New Evaluation Method of Fracture Permeability Based on Stoneley Wave Data and Electric Imaging Log in Tight Fractured Sandstone Reservoir

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Abstract: Quantitative evaluation of fracture permeability is one of difficulties in log interpretation. In recent years, more and more well-logging new technology, such as electrical imaging logging and array sonic logging were widely applied in complex reservoirs evaluation, and also, provided great help in calculating fracture permeability. But, one of the most difficult questions in fracture permeability modeling is how to acquire physical fracture permeability samples, which would be used to calibrate the empirical model. Commonly, the physical fracture permeability samples can be gained from full diameter cores analysis, or interpretation results from formation testing data. But unfortunately, this kind of samples are often very few because of the difficult of fractured full diameter cores analysis and the lacking of testing data focalized fractured intervals. So, this paper put forward a new idea or method to resolve this trouble, which may be called as Dual Calibration method. As we know, the permeability calculated from Stoneley wave (can be called as Stoneley permeability) was total formation permeability, which consist of matrix and fracture permeability. In no fracture intervals, the Stoneley permeability should be equal to the matrix permeability, so we can *calibrate* the Stoneley permeability to matrix permeability, which gained from conventional core analysis or matrix interpretation. In fractured intervals, fracture permeability can be computed from the calibrated Stoneley permeability and the matrix permeability. Generally, an empirical fracture permeability model can be established from fracture aperture and porosity, which often gained from electric imaging processing. So we can *calibrate* this model by fracture permeability acquired from above steps and make the model suit for the target areas. Namely, this idea can be simply described as: the matrix permeability calibrated Stoneley wave permeability, and Stoneley wave permeability calibrate the electric imaging fracture permeability. This method had been used in some oilfields in Western China and good results were produced. In

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our opinions, this method could be regarded as an important supplement when we gained the physical fracture permeability samples difficultly.

1   Introduction

As the primary seepage channel in low-permeability and/or tight fractured pools, fracture has great influence on reservoir productivity. But it was very difficult to calculate the fracture permeability, a parameter which was closely related to the productivity. In recent years, more and more well-logging new technology, such as electric imaging logging and array sonic logging were widely applied in complex reservoirs evaluation. And also, these new technology data provided great help in calculating fracture permeability.

As the main information source of the subsurface rock and fluid, well logging data is one of the most important data for reservoir fracture evaluation. The electrical imaging logging was currently considered to be the relatively best data to identify natural opened fractures accurately, although in theory, all kinds of log data can be used in a certain extent. But it is difficult to be used in calculating fracture permeability quantitatively. Stoneley wave was very sensitive to subsurface opened fractures, but it was difficultly used to identify fractures visually due to multiplicity of fracture recognition compared to electric imaging data. So, we can use them synthetically in fracture evaluation, and some new methods could be put forward to evaluate fracture parameters quantitatively.

2   General idea of fracture permeability quantitative evaluation

Permeability is one of the main parameters for the evaluation of reservoir productivity. Because the fracture permeability is usually far larger than the matrix permeability, the permeability of fractured intervals mainly depends on the fracture permeability. Quantitative evaluation of the fracture permeability is very important to oilfield development and production.

2.1   *Method of fracture permeability modeling*

According to van Golf-Racht (1982), nonporous fractured reservoir could be regarded as ideal fracture system which consist of fractures with width/aperture b, extending length l and surface porosity Φ_f, and the permeability of this kind of model can be deduced as:

$$K_f = \Phi_f \times b^2/12 \tag{1}$$

The equation (1) can only provided reference in practical application due to the great difference between the laboratory conditions and actual reservoir, and the

irregularity of fractures. Usually, the following statistical model was established, if coefficient a was determined in the workarea:

$$K_f = a \times \Phi_f \times b^2 \tag{2}$$

Currently, the fracture permeability models are generally build with the fracture aperture and porosity [Liu and Zhang (2003); Xian, Wu, and Li (2008); Guan, Li, and Zhang (2007); Xiao, Li, and Chen (2009)]. And because of more researching in aperture and porosity, this kind of evaluating model can provided more reliable and accurate fracture permeability.

