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A Method of Calculating Saturation for Tight Sandstone Reservoirs: A Case of Tight Sandstone Reservoir in Dabei Area of Kuqa Depression in Tarim Basin of NW China

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Abstract

The tight sand reservoir in Dabei Area has been the main block of exploration and development of natural gas in Tarim Basin. Because of low porosity and fracture development, there exist errors in calculation of reservoir saturation. According to micro-resistivity image logging and acoustic full-wave logging, the reservoir fractural effectiveness is quantitatively evaluated; the result indicates that the reservoir with Stoneley wave permeability is greater than $0.2 \times 10^{-3}\ \mu\text{m}^2$; the reservoir connection is good. If the FVPA is greater than 0.055%; the fractures are developed. A new matrix saturation model is established based on the conductive pore water in consideration of the influence of low porosity. After modeling and analyzing the effect of porosity and its occurrence on the cementation index, the method for saturation calculation in Kuqa Area is established: the newly established dual porosity model is for fracture developed reservoirs, and the model based on the conductive pore water is for fracture less-developed reservoirs. By comparing the results of saturation in mercury injection experiment from coring section, precision of the calculation method is proven.

Keywords

Tight Sandstone, Fracture, Saturation, Conductive Pore Water

1. Introduction

The tight sandstone reservoir of the Cretaceous Bashijiqike Formation in Dabei Area of Kuqa Depression in Xinjiang Tarim Oilfield is buried below 6000 m; its porosity is generally between 3% and 8%, and its permeability is between 0.01 and 0.1 mD; it belongs to a deep tight sandstone reservoir [1], where micro-fractures are developed, this enhances the heterogeneity of the reservoir; it is more difficult to evaluate the fluid property in the reservoir by well logging. Therefore, in addition to choose a downhole detecting instruments with higher detection precision, studies should be carried out on various logging interpretation methods.

Sulige Gas Field in China was used as example by Li Xia (2013), methods for identifying tight sandstone gas reservoirs were denoted based on conventional logging data, these methods included the contrast method of equivalent P-wave elasticity modulus, A-K intersection combination method, the intersection of P-wave and S-wave ratios with Poisson's ratio and the method of Poisson's ratio and compression coefficient ratio [2]. But in the target zone of 8th Member of Shihezi Formation, the average value of porosity is 8.3%, in Kuqa Area with lower porosity; its adaptability remains to be verified. Yang Shuangding (2005) introduced the subtraction method based on NMR logging data and the method of shift spectrum for identifying tight sandstone gas reservoirs in Ordos Basin [3], but in the article, only the response of pure gas zones was discussed, for the effect of identifying water zone in the tight sandstone was difficult to be determined by using the method. Zhang Yongjun (2012) discussed in detail the methods of using array acoustic logging data for identifying physical foundation, parameter extraction and identifying the reservoir fluid in the tight sandstone gas reservoirs [4]. Guo Zhenhua (2010) applied the characteristic parameters of neutron, resistivity and density logging curves to establish the method for qualitatively evaluate the grade of open flow in the gas zone, certain effect was obtained in the 2nd Member of Shihezi Formation in Daniudi Gas Field [5]. Zhang Haitao (2012) introduced the method of using logging curve for identifying the types of diageneticfacies [6], which expanded the application of logging data in geologic sphere. The methods described by the above scholars have included the current technical means for identifying gas reservoirs by using logging data, in which the methods for logging identification of water zone and gas-water coexistent zone are not discussed in depth, the detecting precision and applicability of the methods for identifying the tight sandstone reservoirs remain to be verified. Li Jun (2009) found that the error in calculating saturation is 15% - 30% by using an indequate m exponent because of the influences of low porosity [7]. Li Yuegang (2015) proposed a new method for calculation gas saturation by variable rock-eletro parameters [8]. But both of them do not carry out special researches on the methods for directly calculating the saturation in the reservoirs with low porosity and low permeability.

In allusion to the issues of deep burial, higher pressure, high temperature and hard for identification of gas and water layers in the tight sandstone gas reservoirs in Dabei Area, by using the logging data as the major means and on the basis of fine evaluation of reservoir fractures, a novel approach for calculating saturation is established in consideration of the influential factors of fractures and low porosity and etc., which can meet the requirements of evaluating the saturation and precision of tight sandstone gas reservoirs in Babei Area of Tarim Basin.

2. Fracture Evaluation and Reservoir Type Division in Tight Sandstone Reservoir

Whether the fractures in tight sandstone reservoirs are grown is the key indicator for determining the value of development in the reservoir, the qualitative and quantitative depiction of fractures is the prerequisite of consequent calculation of saturation in the reservoir. Micro-fractures are generally developed in the tight sandstone reservoirs in Kuqa Depression [9] [10], but actual logging interpretation indicates that a very poor effect is caused in the application of dual induction resistivity logging evaluation. Rock mass is basically not conductive, while the parallel network for conduction in fractures is the foundation that the dual induction logging can be used for identifying fractures in carbonate rock formations, in which the resistivity in the carbonate rock formations should be more than 2000 Ω·m at least. Resistivity of the sandstone is much lower than that of carbonate, which is only 10 - 80 Ω·m. In the sandstone formation, the resistivity in the fractural pores is not evidently different from that of rock skeleton, which is the major cause of resulting in poor effect in fracture evaluation using the dual induction logging.

