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Research on the distribution law of drilling resistance of formation rock based on modified coefficient method

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Abstract: *The drilling strength parameters of formation rocks are important reference basis for drilling engineering design, bit selection, and drilling parameter optimization. Establishing a correlation calculation function between logging data and parameters such as rock compressive strength and drillability level through unit experiments, and obtaining a profile of drilling resistance characteristics that varies with well depth, is a classic technical means in the field of oil and gas well engineering. However, in the case of insufficient core volume, the experimental data obtained is limited, making it difficult to regress and fit the calculation model with high accuracy, which limits the application of this technology to some extent. In this paper, a "correction coefficient method" is proposed to establish a calculation model for parameters such as formation compressive strength and drillability grade based on logging data. First, unit experiment analysis is carried out for the limited core volume of the target block. Secondly, the classical calculation model is modified by using the experimental results. Then, the model is applied to the deep well section of the southern block of the Tarim Basin to analyze the drilling resistance characteristics of formation rock and obtain the change trend conclusions. This method breaks through the limitation of experimental core volume and has good engineering application value and potential.*

Keywords: *Rock drillability; Oil and gas drilling; Deep strata; Logging interpretation; Tarim Basin*

1. Introduction

The drilling strength of formation rock includes the drillability, compressive strength, shear strength, internal friction Angle, mud content and other parameters. Among them, the drillability of rock refers to the ability of rock to resist drilling and crushing, which reflects the difficulty of drilling and crushing rock, and is an important reference basis for drilling engineering design, bit selection and drilling parameter optimization.

The concept of drillability was first proposed by A.G. Rolow[1] in 1927 to indicate the degree of difficulty in breaking rocks. Head[2] proposed the drillability classification method of formation rocks in 1951, which was based on the time (seconds) taken to drill 1/16 inch down with specific parameters. Li Shi-bin[3] proposed a rock drillability classification method based on fractal theory, which can be used to determine the drillability grade value of rock by measuring the fractal dimension of rock cuttings returned from the bottom of the well. Andrews R J[4] combined drilling parameters per meter, stratum type and pore pressure, and carried out inverse calculation of the drillability of the permeability model. Chen Jun-hai[5] proposed a method to determine the drillability grade value of PDC bit by using rock strength scratching test, which fully characterized the influence of changes in complex factors such as mineral composition, cementation strength and microstructure on the drillability grade value of PDC bit, without damaging the overall structure of the core and improving the utilization rate of the core.The oil and natural gas industry standard " Rock drillability measurement and its classification " was first published in 1991[6-7], and subsequently revised in 2000[8] and 2016[9] respectively. The latest drillability standard adopts new methods of drillability testing and grading by weight on bit, equivalent conversion grading or independent grading. The drillability of rocks above medium and hard can be

