

Case Report

Application of pseudo-percolation threshold theory in evaluation of low-porosity and low-permeability reservoir: A case of Chang 8 section at ZJ Oilfield, Northwestern, China

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Because there exists a distinct difference of lithology and physical characteristics between conventional clastic reservoirs and low-porosity and low-permeability reservoirs, Archie formula will not be valid for the latter any more. In addition, well logging evaluation of low-porosity and low-permeability reservoir is one key problem but also the research hotspot in recent years. In this study, Pseudo-Percolation Threshold Theory (PPTT) has been introduced into reservoir evaluation. In this research, it has been proved that the aimed layer is low-porosity and low-permeability by studying the reservoir rock. In addition, Percolation Threshold ϕ_b has been determined by analyzing porosity and permeability of oil-bearing cores and process of geologic evolution. Finally, it has been proved that PPTT is much more reliable than Archie formula for low-porosity and low-permeability reservoir by numerical simulation and oilfield data.

Keywords: Low-porosity and low-permeability reservoirs, Pseudo-Percolation Threshold Theory, oil saturation, reservoir evaluation.

INTRODUCTION

As the first conductivity model in the field of oil exploration, the Archie formula (Archie, 1942) plays an important role in connecting among well logging data, formation porosity, water saturation, and pore structures, and it also acts as a bridge linking the core data and formation parameters. It is noteworthy that the Archie formula is actually conducted on the basis of pure sandstone with high-porosity and high-permeability. Besides, the application range of the Archie formula is valid when the several following conditions are true: (1) The matrix is an insulator or it is not conductive. (2) And

the distributions of porosities are homogeneous. (3) And each fluid saturation of the porosities is also homogeneous. (4) Moreover, all the fluids are mineralized rather than fresh water. (5) Furthermore, electrical properties of the rock are isotropic. However, as for low-porosity and low-permeability reservoir, the Archie formula will definitely confront a big challenge. Since, the Archie formula is based on a set of experimental data from the Gulf of Mexico for constructing an equation as shown in Figure 1, yet the inner physical mechanism of the Archie formula has not been completely comprehended so far. In addition, according to Figure 1, when the porosity is less than 20%, data will not comply with the formula ($F = 1.0 / \phi^m$).

Therefore in order to grasp the physical mechanism of the Archie formula, a large amount of studies have been

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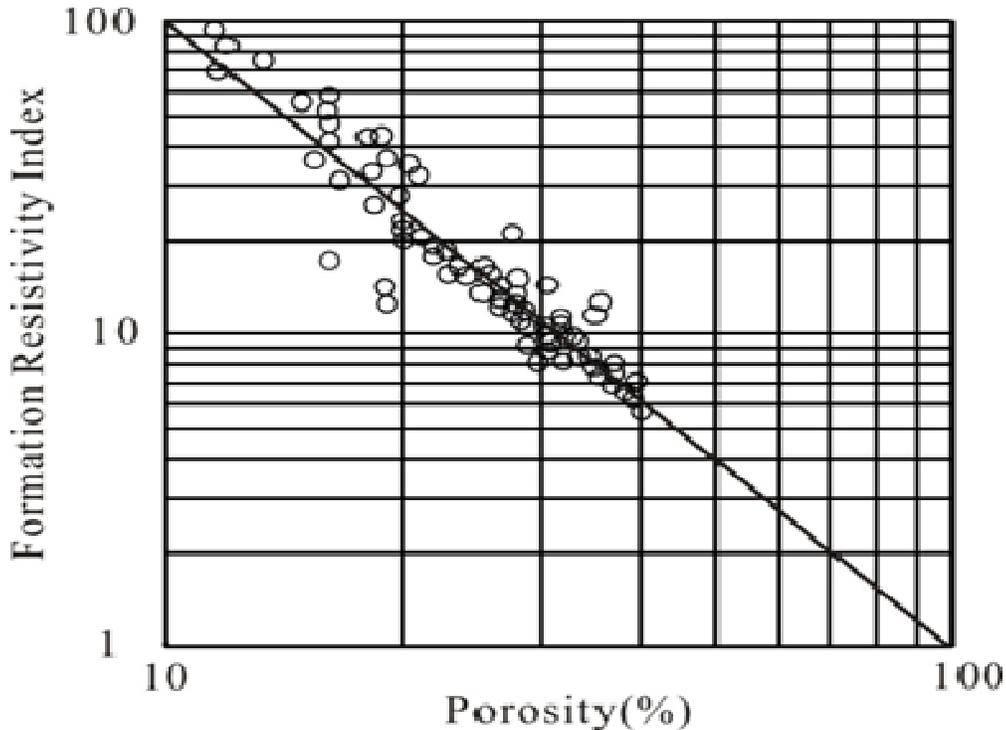


Figure 1. Plot of the Archie experimental data. A line indicates $F = 1.0 / \phi^m$. Here, ϕ represents porosity.

Done until now by scientists. Such as Bussian (1983) received an achievement through a research on conductive responses by a physical simulation. Another researcher Devarajan (2006) contributed to studying the relationship among conductivity, porosity and water saturation, but unfortunately, there is still not an agreed viewpoint about this kind of relationship (Waxman and Smith, 1968; Clavier et al., 1977; Song et al., 2005).

In this study, the Pseudo-Percolation Threshold Theory (PPTT) method (David, 2007) is introduced to evaluate the reservoirs with low-porosity and low-permeability. However, in this research we mainly consider the real Percolation Threshold Theory; hence we call it as Percolation Threshold Theory (PTT) in the following research.