Micro-resistivity imaging logging was one of the effective methods of fracture identification [11], by which the status of fracture near the wellbore could be reflected, its radial extension and connection were difficult to be discriminated. When a low frequency Stoneley wave was used to reflect the mutual seepage of fluids in the fractures or in the pores and the fluid in the wellbore, the radial detecting range could be 1.5 m [12] [13] [14] [15] [16]. Apparent fracture porosity obtained from the micro-resistivity imaging logging is intersected with the permeability of Stoneley wave, by which the connectivity of fractures can be better evaluated. If there were no logging data available, the apparent fracture porosity obtained from the difference between density logging and acoustic logging could be used for reservoir evaluation, but poorer effect is obtained in the evaluation [17]. Based on the selection of acquisition of series logging data in Dabei Area, the micro-resistivity imaging logging is combined with the full-wave acoustic logging in the study for an effectiveness evaluation of reservoir fractures.

Figure 1 is the result of fractural evaluation by using the logging data from electric imaging logging and full-wave acoustic logging in Well Keshen801. It can be seen in the Figure that at 7053 - 7114 m the permeability from Stoneley wave (Track 5) and the reflecting coefficient (Track 8) are high values, which indicates that there exists a good connectivity in formation. At the same time, the parameters of apparent fracture porosity, fracture length and width and its density(Track 10) obtained from electric imaging logging data indicate that fractures are developed in the layer, the identification of acoustic logging shows that there exists good consistence in the fractures. In the Figure, the apparent fracture

