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Research Article

Study on Method of Determining the Safe Operation Window of Drilling Fluid Density with Credibility in Deep Igneous Rock Strata

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It is difficult to determine the safe operation window of drilling fluid density (SOWDFD) for deep igneous rock strata. Although the formation three-pressure (pore pressure, collapse pressure, and fracture pressure) prediction method with credibility improves the accuracy of formation three-pressure prediction, it still has a large error for deep igneous strata. To solve this problem, a modified method of the SOWDFD in deep igneous rock strata is proposed based on the leakage statistics of adjacent wells. This method is based on the establishment of the SOWDFD with credibility. Through statistical analysis of drilling fluid density of igneous rock leaky formation group in adjacent wells, the fracture leakage law of the formation is revealed and the upper limit of leak-off pressure containing probability information is obtained. Finally, the modified SOWDFD with credibility for deep igneous rock strata is formed. In this work, the proposed method was used to compute the SOWDFD with credibility of SHB well in Xinjiang, China. Results show that the modified density window is consistent with the field drilling conditions and can reflect the narrow density window in the Permian and lower igneous strata. Combined with the formation three-pressure prediction method with credibility and the actual leakage law of adjacent wells, it can effectively improve the prediction accuracy of the SOWDFD for deep igneous rock strata. The findings of the study can help in better understanding of the complex downhole geological environment in deep igneous rock strata and making reasonable drilling design scheme.

1. Introduction

The igneous rock strata of deep oil-gas reservoirs have the characteristics of deep burial and complex geological environment [1–4]. This is often accompanied by the development of high and steep structures, holes, and fractures. Poor wellbore stability and narrow pressure window lead to complex downhole problems such as lost circulation and well collapse, which seriously restricts the high quality and fast drilling [5–7]. Drilling geological characteristic parameters (DGCP), mainly involving formation three-pressure and leak-off pressure, are the basic data reflecting the fluid and rock physical properties in the strata and the geological structure [8, 9]. The accurate calculation of DGCP is an important premise to ensure the correct design of well structure and reasonable control of drilling fluid density [10–12]. Leak-off pressure prediction is an important element in the study of DGCP in deep igneous rock strata. At present, the analysis and evaluation of crustal stress and local stress of structural fracture by rock mechanics theory are the main research fields on leak-off pressure of igneous rock strata at home and abroad [13]. In the drilling field, the minimum horizontal in situ stress of incomplete igneous rock strata is generally regarded as the leak-off pressure [14, 15], but the prediction result is too large for large-scale cavernous fractures. Zhang et al. applied model simulations to analyze the critical pressure of closure fracture reopening and propagation [16], but it cannot obtain the whole well section leak-off pressure. Considering the spatial distribution of fracture, some scholars have used fractal theory [17] and pressure transient analysis method [18] to predict the fracture trend and spreading pattern. In the part of studies, seismic and logging data are also used to predict the size and location of fracture [19–21]. However, the prediction accuracy of leak-off pressure is low due to the uncertainty of the original data and calculation model. The formation three-pressure prediction method with credibility is based on probability statistics and Monte Carlo simulation, which changes the traditional single value pressure curve into a distribution interval with probability information [22, 23]. On this basis, the SOWDFD not only is more reliable but also has the function of risk assessment and control. In conventional sand shale formation, fracture pressure is usually referred to as leak-off pressure. However, the fracture pressure based on strength criterion cannot completely replace the leak-off pressure of igneous rock formation with natural fractures.

Therefore, based on the prediction method of formation three-pressure with credibility, this paper develops a modified model of the SOWDFD with credibility. By analyzing the density of drilling fluid in adjacent wells with easily leaking formations of igneous rock and revealing the law of fracture leakage in the formation, the proposed model not only considers the uncertainty of pressure calculation but also involves the results of practical engineering analysis. Also, an empirical study of a deep well in Xinjiang, China, is presented as a test case to illustrate our proposed method and to demonstrate its usefulness. The rest of this paper is organized as follows. In Section 1, the difficulties in drilling deep igneous rock strata are explained. In Section 2, the determination method of the SOWDFD with credibility is introduced. In Section 3, the proposed modified model of the SOWDFD with credibility in deep igneous rock strata is described. In Section 4, an example analysis is illustrated. Finally, according to the findings of this research, summary and conclusions are presented.

2. Difficulties in Drilling Deep Igneous Rock Strata

Igneous rocks are formed by the condensation and crystallization of magma or lava flow at high temperatures. It can be seen from Figure 1 that, due to the influence of lithology, early diagenesis, and tectonics [2], pore and fracture are widely developed and are prone to lost circulation, collapse, and other downhole problems during drilling. Based on the leakage mechanism, igneous rock leakage formation can be divided into high permeability leakage, natural fracture leakage, induced fracture leakage, and cavernous leakage [24]. The degree of permeability loss depends on the pressure difference between wellbore pressure equivalent circulation density (ECD) and formation pore pressure (FPP) and the formation of mud cake. The mechanism of natural fracture leakage is that the ECD is bigger than the fracture reopening pressure (FRP); and the induced fracture leakage is caused by the fact that the ECD is bigger than the minimum between the formation fracture pressure (FFP) and the fracture extension pressure (FEP). In the case of very developed and far extended fractures, the amount of fracture leakage will increase significantly. Cavernous leakage is generally severe leakage or no-wellhead-backflow leakage. Besides, due to the characteristics of deep-buried igneous rock formation, multiple strata, complex pressure system, complex wellbore stability, and strong formation heterogeneity [1], the traditional plugging method is difficult to achieve one-time pressure plugging effect.

To maintain wellbore stability, high-density drilling fluid is easy to cause repeated lost circulation and wellbore collapse in weakly cemented fractured formation, which eventually leads to sidetracking. The formation mechanism of fractures in deep igneous rock strata is diverse and the geological environment is complex. There are great uncertainty in pressure prediction and an unclear understanding of fracture leakage law which will lead to a large error of safe window of drilling fluid density and they are not conducive to the prevention and control of lost circulation risk.

3. Determination Method of the SOWDFD with Credibility

3.1. Calculation Method of Formation Three-Pressure with Credibility. Due to the complexity of the underground geological environment, the incompleteness of data, and the subjective experience of technicians, the calculated drilling geological characteristic parameters have different degrees of uncertainty, and the real values are distributed in a certain range [22, 25]. Aiming at the complex geological environment of deep igneous strata with frequent development of intrusions, faults, and fractures, this paper introduces the formation three-pressure prediction method with credibility, which changes the traditional single-value pressure curve into the distribution interval with probability information, thus improving the understanding of the downhole geological environment. The specific calculation process is shown in Figure 2.