We attempt to set up a new formula for calculating the water saturation and moreover this formula has been proven to be effective by examining two boreholes.

Hereinto, the Formation Resistivity Factor is defined as $F = R_0 / R_w$. R_0 is resistivity with respect to water-filled porous rock, and R_w is resistivity with respect to formation water.

Reservoir rock study

We focus on a reservoir section from the northwestern oilfield in China, and this section is named as the Chang

8 Group, which comes from the YC Formation at ZJ oilfield in south Ordos Basin, as shown in Figure 2. In the process of forming a reservoir rock, because of the tremendous influence generated by mechanical compaction, geological cementation and dissolution (Pan et al., 2011), many clay minerals are produced in the rock crack, as shown in Figure 3 and Figure 4. Besides, Figure 5 and Figure 6 indicate the relationships between Kaolinite contents and the porosity and permeability, respectively. In a similar way, Figure 7 and Figure 8 imply the relationship between Illite contents and the porosity and the permeability, respectively. From above analysis, we can confirm that with increasing of clay contents, both porosity and permeability will decrease. In addition, porous structure is mostly composed of moderate-fine pores throats in the reservoir and this situation can be proved by capillary pressure curves (Wu, 2010), as shown Figure 9. As a result, the range of porosity is mainly from 8% to 14%. Hence, application of Archie formula will bring relatively great error in evaluation of this reservoir.(Figure 10)

Contrast analysis between Percolation Threshold Theory and Archie formula

In order to comprehend the principle of the Archie formula more fully and deeply, we would like to begin by reviewing Archie's Nacatoch data to perceive the relation-

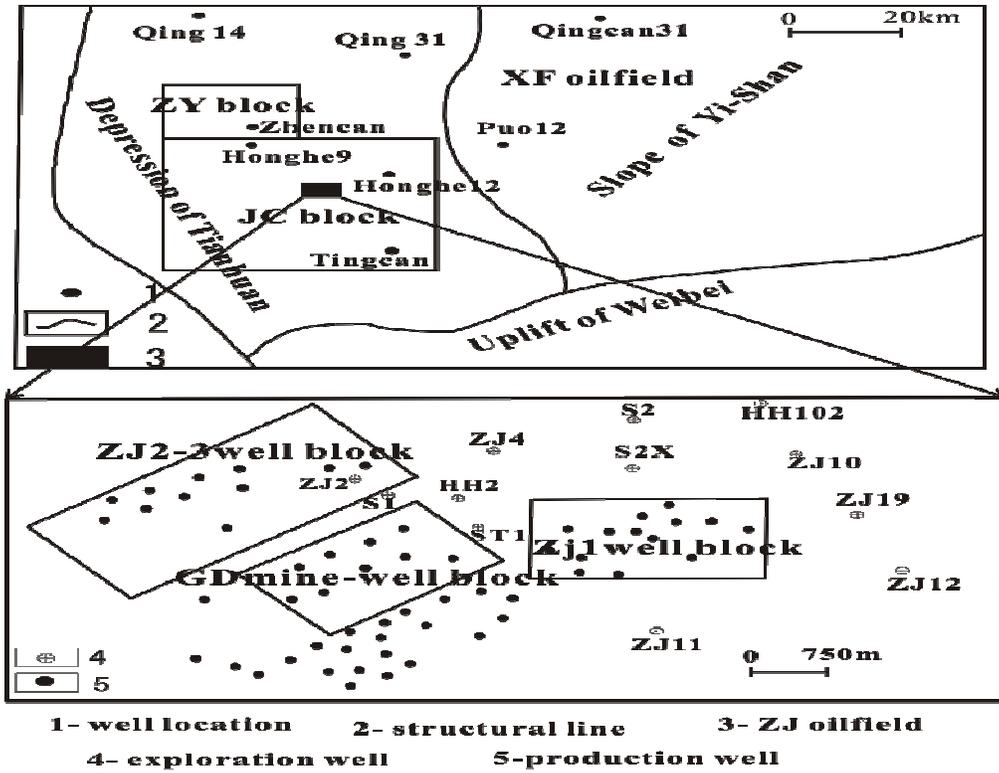


Figure 2. The location of study area (Ding, 2008).

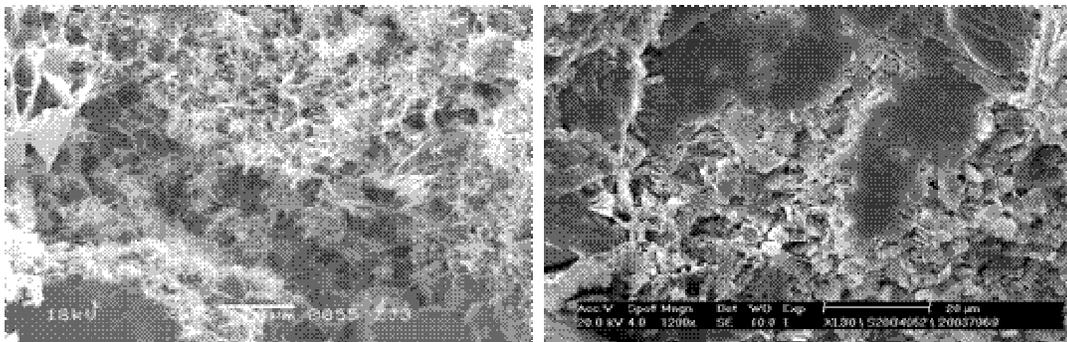


Figure 3. The pores of reservoir rock are full of Illite. Figure 4. Kaolinite is on the surface of reservoir rock.