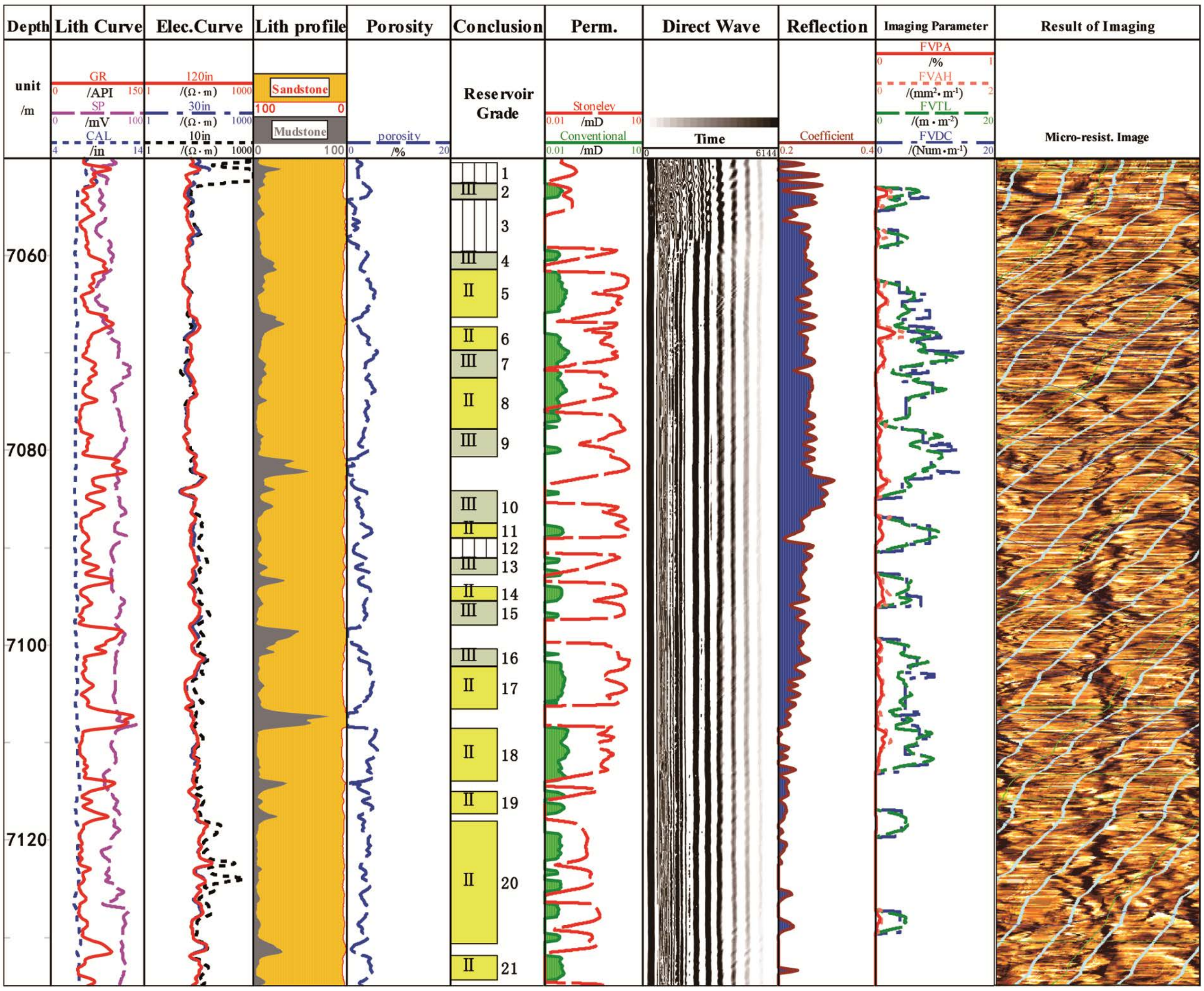

Figure 1. The result of fractural evaluation by using the data of electric imaging logging and full-wave acoustic logging in Well Keshen 801.

porosity in Track 4 is obtained from the porosity difference calculated from the curves of density logging and sonic velocity logging [16], it is commonly corresponded with the fracture in imaging logging, it also indicates that in deep tight sandstone formations, the combination of full-wave acoustic logging with micro-resistivity imaging logging should be the first choice for evaluating the effectiveness of fractures, while the conventional well logging can be a supplement.

For the evaluation of fracture development by taking the reservoir as a characteristic scale, the reservoir characteristic parameters from acoustic and electric loggings are output based on the reservoir. The tight sandstone reservoir types in Dabei Area are classified based on the data of mercury intrusion capillary curve and thin slice analysis. The reservoirs are divided into 4 types, Type I: ϕ (permeability) > 9%, K (porosity) > 1 mD; Type II: ϕ is 6% - 9%, K is 0.1 - 1 mD; Type III: ϕ is 3.5% - 6%, K is 0.055 - 0.11 mD; Dry Layer: ϕ < 3.5%, K < 0.055 mD. In **Figure 1**, the reservoir class in Track 7 is identified according to the

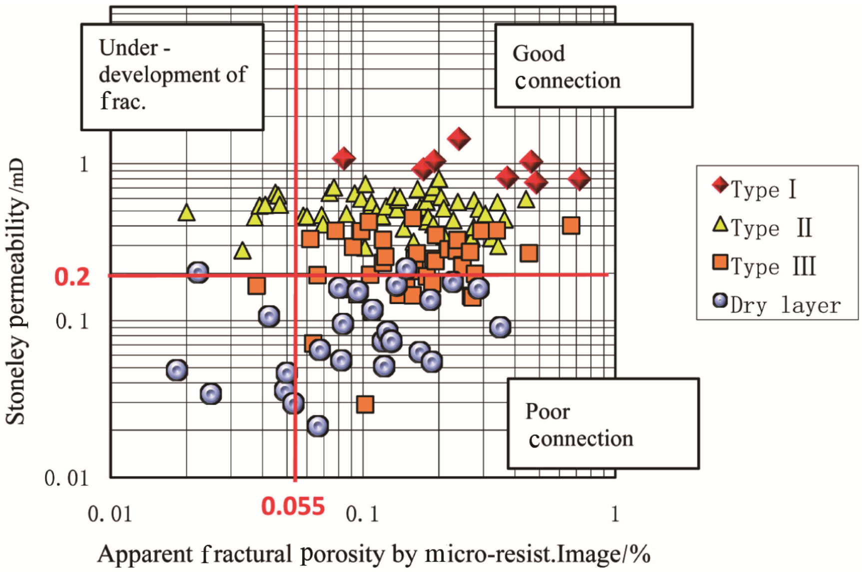

Figure 2. The cross-plot of permeability from Stoneley permeability and apparent fracture porosity in a wellblock of Dabei Area (according to 136 formations data from 8 wells, provided by Tarim Oilfield Company).

above criterion. Figure 2 is the cross plot of Stoneley wave permeability and apparent fracture porosity in a wellblock of Kuqa Area (here the apparent fracture porosity is obtained from the treatment of micro-resistivity imaging logging through core calibration). Based on Figure 2, by taking the apparent fracture porosity of 0.055% as the limit, the reservoirs are divided into fracture developed and fracture less developed reservoirs. By taking Stoneley wave calculated permeability of 0.2 mD as the limit, the reservoir connectivity is divided into a good or bad one. Type I, II and III reservoirs are mostly with good connectivity, the Dry Layer and part of Type III reservoirs are with poor connectivity, they are no productivity. In some of the Type II and III reservoirs, fractures are less developed and are lack of productivity.

3. A Novel Method for Calculating Matrix Saturation in Consideration of Low Porosity and Low Permeability

In a common resistivity logging, fluid type in reservoir can be qualitatively distinguished according to the characteristics of formation invasion, but this method is only suitable for the formations with conventional porosity and permeability. In the tight sandstone reservoirs in deep formation of Dabei Area, permeability is poor, at the same time, as it is influenced by fractures, the curve between the deep induction resistivity and shallow induction resistivity is not very different, the fluid is impossibly identified based on the invasion characteristics (it is shown as the curve in Track III of Figure 1). For a quantitative identification of reservoir fluid and for satisfying the requirement of accurate depiction of geological reserves, the establishment of saturation in tight sandstone reservoirs in Dabei Area is divided into 2 steps, a saturation model which takes account of low porosity and low permeability and is not affected by fractures established first and then takes account of the effect of fractures. The matrix porosity is the key factor for deciding the reserves in the reservoirs, therefore in this chapter, the method for calculating the matrix saturation of tight sandstone reservoirs in Dabei Area is emphatically discussed.