The effective stress method and Eaton method are jointly used to calculate the Eaton index, and the probability statistics are carried out. The results are brought into the Eaton formula to finally obtain the formation pore pressure (FPP) profile with credibility. Aiming at the formation fracture pressure (FFP) and formation collapse pressure (FCP), the probability distribution of rock mechanics parameters and stress coefficients of regional adjacent wells and wells with similar structures are obtained using probability statistics Then, using the Monte Carlo simulation method, the rock mechanics parameters, FPP, and stress coefficient are brought into the calculation formula of FFP and FCP. Finally, through statistical analysis of the calculation results, the FFP and FCP profiles with credibility are obtained.

Using the introduced calculation method, the three profiles of FPP, FFP, and FCP with credibility of SHB well in Xinjiang, China, are obtained, as shown in Figure 3.

3.2. Determination Method of the SOWDFD with Credibility. The main risks of drilling engineering are lost circulation, kick, well collapse, differential pressure sticking, broken drilling tools, and so on. Research shows that the risk mechanisms of some complex drilling problems are clear

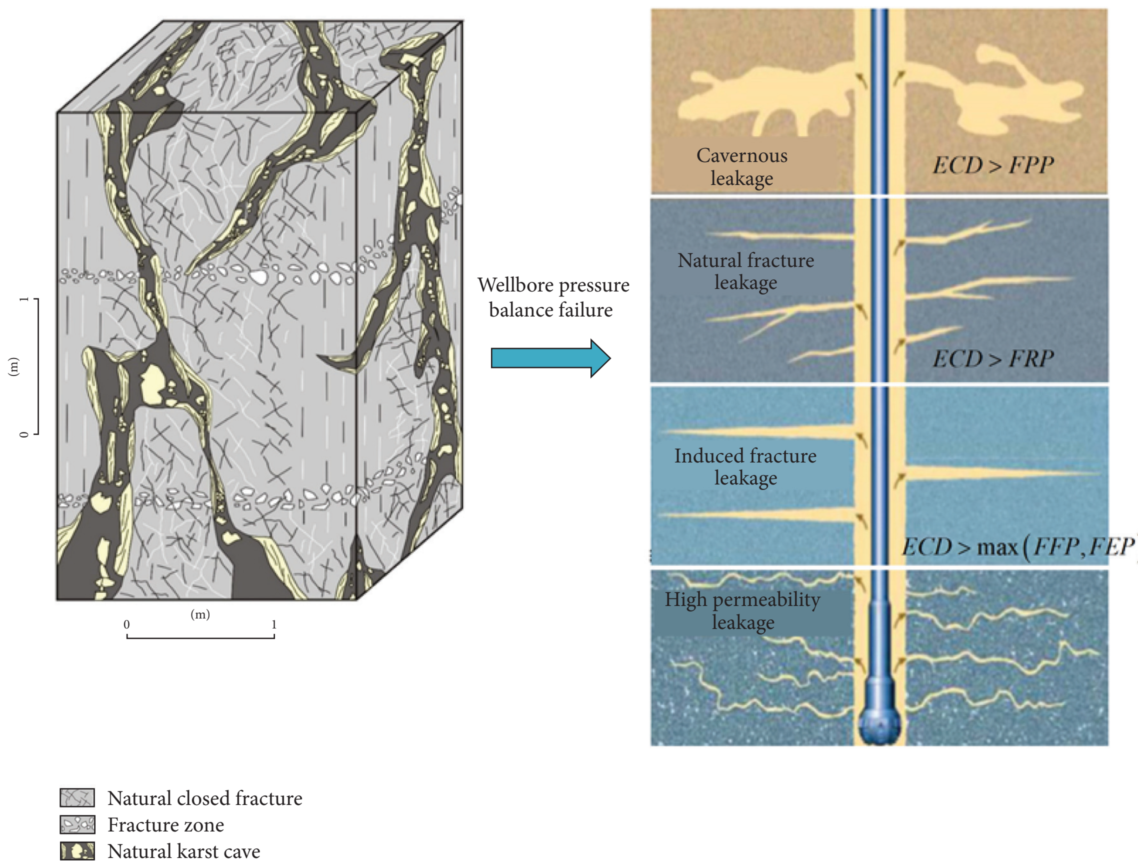


Figure 1: Characteristics of deep igneous strata and mechanism of leakage.

and have explicit risk constraint criteria [26]. Through a comprehensive analysis of the mechanisms and the relationships, the risk pressure constraint criteria of drilling engineering can be obtained as shown in Table 1.

By bringing the FPP, PFP, and FCP profiles with credibility into the pressure constraint criteria, the upper and lower limits of safe mud density at the cumulative probability $j = j_0$ at depth h can be obtained, which are shown as follows:

$$\begin{cases} L(h)_{j=j_0} = \max\left\{\rho_{k,\, j=j_0}(h),\ \rho_{cL,\, j=j_0}(h)\right\}, \\ H(h)_{j=j_0} = \min\left\{\rho_{cU,\, j=j_0}(h),\ \rho_{l,\, j=j_0}(h),\ \rho_{ps,\, j=j_0}(h), \rho_{kl,\, j=j_0}(h)\right\}. \end{cases} \tag{1}$$

Similarly, the lower limit curve $L(h)_{j=j_1}$ and upper limit curve $H(h)_{j=j_1}$ of safe mud density with the cumulative probability of j_1 can be obtained. Then the upper and lower safe mud density profiles with credibility $|j_1 - j_0| \times 100\%$ can be obtained. Finally, the upper limit curve $H(h)_{j=j_0}$ with the cumulative probability of j_0 is taken as the upper limit of the SOWDFD, and the lower limit curve $L(h)_{j=j_1}$ with the cumulative probability of j_1 is taken as the lower limit of the SOWDFD. Eventually, a safe operation window with a credibility level for well structure design is established.

The reservoir of the SHB well belongs to the fault solution reservoir, with igneous rock intrusion and highly developed fractures. Lost circulation and wellbore collapse occur frequently during drilling. The above method is used to establish the safe window of drilling fluid density with credibility in SHB well as shown in Figure 4. A wide mud density window can be seen, which cannot reflect the problem of narrow density window in complex formation with natural fracture and weak cemented igneous rock.