2.2 Acquisition methods of fracture permeability samples

As mentioned above, sufficient representative samples were necessary for fracture permeability modeling, in order to get the calibrated formula coefficient. Therefore, the key problem is how to obtain the fracture permeability samples.

The fracture permeability samples usually acquired from two sources. The one is the results explained form the formation testing and test of oil production data. Its advantage was directly gained from the subsurface and tight coupling with production. But its disadvantages are also obvious, because the testing results were affected by borehole conditions, testing technologies, combined multilayer testing and many other factors. And it is hardly to evaluate the influence of fracture because almost no testing data for the fractured formation.

The other is the laboratory data measured from rock cores with whole diameter and fractures. The permeability, along and perpendicular to the fracture face direction, can be gained from cores in laboratory, and the fracture permeability can be estimated with magnitude accuracy from the difference between the two crossed directions. Its advantage was measured directly from the fractures. But it was very difficult to acquire the data because of the great differences between cores and subsurface conditions.

Due to the above difficulties, this paper puts forward an acquisition idea of fracture permeability samples based on Stoneley wave logging and data processing.

3 Fracture permeability modeling based on permeability samples gained from Stoneley wave

3.1 Basic principles of permeability inversion from Stoneley wave data

In recent years, a great deal of researching shows that Stoneley wave have close relationship with formation properties. Especially, Stoneley wave was sensitive to

the formation permeability and the degree of fracture development [Huang and Li (1994)]. So the permeability can be estimated using Stoneley wave, marked as k_{st}.

Some informations that have no relation with permeability also existed in Stoneley wave which gained from wave data separation processing. The informations include the changes of Stoneley wave propagation time and amplitude caused by changes of formation elastic property and borehole conditions in wave traveling, and the wave attenuation in the rock and the borehole fluid. The Stoneley waveform was synthesized in order to eliminate the influences of these factors and gain the real wave attenuation and propagation velocity. The Stoneley wave slowness Δt_{st_syn} in tight and impermeable rock formation was calculated based on the elastic wave theory and rock cores calibration. Compared to Δt_{st_syn}, the measured Stoneley wave slowness Δ_{st} would increase in permeable formations. The ratio $k_{st} = (\Delta t_{st} - \Delta t_{st\_syn})/\Delta t_{st\_syn}$ can be called as Permeability Index, which can reflect the formation permeability and also eliminate the effect of drilling fluid properties. The formation permeability can be calculated using the empirical function which established based on the rock core permeability k_{core} and k_{st} at the corresponding depth.

The calculated permeability based on Stoneley wave data is the total formation permeability, so the permeability of rock matrix must be deducted to estimate the fracture permeability. The permeability of rock matrix can be obtained by conventional core analysis or matrix parameters interpretation.

3.2 k_{st} calibrated the fracture parameters gained from electrical imaging log

When the fractures cutting the borehole, the propagation of Stoneley wave was just like a piston motion and result in expansion and contraction of wellside in radial direction. And the drilling fluid/mud would flow in and out along fractures and cause attenuation of the Stoneley wave energy. But this will not happen in non-fractured formation.

Therefore, the fracture permeability k_f can be estimated from the difference of permeability in the typical fractured and non-fractured intervals. Then k_f can be used to calibrate the parameters gained from electrical imaging log and establish more accurate and practical permeability model. The specific approach was as follows.

(1) Matrix rock permeability k_b calibrate k_{st} at typical non-fractured intervals

In such non-fractured intervals, k_{st} can only reflect k_b, k_{st} must be calibrated to k_b because the later has higher computation precision than kst from conventional logging data. Then the calibration relation can be used in the whole workarea, and so k_f can be gained from $k_{st} - k_b$ at the fractured intervals.

