

Original Article: An alternative to Geolog software for fast calculation of water saturation using borehole data in a shaly sand reservoir, case study, Ahwaz Oil Field

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ABSTRACT

Water saturation evaluation has a direct effect on estimating hydrocarbon reserves in reservoirs, and inaccuracy in its values would affect the economics of field management and development plans. In shaly reservoirs it is a difficult task due to the heterogeneity nature of shale and the way the shale is distributed in reservoirs. So many scientists proposed models to determine water saturation from well logs in shaly sandstone reservoirs. The scope of this petrophysical study is to use five most commonly applied water saturation models (Archie's equation, Indonesian model, Simandoux, Fertl model, Schlumberger model) to estimate water saturation. Comparative analysis of water saturation calculated from the models and Geolog software was carried out with the aim to determine the most suitable water saturation model, alternative to Geolog software for fast calculation of water saturation in the studied area. The results show that the Fertl model is more consistent with the output of Geolog software and is able to predict water saturation with the least error compared to other methods. This work also clearly shows that the water saturation value was strongly sensitive for input parameter in low porosity and low log resistivity zone.

Introduction

Calculation of water saturation is Estimation of the hydrocarbons in place of a reservoir by volumetric methods requires petrophysical data including porosity and water saturation [4]. Archie [2] found an empirical equation for estimating water saturation in consolidating sandstone related to some formation parameters such as porosity and

formation resistivity which is expressed as follow:

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

Where S_w represents the water saturation, R_t is the logging resistivity ($\Omega.m$); R_w is the formation water resistivity ($\Omega.m$), ϕ is porosity, m represents the cementation factor, n represents

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the saturation index and a is lithologic coefficient.

At first, Archie equation was used for estimating water saturation in reservoir rocks with significant attributes such as clean, homogenous and thin bed, but these properties in heterogenous carbonate rocks may be unrecognized, so water saturation magnitude may be deviated and be overvalued [1].

The presence of shales makes water saturation so difficult to achieve due to the conductivity of shales, which can bypass high resistive hydrocarbons [6] so many scientists developed several methods to evaluate water saturation in shaly sandstone reservoirs based on different assumptions, approaches, models, methods, and laboratory tests, which may therefore lead to underestimation or overestimation in water saturation and hence hydrocarbon saturation.

In the shaly sands containing dispersed clay minerals, the Archie equation, under certain conditions, predicts erroneously high values of in situ water saturation. Therefore, simandoux model [15] and its modified models [3, 7, 10], were developed for the bearing sandstone reservoirs. Moreover, these models were modified in more detail for several kinds of clay types, effects and distributions such as dispersed clay model [17, 5].

In this study due to the lack of data 20 core plugs of a well have been used for measuring formation resistivity factor and evaluating cementation factor and constant a . After that, water saturation values were calculated using log data and water saturation models and compared with the water saturation calculated by Geolog software. This present work aims to:

- 1- discuss five most commonly applied water saturation models (Archie's equation, Indonesian model, Simandoux, Fertl model, Schlumberger model) using bore hole logs

- 2- Find a suitable formula alternative to Geolog software to calculate water saturation faster and easier
- 3- check the effect of the accuracy of the input parameters (R_t , ϕ) on the results

Material and methods

Materials

Well log data: Well logging tools are powerful methods to investigate and analysis the physical properties of the different subsurface formations around the wellbore at a cheaper cost (5% to 15% of total well costs) [11]. Well logging data used in the present study consists of GR (gamma ray log), NPHI (neutron log), RHOB (density log) and resistivity log from a hydrocarbon-bearing reservoir in the Middle East. Bore hole logs are used to determine the petrophysical properties (such as V_{sh} , ϕ_e and S_w) of the shaly sand reservoir.

Methods

Core porosity measurement: The calculated water saturation is function of log porosity. The error in log porosity will affect the quality of water saturation calculation. Thus, the log porosity is calibrated with core porosity measured in laboratory. This calibration is applied to the result to check for minor errors [6, 14]. Core porosity in reservoir condition were determined in Research Institute of Petroleum Industry at multiple stress conditions by using Helium gas in fully automated Core Measurement System, CMS-300 (figure 4).