For sandstone formation, it is generally believable that Archie Theory and its improved method are used for saturation calculations [18] [19] [20] [21] [22], but a non-Archie phenomenon is often induced in a low porosity and low permeability reservoirs [23]. As is shown in **Figure 3**, in a core test conducted in a wellblock of Babei Area, the resistivity increase coefficient is not in a single linear relation with water saturation and it is divided into 4 kinds of relations. Therefore the model for calculating the saturation of tight sandstone reservoirs should be reconsidered.

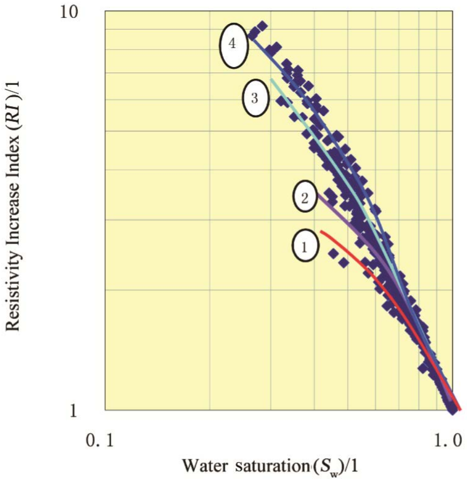

Figure 3. The relation between the resistivity increase coefficient and water saturation test (based on the data from 365 tests at 25˚C and 27 MPa, provided by Tarim Oilfield Company).

According to the Archie theory [18], the relationship between the resistivity increase coefficient and water saturation is:

$$RI = \frac{R_t}{R_o} = \frac{b}{S_w^n} \tag{1}$$

where in Equation (1), the exponent of saturation n is a given value, that is in the cross plot of resistivity increase coefficient and water saturation in a double logarithmic coordinate, the fitting relationship between the both is in a straight line, but there are roughly 4 relationships shown in **Figure 3**. The examination from Relation 1 to Relation 4 indicates that the porosity is raised gradually, which is consistent with the variation trend of resistivity increase coefficient in Archie Phenomenon by Montaron [23] [24]. In allusion to the influence of arrangement of rock particles on porosity, a calculation equation based on probability statistics is introduced [23].

$$\sigma = \sigma_{\mathrm{w}} \left(\frac{P - P_{\mathrm{c}}}{1 - P_{\mathrm{c}}} \right)^{t} \tag{2}$$

As P only represents the conductive formation water in the rock pores, it is simply called a conductive pore water, thus $P = S_{\mathrm{w}}\phi$, if $X_{\mathrm{w}} = P_{\mathrm{c}}$, $\mu = t$, then Equation (2) is turned into

$$R_{\mathrm{t}} = R_{\mathrm{w}} \cdot \left(\frac{1 - X_{\mathrm{w}}}{S_{\mathrm{w}}\phi - X_{\mathrm{w}}} \right)^{\mu} \tag{3}$$

If there exists a rock saturation, there is a rock resistivity

$$R_{\mathrm{o}} = R_{\mathrm{w}} \cdot \left(\frac{1 - X_{\mathrm{w}}}{\phi - X_{\mathrm{w}}} \right)^{\mu} \tag{4}$$

By combination of Equation (3) with Equation (4), a resistivity increase coefficient is obtained

$$RI = \frac{R_{\mathrm{t}}}{R_{\mathrm{o}}} = \left(\frac{\phi - X_{\mathrm{w}}}{\phi S_{\mathrm{w}} - X_{\mathrm{w}}} \right)^{\mu} = \left(\frac{1 - X_{\mathrm{w}}/\phi}{S_{\mathrm{w}} - X_{\mathrm{w}}/\phi} \right)^{\mu} \tag{5}$$

According to Equation (2), $X_{\mathrm{w}} = -0.01$, $\mu = 2$, a tendency plot of resistivity increase coefficient changing with different porosities can be derived (**Figure 4**). The comparison of **Figure 4** and **Figure 3** indicates that the shape of both of them is consistent, that is, the relationship between the resistivity increase coefficient and saturation can be established based on different porosities.