(2) Selection of typical fractured intervals with the help of electrical imaging log data

Because many factors, such as shale bands, conditions of wellbore and fractures induced from drilling, can affected k_{st}, the typical fractured intervals must be selected by the aid of the clear display in electrical imaging log and Stoneley wave log. The parameters gained from electrical imaging data processing must be calibrated by k_{st} in such intervals, and then the fracture permeability model can be established.

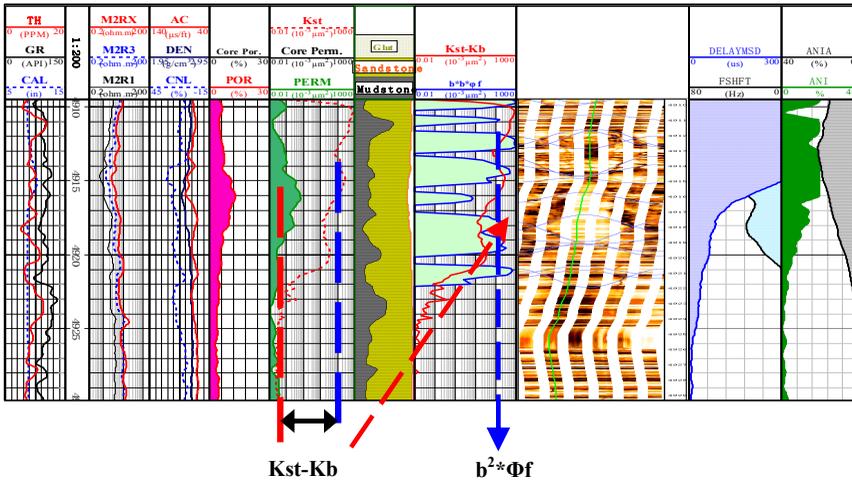**(3) Fracture permeability modeling based on the calibration relation gained from above (1)**

Figure 1: Calibration Method of $(k_{st} - k_b)$ vs. $(a \times b^2 \times \Phi_f)$

The aperture b and porosity Φ_f of fracture can derived with relatively high accuracy from the processing result of electrical imaging data. The coefficient a can be determined from regression of $(k_{st} - k_b)$ vs. $(a \times b^2 \times \Phi_f)$ according to equation (2). And so, fracture permeability can be calculated using fracture aperture and porosity.

By calibrating, the fracture permeability model for the specific workarea is given:

$$K_f = 0.0673 \times b^2 \times \Phi_f \tag{3}$$

where fracture aperture b is in μm, fracture porosity Φ_f is in percent, fracture permeability K_f is in $10^{-3} \mu m^2$. The calibrated modeling relation and its examination are shown in Fig. 2.
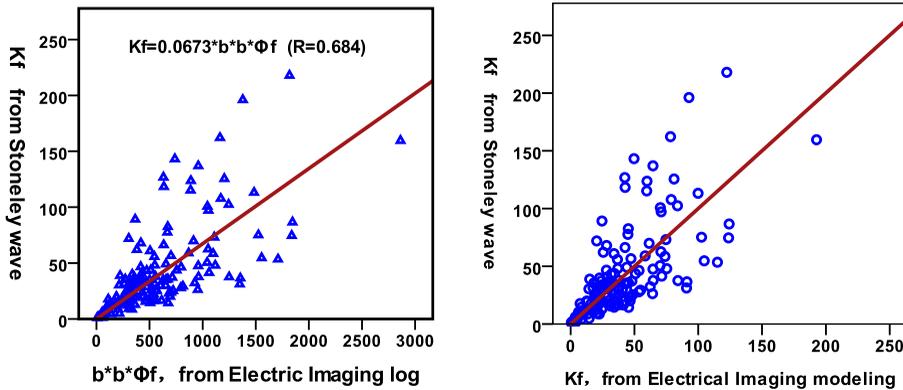
Figure 2: Fracture permeability modeling based on calibration of Stoneley wave to parameters gained from electrical imaging log

4 Application analysis for fracture permeability model

Examination must be done if we want to verify the actual application result of fracture permeability, by formation testing data or measurement data of rock cores in laboratory. Laboratory data were not be used because there are only seldom and unreliable measurement data existed.