Figure 1. Core Measurement System (CMS-300), Research Institute of Petroleum Industry

Up to 12 plugs can be loaded into a carousel. The length, diameter, and core plug identification number are typed into a computer that controls the instrument. Then the confining stresses up to maximum of eight desired for that particular core plug, are entered. After loading all the plugs, the operation is completely automatic and the final output is pore volume.

Formation Resistivity Factors measurement

In order to measure formation resistivity factor typical for the reservoir, a number of core plugs were chosen such that they represent the range of porosity. The plugs were saturated with high salinity brine. Resistivity of the samples (R_o) was measured at several net confining stresses by "Overburden Rig" instrument (figure 2). Increasing the net overburden pressure reduces the pore volume, which is determined by volume of brine extracted from plugs. Formation resistivity factors (FF) have been calculated for each net confining stress from this equation: $FF = R_o / R_w$



Figure 2. Formation resistivity factor apparatus under overburden pressure, Research Institute of Petroleum Industry

Cementation factor (m) and constant (a) were determined by fitting the best line in formation resistivity factor – porosity logarithmic cross plot.

Water saturation calculated by Geolog software

Geolog software, as a petrophysical analysis tool, was employed in this study to obtain water saturation versus depth. To resolve a petrophysical problem, two different approaches are available. The first method is a deterministic method which is generally suitable for simple lithology problems. In this approach, porosity, shale fraction, and shale volumes (saturation) are computed sequentially.

The second method is a multi-mineral approach referred to as Multimin. This approach is applied to complex lithology, where the minerals and rock pore fluids all affect the log responses. In this method, both log measurements and log response parameters are used in the log response equations, which will be solved simultaneously to compute the fraction volumes of formation minerals and fluids. Indonesia and other equations were selected here to compute fluid volumes and thus water saturation.

Several runs were performed according to different water saturation equations. Because of very low clay content in some parts of the reservoir, employing different water saturation equations did not make significant difference between the obtained water saturation logs.

Shale volume calculation

To determine the volume of shale from a Gamma ray log, several empirical formulations have been developed to correct and reduce the rock's shale volume (V_{sh}) as direct functions of IGR (Gamma Ray Index):

$$V_{shlinear} = IGR = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

Where GR_{log} is gamma ray log reading, GR_{min} is minimum gamma ray log reading, GR_{max} is maximum gamma ray log reading.

This linear function of shale content overestimated the volume of shale than normal [13]. So, non-linear methods give more accurate results. Therefore, gamma ray index (IGR) has been corrected by applying the following non-linear correlations:

$$V_{shLarionovOldRocks} = 0.33(2^{2IGR} - 1)$$

$$V_{shLarionovTertiaryRocks} = 0.083(2^{3.7IGR} - 1)$$

$$V_{Clavier} [5] = 1.7 - \sqrt{3.38 - (IGR + 0.7)^2}$$

$$V_{steiber} [16] = \frac{IGR}{3 - 2IGR}$$

Water saturation models using bore hole logs

This work is done after characterizing the clay types in the reservoir to review the calculated water saturation using the appropriate models. The Simandoux model is based on field experience and on laboratory measurements. The modified version is sometimes called the Total Shale Relationship. The equation requires quadratic or iterative solutions and are among the most used ones. It reduces mathematically to the Archie equation when $n=2$ and $V_{sh} = 0$. Below are the expressions for Simandoux equations:

$$SW_{SIMANDOUX} = \frac{a \cdot R_w}{2 \cdot \varphi^m} \left(\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + \frac{4\varphi^m}{a \cdot R_w \cdot R_t}} - \frac{V_{sh}}{R_{sh}} \right)$$

The Fertl (1975) model for shaly sands has the advantage that does not depend upon R_{sh} (shale resistivity). It uses instead a reservoir dependent empirically adjusted $0.25 \leq \alpha \leq 0.35$ parameter α :

$$SW_{Fertl} = \frac{1}{\sqrt{\varphi_e}} \sqrt{\frac{a \cdot R_w}{R_t} + \left(\frac{\alpha \cdot V_{shale}}{2}\right)^2} - \left(\frac{\alpha \cdot V_{shale}}{2}\right)$$

