Identification of Oil Reservoir Meeting Atypical Archie Phenomenon

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Abstract: According to core data, this paper studies variation of resistivity in different pore structures and wettability conditions. The results show that with the increase of pore structure index *m*, the resistivity will increase significantly when the saturation is constant. Similarly, with increasing saturation index *n*, the resistivity will also increase even with the same saturation. With fixed m and n, the calculated formation water saturation will be very high, resulting in hydrocarbon reservoir being ignored. This variation characteristic is significant for the identification of hidden reservoir with atypical Archie formula.

Keywords: Atypical archie phenomenon, Pore structure index, Saturation index, Wettability, Reservoir conductivity.

ARCHIE FORMULA

The water saturation is an important index to evaluate the oil-bearing reservoir and one of the essential parameters for quantitative interpretation of well logging. It is also significant for the evaluation of low resistivity reservoir [1, 2]. Due to the diversity of complex sandstone, its pore structure and wettability are much more different from those of pure sandstone and its lithology, electrical property, oil-bearing property also show 'atypical Archie' phenomenon [3, 4]. Therefore, the water saturation evaluation of study area should be achieved on the basis of Archie Equation. And, in order to build a proper water saturation model [5-7], it is necessary to improve, refine and reinforce the leading factors (*e.g.*, pore structure index *m* and water saturation index *n*) that cause the change of resistivity.

The atypical Archie phenomenon of the reservoir means that the reservoir conductivity generally obeys the Archie equation, whereas two atypical phenomena do exist. The relation of formation factor *F* and porosity *Φ* is nonlinear in the double logarithmic coordinates. Water saturation *Sw* and resistivity growth factor *I* show multifarious variations in the double logarithmic coordinates and their effects on resistivity are different.

Taking practical core data of an oilfield, the influence of pore structure index *m* and saturation index *n* on resistivity is evaluated. With varying *m*, *n* values, the atypical Archie reservoirs are identified, which are later verified by oil testing. Therefore, this method contributes a lot to increase this region's reserves and production.

THE EFFECT OF PORE STRUCTURE INDEX *M* ON RESISTIVITY

Although the distribution and change of pore structure index *m* is affected by various factors, it is mainly decided by rock pore structure, in term of physics, the effect of pore structure on the rock conductivity. Considering the macroscopic properties of rock pore structure, it is porosity and permeability that mainly effect the changes of *m* in complex sandstone reservoir, *i.e.* the index *m* can be expressed as the functions of porosity and permeability. For porosity sandstone reservoirs, considering the microcosmic characteristics of rock pore structure, the value of exponent index *m* is mainly determined by the coupling relationship between reservoir pore space and cross-sectional area of pore throat, in another word, they are directly related to pore-throat ratio [8].

THE DISTRIBUTION OF PORE STRUCTURE EXPONENT INDEX *M*

Fig. (**1**) shows the relationship between the experiment formation factor of rock electricity and porosity in a study area. The distribution of pore structure index *m* varies in muddy sandstone reservoirs of different pore structure, which is quite different from those of pure sandstone whose pore structure index m is usually set to 2. As to reservoirs of category I, when *a*=1, *m*=1.7; and for reservoirs of category II, when *a*=1, *m*=1.44. Fig. (**1**) illustrates that different pore structures have different effects on sandstone resistivity.

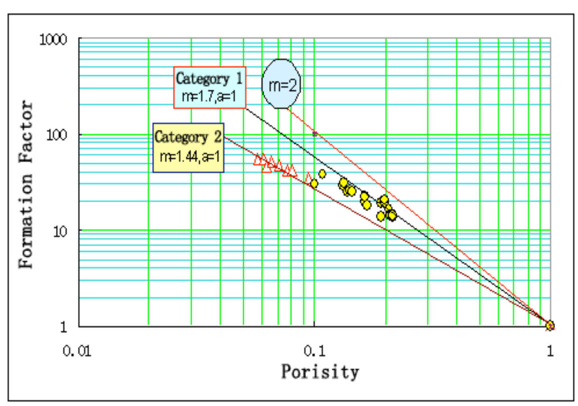

Fig (1). Relationship between different categories of reservoir porosity and formation factors.