Compared with the conventional sand shale formation, due to the abnormal development of pores, fractures, and caves in the igneous rock formation, FFP based on conventional strength criterion is often greater than the formation leak-off pressure (FLP), resulting in poor prediction accuracy of safe mud density window.

4. Modified Method for the SOWDFD with Credibility in Deep Igneous Rock Strata

Because the traditional FFP calculation results based on strength criterion cannot represent the formation leak-off pressure in the igneous rock formation, the upper limit of the SOWDFD is modified by using mud density when leakage occurs in adjacent wells. According to geostatistical principles, in the same geological period and sedimentary conditions, the formation should produce the same response of lithology and engineering characteristics. The smaller the distance between wells is, the more similar the formation lithology and geological structure are [27]. Based on this idea, through the regional drilling data, the fracture leakage

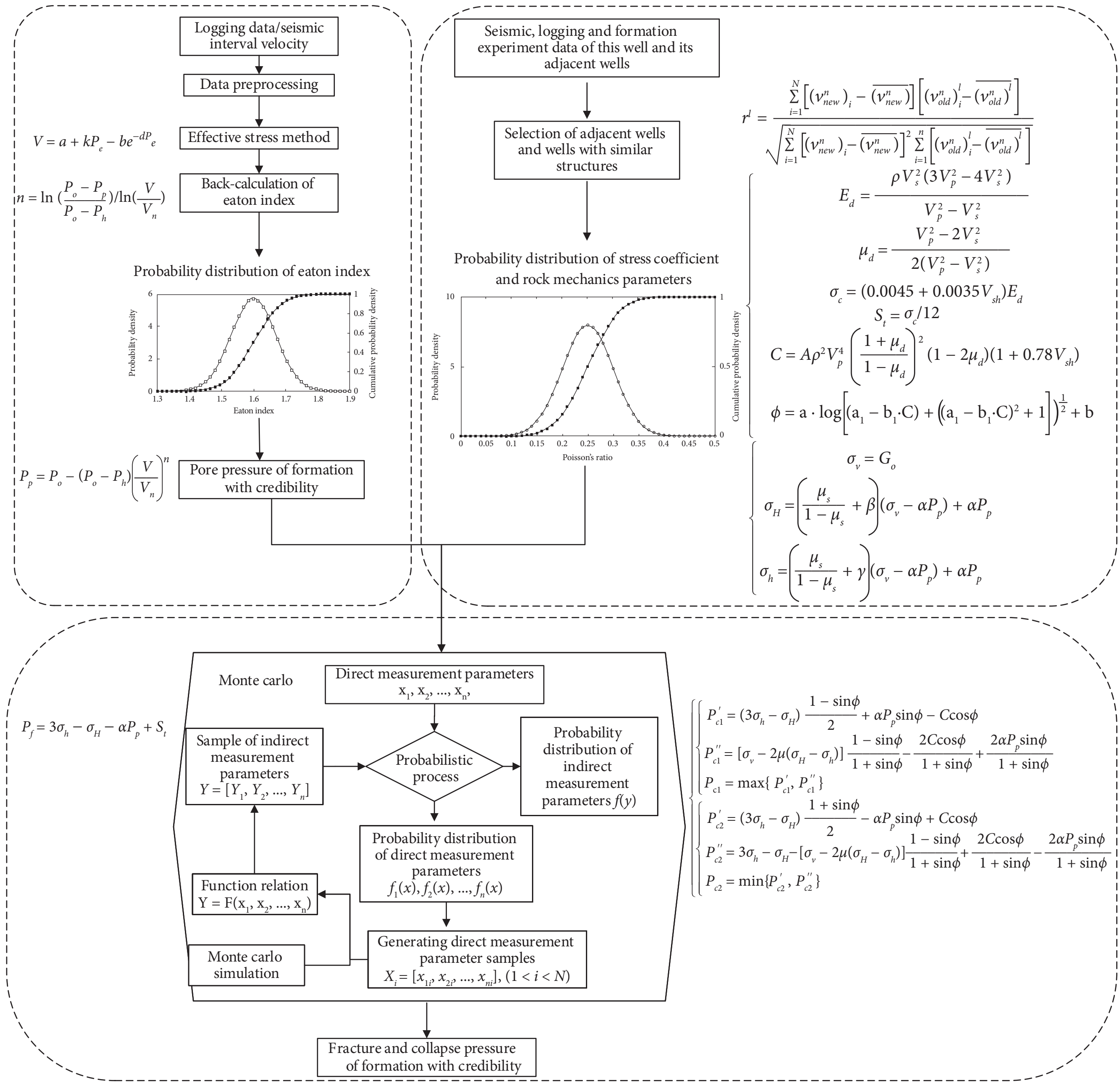


FIGURE 2: Prediction method of formation three-pressure with credibility.

law is revealed by analyzing the formation and leakage characteristics. Considering the spatial variability of geological parameters, the selection of adjacent wells and similar structural wells is particularly important. Introducing the concept of variogram [28], let $p_{\delta_k}(G)$ be the regionalized random variable of formation leakage pressure, G represents the plane coordinate (x, y), δ_k represents the depth coordinate of layer K, d represents the distance between wells, and the variogram formula is as follows:

$$\gamma^{\#}(d) = \frac{1}{2N(d)} \sum_{i=1}^{N(d)} \left[p_{\delta_k}(G_i) - p_{\delta_k}(G_i + d)^2 \right], \qquad (2)$$

where $N(d)$ denotes the number of pairs of well with a distance of d. The variogram of different well distance d_j is calculated, and then the discrete points $[d_j, \gamma^{\#}(d_j)]$ $(j = 1, 2, \ldots, m)$ are fitted to determine the theoretical model parameters of the variation curve. Finally, two times of the variable range is taken as the sample space for the selection of adjacent wells [29].