The Poupon-Leveaux Indonesia model was developed by field observation rather than from

experimental laboratory measurements. The formula was empirically modeled in water-bearing shaly sands, but the detailed functionality for hydrocarbon-bearing sands is unsupported except by common sense and longstanding use. The model is based on readily available standard log analysis parameters, and gives practical results that are comparatively easy to calculate. equation may work well with fresh formation water. The parameter R_{shale} (resistivity of shale) is usually taken from the resistivity reading of a nearby pure shale, assuming that the clay cements & silt, and the shale nature, are similar to those of the shaly sand.

$$S_{windonesia} = \left(\frac{\sqrt{\frac{1}{R_t}}}{\left(\frac{V_{sh}^{(1-0.5V_{sh})}}{\sqrt{R_{sh}}} \right) + \sqrt{\frac{\varphi_e^m}{a \cdot R_w}}} \right)^{\frac{2}{n}}$$

The Schlumberger modified Simandoux equation by introducing the factor $(1-V_{sh})$ to have an equation which gives the conductivity of shaly formation as follows:

$$\frac{1}{R_t} = \frac{\varphi^2}{(1 - V_{sh})R_w} S_w^2 + \frac{V_{sh}}{R_{sh}} S_w$$

or

$$SW_{Schlumberger} = \frac{(1 - V_{sh}) \cdot R_w}{2 \cdot \varphi^m} \left(\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + \frac{4\varphi^m}{(1 - V_{sh}) \cdot R_w \cdot R_t}} - \frac{V_{sh}}{R_{sh}} \right)$$

Area of study and field description

The Ahwaz oil field (Figure 3) is located at the south west of Dezful Embayment. The Ahwaz field is bounded between Ramin and Sardarabad fields in north, Marun field in east, Band Karkheh in West and Susangerd, Ab-Timor and Mansouri fields in South. Ahwaz field was discovered in 1962/63 and subsequent drilling has confirmed two reservoirs (Asmari and Bangestan). It is one of the largest hydrocarbons bearing structures in the world, and actually it is a large northwest-

southwest trending anticline with a subsurface area of 80 by 6.5 km. Currently.

This study is concerned only with Asmari reservoir. The structure is a northwest-southeast trending asymmetric anticline. The reservoir is separated into 8 zones. Zone 1, 6 and 8 were mainly carbonate whereas zone 2, 3, 4 and 5 were mainly sandstone, and zone 7 was locally sandy. This present study is on the shaly-sand zones. Ahwaz oil field contour lines and selected wells' locations are presented in figure 4.



Figure 3. location of Ahwaz Oil Field (James and Wynd. 1965)

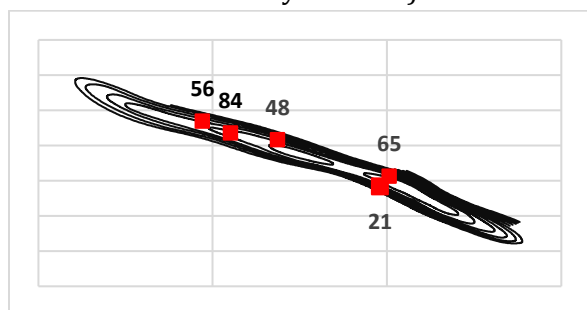


Figure 4. location of selected wells on Ahwaz Oil Field contour lines

Discussions and Results

The scope of this work is to calculate the petrophysical characteristics of the shaly sand reservoir, especially the water saturation (SW) and compare it with the output of Geolog software to Find a suitable formula alternative to Geolog software to calculate water saturation faster and easier.