4.1 Model examination by permeability of formation testing

The permeability of formation testing can reflect the influences of rock matrix and fractures. So, the testing permeability mu be taken away by matrix permeability which calculated based on conventional well-log interpretation. But very often, the testing permeability could be directly regard as fracture permeability because the permeability of fractures is usually far higher than of matrix in fractured intervals of low porosity and low permeability tight reservoir. Of course, the testing permeability was only in the order of magnitude accuracy because of the influence of testing technologies and other factors.

The model calculating results are compared with the testing permeability in fractured intervals, as shown in Table 1 and Fig. 3. We can conclude that the two permeability are of the same order of magnitude, and this also demonstrates the applicability of the model. In Table 1, $K_f h/H$ is the thickness weighted average value of K_f in the testing well interval, in which H is the whole thickness of testing interval and hi is the fractured thickness along the wellbore direction.

Table 1: The model calculating results vs the testing permeability

| No	Well	Depth	Geology horizon	Testing permeability K_a	Matrix Permeability K_b	$K_a - K_b$	$K_f h / H$
1	CM202	4846.5-4897.0	$E_{2-3}s^1$	68.50	0.39	68.11	45.62
2	CM202	5022.0-5046.0	$E_{2-3}s^3$	10.55	0.74	9.81	29.10
3	CM202	5140.5-5145.0	$E_{1-2}k^2$	85.29	0.24	85.05	123.55
4	CM204	5199.0-5219.0	$E_{2-3}s^3$	0.52	0.34	0.18	6.86
5	CM204	5001.5-5072.0	$E_{2-3}s^1$	24.50	0.33	24.17	6.34
6	CM204	5300.0-5347.0	$E_{1-2}k^2$	0.23	0.06	0.17	9.33
7	CM201	4781.0-4806.0	$E_{2-3}S^1$	2.14	0.57	1.58	4.27
8	CM201	4980.0-4990.0	$E_{2-3}S^3$	5.51	1.36	4.15	11.47
9	CM3	5362.0-5381.0	$E_{2-3}S^1$	13.16	0.13	13.03	1.4
10	CM2-8	5266.0-5294.0	$K_1 bs$	9.04	0.19	8.85	14.68
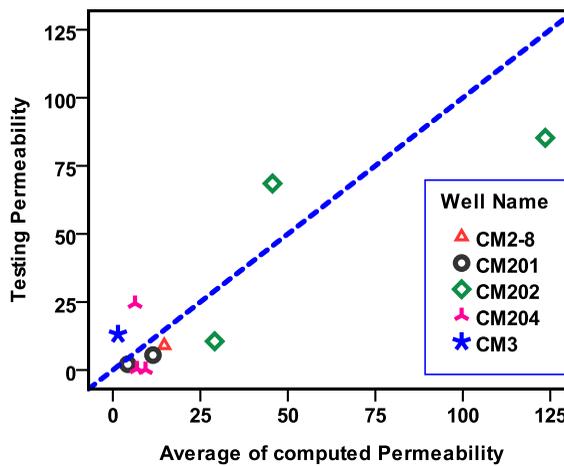
Figure 3: Comparison and examination of testing vs. computed permeability

4.2   Model examination by reservoir productivity

The studying area is in a typical high-yield gas field with low porosity and permeability, and the Qaof (Absolute Open Flow) can be taken as an important indicator of productivity. The relation of Kf and Qaof can be analyzed to examine the effectiveness of K_f model (Equation 3) because K_f is the main parameter affecting the production of gas well and K_f is mainly dependent on fractures in low porosity and permeability reservoir.

The accumulated value of $K_f h = \sum_i (K_{fi} \cdot h_i)$, product of all fracture's permeability K_{fi} and their thickness h_i, was computed in perforated intervals in every well. This parameter can be called as Accumulation Fracture Productivity Coefficient

(AFPC). So AFPC can reflect the contribution of fracture to production in perforated intervals because K_f was calculated from aperture b and porosity Φ_f. Table 2 gives AFPC and Qaof values of all well, and their correlativity is shown in Fig. 4.