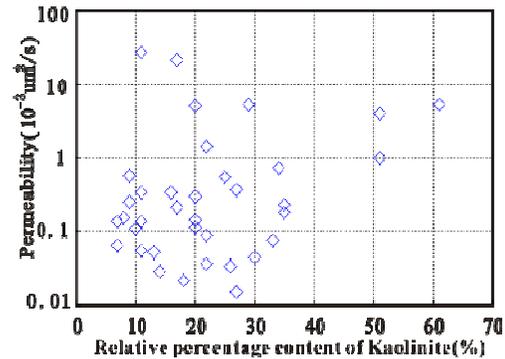
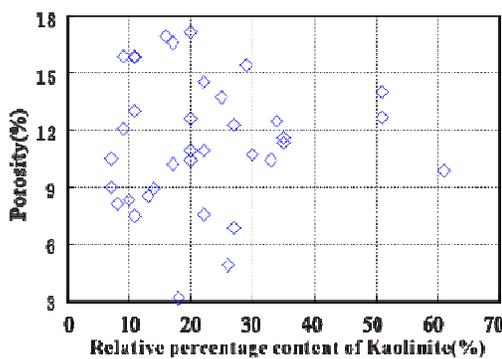


Figure 5. The cross-plot of porosity and Kaolinite contents. Figure 6. The cross-plot of permeability and Kaolinite contents.

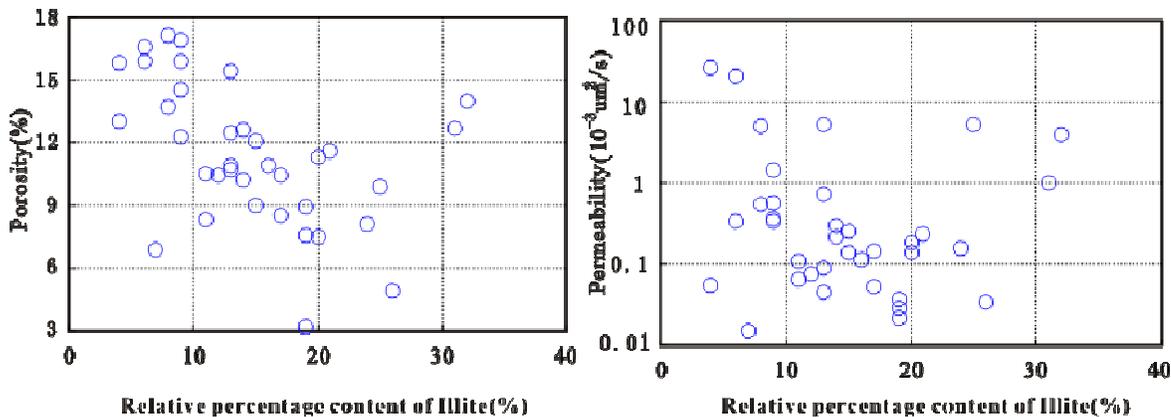


Figure 7. The cross-plot of porosity and Illite contents. Figure 8. The cross-plot of permeability and Illite contents.

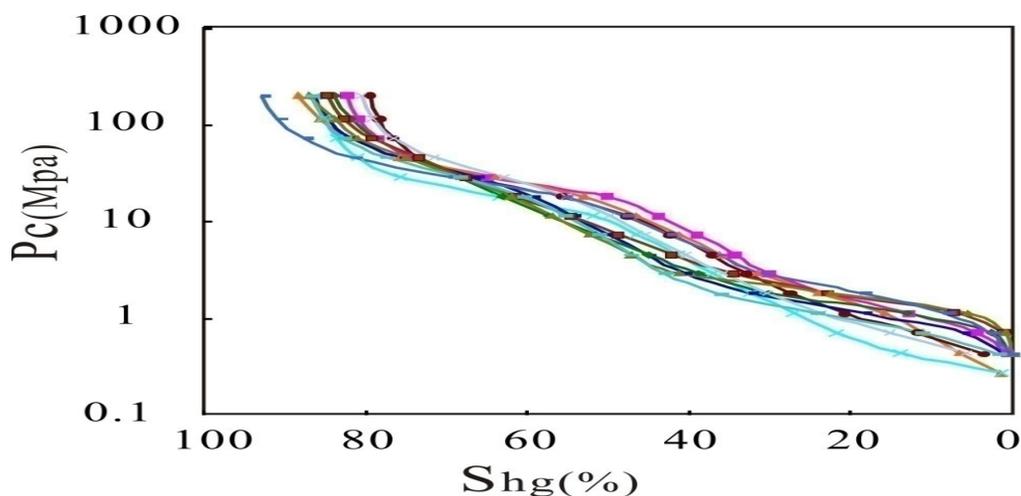


Figure 9. Mercury-injection curves of reservoir rocks. Here, P_c stands the pressure of mercury (Hg). S_{hg} stands the content of injection mercury.

