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Review Article

Main Evaluation Factors of Fractured Formation Leakage in Bohai Bay Basin

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Abstract

In the central area of the Bohai Oilfield including Bozhong block, the geological structure is complex, faults and fractures are extensively developed and the formation is broken. As consequence, there is leakage to some extent in most exploratory wells in Bozhong Block, significantly affecting the drilling efficiency and increasing drilling risks. The problem of well leakage in this block needs to be addressed urgently. For this purpose, the research group firstly researches into the wellbore leakage mechanism, and then establishes a regional leakage pressure prediction model by depiction of the main controlling factors of leakage and preliminarily obtains the following findings: (1) the leakage in Bozhong Block mainly occurs at the depth of 2700-3400m, with Member 2 and Member 3 of Shahejie Formation as the main leakage zones and the fractures and faults as the main leakage passages; (2) the fracture index that can most clearly reflect the well leakage characteristics in Bozhong Block is the fracture evaluation index obtained using the resistivity ratio method, and may be considered as a main controlling factor for evaluation of fractured leakage; (3) according to the statistics on leakage of 22 wells in Bozhong Block, there are nine wells with leakage, totaling 13 leakage points. Based on the statistics and modeling, a leakage pressure prediction model for this block is obtained preliminarily. The research on the leakage mechanism and leakage pressure prediction of fractured formation in Bozhong Block is helpful for reasonable optimization of borehole trajectory, improvement of leakage control of fractured reservoirs, reduction of drilling cost and raising of operation efficiency.

Keywords: well leakage; fracture; leakage pressure

Introduction

The Bozhong area is located on the slope zone of Huanghekou Depression and Laibei Low Uplift, with complex geological structure, extensively developed faults and fractures and broken formation, which lead to certain leakage in most exploratory wells in the blocks. The site data statistics show that there is apparent leakage in four of the nine exploratory wells in Bozhong 34-9 Block, and the leakage rate exceeds $5m^3/h$ in five of the thirteen wells in Bozhong 19-6 Block. The problem of leakage is common and greatly affects the drilling efficiency.

In recent years, people are faced with more complicated geological conditions during oil and gas well drilling, which becomes more difficult. In order to save costs, the long open-hole drilling method is usually adopted in most oil fields [1, 2]. This method can greatly reduce the drilling cost if applied successfully, but it requires penetration of multi-pressure series of strata, and meanwhile a high wellbore liquid column pressure is needed to maintain the pressure balance in the high pressure formation. So it is easy to fracture the weak formation or cause fractures to open, thus resulting in well leakage. To plug wells under a multi-pressure system, the lower-pressure thief formation shall be plugged on the one hand, and the pressure balance in the high-pressure formation shall be maintained on the other hand. However, given a fixed density, the pressure of the wellbore working fluid increases linearly with the depth, and sometimes even a complex condition such as leakage of down hole high-pressure formation fluid to the lower-pressure formation occurs. The well leakage problem has become a technical bottleneck for cost reducing and benefit increasing in development of gas and oil fields [3-6]. In order to satisfy the requirements for safe and efficient drilling as well as reservoir protection, scholars at home and abroad have made a lot of studies on leakage control of formations that are prone to leakage and have a low pressure bearing capacity.

Xu Tongtai et al (1997) believed that there were three preconditions for occurrence of well leakage: first, the pressure of the well-bore working fluid must be greater than the formation pore pressure; second, there exist the leakage passage and sufficient liquid storage space; and third, the opening size of the leakage passage shall be larger than the particle size of solid phase in the working fluid [7]. They thought that the common methods for extraction of fracture characteristics included resistivity ratio method, porosity ratio method and curve change rate method [8]. Wang Weibin et al (2005) thought that large fracture systems or karst caves contributed largely to regional severe well leakage, and well leakage was more likely to occur under complex pressure conditions, such as pressure transition zone and abnormal high-pressure zone [9].

Leakage pressure is an important parameter for segmented design of drilling fluid density. A reasonable drilling fluid density can effectively prevent artificially-induced fractured leakage. To solve the problem of poor reliability of leakage pressure prediction, domestic and overseas scholars have conducted researches on leakage pressure calculation models, which can be divided into mechanical model and statistical model depending on model principles.