According to the statistical analysis of the leakage data of adjacent wells, the main fractured leakage layers of adjacent wells are determined. Taking drilling fluid density in the bare hole section of the leakage layers as a random variable ρ, the densities of drilling fluid before and after the leakage are statistically analyzed. Supposing that the observation sample of the variable ρ is $\rho_i\,(i = 1, 2, \ldots, n)$, the probability

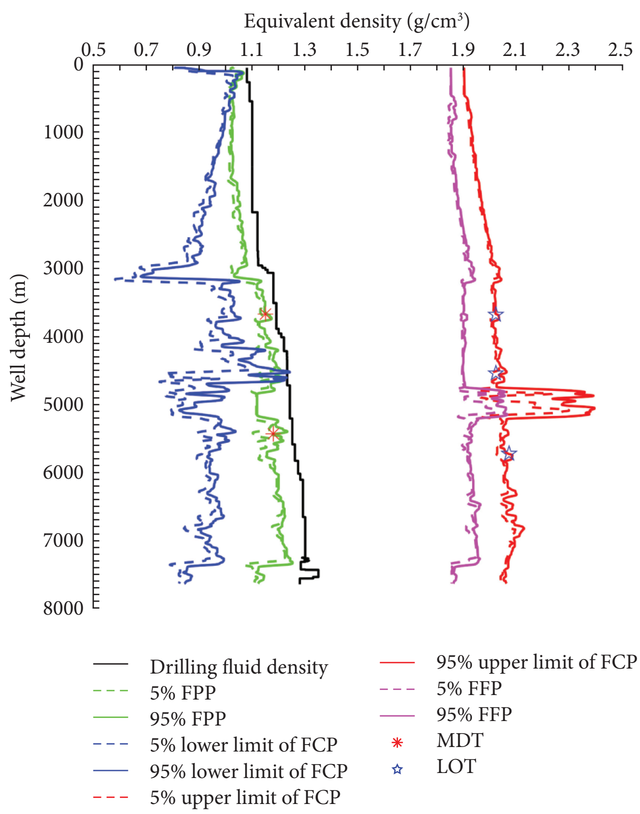


Figure 3: The three profiles of FPP, FFP, and FCP with credibility of SHB well.

distribution function $f(\rho)$ (equation (3)) and cumulative probability distribution function $f(\rho)$ (equation (4)) of the random variable $f(\rho)$ can be determined by using the normal information diffusion estimation method for small samples [30].

$$f(\rho) = \frac{1}{\sqrt{2\pi}nh}\sum_{i=1}^{n}\left\{\exp\left(-\frac{(\rho-\rho_i)^2}{2h^2}\right)\right\}, \quad (3)$$

$$F(\rho) = \frac{1}{\sqrt{2\pi}nh}\sum_{i=1}^{n}\int_{-\infty}^{\rho}\exp\left(-\frac{(t-\rho_i)^2}{2h^2}\right)\mathrm{d}t, \quad (4)$$

where h represents the diffusion coefficient, which can be calculated using the following equation:

$$h = \frac{\gamma(\rho_{\max}-\rho_{\min})}{n-1}, \quad (5)$$

where $\rho_{\max}$ is the maximum value in the observation sample and $\rho_{\min}$ is the minimum value in the observation sample. The values of γ can be obtained from Table 2 [30].

Based on the statistical results, the minimum density of drilling fluid $\rho_{\min}$ and the corresponding cumulative probability $F(\rho_{\min})$ for a regional adjacent well to leak off at this fractured leakage layer can be obtained. The practical significance is that when the fractured leakage layer is drilled, almost no lost circulation occurred when the drilling fluid density is less than $\rho_{\min}$, and when it is greater than $\rho_{\min}$, the risk probability of lost circulation is $F(\rho_i)$.

According to the need for lost circulation prevention and control, the upper limit of the SOWDFD in the fractured leakage layer is modified. The modified upper limit is as follows:

$$H(h) = \begin{cases} \rho_{\min} & R = 0 \\ \rho_i & \left\{R = F(\rho_i), \rho_{\min} < \rho_i < \min\left\{H(h)_{j=j_0}, \rho_{\max}\right\}, \right. \end{cases} \quad (6)$$

where $H(h)_{j=j_0}$ represents the upper limit of the SOWDFD with credibility, $\rho_{\max}$ represents the maximum drilling fluid density in the bare hole section of adjacent drilled well in this fractured leakage layer, and R is the corresponding lost circulation risk.

When the fractured leakage layer is thick, to take targeted plugging measures, the upper limit of the SOWDFD needs to be finely modified by sections. For the wider fractures with serious leakage, cement injection can be used to plug the leakage, and the drilling fluid density $\rho_{\min}$ with zero risks can be selected for modification. For microfractures with light leakage, the method of plugging while drilling can be used. The drilling fluid density ρ_i with a certain leakage risk is selected to modify the upper limit of the density window. If the fractured leakage layer is thin, the upper limit of the SOWDFD can be modified uniformly.

Compared with the traditional computational method of SOWDFD, the proposed modified method of SOWDFD with credibility not only considers the uncertainty of calculation results but also involves engineering statistical analysis results of lost circulation mud density in adjacent wells. A more accurate prediction result of SOWDFD is obtained.

5. Example Analysis

SB oilfield in Xinjiang, China, has a well-developed stratum with a buried depth of more than 7500 m. The main reservoir types are karst cave type, fracture type, and fracture-pore type, which are characterized by high temperature (>150 °C) and high pressure (>80 MPa). The pore pressure of the formation above the reservoir is normal (<1.2). There are thick igneous strata, and the uniaxial compressive strength is between 100 and 250 MPa.

At present, they are mainly drilled in No.1 and No.5 fault zones. The No.1 fault zone is dominated by translation and pull-apart movement, and its tectonic setting is relatively simple. The northern segment of the No.5 fault zone is dominated by compression, and the middle part of the No.5 fault zone is dominated by tension and torsion. There are well-developed faults and significant heterogeneity in strata. The drilling risk of Paleozoic strata is high and makes construction difficult. The Permian dacite formation is characterized by natural and multiscale fractures, low leakage pressure, and easy-to-form induced fractures, leading to the leakage with no backflow in the wellhead. The Silurian strata are characterized by well-developed sandstone and mudstone, low bearing capacity, and well-developed faults and contain a large number of open and closed fractures. The Ordovician Sangtamu strata, with

Table 1: Pressure constraint criteria of drilling engineering risks.