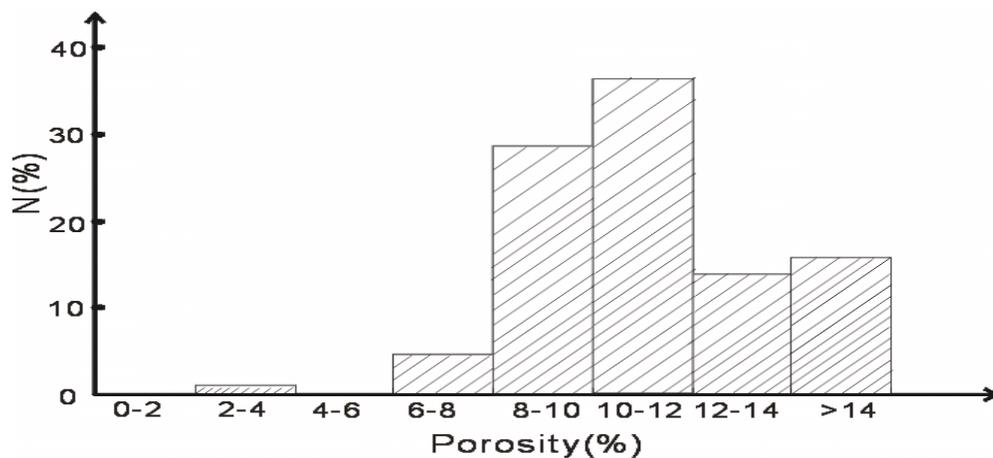


Figure 10. The histogram of the porosity distribution. Here, N stands for account of rock.

ship (Berg, 1998) between Formation Conductivity Index and porosity using Figure 11. In the light of the Archie

formula, the relationship between Formation Conductivity Index and porosity can be expressed by the following

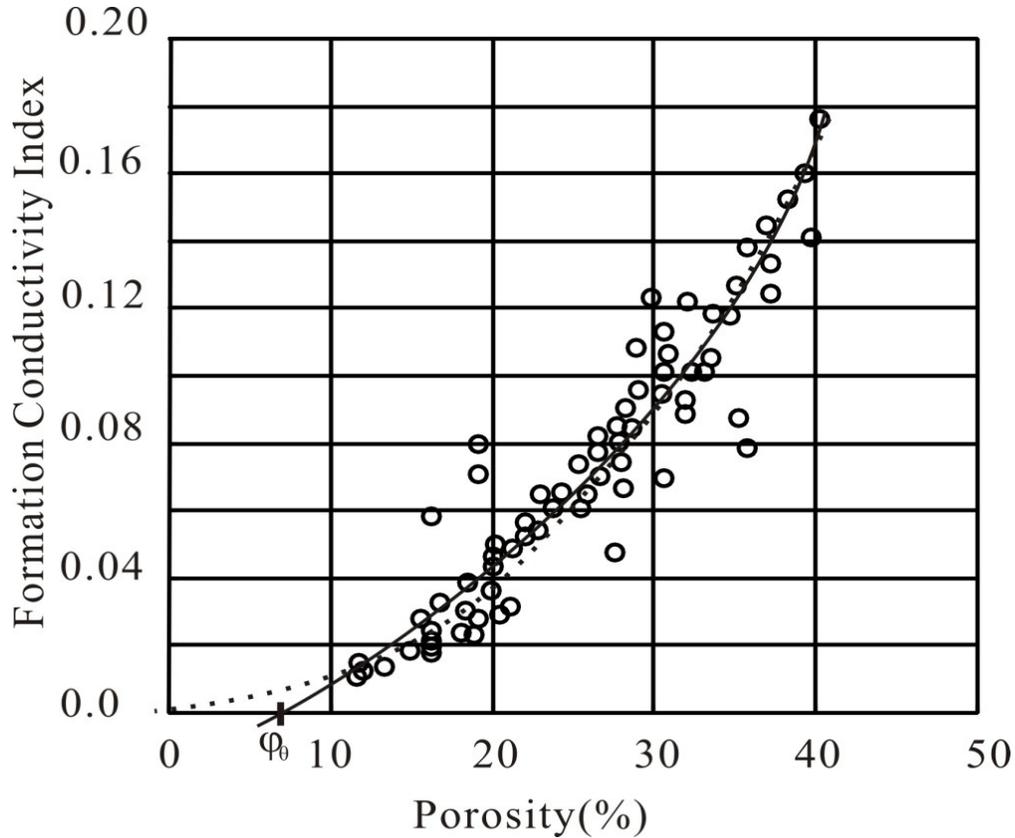


Figure 11. The relationship between Formation Conductivity Index and Porosity (Berg, 1998).

equation:

$$F = \frac{1.0}{a} \phi^m \quad (1)$$

(according to Archie's Nacatoch data, $m=2$ and $a=1.0$), and hence the point (0,0) is actually on that curve (shown by dotted line) given by as represented in Figure 11. However, the general tendency shaped by Archie's Nacatoch data surprisingly manifests that the relationship between Formation Conductivity Index and porosity does appear to be like the solid line instead of the dotted line in Figure 11. The cross-point between that solid curve and the horizontal axis is exactly located at the positive half of porosity-axis as revealed in Figure 11, and meanwhile this special value of the porosity is regarded as Pseudo-Percolation Threshold (PPT) which is denoted as ϕ_p . The valid porosity can be gained through this expression: $\beta_c = \phi - \phi_p$. And thereby the relationship between Formation Conductivity Index and valid porosity can be described by Formula (2) which is also known as Pseudo-Percolation Threshold Theory (PPTT) (David, 2007).

$$\frac{\partial(\sigma_0/\sigma_w)}{\partial(\phi - \phi_p)} \propto (\phi - \phi_p) \quad (2)$$

Here, σ_w represents conductivity of formation water; and σ_0 stands for the conductivity of reservoir rock. Through transforming the Formula (2), we can rewrite it into Formula (3).

$$\frac{\partial(\sigma_0/\sigma_w)}{\partial(\phi - \phi_p)} = a_0(\phi - \phi_p) \quad (3)$$

Here, a_0 is a coefficient. In view of the natural boundaries (Jia et al, 2010), the Formula (3) can be changed into the following form:

$$\frac{\sigma_0}{\sigma_w} = \left(\frac{\phi - \phi_p}{1 - \phi}\right)^2 \quad (4)$$

In fact the exponent which is equal to 2 in Formula (4) is obtained according to mathematical statistics and physical boundary.