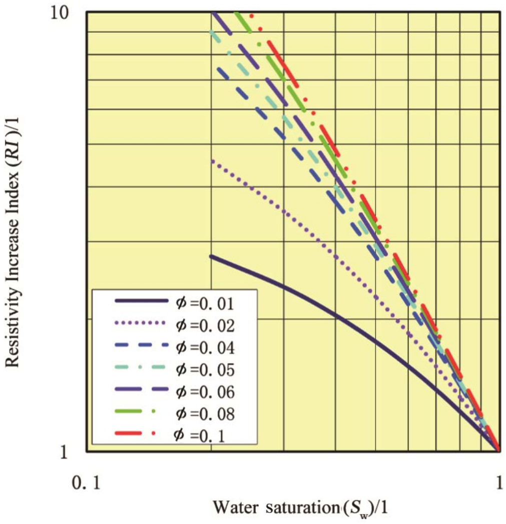

Figure 4. The relationship between resistivity increase coefficient and water saturation test ($X_{\mathrm{w}} = -0.01, \mu = 2$).

If a cementation index equation is introduced

$$\frac{R_{\mathrm{o}}}{R_{\mathrm{w}}} = \frac{a}{\phi^{m}} \tag{6}$$

It is combined with Equation (5), a new equation for saturation calculation is obtained:

$$S_w = \left(1 - \frac{X_w}{\phi}\right) \cdot \left(\frac{aR_w}{\phi^m R_t}\right)^{\frac{1}{\mu}} + \frac{X_w}{\phi} \tag{7}$$

In the equation, the effect of different porosities on the resistivity increase coefficient is taken into account, which is suitable for quantitative calculation of saturation in the reservoirs with low porosity.

4. The Method for Saturation Evaluation in Tight Sandstone Reservoirs in Dabei Area and Its Effect

In the conductive pore water, only the effects of low porosity and high irreducible water are taken into account without taking the fractures into account. By using the idea of dual porosity medium theory, the pore space volume is divided into 2 parts, which include the matrix pores and fractures. For the rock per unit volume, the volume that the rock takes is ϕ_f, then the volume that the matrix pores take is $\phi_b = 1 - \phi_f$ where because the matrix pores are smaller, it can be considered that there is no mud invasion, while because of good permeability in the fractures, it is easy for mud invasion. Based on the above rock model, the rock resistivity R_{tb} of matrix pores can be calculated through rock resistivity R_t and fracture pore ϕ_f, the equation for calculation is :

$$R_{tb} = \frac{R_t R_{mf}\left(1 - \phi_f^{m_f}\right)}{R_{mf} - R_t \phi_f^m} \tag{8}$$

1) The matrix saturation: in consideration of the impact of porosity and irreducible water on the matrix saturation, the equation based on conductive pore water is used.

$$S_{wb} = \left(1 - \frac{X_w}{\phi}\right) \cdot \left(\frac{aR_w}{\phi^{m_b} R_t}\right)^{\frac{1}{\mu}} + \frac{X_w}{\phi} \tag{9}$$

where, the cementation index m_b of the matrix pores can be obtained through a litho-electric experiment of small cores sampling from the area, as shown in Table 1. The m_b of the conglomeratic sandstone is bigger than that of the other sandstones, it is not much different between the mid and fine sandstones, therefore in practical processing, the cementing indexes are established based on the lithologic property.

Table 1. The lithology-based statistics of matrix pore structure index

Lithology	Pebbly sandstone	Mid-sandstone	Fine-sandstone
m_b	2.017	1.943	1.966

2) The water saturation in fractures: according to the permeability property of dual pore types, $S_{xof} = 1.0$ can be obtained from:

$$S_{\mathrm{wf}}^{\mathrm{nf}} = \frac{\left(1/R_{\mathrm{t}}\right) - \left(1/R_{\mathrm{XO}}\right) + \left(1/R_{\mathrm{mf}}\right)\phi_{\mathrm{f}}^{m_{\mathrm{f}}}}{\left(1/R_{\mathrm{w}}\right)\phi_{\mathrm{f}}^{m_{\mathrm{f}}}} \tag{10}$$

To examine the impact of pore space of fractures and etc in the reservoirs on the cementing index m, the rock core is simplified into a regular hexahedron, the length of its edge is a, a oblique crossing joint with the dip angle as β and its width as d_{f} breaks through the whole hexahedron, where pores and holes are developed internally. It is also simplified as a regular hexahedron with its length of edge as b, and the pores and holes are parallel with fractures (see the model shown in **Figure 5**). Based on the geometric relationship and Archie equation, m_{f} is calculated as