Risk type	Safe density window boundary conditions (g/cm^3)
Lower limit of kick	$\rho_k = P_p + S_b + \Delta\rho$
Lower limit of wellbore collapse	$\rho_{cL} = P_{c1} + S_b$
Upper limit of wellbore collapse	$\rho_{cU} = P_{c2} - S_g$
Upper limit of differential pressure sticking	$\rho_{ps} = P_p + (\Delta P/h \times 0.0098)$
Upper limit of lost circulation	$\rho_l = P_f - S_g - S_c$
Upper limit of lost circulation during well killing	$\rho_{kl} = P_f - S_g - S_k \times (h_{p\,\max}/h)$

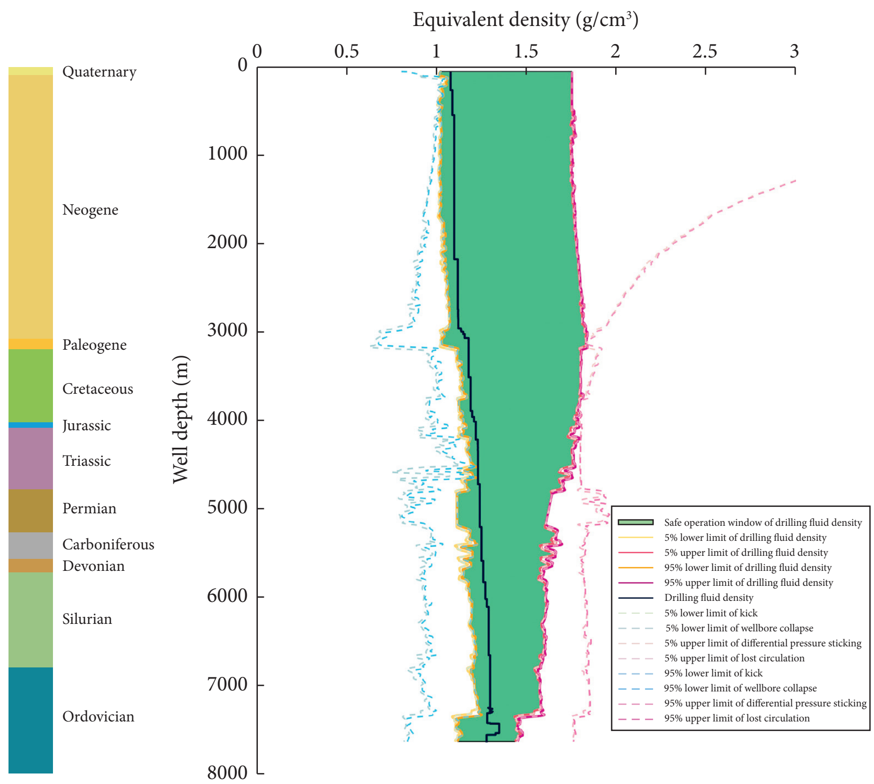


Figure 4: SOWDFD with credibility of SHB well.

Table 2: Relationship between γ and sample number n.

n	γ	n	γ	n	γ
3	0.849321800	8	1.395189816	13	1.420698795
4	1.273982782	9	1.422962345	14	1.420669671
5	1.698643675	10	1.416278786	15	1.420693321
6	1.336252561	11	1.420835443	16	1.420692226
7	1.445461208	12	1.420269570	≥17	1.420693101

gabbro intrusions, have high collapse stress and high rock debris density, so high-density drilling fluid is needed to maintain wellbore stability. The Ordovician strata are highly fractured and poorly cemented due to the influence of compression structure. After being uncovered, the borehole collapses seriously, leading to frequent sticking during drilling.

Based on the drilling practice in the SB block, it can be known that the regional geological conditions are not well understood, the SOWDFD prediction is not accurate, and the wellbore structure design cannot accurately isolate the risk layers. In the process of drilling, the frequent occurrence of lost circulation and collapsing sticking seriously restricts the efficient exploration and development in this area.

The proposed method in this paper is used to establish the SOWDFD with credibility for the SHB well; and, based on the probability statistics' results of drilling fluid density in igneous fractured and leakage layers of adjacent wells and similar structural wells, the SOWDFD with credibility is modified. According to the statistical analysis of more than 20 adjacent drilled wells, it is found that the drilling risks are mainly concentrated in the Permian layer, Silurian low-pressure-leakage layer, the Sangtamu intrusive-body-collapse layer, and Ordovician fracture-collapse layer. The statistical results of drilling fluid density in the bare hole section of the layers are shown in Figure 5.

It can be seen from Figure 5 that the density of drilling fluid used in the Permian layer of the SHB adjacent well is between 1.22 and 1.34. The minimum density for lost