According to Formula (4), we portray a curve illustrated in Figure 12, and moreover the solid line does correspond to the part of connected porosity. The Figure 12 suggests that in the range of high porosity, the relationship between porosity and Formation Conductivity Index exists to be a kind of exponential function. Concretely speaking, when the porosity decreases to the special value of PPT: ϕ_p , at the same time, the numerical

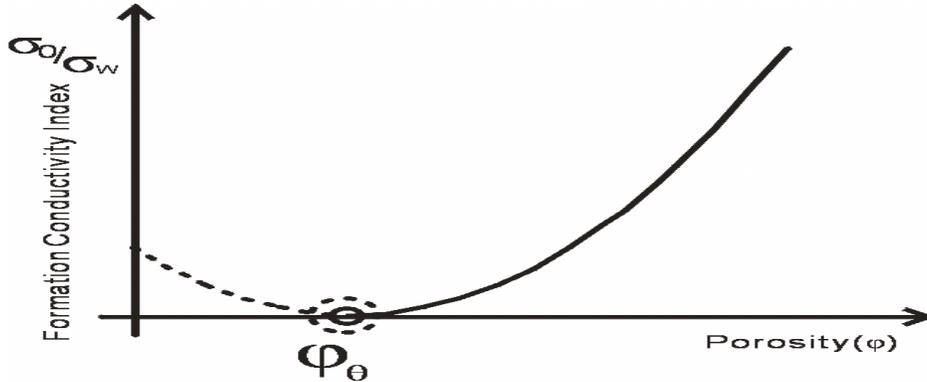


Figure 12. The relationship between Formation Conductivity Index and porosity.

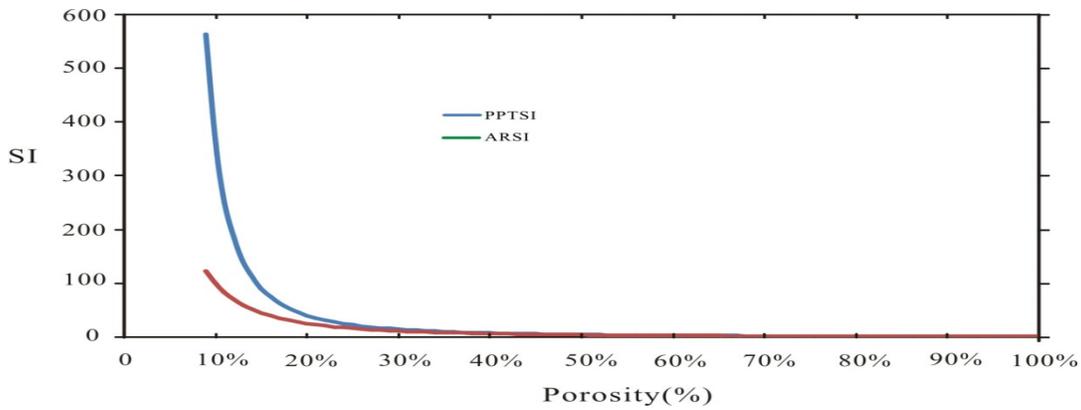


Figure 13. Comparison between numerical modeling results of Archie formula and PPTT.

value of Formation Conductivity Index will reach the lowest point: 0. On the other side, the dotted line is corresponding to the part of isolated porosity, and actually the numerical value of conductivity should be equal to 0.0 without the conductive matrix.

Because during the production of oilfield, electrical data are available in the form of resistivity instead of conductivity, hence we change the Formula (4) into Formula (5):

$$\frac{R_0}{R_w} = \frac{1.0}{\left(\frac{\phi - \phi_{\theta}}{1 - \phi_{\theta}}\right)^2} \quad (5)$$

The formula of Formation Resistivity Index is described by Formula (6):

$$\frac{R_t}{R_0} = \frac{b}{S_w^n} \quad (6)$$

Hence, the formula of water saturation can be obtained by Formula (5) and Formula (6):

$$S_w = \left(\frac{1.0 - \phi_{\theta}}{\phi - \phi_{\theta}}\right)^2 \cdot \frac{b \cdot R_w}{R_t}^{\frac{1}{n}} \quad (7)$$

Here, the values of b and n depend on the character of reservoir rock. ϕ_{θ} is Porosity Percolation Threshold.

Now we study the difference between water saturation of PPTT and that of Archie formula.

According to PPTT, water saturation can be calculated by the formula (8):

$$PPTS_w = \left(\frac{1.0 - \phi_{\theta}}{\phi - \phi_{\theta}}\right)^m \cdot \frac{b \cdot R_w}{R_t}^{\frac{1}{n}} \quad (8)$$

In addition, the water saturation can be calculated by of Archie formula (9):

$$ARS_w = \left(\frac{1.0}{\phi}\right)^m \cdot \frac{b \cdot R_w}{R_t}^{\frac{1}{n}} \quad (9)$$

For the same one reservoir, n , b , R_w and R_t are identical. In order to simplify, we only need to compare the $PPTS_w$ and ARS_w by contrasting $PPTSI$ and $ARSI$. Hereinto, it is assumed that m equal to be 2.0 and ϕ_{θ} to be 0.05.