Jin Yan et al (2007) took statics of well leakage occurrence rate, leakage causes, leakage passage properties and other data at different horizons of Ordovician system in Tazhong-I slope break zone, and believed that leakage in different formations and different cases has different leakage mechanisms, therefore it was hard to build a leakage pressure model theoretically. By fitting based on the distribution law of leakage rate and leakage pressure difference at different horizons, they acquired an equation with leakage rate as the independent variable and leakage pressure difference as the dependent variable. With the leakage rate, the leakage pressure difference was calculated, which was then added with the borehole pressure at the leakage position to get the leakage pressure [10].

In this paper, the formationwith fractured leakage in Bozhong Block is taken as the study object and the research on leakage mechanism is carried out for the leaking wells in the block. Through extraction of regional rock mechanical characteristics and comparison of fracture properties, the leakage mechanism is preliminarily understood. And by analysis and modeling of the data on multiple leaking exploratory wells for different formations and lithology in combination with the pressure measurement data and mud logging data, a statistical model for formation leakage pressure is obtained.

Extraction of Rock Mechanical Characteristics

Calculation of dynamic mechanical parameters

Assuming the rock is an isotropic infinite elastic medium, the S-wave slowness, P-wave slowness and densitydata can be used to calculate the dynamic Poisson's ratio (Equation 1), dy-namic Young's modulus (Equation 2), dynamic shear modulus (Equation 3) and dynamic bulk modulus (Equation 4) using the following calculation models:

$$\mu_d = \frac{\Delta t_S^2 - 2\Delta t_C^2}{2(\Delta t_S^2 - \Delta t_C^2)} \quad (1)$$

$$E_d = \frac{\rho_b}{\Delta t_S^2}\frac{3\Delta t_S^2 - 4\Delta t_C^2}{\Delta t_S^2 - \Delta t_C^2} \times 10^9 \quad (2)$$

$$G_d = \frac{\rho_b}{\Delta t_S^2} \times 10^9 \quad (3)$$

$$k_d = \frac{\rho_b}{\Delta t_S^2}\frac{3\Delta t_S^2 - 4\Delta t_C^2}{\Delta t_S^2 \Delta t_C^2} \times 10^9 \quad (4)$$

Conversion of dynamic and static mechanical parameters

As there are errors between the ideal infinite elastic medium and the actual condition, the rock dynamic and static mechanical parameters are converted based on laboratory physical experiment data as well as site logging data. The specific calculation models include static Poisson's ratio (Equation 5), static Young's modulus (Equation 6), static shear modulus (Equation 7) and static bulk modulus (Equation 8).

$$\mu'_d = 0.5341\mu_d + 0.1252 \quad (5)$$
$$E'_d = 1.5230E_d + 243.33 \quad (6)$$
$$G'_d = 1.5230G_d + 221.59 \quad (7)$$
$$k'_d = 1.5230k_d + 243.33 \quad (8)$$

Calculation of failure criterion parameters

According to the existing data and rock failure characteristics, it is suggested that MohrCoulombcriterion be used for mechanical analysis for this block. The failure criterion parameters are calculated on the basis of static mechanical parameters and logging data, including rock drillability extremum (Equation 9), compressive strength (Equation 10), cohesion (Equation 11) and internal friction angle (Equation 12), with specific calculation models as follows:

$$K_d = \exp(-0.00534\Delta t_c + 2.8505) \quad (9)$$
$$\sigma_c = 0.0045E'_d(1-V_{sh}) + 0.008V_{sh}E'_d \quad (10)$$
$$C = 0.0333\sigma_c K_d \quad (11)$$
$$\emptyset = 36.545 - 0.4952C \quad (12)$$

Thus, the rock mechanical characteristic parameters in this area can be obtained by calculation. As follows:

