SCA-9851

PETROPHYSICAL EVALUATION OF LOW RESISTIVITY SANDSTONE RESERVOIRS

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ABSTRACT

There are many reasons for low resistivity pay zones phenomenon. It is of crucial importance to know the origin of this phenomenon. The problem with these zones is that the resistivity data interpretation indicates high water saturation, but oil or even dry oil will be produced. This paper discuss the different reasons sandstone reservoir can have low resistivity. Clean oil bearing sandstone has high resistivity, but when this rock contains shale, or heavy minerals such as pyrite, the resistivity can become low.

This paper deals with the case of shaly sand formation as a low resistivity pay zone. Different shaly sand models will be applied. It has been found that the modified total shale sand model gives good results. Field example is presented to show the results of different models.

INTRODUCTION

The reasons for low resistivity phenomenon are classified mainly into two groups. The first consists of reservoirs where the actual water saturation can be high, but water free hydrocarbons are produced. The mechanism responsible for the high water saturation is usually described as being caused by microporosity. The second group consists of reservoirs where the calculated water saturation is higher than the true water saturation. The mechanism responsible for the high water saturation is described as being caused by the presence of conductive minerals such as clay minerals and pyrite in a clean reservoir rock. The resistivity data must be corrected for the effect of these conductive minerals to reduce the calculated water saturation to the more reasonable levels associated with water free hydrocarbon production.

Most formations logged for potential oil or gas production consist of rocks which without fluids would not conduct an electrical current. There are two types of rock conductivity: a) Electrolytic conductivity which is a property of for instance water containing dissolved salts and b) Electronic conductivity which is a property of solids such as graphite and metal sulfides such as pyrite. This paper deals with the case of low resistivity pay zone incurred by the occurrence of clay minerals and Pyrite. Field example will be provided to show how to deal with this problem.

SHALE SAND MODELS AND WATER SATURATION

In the last years, a considerable number of shaly sand models relating resistivity to water saturation have been proposed, for details of algorithms for shale sand models see some references (Patchett and Rausch, 1967; Tixier et al , 1968; Fertl and Hammack, 1971; Zemanek, 1989; Aguilera, 1990; Hamada, 1996). All these models are composed of two terms, a clean sand term described generally by Archie's equation and a shale term. The shale term could be fairly simple or very complicated.

(Simandoux , 1963 ; Poupon et al, 1954) have shown that in some cases it is possible to use the following total shale model equation to calculate water saturation,independently of the distribution of shale:

$$S_w = (aR_w / \phi^2 R_t + (aR_w V_{sh} / 2 \phi^2 R_{sh})^2)^{0.5} - (aR_w V_{sh} / 2 \phi^2 R_{sh}) \quad (1)$$

The above equation has been widely accepted and applied in many areas including Nigeria, Argentina, Egypt', USA, Saudi Arabia and Libya. One limitation is that the porosity exponent is taken as 2 and the value of aRw has to be accurately identified. To overcome this limitation, we introduce both cementation exponent m and saturation exponent n as variables and rewrite Equation 1. The modified total shale equation will be used in the analysis of the field example.

FIELD EXAMPLE

This example is taken from a shaly sandstone formation with low resistivity. This well has been discussed and evaluated previously (Aguilera 1990) using one of the shale sand modeling technique developed by Schlumberger. Figure 1 shows SP, resistivity, neutron and density logs. In this example, the total shale model (Equation 1) was used after modification for the evaluation. This model was modified to include a, n and m constants. The Humble formula constants were selected which were a = 0.62 and m = 2.15. Equation 1 was modified to include the shale term A_{tsh} to the following form:

$$R_t / A_{tsh} = a R_w \phi^{-m} S_w^{-n} \quad (2)$$

The total shale group A_{tsh} is given by

$$A_{tsh} = 1 + \phi^m R_t / a R_w (2B_{tsh}^2 - 2B_{tsh} (aR_w / \phi^m R_t + B_{tsh}^2)^{0.5}) \quad (3)$$

and

$$B_{tsh} = a R_w V_{tsh} / 2\phi^m R_{tsh} \quad (4)$$

For a clean formation B_{tsh} becomes zero and A_{tsh} becomes unit. A_{tsh} decreases with V_{sh} while B_{tsh} is increases with the V_{sh}. For a shale layer, R_t in Equation 3 will be equal to R_{sh}.