$$PPTSI = \left(\frac{1.0 - \phi_{\theta}}{\phi - \phi_{\theta}}\right)^2 \quad (10)$$

$$ARSI = \left(\frac{1.0}{\phi}\right)^2 \quad (11)$$

The Figure 13 describes the changes of two SI with the porosity. Figure 13 indicates that water saturation calculated by Archie formula and that calculated by PPTT

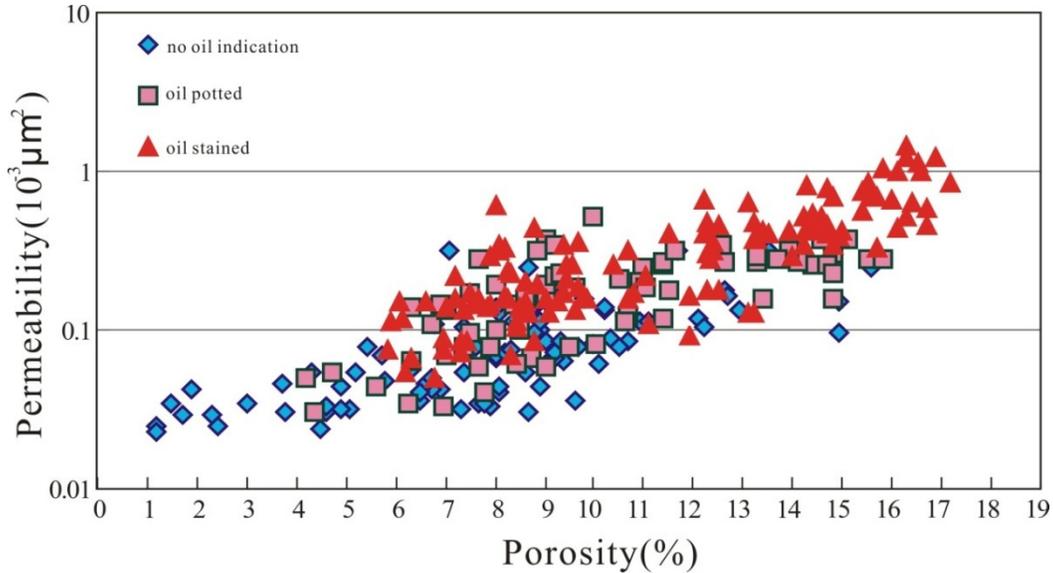


Figure 14. Crossplots of porosity and permeability of oil-bearing cores from Chang 8 oil formation, Zhenjing OilField (Hou and Liu, 2011).

are almost the same in the range of porosity being larger than 20%. However, there will emerge the larger difference during the range of porosity being less than 20%. Hence, it means that the oil saturation which is calculated by Archie formula will be greater than that is calculated by PPTT in the scope of porosity being less than 20%. Therefore, the oil saturation which is calculated by Archie formula is a wrong result. In addition, with the decreasing of porosity, the error will become larger. Moreover, the porosity of low-porosity and low-permeability reservoir is usually less than 20%. Obviously, there will be a large difference between valid oil saturation and oil saturation which is calculated by Archie formula.

Hereinto, $PPTSI = \left(\frac{1.0 - \phi_{\vartheta}}{\phi - \phi_{\vartheta}}\right)^2$ corresponds to

$$PPTS_w = \left(\frac{1.0 - \phi_{\vartheta}}{\phi - \phi_{\vartheta}}\right)^m \cdot \frac{b \cdot R_w}{R_t}^{\frac{1}{n}} \quad \text{and}$$

$$ARSI = \left(\frac{1.0}{\phi}\right)^2 \text{ corresponds}$$

$$ARS_w = \left(\frac{1.0}{\phi}\right)^m \cdot \frac{b \cdot R_w}{R_t}^{\frac{1}{n}}$$

Application of PPTT and its analysis

In order to application of PPTT, firstly we should confirm the parameters of Formula (8). In fact, there are eight parameters in Formula (8), however we only state PPT: ϕ_{ϑ} here. The other seven parameters can be calculated

by conventional approaches. We employ the cross-plots of porosity and permeability of oil-bearing cores to analysis PPT. Now we introduce well logging data and cores in the oilfield to

experiment data of oil-bearing examine the effect of PPTT. As shown in Figure 14 (Hou and Liu, 2011), there will be no any oil indication in the range of porosity being less than 4%. Hence, 4% is regarded as limit of oil porosity. However, what is the relationship between limit of oil porosity and Pseudo-Percolation Threshold of oil porosity? In fact, limit of oil porosity is nowadays but it cannot stand for the limit of oil porosity in the accumulation period. Hou and Liu (2011) used the following method to recover porosity of the accumulation period from nowadays porosity. Firstly, the accumulation period of limit of oil porosity is confirmed, and then the difference between porosity of accumulation period and nowadays porosity is calculated, finally the porosity of accumulation period can be calculated by adding the difference of two period's porosity to nowadays limit of oil porosity. Figure 15a describes nowadays porosity profile. According to the research of geology, the burial depth of Chang 8 section has been increased by 630m. Hence, porosity profile during accumulation period can be obtained by pushing nowadays porosity profile up 630m, as shown in Figure 15b. Consequently, the difference of two period's porosity is deduced to be 6.5%. Hence, they thought that the limit of oil porosity is 10.5% which is the sum of the difference of two period's porosity and nowadays porosity. However, the value of 6.5% is just average difference. Hence, using this average difference to calculate Pseudo-Percolation Threshold will bring a large error. Besides, considering the natural formation