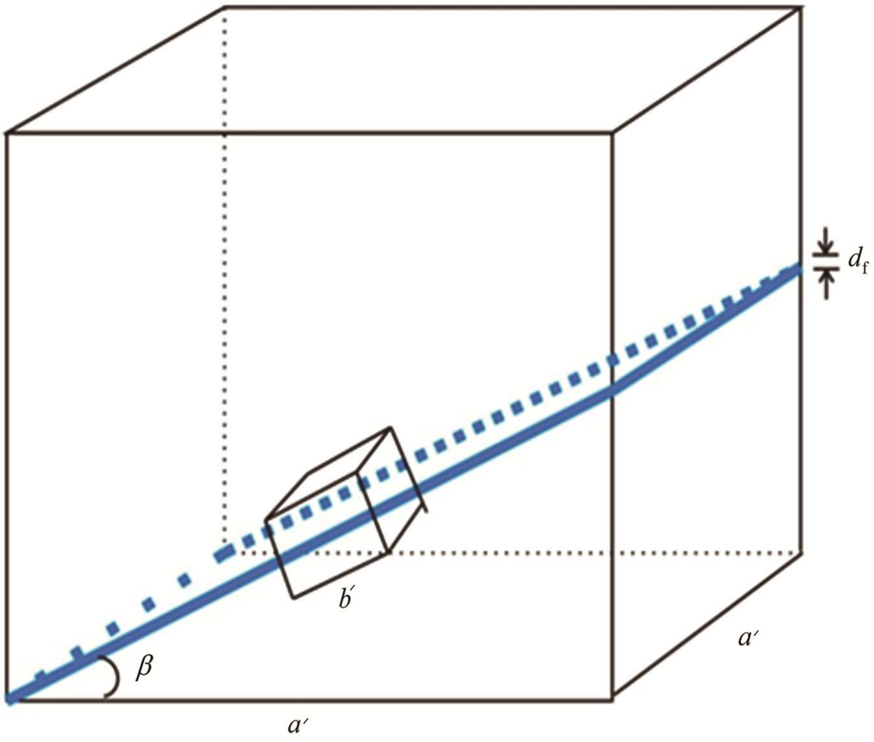

Figure 5. The analytical model of pore-frature style.

$$m_{\mathrm{f}} = -\frac{\log\left[a'\cdot\left(\frac{1}{b'+d_{\mathrm{f}}} + \frac{a'-b'\cdot\cos\beta}{a'\cdot d_{\mathrm{f}}\cdot\cos\beta}\right)\right]}{\log\left\{\left[\left(\frac{a'^2}{\cos\beta} - b'^2\right)\cdot d_{\mathrm{f}} + b'^3\right]\Big/ a'^3\right\}} \tag{11}$$

According to Equation (11), make the edge length of rocks as 1, the relationship between the pore cementing index, width and dip angle of the fractures shown in **Figure 6** is obtained, with the increase of its dip angle and width (d_{f} in the Figure is the fractural width) the bond index m_{f} also increases.

In consideration of fractures with narrow width in the area, but their dip angles are generally larger, the bond index of fractures m_{f} takes 1.2 - 1.5.

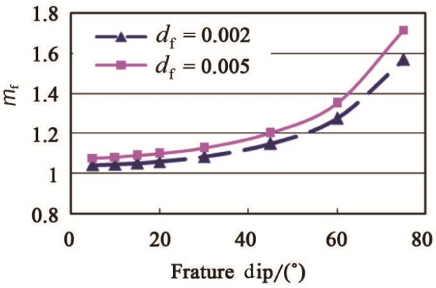

Figure 6. The relation between the pore structure index, its dip angle and width.

3) The total water saturation: the total water saturation S_w in the formation is calculated with the following equation:

$$S_w = \frac{\phi_b S_{wb} + \phi_f S_{wf}}{\phi_b + \phi_f} \tag{12}$$

The result of well data process in a wellblock of Dabei Area indicates that when the apparent fractural pore is bigger than 0.055%, the saturation based on dual pores is 1.5% bigger than that of the one calculated with conductive pore water. Therefore the method for saturation calculation in the well block is: when the apparent fractural pore is smaller than 0.055%, the equation based on conductive pore water is used for saturation calculation. When the apparent fractural pore is bigger than 0.055%, the dual pore equation for saturation calculation is used (**Figure 7**). **Figure 8** is the result of reservoir parameter logging process for Well Dabei102 in Dabei Area. As shown in **Figure 8**, the logging calculated porosity and permeability are close to the testing result in Track 6 and Track 7, at the same time, the saturation in Track 8 that is calculated in this paper is roughly equal to the result of mercury intrusion test. **Table 2** is the relative error statistics between core saturaion and calculationg saturation from Well Dabei102. The error range is 0.01% - 26.04%, the average is 8.8%. **Table 2** indicates that the method presented in this paper can be deployed for quantitative calculation of saturation in tight sandstone reservoirs in Dabei Area.

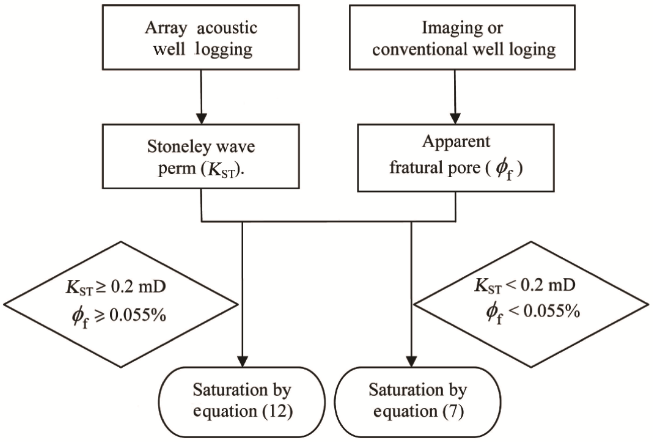

Figure 7. The flow diagram of the saturation calculating method and classification in Dabei Area.