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accurately measured. The study obtained the normalized correlation between rock drillability and acoustic logging. Shi Xiang-chao[10] established the drillability model of bottom-hole rock under the spherical coordinate system, which can better reflect the distribution law of drillability grade value of bottom-hole rock. Han Lili[11] proposed a prediction method of rock drillability based on particle swarm optimization correlation vector machine (PSO-RVM). Five parameters, including rock depth, acoustic time difference, resistivity, rock density and mud content, were selected as the basic parameters for evaluating rock drillability. Li Chun-shan[12-13] obtained a calculation model for calculating rock drillability grade by using the element content of rock cuttings and the method of multiple regression analysis, which can be used to evaluate rock drillability in real time. Zhang Hui[14] proposed a method and device for predicting rock drillability stage value of PDC bit at different temperatures, which directly predicted rock drillability stage value of PDC bit at different temperatures by using acoustic logging and ground temperature data of drilling site. Li Zhong-hui[15] established a five-parameter radar map to describe the drilling resistance of formation rocks by applying the normalization method based on the relationship between different acoustic time difference and rock hardness, internal friction Angle, uniaxial compressive strength, abrasive grade and rock drillability grade. Zhou Qi-cheng[16] derived and analyzed the fractal dimension in combination with the fractal theory, and determined the relationship between the fractal dimension of returned cuttings and the quality and size of cuttings. BP neural network is used to establish the mapping relationship between the fractal dimension of cuttings, logging data and drillability extreme value in FuLing shale gas block. Yang Ying-xin[17] proposed a drillability test and classification method using the classification test of bit weight, equivalent conversion classification or independent classification, which can effectively solve the drillability test problem of rocks above medium and hard. Li Qian[18] established a nonlinear multiple regression model using logging parameters to predict rock drillability, and used a variety of artificial neural network methods to predict rock drillability. The results show that the BP-RBF double-cascade neural network model has better prediction effect and is more suitable for deep formation rock drillability prediction in the East China Sea. Xie Zhi-jiang[19] proposed a coal and rock drillability classification method based on mechanical specific energy drillability evaluation index combined with extreme learning machine. Xu Meng-guo[20] based on Rock Engineering system (RES) theory. The rock mechanical properties and drilling construction parameters are comprehensively considered as a complete system, and the overall interaction strength matrix GRSE is constructed by artificial neural network coding method, and the classification comprehensive prediction model of rock drillability is established. Zhang De-jun[21] proposed a practical method to identify the formation lithology near the bit in real time by using real-time data such as drilling time and torque, as well as key parameters such as DC index and drillability level, overcoming the limitations of traditional static lithology identification methods.

Based on the analysis of typical rock resistance characteristics of deep Wells in the southern margin of Junggar Basin, a method of regression fitting using logging data based on "modified coefficient method" is proposed in this paper. This method breaks through the limit of experimental core quantity and can obtain more accurate calculation results under the condition of scarce core quantity.

2. Experimental test of drilling resistance of deep formation rocks in the southern margin area

In order to obtain the mechanical properties and drilling resistance of rock in deep strata in the southern margin area, outcrop rock blocks of Qingshuihe Formation, Tou Tunhe Formation and Kalaza Formation were obtained by field investigation, as shown in Fig 1. A total of 33 sets of standard samples were processed, and experiments on compressive strength and PDC bit drillability were carried out respectively.

(a)Kalaza Formation

(b)Qingshuihe Formation

Figure 1: Outcrop rock samples of typical strata in the southern margin area

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After cutting and coring the outcrop, the triaxial compressive strength test was carried out respectively. The experimental rock samples are shown in Fig 2.

Figure 2: φ25.4mm core sample for experiment

2.1 Experimental test of rock compressive strength

Triaxial compressive strength tests were carried out on rock samples from Qingshuihe Formation (Q1, Q2, Q3), Toutunhe Formation (T1, T2, T3) and Kalaza Formation (L1, L2, L3) respectively, and the experimental data results of rock compressive strength, elasticity modulus, Poisson's ratio, cohesion and internal friction angle were obtained. As shown in Fig 3.