To evaluate Cementation factor (m) and constant (a) 20 core plugs of one well were

chosen such that they represent the range of porosities typical for the reservoir. The plugs were saturated with reservoir brine (186000ppm). The resistivity of reservoir brine is equal to 0.045052 @ 25C. resistance of a fully brine saturated rock (R_o) is proportional to the amount of brine and the resistivity of the brine itself (salinity) and it has been corrected by using Arp's formula for each measurement. The salinity effect can be removed by dividing R_o by the brine resistivity, R_w , To give the formation resistivity factor $F = \frac{R_o}{R_w}$

Formation factor is inversely proportional to porosity $F = \frac{a}{\phi^m}$. The cementation factor (m) is a function of the shape and distribution of pores. It is determined from a plot of the formation resistivity factor versus porosity on a log-log plot. Such a plot generally can be approximated by a straight line, which has the slope (m). the intercept of this line with formation factor axis is the constant (a). table 1 shows the amount of porosity and formation factors in 2000 psi.

Table 1. Porosity and formation resistivity factor for a shaly-sand reservoir

Sample No.	Porosity (fraction)	Formation resistivity factor
1	0.1309	49.8328
2	0.1233	56.26
3	0.0835	102.19
4	0.2039	18.73
5	0.2587	15.04
6	0.2952	10.3838
7	0.2419	12.4259
8	0.1585	23.6978
9	0.1968	21.7443
10	0.2241	15.8908
11	0.2225	20.5251
12	0.1585	27.7074
13	0.2204	16.2934
14	0.0937	62.3791
15	0.1927	20.0109
16	0.1390	30.3725

17	0.1179	41.4773
18	0.1006	43.0888
19	0.0911	74.3358
20	0.1398	33.6908

According to figure 5, the correlation coefficient of straight line ($R^2 = 0.898$) is acceptable therefore in this shaly-sand cementation factor is 1.615 and a constant is 1.4646.

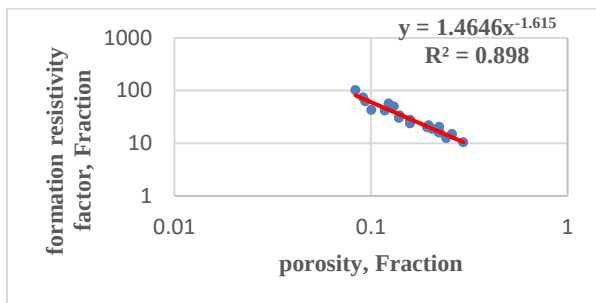


Figure 5. Formation resistivity factor vs porosity

The value of R_{sh} is considered as an average value of $1.4 \Omega.m$ obtained from log data where V_{sh} is more than 0.95 and R_w is $0.0625 \Omega.m$ measured in the laboratory. In this work, the volume of shale was calculated with all the presented models (Figure 6) and, Larionov (old rock) model was chosen as an average model with a lower error probability.

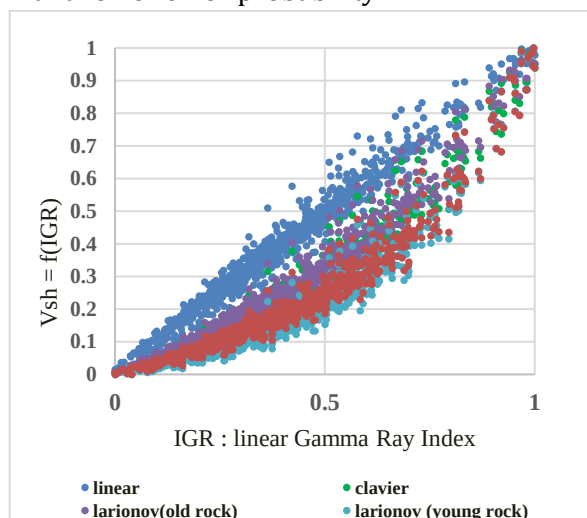


Figure 6. Shale volume calculated by 5 empirical models

Five water saturation models were applied to calculate water saturation from bore hole logs. The comparison between these models with Geolog software output is presented in Figure 7. Fertl's model has the most agreement and Archi's model has the least agreement with the output of Geolog software. The less agreement of Fertl model and the output of Geolog software in well 51 is due to the presence of thin carbonate layers in the selected interval. Compared to Indonesia² and Simandoux models, the Schlumberger model shows less difference with the output of Geolog software. Also, the results indicate that in places where the water saturation is less than 20%, the output of all the models is almost the same.