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THE EFFECT ANALYSIS OF PORE STRUCTURE EXPONENT INDEX *M* ON RESISTIVITY

According to/In light of Archie Equation:

$$S_w = \sqrt[n]{\frac{abR_w}{R_t \phi^m}}$$

This equation is rewritten as:

$$R_t = \frac{a*b*R_w}{S_w{}^n * \Phi^m}$$

Taking partial derivatives of exponent index *m*:

$$\frac{\partial R_t}{\partial m} = -m*\frac{a*b*R_w}{S_w^n * \Phi^{m+1}}$$

Where *Sw* represents water saturation, *a*, *b*, *m*, *n* are coefficients in Archie Equation, *Rw* is formation water resistivity, *Rt* is formation resistivity, and *Φ* is porosity.

Assuming *a*=1, *b*=1, *n*=1.6, *Sw*=50%, *Rw*=0.23, the relationship between porosity *Φ* and formation resistivity *Rt* with different pore structure index *m* is shown in Fig. (**2**).

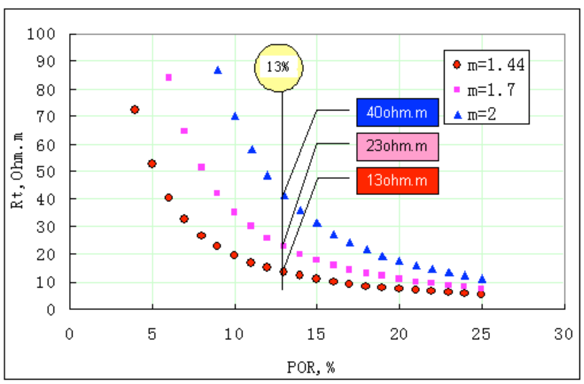

Fig (2). Formation resistivity changes with porosity under different *m*.

As can be seen in the figure, the effect of pore structure exponent index on resistivity is larger under the condition of low porosity. When the reservoir porosity is between 8%-13%, the effect of pore structure exponent index on resistivity is more than 50%.

It also can conclude that under the condition of 13% porosity, when *m*=1.44, *Rt*=13 $\Omega \cdot m$; when *m*=1.7, *Rt*=23 $\Omega \cdot m$; when *m*=2, *Rt*=40 $\Omega \cdot m$. Compared with reservoir resistivity of pure sandstone that decreases by 43% in category I and 67.5% in category II. If taking category I reservoir in the study area as conventional resistivity reservoir, the resistivity of category II reservoir will decrease by 43.5% under the same condition. Therefore, reservoirs with low pore structure exponent index *m* seem more inclined to form low resistivity reservoirs. Most of the low resistivity reservoirs in this region result from low *m*.

The effects of *m* on resistivity are not obvious for reservoirs with high porosity. However, the effects are much more evident when porosity is lower.

THE EFFECT OF SATURATION EXPONENT INDEX *N* ON RESISTIVITY

Saturation exponent index *n* is microcosmic distribution index of oil saturation, which is closely related to the wettability of rock.

THE RELATION BETWEEN WETTABILITY AND SATURATION EXPONENT *N*

Saturation index n varies a lot with the change of wettability. Different wettability will result in different microcosmic distribution of oil (gas) of rock reservoir space and cause changes in rock conductive path and conductivity.

According to domestic and foreign research of recent years, *n* of hydrophilic rock is generally in the range of 1.5-2.3, and that of oil-wet rock is in the range of 2.4-10 or even higher, illustrating that *n* of lipophilic formation is higher than that of hydrophilic formation [9].

THE DISTRIBUTION OF RESERVOIR SATURATION EXPONENT INDEX N IN THE STUDY AREA

Fig. (**3**) is the statistics chart of saturation exponent index in the core electricity experiment of this oilfield. The results show that the distribution of saturation value of exponent index *n* is wide, usually 1.4, 1.6, 1.85, which is quite different from the pure sandstone where n is equal to 2. On the one hand, this reflects the hydrophilic and strong hydrophilic characteristics of this region, on the other hand, it reveals the diversity of oil and gas distribution in microscopic pores of sandstone.

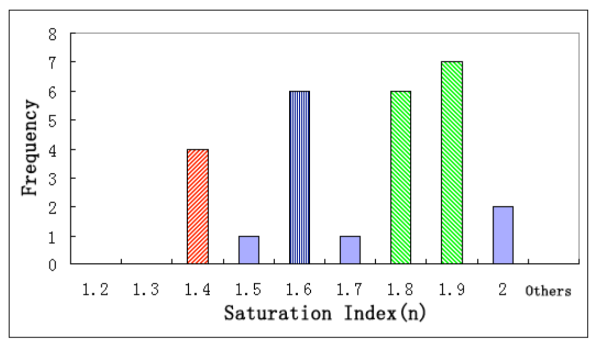

Fig (3). Core distribution value of exponent *n*.