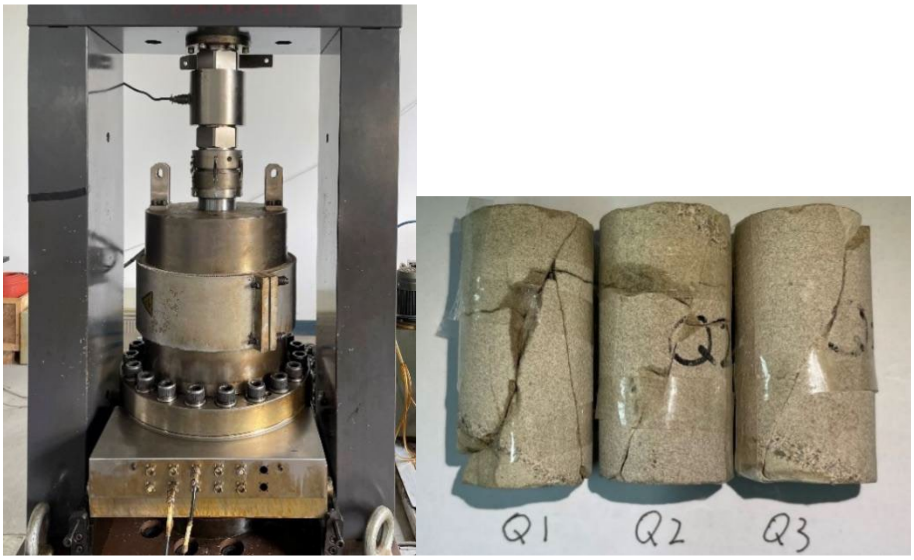
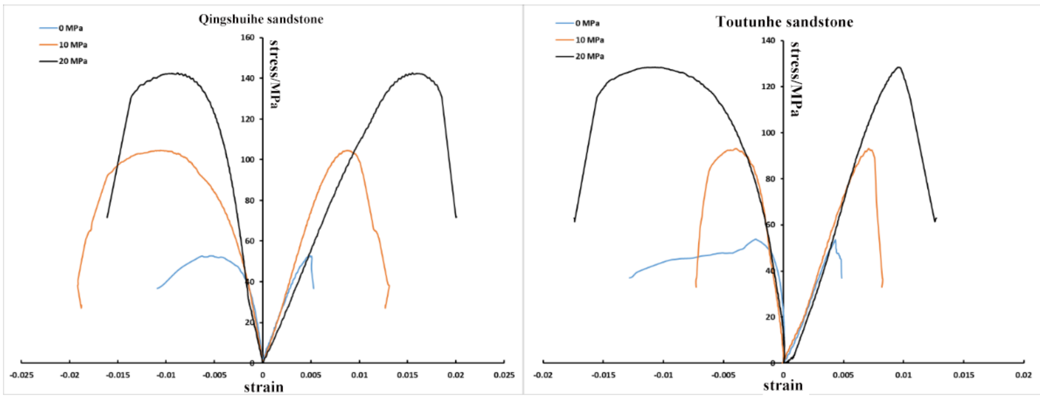


Figure 3: Triaxial compressive strength test equipment and core failure form

The stress-strain curve of the core sample is shown in Fig 4.



(a) Qingshuihe *(b) Toutunhe*

Figure 4: Core triaxial stress-strain curve

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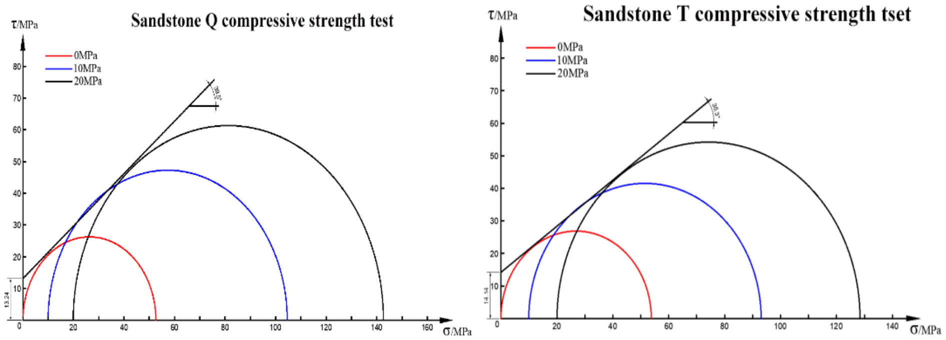
The mechanical property parameters of rock samples can be obtained by calculating and drawing the stress Mohr circle diagram of rock samples, as shown in Fig 5.



(a) Qingshuihe sandstone *(b) Toutunhe sandstone*

Figure 5: Mohr-Stress circle of typical outcrop triaxial compressive test

The experimental data results are shown in Table 1.