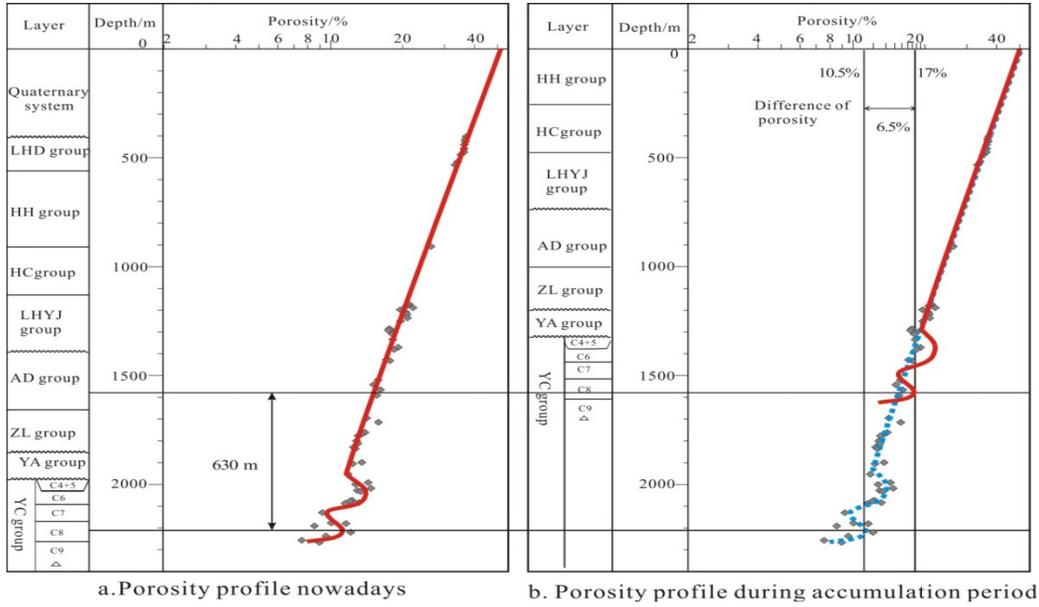


Figure15. Estimation of porosity during accumulation period, Chang 8 oil formation, Zhenjing OilField (Hou and Liu, 2011).

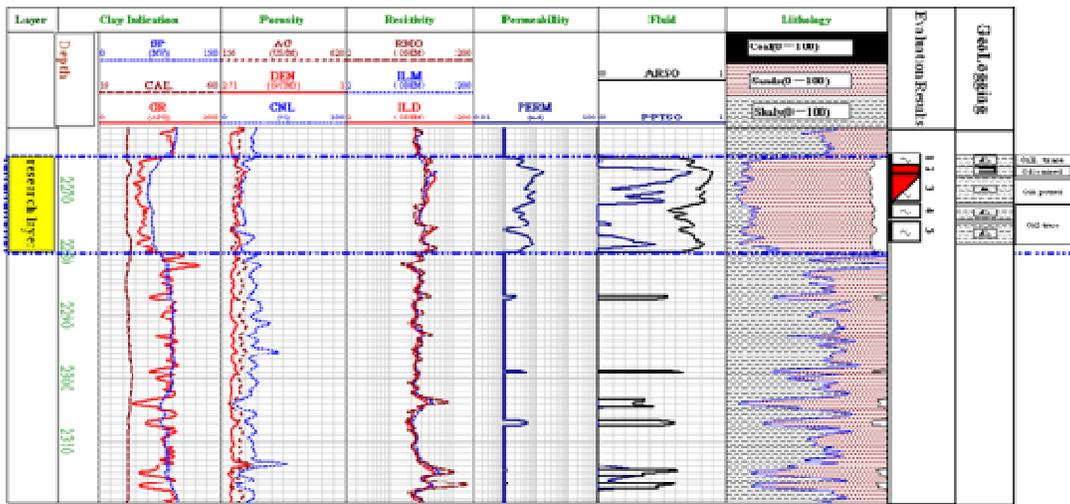


Figure 16. Logging data of Borehole A in the ZJ oilfield. Hereinto, ARCSO is oil saturation which corresponds to Archie formula, and PPTTSO is oil saturation which corresponds to PPTT method. Oil stained: the area of oil-bearing is 40%-75% in the core. Oil potted: the area of oil-bearing is 5%-40% in the core. Oil trace: the area of oil-bearing is less than 5% in the core.

compaction, limit of oil porosity still is the smallest porosity which is the oil can be injected during accumulation period; hence firstly the limit of porosity is injected fully by fluid. In this situation, it is very difficult to change the volume of the limit of oil porosity during the accumulation period. Based on above consideration, we can think that the limit of porosity equals to about Pseudo-Percolation Threshold ($\phi_{ij}=4\%$). In addition, the resistivity of formation: R_w is 0.0832ohm-m (Huang, 2006) and both of n and m are supposed to be 2.0.

Besides the oil saturation can be calculated by Formula (12).

$$S_o = 1.0 - S_w \quad (12)$$

According to above analysis, these parameters have been used to calculate the oil saturation. Now, we examine the validity of the methodology by two well-logging data.