Table 2: Model examination by reservoir productivity

Well	Qaof	Top depth	Bottom depth	Fracture Density	Fracture Permeability	AFPC
	$(10^4 m^3/d)$	(m)	(m)	$(/m)$	$(10^{-3}\mu m^2)$	$(10^{-3}\mu m^2 \cdot m)$
CM2-20	40	4944.5	5104.5	0.075	10.376	98.04
CM2-17	96	4857.0	5245.0	0.044	15.328	210.23
CM2-16	121	4860.0	5045.0	0.519	2.642	119.18
CM2-14	335	4733.5	5061.0	0.400	27.125	1988.40
CM2-12	264	4727.5	5053.5	0.414	19.158	1672.96
CM2-23	169	4894.0	5199.0	0.518	20.961	2632.17
CM2-8	171	4656.0	4999.5	0.452	3.391	354.02
CM2-B1	293	4757.5	5081.0	0.414	15.119	1458.48
CM2-7	449	4700.0	5009.0	0.806	20.668	2998.56
CM2-6	334	4717.2	5061.5	0.465	21.716	2594.69
CM2-22	328	4894.5	5209.0	0.630	21.597	2442.20
CM202	281	4846.5	5046.0	0.551	0.794	83.144
CM2-2	457	4775.0	5120.0	0.458	23.229	2088.70
CM2-1	569	4865.0	5176.0	0.601	27.015	3273.09

Fig. 4 shows a good linear relationship between AFPC and Qaof except several wells. And this tendency reflects the fracture's great contribution on reservoir productivity. But this analysis only demonstrates their correlative tendency according to the fractures evaluation. The relationship is difficult to quantificationally describe because there are many factors affect the K_f.

4.3   *Applicability of this idea*

Just as the analysis like above, the implement of the idea or method presented in this paper demands the existence of electrical imaging log and array sonic log (Stoneley wave data) in the cored well intervals. These data can be used to determine the existence of fractures and satisfied the demands of quantitative evaluation of K_f.

One of the advantages of this method lies in that the mudcake only affect the propagation of Stoneley wave a little because the mudcake can prevent the flow of well fluid but cannot keep from the transmission of pressure, and the pressure can affect the travelling velocity of Stoneley wave. But its disadvantage is that the propagation of Stoneley wave can be affected by the content and structure of shale and the reflection of different acoustic impedance interfaces, and this influence was hard to correct. So we must keep caution when this method be used.

So, the idea or method presented in this paper can only be as an important supplement. When not enough cores with whole diameter and specific formation testing
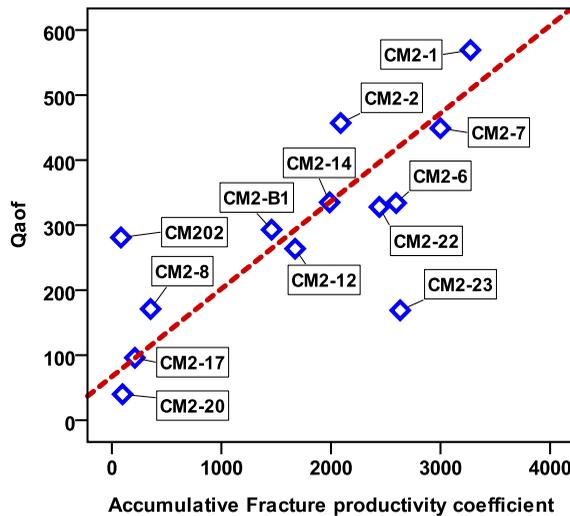
Figure 4: Relationship of Qaof and AFPC in perforated intervals

data can be used, the permeability samples induced from Stoneley wave can be regard as an important supplement. Of course, it is best if we can get enough data from the core measurement or formation testing. And in these conditions, the model and its calculated results is more believable.

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