Taking the logarithm of both sides of Equation 2, we get the following Equation.

$$\text{Log } R_t / A_{tsh} = -m \text{ Log } \phi + \text{Log } (aR_w) - n \text{ Log } S_w \qquad (5)$$

Equation (5) indicates that a log-log plot of R_t / A_{tsh} versus ϕ is a straight line with slope of -m, providing that aR_w and S_w are constant. The resistivity index for a shaly formation is calculated using the following form.

$$I_{tsh} = (R_t / A_{tsh})_h / (R_o / A_{tsh})_w \qquad (6)$$

and water saturation Sw is derived from the relation

$$S_w = I_{tsh}^{-1/n} \qquad (7)$$

From the log-log plot, it is also possible to calculate S_w with the use of the Equation.

$$S_w = (\phi_w / \phi_h)^{m/n} \qquad (8)$$

where ϕ_w is the porosity reading on 100% water saturation line of the Picket (1973) cross plot and ϕ_h is the porosity of the hydrocarbon bearing interval.

Table 1 shows the values of R_t , ϕ ,V_{tsh} as reported by Schlumberger. Also shown are values of A_{tsh}, B_{tsh} and I_{tsh} values as calculated by equations (3), (4) and (6) respectively. The last column includes values of R_t / A_{tsh} that are cross plotted against ϕ on log-log coordinates, Figure 2. The slope of the straight line through points 4 and 5 gives m = 2.15 ; the intersection of the porosity axis at 100 % porosity gives a = 0.62. This validates the assumed values. If the straight line did not go through points 4 and 5, new values of a and m could be assumed for a new try. The water saturation was calculated using Equations 7 & 8. In this calculation.we have used R_w = 0.17 ohm metere, R_o = 1.29 ohm meter, R_{tsh} = 1.19 ohm meter, a = 0.62, m = 2.15 and n = 2. Table 2 shows water saturation values from Archie's equation, Schlumberger program (Saraband, Coriband) and from Equations 7 & 8.

The difference between water saturation values derived from Archie's formula and other shaly sand equations indicates the importance of using a shale sand model for this example. Also It is obvious that there is not really a difference between Schlumberger values and Picket crossplot values. Picket plot of modified total shale Equation (5), does not need previous knowledge of m and aR_w. Based on the points pattern shown on the cross plot, these parameters can be determined by trial and error. But it needs the existence of a nearby water section

CONCLUSIONS

When clean reservoir rock contains clays or heavy minerals such as pyrite, the resistivity becomes low. Clay minerals increase rock conductivity by increasing the conductivity of bulk water in the pore spaces. Extra rock conductivity is caused by pyrite which creates electronic conductivity that is usually comparable to or even higher than formation water electrolytic conductivity. These are the main reasons to low resistivity pay zone phenomenon.

To evaluate a low resistivity pay zone, we must identify the origin of the low resistivity phenomenon. In the case of clay minerals, there are several models to correct the water saturation value. The choice of the model is controlled by the type, the distribution and the volume of clay minerals in the pay zones. The modified total shale sand model presented in the paper is quite adequate to get an accurate value of water saturation from the apparent water saturation value derived directly from the log data using Archie's formula. But in the case of pyrite, the main problem is how to estimate its volume and distribution and correct the formation resistivity and then calculate water saturation by Archie'formula or by a shale sand model.

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Table 1 Data for water saturation calculation in a shaly sand formation.

Data points	Resistivity (R_t)	Porosity (ϕ)	Shale volume (V_{sh})	B_{tsh}	A_{tsh}	R_t / A_{tsh}	I_{tsh}
1	8.40	0.27	0.13	0.072	0.449	18.67	6.5
2	7.50	0.24	0.18	0.123	0.378	19.87	5.84
3	8.40	0.26	0.15	0.094	0.412	20.35	6.25
4	1.80	0.28	0.00	0.00	1.00	1.80	1.0
5	1.75	0.31	0.00	0.00	1.00	1.75	1.0

Table 2 Water saturation values from different shale sand models.

Data points	Archie's Eq.	Schlumberger	Eq. 7	Eq. 8
1	0.54	0.39	0.39	0.39
2	0.62	0.42	0.41	0.42
3	0.55	0.37	0.40	0.39
4	1.00	1.00	1.00	1.00
5	1.00	1.00	1.00	1.00