S/N	Horizon	Statistical value	Dynamic Young's modulus	Dynamic Poisson's ratio	Dynamic bulk modulus	Dynamic shear modulus	Static Young's modulus	Static Poisson's ratio	Static bulk modulus	Static shear modulus
			Gpa	-	Gpa	Gpa	Gpa	-	Gpa	Gpa
1	Upper Member of Minghuazhen Formation	Average	1.08	0.25	0.99	1.02	1.86	0.26	1.71	1.77
		Max.	1.37	0.40	1.20	1.42	2.30	0.34	2.02	2.37
		Min.	0.80	0.14	1.43	0.86	1.45	0.12	2.37	1.53
2	Lower Member of Minghuazhen Formation	Average	1.02	0.25	0.98	0.98	1.78	0.26	1.69	1.72
		Max.	1.38	0.50	1.19	1.16	2.32	0.39	2.01	1.99
		Min.	0.87	0.14	0.82	0.72	1.55	0.20	1.45	1.32
3	Guantao Formation	Average	1.10	0.25	1.01	0.98	1.89	0.26	1.73	1.71
		Max.	1.38	0.38	1.19	1.16	2.32	0.33	2.01	1.98
		Min.	0.94	0.08	0.73	0.72	1.65	0.17	1.32	1.33
4	Member 1 of Dongying Formation	Average	1.24	0.23	1.17	1.10	2.11	0.25	1.98	1.89
		Max.	1.60	0.31	1.55	1.34	2.65	0.29	2.54	2.25
		Min.	0.72	0.14	0.89	0.79	1.32	0.20	1.55	1.43

5	Upper Member 2 of Dongying Formation	Average	1.14	0.23	0.99	1.03	1.96	0.25	1.70	1.79
		Max.	1.46	0.44	1.52	1.40	2.44	0.36	2.50	2.35
		Min.	0.86	0.13	0.81	0.92	1.54	0.12	1.43	1.63
6	Lower Member 2 of Dongying Formation	Average	1.25	0.23	1.18	1.17	2.12	0.25	1.99	2.00
		Max.	1.60	0.38	1.69	1.84	2.65	0.33	2.75	3.00
		Min.	1.02	0.11	1.03	0.86	1.78	0.12	1.76	1.54
7	Member 3 of Dongying Formation	Average	1.25	0.25	1.21	1.17	2.12	0.26	2.03	2.00
		Max.	1.75	0.35	1.71	1.88	2.87	0.31	2.79	3.06
		Min.	1.16	0.10	0.91	1.02	1.98	0.18	1.59	1.77
8	Member 2 of Shahejiew Formation	Average	1.53	0.27	1.34	1.44	2.54	0.27	2.23	2.40
		Max.	1.69	0.31	1.93	1.78	2.78	0.29	3.11	2.91
		Min.	1.18	0.10	1.19	1.12	2.01	0.18	2.01	1.92

Evaluation of Regional Fractures and Identification of Main Controlling Factors

Fracture evaluation

Fracture evaluation based on resistivity ratio method

Firstly, it is required to calculate the invasion-corrected true resistivity by Equation 13, where R_{30} represents deep resistivity R_D while R_{10} represents shallow resistivity R_S,

$$R_t = 2.589R_D - 1.589R_S \quad (13)$$

And then Equation 14 is used to calculate RTC.

$$R_{RM} = \frac{R_t - R_S}{R_S} \quad (14)$$

As can be seen from the equation, RTC primarily reflects the difference between permeable formations caused by fracture.

Fracture evaluation based on tri-porosity ratio method

Firstly, the shale content V_{sh} is calculated using Equation 15,

$$SH = \frac{GR - GR_{min}}{GR_{max} - GR_{min}}, \quad V_{sh} = \frac{2^{GCUR \cdot SH} - 1}{2^{GCUR} - 1} \quad (15)$$

And then the acoustic porosity (Equation 16), the density porosity (Equation 17) and the neutron porosity (Equation 18) are calculated respectively.

$$\emptyset_s = \frac{\Delta t - V_{sh}\Delta t_{sh} - (1 - V_{sh})\ \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \quad (16)$$

$$\emptyset_{DEN} = \frac{\rho - V_{sh}\rho_{sh} - (1 - V_{sh})\ \rho_{ma}}{\rho_f - \rho_{ma}} \quad (17)$$

$$\emptyset_{CN} = \frac{H - V_{sh}H_{sh} - (1 - V_{sh})\ H_{ma}}{H_f - H_{ma}} \quad (18)$$

The values of key parameters in above equations are shown in the table below:

Superscript	***Δt***	ρ	***H***
Unit	μs/***ft***	***g/cm³***	***%***
sh	52	2.86	0.04
f	187	1	1
ma	55	2.71	0

By substituting the calculated values in Equation 19 and Equation 20, the fracture evaluation index P2 based on the tri-porosity ration method can be obtained.

$$\emptyset_t = \sqrt{\frac{\emptyset_{DEN}^2 + \emptyset_{CN}^2}{2}} \qquad (19)$$

$$P_2 = \frac{|\emptyset_t - \emptyset_S|}{\emptyset_t} \qquad (20)$$

It can be seen from Equation 19 that P2 mainly reflects the difference between primary porosity and secondary porosity, and such difference is in direct proportion to the degree of fracture development.