Figure 16 shows the Logging data of Borehole A in ZJ oilfield. Hereinto, ARCSO is oil saturation which corresponds to Archie formula, and PPTTSO indicates oil

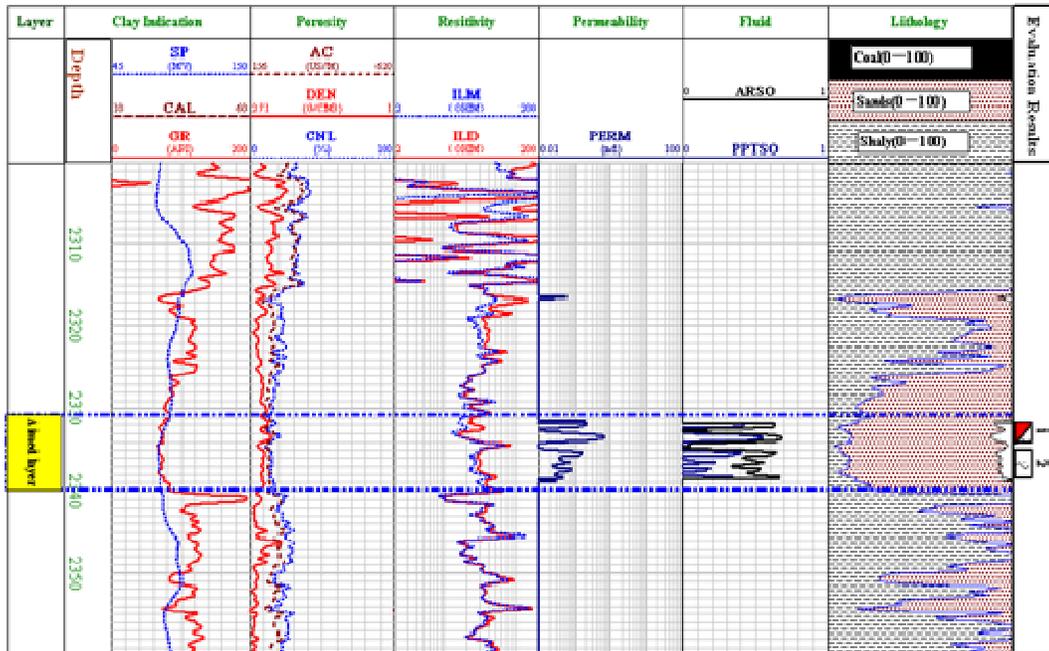


Figure 17. Logging data of Borehole B in the ZJ oilfield. Hereinto, ARCSO is oil saturation which corresponds to Archie formula, and PPTSo is oil saturation which corresponds to PPTT method.

saturation which corresponds to PPTT method. According to Archie formula, the oil saturation is larger than 70% in the whole aimed interval which is marked with yellow color. However, there is a very bad agreement between geologging information of oil-bearing cores and oil saturation of Archie formula, as shown in Figure 16. Obviously, geologging information indicates that oiliness of the interval from 2272m to 2277.5m is just oil trace, which means that there is nearly oil which is stored in this interval. However, oil saturation of Archie formula definitely indicates that the oil saturation is greater than 60%. Therefore, the contrast between calculated results of Archie formula and geologging information shows that the oil saturation which is calculated by Archie formula will be not accurate in the interval. In addition, the porosity in entire aimed internal is less than 15%, hence we will obtain a wrong result if we still use the Archie formula to calculate the oil saturation. Fortunately, the oil saturation which is calculated by PPTT is very well consistent with geologging information of oil-bearing cores. As shown geologging information in Figure 16, the interval from 2266m to 2267.5m shows the oil stained indication, which means that the area of oil-bearing is 40%-75%, however for other parts of the core, the oil-bearing grade are oil trace or oil potted, and oil-bearing grade all are very low. Consequently, according to the PPTT, the evaluated results are very well consistent with geologging information of oil-bearing cores. Hence, PPTT can be a powerful tool to help us obtain an accurate evaluated result in low-porosity and low-permeability reservoir.

Figure 17 shows Well Logging data of Borehole B in ZJ oilfield. As mentioned in Figure 16, ARCSO is oil saturation which corresponds to Archie formula, and PPTSo indicates oil saturation which corresponds to PPTT method. The Figure 17 indicates that there is a distinct difference between two results of two methods in the aimed layer. According to the PPTSo, we have obtained two evaluation results, 1-result is oil-water bearing layer (which means that the ratios of water and oil are almost the same in fluid) and 2-result is regard as to be water bearing layer with oiliness (which means that the ration of water is less than 5%). ARCSO indicates a result which is almost the same with 1-result of PPTSo at the depth from 2331.750m to 2334.250m. However, there is a large difference between ARCSO and 2-result of PPTSo at the depth from 2335.000 to 2338.500. As shown the curve of permeability in Figure 17, petrophysical property of the layer is very bad from 2335.000 to 2338.500 and the permeability is less than 0.04 md. Though it shows some oiliness from the resistivity, the part of oil saturation is invalid due to invalid porosity. In this case, PPTT can overcome the problem. Hence, we can conclude that ARCSO and PPTSo are equable in reservoir with good petrophysical property; however, there will be a large difference in the reservoir with poor petrophysical property.

CONCLUSIONS

Archie formula is based on experimental data of pure

sandstone with high porosity and high permeability. However, it will encounter a great challenge for the low-porosity and low-permeability reservoir. Theoretically, PPTT can overcome these problems and its feasibility and validity have been validated by two boreholes. In this study, the limit of oil porosity has been used as oil Pseudo-Percolation Threshold and its rationality has been analyzed theoretically. In addition, it has been proved that the oil saturation of PPTSo is much more reasonable and reliable than that of ARSo by contrast with geologging information. For the reservoir with good petrophysical property, ARSo and PPTSo are equable. Nevertheless, in the situation with reservoir of poor petrophysical property, there will be a large difference of oil saturation.

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