It must be noted that the accuracy of water saturation calculated by these models is highly dependent on the accuracy of the input parameters. Figure 11 is drowned for a rock with 43% shale volume and 29% porosity with R_t from 1 to $40 \Omega.m$. the results show that for R_t less than $10 \Omega.m$ a small change in R_t will cause a high error in the calculated water saturation however For R_t higher than $10 \Omega.m$, increasing the R_t will not affect the calculated water saturation.

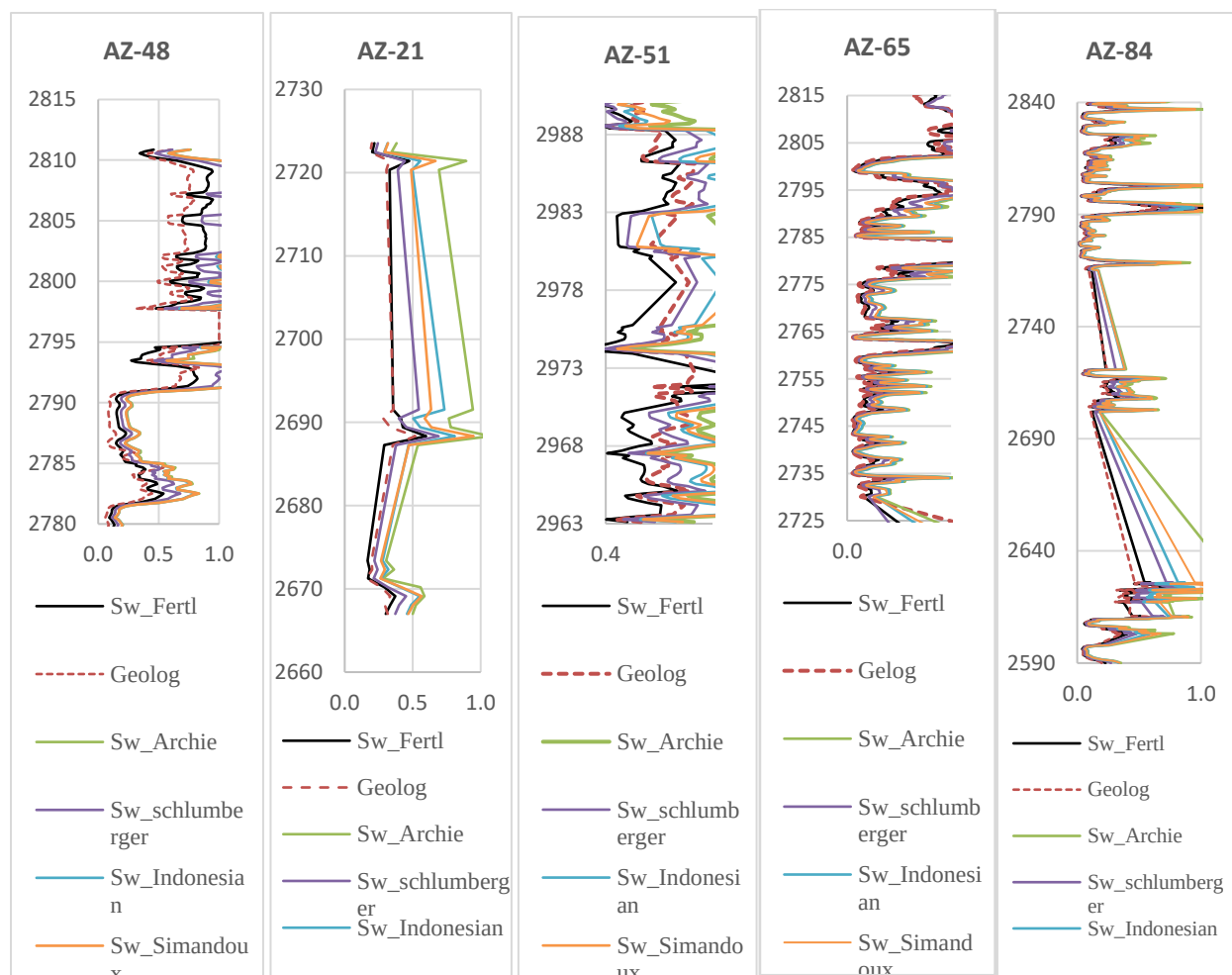


Figure 7. Water saturation vs depth calculated by 5 models compared with Geolog software output