Fracture evaluation based on curve change rate method

The curve change rate is calculated respectively for four curves, i.e. acoustic curve, density curve, neutron curve and resistivity curve, by using Equation 21:

$$\Delta X_i = \frac{|X_{i-1} - X_i| + |X_{i+1} - X_i|}{X_i} \qquad (21)$$

Where X can be substituted by any of the four curves, and then the curve corresponding to the change rate can be obtained. As can be seen from Equation 21, this model mainly reflects the difference in change rate at the fracture among the four curves.

Identification of main controlling factors of well leakage

Based on the three mathematical models depicting fracture characteristics as described in 2.1, calculation is made for #5 Well to get three different fracture characteristic curves: RRM, P2 and CC (including resistivity R10CC, acoustic DtCC, density DenCC, and neutron porosity CnCC), which are observed to understand their characteristics and laws at the leakage horizon. Figure 1 shows the characteristic curves of the fracture at the lea-kage horizon of #5 Well.

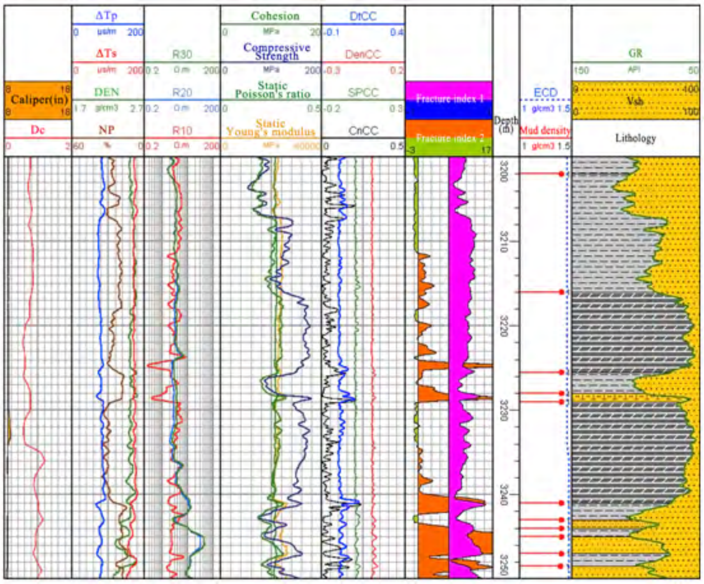

Figure 1: Characteristic Curves of Fracture at Leakage Horizon of #5 Well.

Leakage occurs at the measured depth of 3234.25m. At the time of leakage, the displacement is 1.5m^3/min, the pumping pressure is 12.5Mpa, the leakage rate is 40m^3/h, the drilling fluid density is 1.39g/cm^3, the drilling fluid type is HIBDRILL, and the accumulated drilling fluid leakage is 38m^3. According to observation, there is no obvious difference before and after leakage for R10CC and P2 curves, while RRM curve has high response sensi-tivity at the leakage horizon, which shows that RRM can well indicate the occurrence of leakage and may be taken as the main controlling factor for judgment of fractured leakage.

Further, the three fracture evaluation index curves are projected onto the seismic profile (CDP6300), as shown in Figure 2. According to time-depth relation, the depth of 3234.25m corresponds to the time of 2480ms.

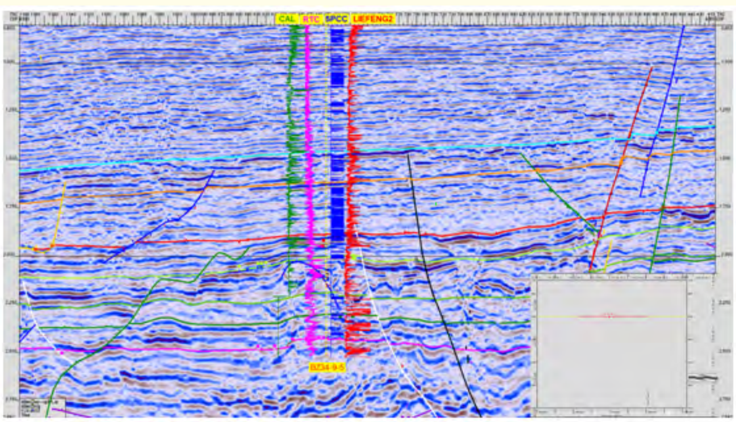

Figure 2: Seismic Profile (CDP6300) for Three Fracture Evaluation Index Curves(RTC SPCC LIEFENG2) of #5 Well.