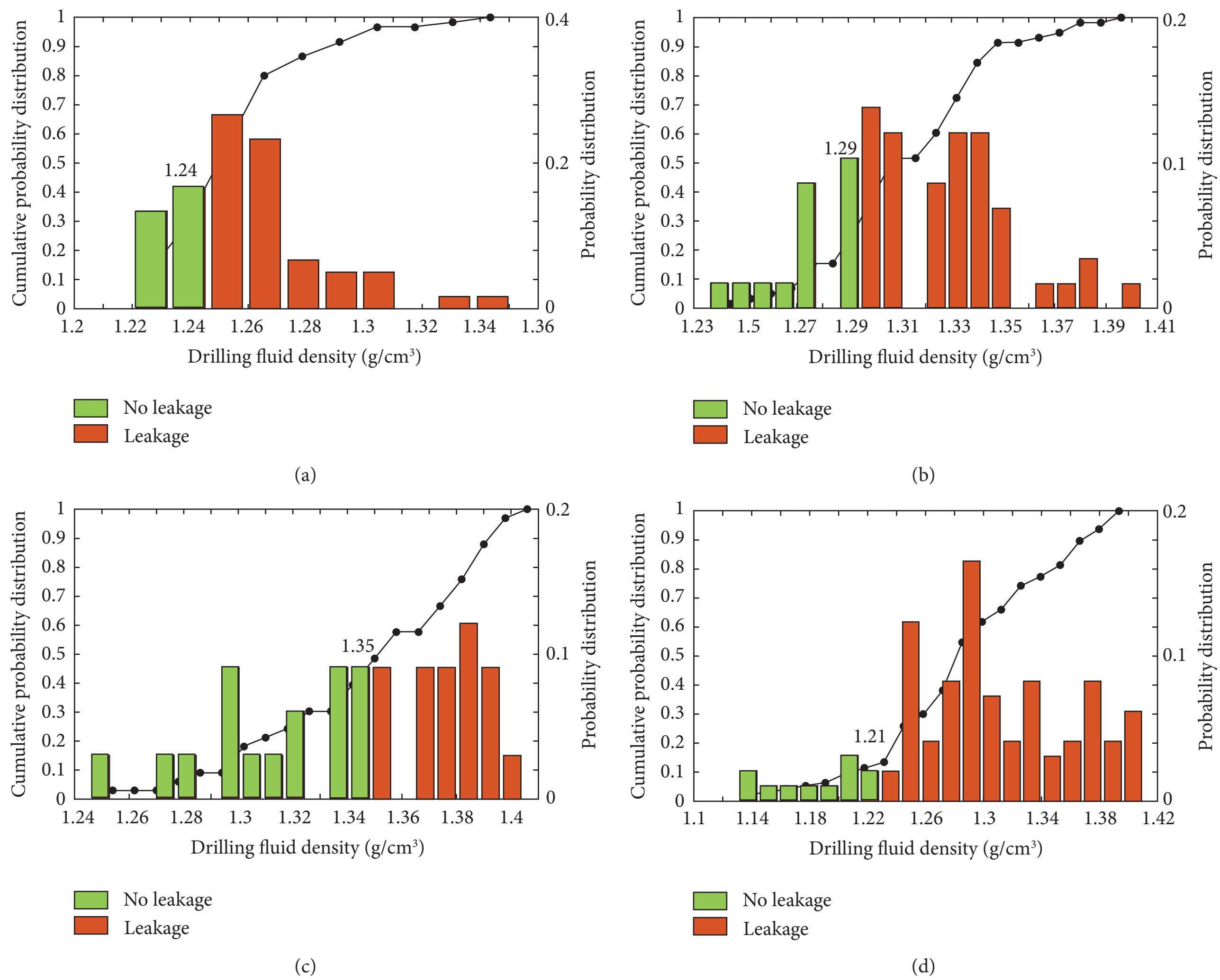


Figure 5: Probability distribution of drilling fluid density in leakage layers of adjacent wells of SHB well. (a) Permian. (b) Silurian. (c) Ordovician Sangtamu layer. (d) Lower layers of Ordovician Sangtamu layer.

circulation is 1.24, of which cumulative probability is 40%. The density of drilling fluid used in Silurian layer is between 1.24 and 1.4. The minimum density for lost circulation is 1.29, of which the cumulative probability of leakage is 35%. The density of drilling fluid used in the Ordovician Sangtamu layer ranges from 1.24 to 1.42. The minimum density for lost circulation is 1.35, of which the cumulative probability is 48%. The density of drilling fluid used in the lower Ordovician Sentamu layers ranges from 1.14 to 1.4. The minimum density for lost circulation is 1.21, of which the cumulative probability is 18%.

The minimum drilling fluid densities when leakage occurs in each layer are selected to modify the SOWDFD with credibility, which is shown in Figure 6. It can be seen from Figure 6 that the modified drilling fluid density window has a narrow density range below the Permian strata, which can easily lead to lost circulation; and the 6 encountered locations of lost circulation are marked with red pentagram in Figure 6. The Ordovician strata have the most serious lost circulation; and the calculation results are consistent with the actual situation. Compared with the measured data (MDT : Pore Pressure Measurement; LOT : Fracture Pressure Test), the three-pressure profiles with credibility are more reliable than the traditional single value profiles, which can be seen from Figure 7(a) and Figure 3. It can be seen from Figure 7(b) that the SOWDFD determined by traditional method cannot reflect the narrow density window of the strata below Permian layer, and it also has some uncertainty due to the error of the formation three-pressure profiles. Through the above analysis, it can be