Table 2. The relative error between core saturaion and calculating saturation.

Depth/m	Porosity/%	Permeability /mD	Core saturation/%	Calculation saturation/%	Relative error/%
5319.887	6.65	0.114	45.66	48.08	5.30
5320.237	8.27	0.071	45.67	47.09	3.10
5320.307	8.77	0.085	45.68	46.58	1.98
5320.437	7.40	0.064	45.68	45.69	0.01
5320.497	8.40	0.095	45.68	45.34	0.75
5320.606	7.75	0.103	45.68	45.54	0.32
5320.737	5.56	0.064	45.69	46.53	1.84
5320.917	4.04	0.062	45.69	49.32	7.94
5321.097	5.41	0.054	45.70	47.98	4.99
5321.387	7.54	0.064	45.71	41.28	9.69
5321.457	7.92	0.002	45.71	38.93	14.83
5321.557	7.82	0.034	38.71	36.25	6.36
5321.657	6.60	0.054	35.72	34.35	3.83
5321.827	5.67	0.073	36.72	39.44	7.40
5322.137	3.34	0.002	55.73	71.33	27.99
5322.396	3.46	0.057	53.74	58.01	7.94
5322.517	5.19	0.039	45.75	45.74	0.01
5322.637	6.35	0.065	45.48	47.92	5.36
5322.757	8.74	0.141	45.52	45.73	0.46
5322.896	8.56	0.195	45.57	44.00	3.45
5323.046	8.92	0.106	45.61	42.03	7.85
5323.247	8.90	0.126	45.68	38.98	14.67
5323.347	8.49	0.039	45.71	37.29	18.42
5323.527	7.82	0.004	45.77	33.85	26.04
5323.637	6.04	0.186	35.78	30.15	15.74
5323.777	5.20	0.070	37.79	33.03	12.58
5323.937	5.64	0.061	45.79	40.32	11.95
5324.177	3.56	0.057	45.80	53.27	16.32
5324.437	4.37	0.063	45.81	55.33	20.79
5324.537	3.36	0.050	55.81	54.98	1.49
5324.836	5.77	0.061	57.82	51.90	10.24
5324.987	6.12	0.066	45.82	53.40	16.54
5325.197	4.69	0.057	45.83	52.18	13.86
5325.336	6.00	0.059	45.83	49.88	8.83
5325.467	6.91	0.067	45.84	44.60	2.70
5325.637	6.27	0.080	45.84	41.69	9.06
5325.787	8.11	0.063	45.85	42.20	7.96
5325.887	7.27	0.064	45.85	43.90	4.26
5326.017	6.79	0.068	45.86	50.32	9.73
5326.197	7.40	0.070	62.86	58.61	6.76
5326.327	5.12	0.086	65.87	57.02	13.43
5326.467	3.01	0.087	45.87	50.69	10.51
5326.637	4.08	0.070	45.88	48.19	5.04
		Average			8.80