By locally zooming in the seismic profile of #5 Well (INLINE2411), it can be seen that transition of forma-tion exists at the depth of occurrence of well leakage (corresponding to 2480ms), and RRM (the pink curve) can reflects the characteristics of leakage occurrence well.

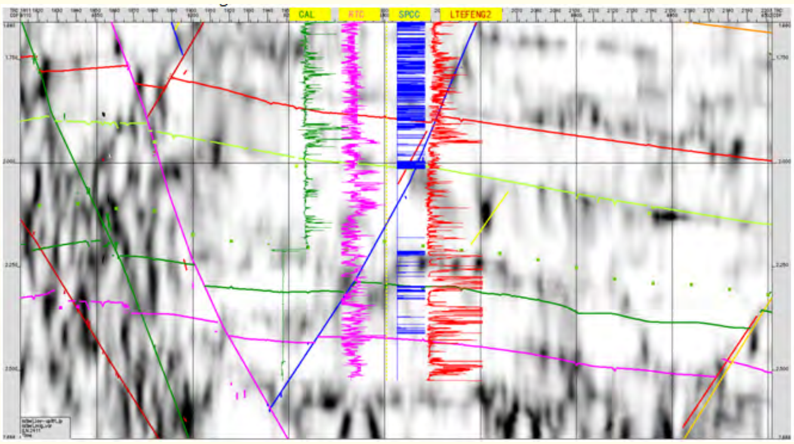

Figure 3: Local Zoom-in of Seismic Profile of #5 Well (INLINE2411).

Through comparison, it is found that the RRM fracture evaluation curve can reflect the potential factors of well leakage well when applied in BZ Block. However, RRM can only be used as a necessary factor rather than a sufficient factor to judge the occurrence of leakage.

Prediction of Well Leakage Pressure by Statistical Method

According to the statistics on leakage problems of 22 wells in Bozhong Block, there are 9 wells with leakage, totaling 13 leakage points. The leakage pressure difference is calculated by comparison between pore fluid pressure and wellbore pressure at all leakage depths. Based on the leakage pressure difference as well as well history data, the wellbore leakage statistical model (Equation 22) is obtained. See Figure 4 for statistical relation between leakage pressure and leakage rate.

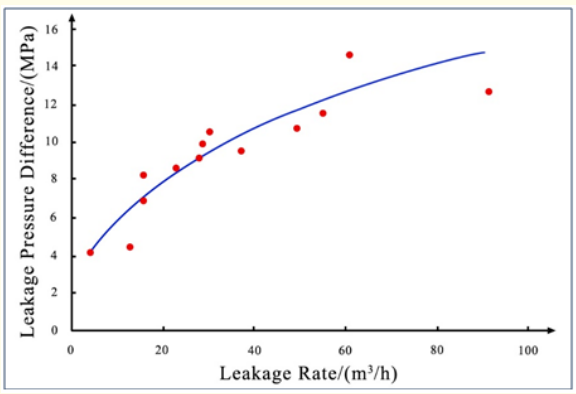

Figure 4: Statistical Relation between Leakage Pressure and Leakage Rate.

Conclusions

1. The leakage in Bozhong Block mainly occurs at the depth of 2700-3400m, with Member 2 and Member 3 of Shahejie Formation

as the main leakage zones and the fractures and faults as the main leakage passages.

2. The fracture index that can most clearly reflect the well leakage characteristics in Bozhong Block is the fracture evaluation index obtained using the resistivity ratio method, and may be considered as a main controlling factor for evaluation of fractured leakage.
3. According to the statistics on leakage of 22 wells in Bozhong Block, there are 9 wells with leakage, totaling 13 leakage points. Based on the statistics and modeling, a leakage pressure prediction model for this block is obtained preliminarily.

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