results if Archie's equation is used because the clay is considered to be a conductive medium. Therefore, several models were developed for calculating water saturation in shaly formations. These models are evaluated and compared in this study.

1.2. Water saturation models for shaly sand reservoirs

Presence of shale in the formation has been considered as a very disturbing factor and shown severe effects on petrophysical properties due to reduction in effective porosity, total porosity and permeability of the reservoir (Ruhovets and Fertl, 1982; Kamel and Mohamed, 2006). Moreover, the existence of shale causes uncertainties in formation evaluation, proper estimation of oil and gas reserves, and reservoir characterization (Shedid et al., 1998; Shedid, 2001; Shedid-Elgaghah et al., 2001).

For shaly sandstone reservoirs, different models have been developed depending on different factors, such as; (1) input parameters and their sources such as; routine core analysis, special core analysis and well logging data, (2) development approach such as; field or laboratory based, empirical or theoretical correlation, and (3) shale distribution and the model's dependency on types as laminar, structural or dispersed. Different shale distributions inhibit different electric conductivity, permeability, and porosity. The distribution of clay within porous reservoir formations can be classified into three groups (Glover, 2014), as illustrated in Fig. 1,:

1. *Laminated*: Thin layers of clay between sand units.
2. *Structural*: Clay particles constitute part of the rock matrix, and are distributed within it.
3. *Dispersed*: Clay in the open spaces between the grains of the clastic matrix.

In this study, the five popular shaly sand water saturation models are evaluated and compared using actual field well logging data. Furthermore, sensitivity analysis of the effects of coefficients (a, m, and n) involved in these models on computed water saturation is undertaken.

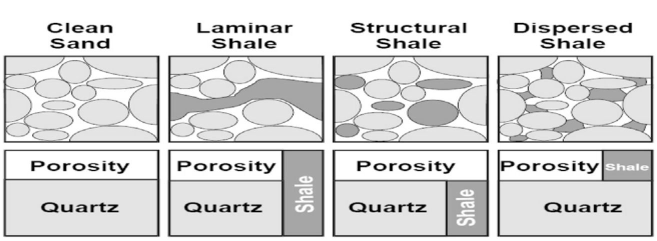

Fig. 1. Different shale distribution modes (Glover, 2014).

1.2.1. Laminated shale model

Poupon et al. (1954) developed a simplified model to determine water saturation in laminated shaly sand formations. Their approach described shale as multiple thin parallel layers of 100% shale interbedded with clean-sand layers within the vertical resolution of the resistivity-logging tool. The laminated shale does not affect the porosity or permeability of the sand streaks themselves. However, when the amount of laminar shale is increased and the amount of porous medium is correspondingly decreased and finally overall porosity is reduced in proportion. This model is given by the following equation:

$$S_w = \sqrt{\frac{aR_w(1-V_{sh})}{\phi^m}\left(\frac{R_{sh}-V_{Lam}R_t}{R_t R_{sh}}\right)} \quad (2)$$

where R_{sh} is the average value of the deepest resistivity curve reading in shale (ohm-m), V_{sh} is volume of shale in the formation (%), V_{lam} is the volume of laminated shale in the formation (%), and φ is the total porosity (%).

1.2.2. Dispersed shale model

Dispersed shale distribution is composed of clay minerals that form in-place after deposition due to chemical reactions between the rock minerals and the chemicals in the formation water. The dispersed shale is composed of clay particles, fragments or crystals to be found on grain surface that occupy void spaces between matrix particles and reduce the effective porosity (φ_e) and permeability significantly.

DeWitte (1950) developed a model for estimating water saturation in dispersed shaly sand formations. He assumed that the formation conducts electrical current through a network composed of the pore water and dispersed clay. The dispersed shale in the pores markedly reduces the permeability of the formation. This model is given by the following equation:

$$S_w = \frac{1}{1-q}\sqrt{\frac{aR_w}{\phi_{im}^2 R_t}+\frac{q^2}{4}} - \frac{q}{2} \quad (3)$$

where φ_{in} is the inter-matrix porosity (%), which is assumed to be equal to sonic porosity in shaly sand (%). The parameter q is called the sonic response and for dispersed shale distribution response, q could be described as:

$$q = \frac{\phi_s - \phi_D}{\phi_s} \quad (3\text{-A})$$

where φ_s is sonic porosity (%), φ_D is density porosity (%)

1.2.3. Simandoux's model

Simandoux (1963) developed a model for estimating water saturation in shaly sand formation. The model was a result based on laboratory studies performed on a physical reservoir model composed of artificial sand and clay in the laboratories of the Institute of French Petroleum (IFP). The Simandoux model remains one of the most popular, shaly sand water saturation models, and a highly influential framework for later studies in this field. The Simandoux equation works regardless of shale distribution and is given by the following equation:

$$S_w = \frac{aR_w}{2\phi^m}\left[\left(\frac{-V_{sh}}{R_{sh}}\right)+\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2+\left(\frac{4\phi^m}{aR_wR_t}\right)}\right] \quad (4)$$

All parameters involved in the above equation are defined above for the previously-listed models/equations.

1.2.4. Indonesian equation

Poupon and Leveaux (1971) developed a model to determine water saturation in laminated shaly formations. This model is widely known as