The characterization method and effectiveness research for crack parameters in Tight Sandstone Reservoir

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Abstract. When natural cracks in oil & gas development of tight sandstone remain valid, effective crack degree is the decisive factor of reservoir enrichment and high production. Taking the reservoir of the Bashijiqike Formation in Kuqa depression, Tarim Basin as an example, the crack parameters were characterized by a mathematical model and algorithm, which lays a theoretical foundation for the study of crack validity. According to crack parameters processed by electric imaging and static modulus date of rock mechanics, control conditions that constrain crack development such as crack permeability, the normal stress on crack surface and the angle between maximum principal stress and crack strike were obtained. In addition, quantitative expressions between constraints on crack development and productivity were established and the main control factors of fracture validity were confirmed. In the end, the crack development degree and effectiveness were comprehensively evaluated.

1. Introduction

The cracks’ effectiveness refers to the availability of natural cracks that are open under reservoir conditions and provide valid flow space for fluids. However, the research on the judgment of its effectiveness and the quantification of its effectiveness is mainly focused on the evaluation of the quantitative parameters of crack. The method of characterization of crack quantitative parameters is the basis of crack effectiveness evaluation. But the previous studies on cracks quantitative parameters tend to have large differences. For example, the crack width parameter obtained through the core, deep and shallow lateral logging data, and well test data varies greatly and always lacks a solid theoretical basis. In addition, in order to solve the important role of cracks in oil and gas accumulation and oil & gas development in the process of oil and gas seepage, the study of crack effectiveness is crucial, and a set of crack effectiveness evaluation methods and quantitative indicators based on oil and gas production capacity should be established.

With superior oil and gas geological conditions and good prospects for natural gas exploration, the Cretaceous Bashijiqike Formation in the Keshen area of Kuqa Depression is the main block and stratum of natural gas exploration and development in the Tarim Basin. Through a large number of production wells for statistical data analysis, the average gas production per well can reach $37 \times 10^4 \text{m}^3/\text{d}$ in the study.
area. According to the literature and previous studies [2-4], the development of structural crack is the main reason for the high yield of reservoirs [5-6]. But so far, there has not been a systematic and complete method for quantitative characterization of parameters and effectiveness evaluation of cracks in tight sandstone reservoirs. In this context, in order to provide a basis for the next adjustment of exploration plan and capacity building, the study should be considered from various aspects, such as the quantitative parameters of cracks, development control conditions and oil & gas productivity.

2. Characterization of crack quantitative parameters
In the study area, imaging dates for the Ks2- Ks8 wellblock are complex (including FMI, FMI-HD, EI, STAR-II, XRMI, etc.), which mainly uses Schlumberger's Techlog software by improved algorithms to explain and evaluate. The quantitative evaluation of crack parameters under water-based mud conditions is mainly completed by calculating quantitative parameters such as crack length, crack density, crack width and crack porosity.

2.1. Crack parameter calculation method
(1) crack width: According to the research results of S. Mluthi and P. Souhaite, the following relationship is obtained [7]:

$$ W = aAR_m R_{xo}^{1-b} $$

In the formula: 
- W: Crack width, mm; 
- $R_m$: mud resistivity, Ω·m.; 
- $R_{xo}$: Invaded zone resistivity, Ω·m.; 
- $a, b$: Instrument-dependent constant; 
- A: Abnormal area of conductance caused by crack, m$^2$. A value can be calculated by the follow formula:

$$ A = \frac{1}{U_e} \int_{h_0}^{h_n} [I_e(h) - I_{bm}] dh $$

In the formula: 
- $U_e$: The potential difference between the measuring electrode and the return electrode, V; 
- $I_e(h)$: Current value of the electrode at the depth h, μA; 
- $I_{bm}$: current measured value at natural cracks, μA; 
- $h_0$: Depth at the beginning of the effect of the crack on the measured value of the electrode, m; 
- $h_n$: Depth at the end of the effect of the crack on the measured value of the electrode, m.

(2) crack length: The sum of the lengths of the crack tracks per unit area of the well wall. The computation formula is:

$$ F_l = \frac{1}{2nRLC} \sum_{i=1}^{n} L_i $$

In the formula: 
- $F_l$: Crack length, m; 
- $R$: Borehole radius, m; 
- $L$: Statistical well length, m; 
- $C$: Wellbore coverage rate of electrical imaging, dimensionless. 
- $L_i$: The length of the ith crack on the electrical image, m.