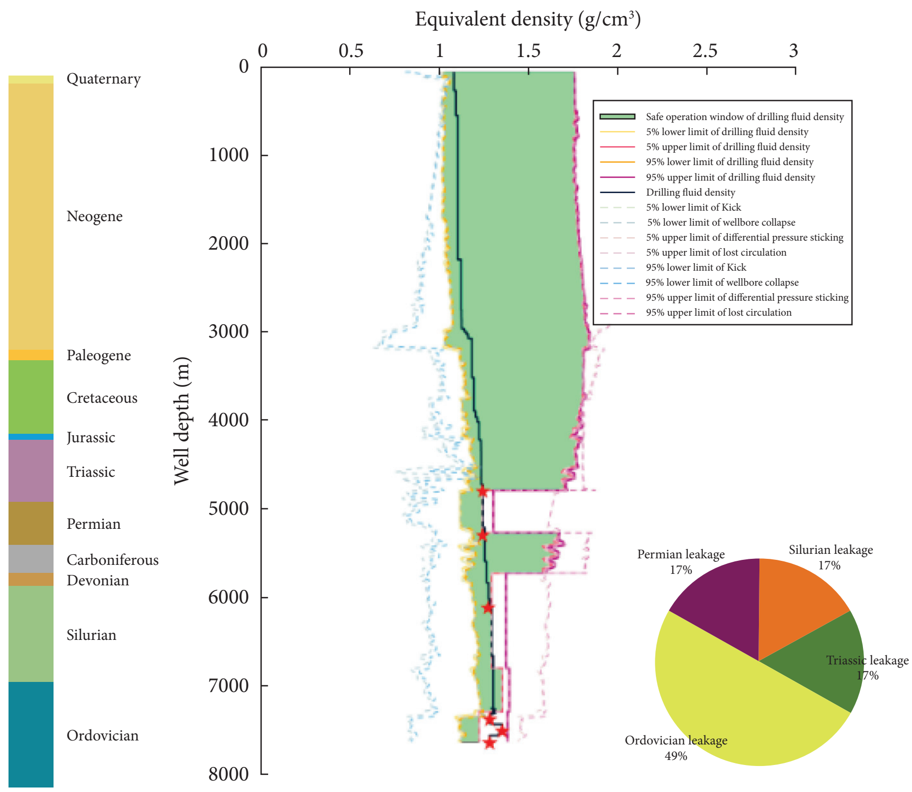
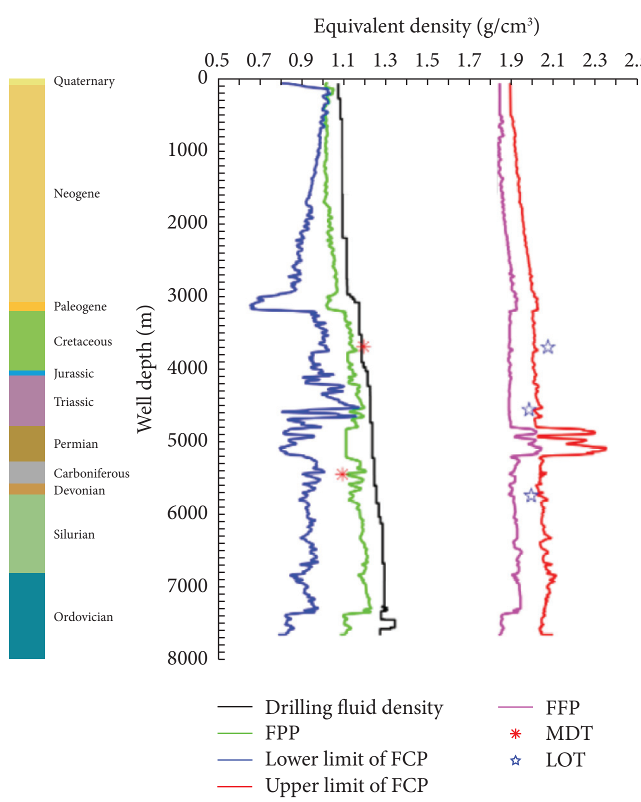
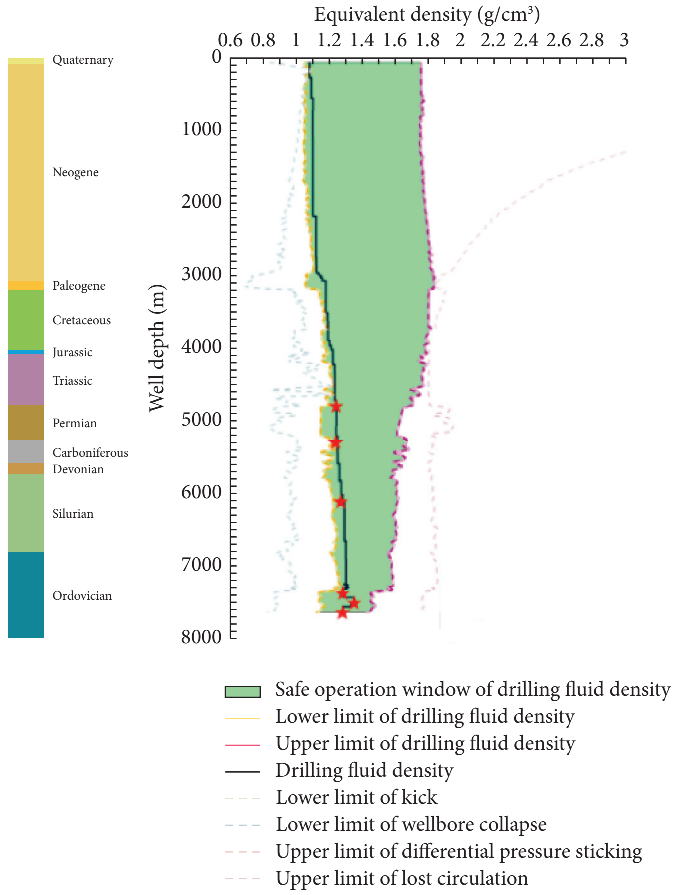


Figure 6: SOWDFD with credibility after modification of fractured leakage of SHB well.



(a)

Figure 7: Continued.



(b)

FIGURE 7: The three-pressure profiles and SOWDFD determined by the traditional method.

proved that the proposed modified model in this paper is scientific and effective.

6. Summary and Conclusions

(1) Aiming at the complex problems of deep igneous rock strata with fracture development, narrow mud density window, frequent occurrence of lost circulation, and well collapse in the drilling process in SB block, the formation three-pressure profiles with credibility are established by analyzing the uncertainty in the calculation process. Based on the reliability theory, the SOWDFD with credibility is established by introducing the drilling risk pressure constraint criterion.

(2) In this paper, a new modified model of the SOWDFD with credibility for the deep igneous strata is proposed. Firstly, the fractured leakage layer is determined based on the adjacent drilled wells in this area. Secondly, the leakage mud density and its risk probability are determined by statistical analysis of the drilling fluid density in the bare hole section of the fractured leakage layer. Finally, the SOWDFD is modified according to the need for lost circulation prevention and control.

(3) The example analysis shows that the SOWDFD with credibility obtained by this method is consistent with reality. It shows that this method can be used to establish a safe operational window of drilling fluid density in this area. This method can provide technical guidance and a scientific basis for making a reasonable drilling design scheme and preventing downhole engineering risks during drilling.

Nomenclature

P_p: Formation pore pressure, MPa
P_o: Overburden pressure, MPa
P_h: Hydrostatic column pressure, MPa
V: Layer speed, km/s
V_n: Normal compaction layer speed, km/s
V_p: Compressional wave velocity, km/s
V_s: Shear wave velocity, km/s
n: Eaton index, dimensionless
P_e: Vertical effective stress, MPa
a, k, b, d: Empirical coefficient, dimensionless
σ_h: Minimum horizontal formation stress, MPa
σ_H: Maximum horizontal formation stress, MPa
σ_v: Vertical formation stress, MPa
ϕ: Internal friction angle, °

σ_c: Uniaxial compressive strength, MPa
S_t: Uniaxial tensile strength, MPa
μ_d: Dynamic Poisson's ratio, dimensionless
E_d: Dynamic Young's modulus, MPa
α: Effective stress coefficient, dimensionless
C: Cohesion pressure, MPa
P_f: Formation fracture pressure, MPa
P_c: Formation collapse pressure, MPa
S_b: Swabbing pressure coefficient, g/cm^3
$\Delta\rho$: Additional drilling fluid density value, g/cm^3
S_g: Activation pressure coefficient, g/cm^3
S_f: Safety increment of formation fracture pressure, g/cm^3
S_c: Circulating pressure loss coefficient, g/cm^3
S_k: Kick allowance, g/cm^3
ΔP: Allowable value of differential pressure sticking, MPa
$h_{p\max}$: Depth of maximum formation pore pressure in bare hole section, m
h: Well depth, m
μ: Expected density of drilling fluid in bare hole section of lost circulation layer, g/cm^3
σ: Standard deviation of drilling fluid density in bare hole section of lost circulation layer, g/cm^3.