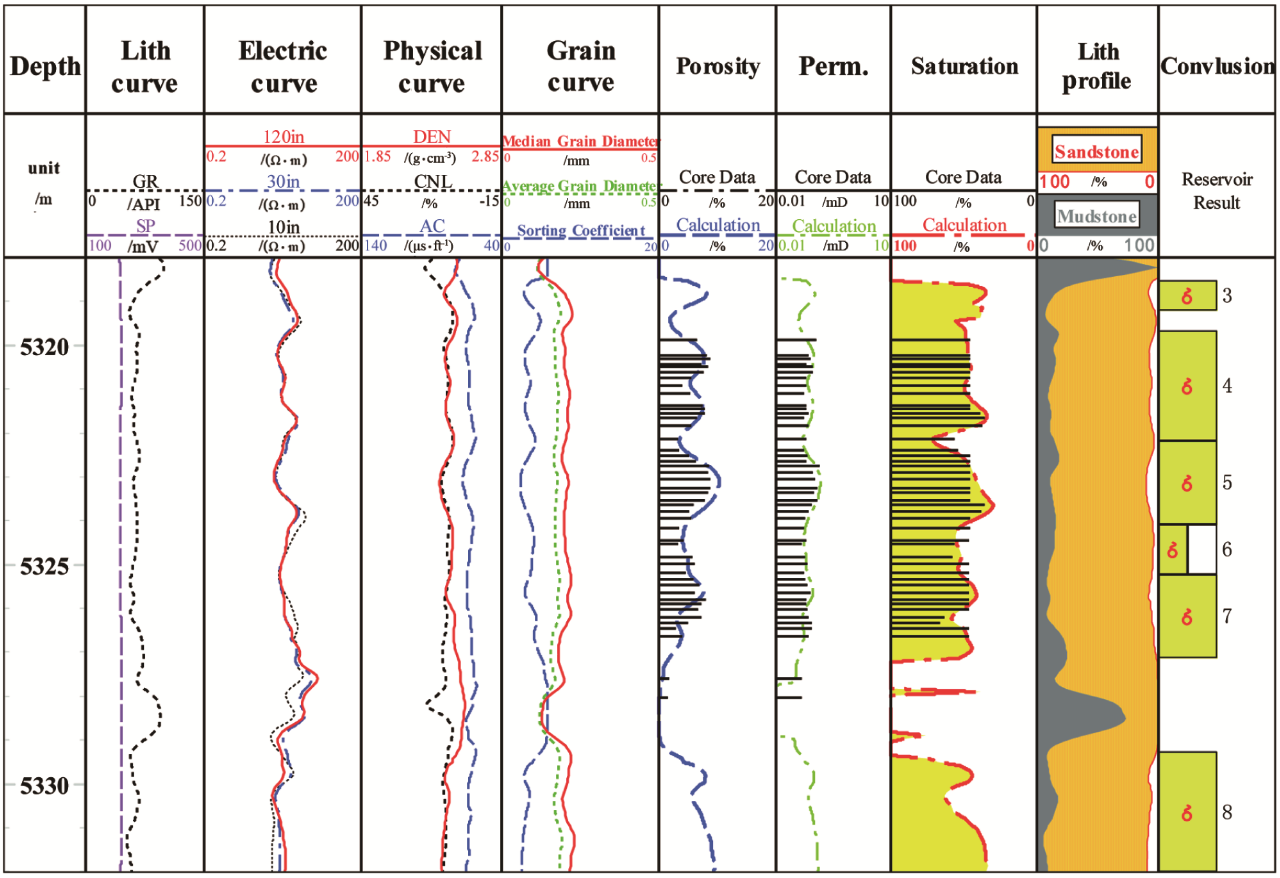

Figure 8. The results of saturation calculation in Well Dabei102.

5. Conclusions

The accurate evaluation of fractures is an essential and important step in tight sandstone reservoir evaluation. The micro-resistivity logging and full wave acoustic logging can be used for a better fracture evaluation. The micro-resistivity logging imaging cab be used for obtaining the intersection of apparent fractural porosity and Stoneley wave permeability; the difference between porosities calculated by density and acoustic loggings can be used for obtaining the apparent fractural porosity for evaluation. If there are no data of micro-resistivity logging, the evaluation should be carried out by using the difference between porosities calculated by density and acoustic loggings, but the result is poorer. The tight sand reservoirs in Dabei Area can be divided into 4 types by stoneley permeability and apparent fractural porosity.

Influenced by physical property, the resistivity increase index is not a given value. The effects of low porosity and high irreducible water on the saturation of tight sandstone reservoirs are taken into account in the saturation model established by using conductive pore water. The *RI*-S_w relationship established in the study is consistent with the result of rock core testing, which indicates that the method is suitable for the evaluation of tight sandstone reservoirs.

According to the result of evaluation from Dabei Area, it indicates that when the apparent fractural porosity is less than 0.055%; the equation based on conductive pore water is used for calculation; when the apparent fractural porosity is more than 0.055%, the equation based on the theory of dual porous media is deployed. And the concrete operation flow can be seen in Figure 7. The relative error statistics between core saturaion and calculating saturation from WellDabei102 is from 0.01% to 26.04%, the average is 8.8%. The formation saturation calculated with the method is conformed to that of mercury intrusion in core testing, which further validates that the method is correct.

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Nomenclature

RI is the resistivity increasing index, dimensionless;

R_t is the formation true resistivity, Ω·m;

R_o is the full water saturated formation resistivity, Ω·m;

S_w is the water saturaton,%;

n is the exponent of saturation, dimensionless;

b is coefficient of saturation, dimensionless;

σ is the formation conductivity, 1/(Ω·m);

σ_w is the formation water conductivity, 1/(Ω·m);

P is the volumetric ratio of unit rock fluid in the whole rock, %;

P_c is the lower limit value of conduction in pore fluid in the unit rock, %;

t is a proportional coefficient, dimensionless;

R_w is formation water resistivity, Ω·m;

X_w is the volume of conductive pore water , %;

ϕ is the formation porosity, %;

μ is a proportional coefficient, same as t, dimensionless;

a is the coefficient in the formaiton resistivity Factor-Porosity relationship, dimensionless;

m is the exponent in relationship: $F = a\phi^{-m}$, dimensionless;

R_{tb} is the resistivity of matrix pores, Ω·m;

ϕ_b is the porosity of matrix pores, %;

ϕ_f is the porosity of fracture, %;

R_{mf} is the mud filtrate resistivity, Ω·m;

m_f is the exponent in relationship: $F = a\phi^{-m}$ only for fracture, dimensionless;

m_b is the exponent in relationship: $F = a\phi^{-m}$ only for matrix pores, dimensionless;

S_{wb} is the water saturaton in matrix pores,%;

S_{wf} is the water saturaton in fracture,%;

n_f is the exponent of saturation for fracture, dimensionless;

R_{XO} is the resistivity of flushed zone, Ω·m;

a' is the length of edge in the analytical model, m;

b' is the length of small pore in the analytical model, m;

β is the incliation of fracture, radian;

d_f is the width of fracture, m.