(3) crack density: Number of cracks per unit length of the well wall. The computation formula is:

$$ F_d = \frac{1}{L} \sum_{i=1}^{n} L_i $$

Correction factor is introduced to correct the crack density: The angle of the crack on the wall of the unit length should be considered, and the number of cracks with a certain contribution rate can be calculated by correcting the number of cracks.

$$ k = \frac{1}{\cos Q} $$

Corrected crack density:

$$ F'_d = k \times F_d = \frac{1}{\cos Q \times L} \sum_{i=1}^{n} L_i $$

(6)
In the formula: $F_d$: The crack density, a/m; $F'_d$: Corrected crack density, a/m.

(4) Crack porosity: Cumulative area of cracks per unit area of well wall. The computation formula is:

$$\phi_f = \frac{1}{2\pi R L C} \sum_{i=1}^{n} L_i W_i$$

The improved crack porosity: Cumulative volume of cracks per unit volume of well wall. The pore volume formula is

$$\phi_f = \frac{V_f}{V} = \frac{r \times \cos \theta}{R \times L} \sum_{i=1}^{W_i}$$

In the formula: $\phi_f$: Crack apparent porosity, %; $W_i$: The width of the ith crack on the electrical image, mm.

Figure 1. Model diagram of crack parameter improvement method

(5) Crack permeability:

First of all, cracked reservoir engineering shows that in the case of a simplified block with parallel flow direction of crack (as shown in Figure 2), flow through the crack is as follows:

$$Q = ab \frac{b^2 \cos^2 \alpha}{12 \mu} \frac{\Delta p}{\Delta L}$$

On the other hand, the flow through the crack by the classic Darcy law is as follows:

$$Q = ah \frac{K_c}{\mu} \frac{\Delta p}{\Delta L}$$

Combined with the above formula, the crack permeability calculation model is simplified to:

$$K_f = \frac{b^3}{12h} \cos^2 \alpha$$

Figure 2. The crack diagram model
The high-angle crack developed in the study area is similar to the crack (2) in the model, and its crack porosity can be expressed as:

$$\phi_f = \frac{a \times l \times b}{a \times l \times b} \times \frac{1}{\cos \alpha} = \frac{b}{h \cos \alpha}$$ (12)

Finally, bring it into the theoretical calculation formula of crack permeability:

$$K_f = \frac{b^2}{12} \times \cos^2 \alpha \times \phi_f \times 10^{-7}$$ (13)

The theoretical formula of relation between well testing permeability and crack permeability:

$$K_j = \frac{\sum_{i=1}^{n} (K_{ff} \times b_i)}{H}$$ (14)

In the formula: $a$: The cube width in the model; $l$: The cube length in the model; $h$: The cube thickness in the model; $b$: Crack width; $\phi_f$: Crack porosity; $a$: The angle between crack and flow direction; $K_{ff}$: Theoretical crack permeability; $K_j$: Crack permeability in test section; $\mu$: viscosity; $\Delta p$: unit pressure.

2.2. Characterization methods of crack derived parameter
(1) The normal stress of crack surface: in order to evaluate the effectiveness of crack, the concept of normal stress of crack surface was introduced. First, three-axis principal stress parameters $\sigma_H$, $\sigma_h$ and $\sigma_v$ are calculated according to the rock mechanics model. Secondly, the angle $\theta$ between the maximum principal stress direction and the crack strike was obtained by imaging log data. Finally, the crack dip of each well was calculated and the normal stress of crack surface $\sigma_n$ was obtained (figure 3).

$$\sigma_n = \sum_{i=1}^{n} \rho H_i + \sum_{i=1}^{n} \rho D_i$$ (15)