Data Availability

All data included in this study are available upon request to the corresponding author.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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References

[1] X. Guo, D. Hu, Y. Li et al., "Theoretical progress and key technologies of onshore ultra-deep oil/gas exploration," *Engineering*, vol. 5, no. 3, pp. 458–470, 2019.
[2] W. Jinghong, Z. Caineng, J. Jiuqiang, and Z. Rukai, "Characteristics and controlling factors of fractures in igneous rock reservoirs," *Petroleum Exploration and Development*, vol. 38, no. 6, pp. 708–715, 2011.
[3] Q. Fu, "Status and prospect of igneous oil and gas exploration and development in China," *Oil Drilling & Production Technology*, vol. 39, no. 1, pp. 25–32, 2017.
[4] W. Yao, Z. Chen, T. Hu et al., "Storage space, pore structure, and primary control of igneous rock reservoirs in Chepaizi Bulge, Junggar Basin, western China: significance for oil accumulation," *Journal of Petroleum Science and Engineering*, vol. 195, Article ID 107836, 2020.
[5] N. J. Mark, N. Schofield, S. Pugliese et al., "Igneous intrusions in the Faroe Shetland basin and their implications for hydrocarbon exploration; new insights from well and seismic data," *Marine and Petroleum Geology*, vol. 92, pp. 733–753, 2018.
[6] K. Ke, Z. Wang, Y. Zhou et al., "Pre-spud quantitative description method for fracture in thief formation of steeply-folded structure," *Fault-Block Oil and Gas Field*, vol. 22, no. 02, pp. 263–265, 2015.
[7] J. Liu, W. Zhang, Y. Yu et al., "Analysis on wellbore stability in Permian igneous rock formation," *Journal of Safety Science and Technology*, vol. 15, no. 1, pp. 75–80, 2019.
[8] J. Zhang and S. Yin, "Real-time pore pressure detection: indicators and improved methods," *Geofluids*, vol. 2017, Article ID 3179617, 12 pages, 2017.
[9] T. Ma, N. Peng, P. Chen et al., "Study and verification of a physical simulation system for formation pressure testing while drilling," *Geofluids*, vol. 2018, Article ID 1731605, 18 pages, 2018.
[10] J. Deng, Y. Chen, M. Chen et al., *Wellbore Stability Prediction technology*, Petroleum Industry Press, Beijing, China, 2008.
[11] S. Li, J. George, and C. Purdy, "Pore-pressure and wellbore-stability prediction to increase drilling efficiency," *Journal of Petroleum Technology*, vol. 64, no. 2, pp. 98–101, 2012.
[12] Y. Xu, H. Zhang, and Z. Guan, "Dynamic characteristics of downhole bit load and analysis of conversion efficiency of drill string vibration energy," *Energies*, vol. 14, no. 1, p. 229, 2021.
[13] Y. Wang, "Lost circulation law in fractured strata with stress sensitivity," *Xinjiang Petroleum Geology*, vol. 36, no. 4, 2015.
[14] B. A. Eaton, "Fracture gradient prediction and its application in oilfield operations," *Journal of Petroleum Technology*, vol. 21, no. 10, pp. 353–361, 1969.
[15] L. Shi, H. Jiang, and Q. Guo, "Analysis on the leakage pressure of thief formation," *Oil Drilling & Production Technology*, vol. 32, no. 3, pp. 40–44, 2010.
[16] R. Zhang, X. Shi, Z. Nie et al., "Critical pressure of closure fracture reopening and propagation: modeling and applications," *Journal of Petroleum Science and Engineering*, vol. 158, pp. 647–659, 2017.
[17] H. Li and S. Peng, "Prediction of inter-well fractures with fractal technique," *Journal of China University of Petroleum (Edition of Natural Sciences)*, vol. 26, no. 6, pp. 33–35, 2002.
[18] M. Mosaheb and M. Zeidouni, "Pressure transient analysis for characterization of lateral and vertical leakage through faults," in *Proceedings of the Carbon Management Technology Conference*, Houston, TX, USA, 2017.
[19] H. Huang, X. Liu, Y. Cai et al., "Igneous rock fracture prediction with well logging and seismic data," *Oil Geophysical Prospecting*, vol. 50, no. 5, pp. 942–950, 2015.
[20] X. Fan, Y. Tian, H. Xia et al., "How to locate leak zone by logging data," *Natural Gas Industry*, vol. 27, no. 5, pp. 72–74, 2007.
[21] Y. Ma, B. Tang, X. Zhang et al., "A fracture identification method based on S-wave velocity difference: a case study form the volcanic strata in the Junggar Basin," *Natural Gas Industry*, vol. 36, no. 6, pp. 36–39, 2016.
[22] Y.-N. Sheng, Z.-C. Guan, and Y.-Q. Xu, "Quantitative description method for uncertainty of formation pore pressure," *Arabian Journal for Science and Engineering*, vol. 43, no. 5, pp. 2605–2613, 2018.
[23] Y. N. Sheng, Z. C. Guan, T. Zhao et al., "Study on method of determining the formation pressure with credibility," *Science Technology and Engineering*, vol. 16, no. 2, pp. 37–42, 2016.
[24] D. Li, Y. Kang, X. Liu et al., "The lost circulation pressure of carbonate formations on the basis of leakage mechanisms," *Acta Petrolei Sinica*, vol. 32, no. 5, pp. 900–904, 2011.

[25] T. Ma, T. Tang, P. Chen, and C. Yang, "Uncertainty evaluation of safe mud weight window utilizing the reliability assessment method," *Energies*, vol. 12, no. 5, p. 942, 2019.

[26] Z. Guan, Y. N. Sheng, M. Luo et al., "A new quantitative evaluation method for drilling risk based on uncertainty analysis," *Kuwait Journal of Science*, vol. 45, no. 3, 2018.

[27] H. Sun, *Geostatistics with Application*, China University of Mining and Technology Press, Xuzhou, China, 1990.

[28] J. Hou, *Practical Geostatistics*, Geological Publishing House, Beijing, China, 1998.

[29] K. WeiZ. Guan et al., "Assessment method for uncertainty of geological parameters in well drilling," *Journal of China University of Petroleum (Edition of Natural Sciences)*, vol. 39, no. 5, pp. 89–93, 2015.

[30] F. Gong, X. Li, and J. Dend, "Probability distribution of small samples of geotechnical parameters using normal information spread method," *Chinese Journal of Rock Mechanics and Engineering*, vol. 25, no. 12, p. 2559, 2006.