THE SENSITIVITY ANALYSIS OF EFFECTS OF SATURATION EXPONENT INDEX *N* ON RESISTIVITY

Considering the diversity of saturation exponent index *n* (Fig. **3**), fully understanding the effects of *n* on resistivity is significant for us to choose appropriate parameter and correctly identify the fluid property in practical data processing.

With Archie formula, this equation is rewritten as:

$$R_t = \frac{a*b*R_w}{S_w{}^n * \Phi^m}$$

Taking partial derivatives of exponent *n*:

$$\frac{\partial R_t}{\partial n} = -n*\frac{a*b*R_w}{S_w^{n+1} * \Phi^m}$$

Where, Sw=50%,

When n=1.4, I=2.3;

When n=1.6, I=3.03;

When n=1.85, I=3.6;

When n=2, I=4.

When a=1, b=1, m=1.7 and water saturation Sw=50%, Resistivity Rt versus porosity with different saturation index n is shown in Fig. (**4**).

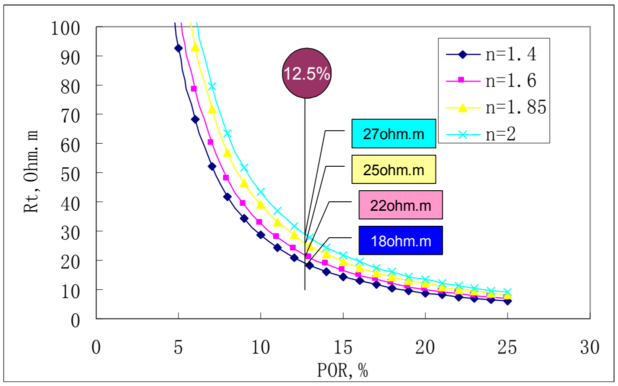

Fig (4). Relation of formation resistivity with the change of porosity under the condition of different values of *n*.

When the rock wettability is hydrophilic, low resistivity is more likely to be formed, and the more hydrophilic the formation is, the lower the resistivity is. When porosity is low or medium, the effects of n on resistivity are almost the same. This is because the amount of bound water adsorbed on the rocks is equal when the surface area is the same.

Under the condition of 12.5% porous, when n=1.4, Rt=18$\Omega \cdot m$; when n=1.6, Rt=22$\Omega \cdot m$; when n=1.85, Rt=25$\Omega \cdot m$; when n=2, Rt=27$\Omega \cdot m$. Taking saturation exponent index n=1.85 as a standard, when n=1.6, the resistivity decreases by 12%; when n=1.4, the resistivity decreases by 28%.

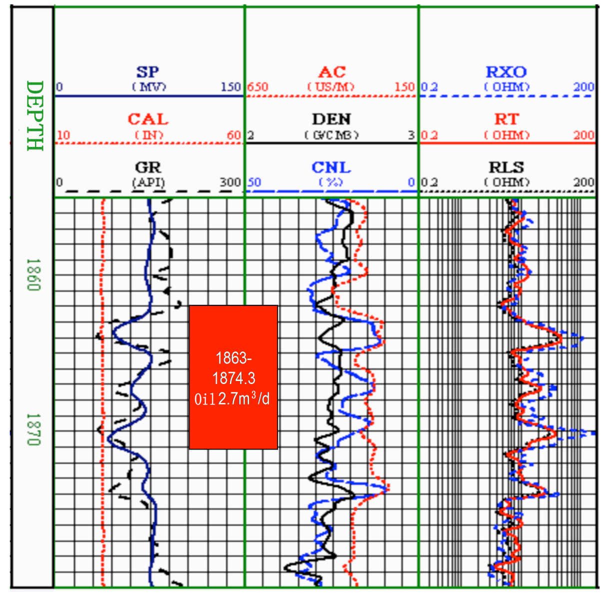

Fig (5). Logging response characteristics of high-density oil reservoir of one well.

The results demonstrate that saturation exponent index n has an important effect on reservoir resistivity, which needs to be paid especial attention to during practical data processing.