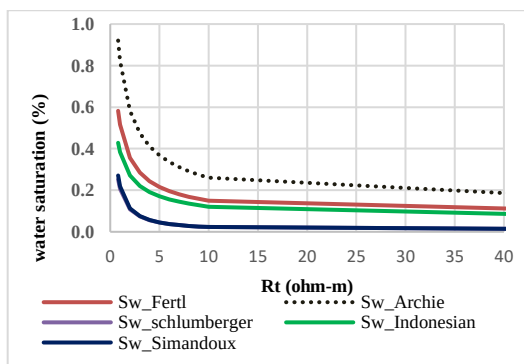


Figure 8. The effect of R_t on water saturation calculated with 5 models

The effect of shale volume on the calculated water saturation is presented in Figure 12. According to the obtained results for a rock with 30% porosity and R_t 40 $\Omega.m$, the Indonesia model shows the most sensitivity and the Fertl

model shows the least sensitivity to the volume of shale in the reservoir rock.

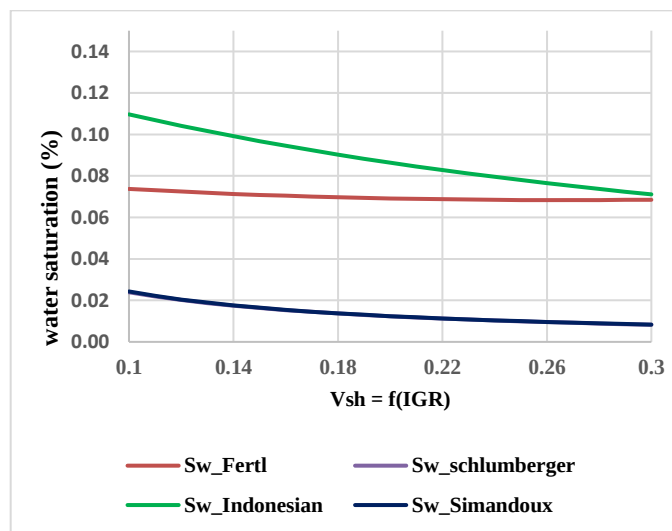


Figure 9. The effect of shale volume on water saturation calculated with 5 models

Conclusion

Based on the results achieved, the following conclusions can be drawn:

- An inappropriate choice of water saturation model may result in considerable error in the resulting water saturation estimates even at conditions that all supporting data used are the same. And it can result in overestimation or underestimation over the hydrocarbon accumulation volume.
- Fertl model is a suitable alternative to Geolog software to calculate water saturation faster and easier
- In places where the water saturation is less than 20%, the output of all the models is almost the same.
- The results show that for R_t less than 10 $\Omega.m$ a small change in R_t will cause a high error in the calculated water saturation however For R_t higher than 10 $\Omega.m$, increasing the R_t will not affect the calculated water saturation.
- the Indonesia model shows the most sensitivity and the Fertl model shows the least sensitivity to the volume of shale in the reservoir rock.

Abbreviations

a	Tortuosity factor., unitless
F	Formation resistivity factor., unitless
GR	Gama ray log reading., API
m	Cementation exponent., unitless
n	Water saturation exponent., unitless
Rw	Formation water resistivity., $\Omega.m$
Rt	True resistivity in the un-invaded zone., $\Omega.m$
Rsh	Resistivity of shale., $\Omega.m$
Sw	Water saturation., (fraction)
Vsh	Shale volume., (fraction)
Vs	Sand volume., (fraction)
ϕ	Porosity., (fraction)
ϕ_e	Effective porosity (fraction)

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