In the formula: $l = \sin \theta \cdot \sin(dip)$; $m = \cos \theta \cdot \sin(dip)$; $n = \cos(dip)$; $Ho$: Vertical depth without density logging, m; $\rho_0$: Average density of unlogged wells segment, g/cm$^3$; $\rho$: logging density value, g/cm$^3$; $i$: sampling interval depth, m; $PR$: Poisson’s ratio, decimals; $E$: Young’s modulus, Gpa; $\alpha$: Biot
coefficient; The coefficient of $\beta_1$ and $\beta_2$ in the same fault block is constant; $\sigma_n$: normal stress of crack plane; $\sigma_H$, $\sigma_h$: the maximum and minimum horizontal principal stress, Mpa; $P_p$: pore pressure, Mpa; $P_o$: overburden pressure, Mpa; $\sigma_v$: overburden formation pressure; $\theta$: the angle between the maximum principal stress direction and crack strike, $dip$ is crack dip. The validity of crack is analyzed by the stress intensity on crack surface.

Through the numerical simulation of experimental data and the analysis of reservoir geological environment, it is considered that the greater the stress acting perpendicular to crack surface, the smaller the crack opening degree and the poor the crack elongation, then the cracks’ effectiveness is correspondingly worse. As shown in Fig. 4, as the normal stress applied to the core increases from (0 to 26) MPa, the crack width on the rock sample is smaller.

![Figure 4. Experiment of the crack opening degree under different pressure](image)

(2) Angle between maximum principal stress and crack strike: The maximum principal stress refers to the maximum horizontal principal stress at the current formation, and its direction is critical for crack evaluation and subsequent fracturing. When the direction of the crack system (effective crack) is consistent with the direction of current maximum horizontal principal stress or the angle is very small, the crack can maximize the role of the percolation channel. On the contrary, when the vertical or oblique angles of the two are large, the percolation effect of the crack is greatly reduced, which may make the crack close under the action of strong stress.

![Figure 5. The diagram of angle between maximum principal stress and crack strike](image)
3. Establishment and evaluation of quantitative characterization index of crack validity
In the early stage, the effectiveness of the tight sandstone reservoirs in the study area is mainly based on matrix, but it is found that tectonic crack development is the main reason for its high yield. At present, only some cracks with high angles and long extensions can be evaluated, but the evaluation accuracy is low and the evaluation method is single [8-10]. Therefore, it is necessary to systematically research the main controlling factors of crack validity. Classification evaluation criteria of crack characteristic parameters were established, which forms well logging evaluation technology for cracks in tight sandstone reservoir.

3.1. Effectiveness of crack porosity
Firstly, well test data are used for analysis. Then the gas production at different production pressure differences, different reservoir thicknesses and different time periods is converted into gas production $J_g$ under the same production pressure differences, unit reservoir thickness and unit time, which contributes to the effects contrast. In the end, the validity of fractures in tight sandstone reservoir can be further evaluated.

$$J_g = \frac{Q_g}{\Delta p \cdot h}$$  \hspace{1cm} (16)

In the formula: $Q_g$: Test well yield, $10^4 \times m^3/d$; $J_g$: Gas PI per meter, $m^3/(Mpa.m.d)$; $h$: Test section of the reservoir thickness, m; $t$: Production time, d; $\Delta p$: Producing pressure differential, Mpa.

In the study area, the fracture porosity calculated through the electrical imaging log data of each well is respectively establish fitting relationship with the gas PI per meter of the single well. Classification and evaluation of crack porosity effectiveness based on gas well production (figure 6).

![Figure 6: The diagram between crack porosity and gas PI per meter](image)

3.2. Effectiveness of crack permeability
Combined with the theoretical permeability formula, the average crack permeability and the test permeability of 27 wells in the study area were calculated to obtain the effective permeability of cracks:

$$K_f = 2.88 \times K'_f^{0.934}$$  \hspace{1cm} (17)

By analyzing the relationship between the effective permeability of cracks in multiple wells and the gas PI per meter, it is found that the larger the average crack permeability, the larger the gas PI per meter and the higher the reservoir productivity (figure 7).
3.3. Effectiveness of normal stress on crack surface

Figure 8 shows the relationship between the normal stress on the crack surface and the gas PI per meter of multiple wells in the study area. It can be seen from the figure that the smaller the normal stress on the crack surface, the larger the gas PI per meter, the higher the reservoir productivity and the better crack effectiveness. The normal stress on the crack surface is less than 38 MPa, gas PI per meter (> 300 m³/(Mpa.m.d)) is high. With high productivity, it is considered that the crack in this area is effective. When the normal stress on the crack surface is greater than 60 Mpa, the gas PI per meter is approximately zero. At this time, the crack is basically invalid and the production capacity is very low.