PRACTICAL APPLICATIONS

As pore structure exponent index m depending on the pore structure, the longer the radius is, the larger the m is. The changes of pore structure exponent m is closely related to the interstitial contents of the sandstone that mainly include calcite, clay and secondary enlargement quartz in the study area. The increase of the interstitial contents makes pore-filling situation complex and enlarges the water capacity of the pellicles and capillaries. As a consequence, the value of m decreases as the amount of interstitial contents increases. Similarly, when the amount of interstitial contents

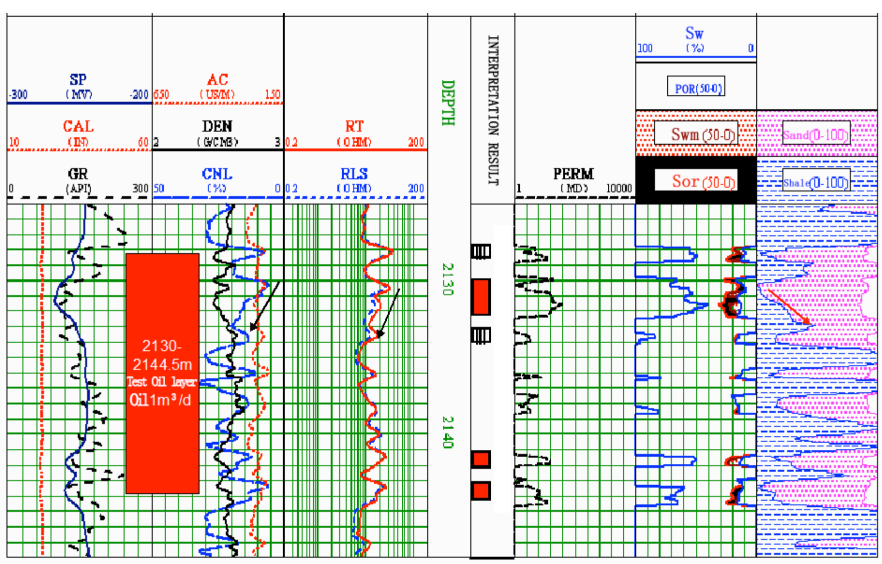

Fig (6). Low resistance response characteristics caused by the value of *n* of oil reservoir in one well.

increases, excellent micro-fine conductive capillary channels are more likely to be formed in roar hole, which results in overall decrease of resistivity.

As to the logging response, density increases significantly, which illustrates the specific characteristics of low resistivity reservoirs in study area. After accurate analysis of logging data, it is found that this type of reservoirs belongs to category II, which is relatively common in the study area. Fig. (**5**) shows around 1863-1874.3m of a well, the density value is above 2.4 g/cm^3. After evaluation, m is set to be 1.44 when calculating oil saturation (*So*=67%). After oil testing, daily oil production is 2.7 m^3 and no water is produced. Many similar oil reservoirs are found after secondary interpretation of logging data in the whole area.

Generally speaking, saturation exponent index *n* and median grain diameter shows a positive correlation. When median grain diameter is small, it means the rock particles are fine with strong hydrophilicity, which can strengthen the electric conduction. Therefore, the main electrical response characteristics with the changes of *n* is that the response of natural gamma curve or compensated neutron log will increase when the rock particles become fine. Fig. (**6**) shows that, when the internal porosity of one well remains constant around 2130-2133m, the value of neutron rises, rock particles become fine and the value of *n* decreases, which results in low resistivity of the reservoir. Taking *n*=1.4 to calculate oil saturation of this layer (*So*=60%). After oil testing, daily oil production is 1 m^3 and no water is produced, demonstrating that the capacity of oil production of the reservoir is poor.

CONCLUSION

Rock electrical data plays an important role in well logging interpretation, reservoir evaluation and reserve forecasting. At present, the empirical Equation proposed by Archie is still widely used in the electric logging interpretation. However, more and more experiments and studies show that the simple Archie relation cannot describe all the electric characteristics. Without the transformation of ideas, similar reservoirs discussed in this paper will not be found.

Based on changed *m* and *n*, water saturation is calculated by utilizing Archie Equation and a general survey of old wells in the study area is conducted, which helps to find a lot of oil reservoirs meeting atypical Archie phenomenon. This method is effective and proposes a new thought to increase reserves and production in this area.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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