Figure 8. The diagram between normal stress on the crack surface and gas PI per meter

3.4. Effectiveness of angle between maximum principal stress and crack strike

In the study area, by analyzing the relationship between the angle between maximum principal stress and crack strike and the gas PI per meter in 30 wells, it can be seen from Fig. 9 that there is a negative correlation between the two parameters. When the angle is less than 34°, the crack has a good opening property, which plays an important role in percolation channel to achieve high yield maximally. When the angle is greater than 45°, the crack has poor opening under the action of geostress extrusion and the productivity is lower.
3.5. **Established quantitative characterization index of crack effectiveness**

Combined with the productivity test results, the normal effective stress on crack surface and the angle between maximum principal stress and crack strike, the two most important parameters, are optimized to evaluate the crack effectiveness among three fracture factors closely related to productivity through the multi-well analysis and application. The quantitative evaluation criteria for the validity of crack porosity, crack permeability, normal effective stress on crack surface method and angle between maximum principal stress and crack strike method were established (table 1).

| Fracture classification | I       | II      | III     | IV      |
|-------------------------|---------|---------|---------|---------|
| \( J_g / \text{m}^3/(\text{Mpa.m.d}) \) | > 300   | 300-100 | < 100   | < 1     |
| \( \phi'_f / \% \)     | > 0.035 | 0.035-0.025 | < 0.025 | < 0.02  |
| \( K_f / \text{mD} \)   | > 0.2   | 0.075-0.2 | 0.05-0.075 | < 0.05 |
| \( \sigma_n / \text{Mpa} \) | < 38    | 38-48   | 48-60   | > 60    |
| \( \theta / ^\circ \)   | < 34    | 34-45   | 45-60   | > 60    |

### 4. Comprehensive evaluation

According to the characteristics of reservoir space and the control factors of crack validity of ultra-deep fractured reservoirs in the study area, the crack identification, quantitative evaluation and crack effectiveness classification evaluation techniques for fractured tight sandstone gas reservoirs are applied. Comprehensive parameters such as crack parameters, crack effectiveness, and crack development degree are used to comprehensively evaluate the reservoir and provide technical support for exploration and development.
Figure 10. The diagram of identification and comprehensive evaluation in cracked reservoir of Well KS8-5

Through the comprehensive analysis of electrical imaging and conventional logging date, the effective interval of cracks in KS8-5 well is clarified. First, the number of cracks and the location of crack development are effectively identified by electrical imaging from the 6th channel in FIG. 10. Secondly, the crack parameters of the 8th, 9th, 10th, 11th, 12th and 13th channel in the figure are classified and evaluated. Comprehensive evaluation of electrical imaging logging shows that effective fracture development sections are 6860~6910m and 6920 ~ 7000m (figure 10). Finally, combined with the quantitative evaluation criteria of crack effectiveness, the cracks development in the reservoir sections as a whole is good. The normal effective stress on the crack face is 29.9MPa and the angle between maximum principal stress and crack strike is in the range of 30°, which belongs to the class I effective crack. The acidification test of 6912m~6995m was 645,000 cubic meters of gas per day, and the test conclusion was gas layer. Through the comprehensive analysis of core observation, acoustic imaging logging and conventional logging, the quantitative parameters and effectiveness characterization methods of the cracks in tight reservoirs are applied to study, and the results are in good agreement with the actual test data, which provides an effective method and technical means for the evaluation and development in fractured tight oil & gas reservoirs.

5. Conclusion
For ultra-deep fractured tight sandstone reservoir in the KS block of Kuqa depression, multiple control parameters that constrain crack development such as the crack porosity, crack permeability, normal stress on crack surface and angle between maximum principal stress and crack strike were obtained by electrical imaging and static modulus date of rock mechanics. In addition, a quantitative expression of the relationship between crack validity parameters and productivity is established. Finally, the main control factors of crack availability in tight sandstone reservoir are optimally selected and the
quantitative parameters and standard methods of fracture availability are established. The example shows that the new method has good application effect, high reliability and applicability.

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