Table 1: Mechanical property parameters of rock in typical stratum outcrop

Rock type	Compressive strength /MPa	Elastic modulus /GPa	Poisson's ratio	Cohesion /MPa	Internal friction angle /°
Qingshuihe sandstone	51.45	14.03	0.31	12.98	35.8
Toutunhe sandstone	52.58	15.69	0.28	13.96	36.3
Kalaza conglomerate	24.37	9.86	0.16	8.41	35.44

In the above experimental data, the sandstone of Qingshuihe Formation and Tou Tunhe Formation has similar mechanical properties and belongs to the medium strength rock type. The gravel-bearing core strength of Kalaza Formation is lower than the other two, but the inhomogeneity is stronger and the cementation strength of gravel particles is not high.

2.2 Rock drillability test analysis

The drillability of rock is a comprehensive index to measure the ability of rock to resist the crushing of drill bit. It has important application value in drilling engineering, such as guiding bit selection, selecting bit parameters and predicting drilling rate. Different from the compressive strength and shear strength of rock, rock drillability is a dynamic parameter of rock under specific drilling conditions.

The experiment was carried out in accordance with the oil and gas industry standard "SY/T 5426-2016", that is, the micro-bit was used to adopt three gears of drilling parameters of 500N, 1000N and 2000N respectively, the rotating speed was 55r/min, the drilling depth was 3.0mm, and the pre-drilling depth was 1.0mm. When drilling with a micro-bit, the drilling time (s) to a further depth of 3mm is recorded, and then converted to a logarithm base 2 to represent the drillability level. The Rock drillability test equipment and micro-bit are shown in Fig 6.

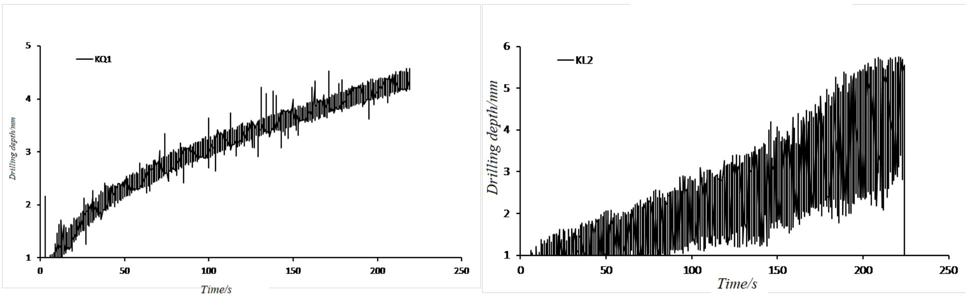
Figure 6: Rock drillability test equipment and micro-bit

Drillability tests were carried out on Qingshuihe Formation sandstone, Toutunhe Formation sandstone and Kalaza Formation conglomerate respectively in the southern margin area. Some drillability test bottom holes are shown in Fig 7.

(a) Qingshuihe Formation sandstone (b) Rock mass of Toutunhe Formation (c) Rock mass of Kalaza Formation

Figure 7: Rock drillability test microbottom

The original drilling depth-time curves for the drillability measurement of Qingshuihe Formation and Kalaza Formation are shown in Fig 8.



(a) Qingshuihe Formation (b) Kalaza Formation

Figure 8: Experimental curve of drillability of typical strata rock

The data results of the drillability grades of the three formations are shown in Table 2.

Table 2: Data results of drillability class of typical strata

<table>
<tr><th>number</th><th>value of number</th><th>mean value</th><th>number</th><th>value of number</th><th>mean value</th><th>number</th><th>value of number</th><th>mean value</th></tr>
<tr><td>Q1</td><td>7.15</td><td rowspan="4">8.26</td><td>T1</td><td>7.48</td><td rowspan="4">7.53</td><td>L1</td><td>7.23</td><td rowspan="4">6.78</td></tr>
<tr><td>Q2</td><td>8.46</td><td>T2</td><td>7.41</td><td>L2</td><td>6.12</td></tr>
<tr><td>Q3</td><td>8.28</td><td>T3</td><td>7.49</td><td>L3</td><td>7.08</td></tr>
<tr><td>Q4</td><td>9.15</td><td>T4</td><td>7.76</td><td>L4</td><td>6.69</td></tr>
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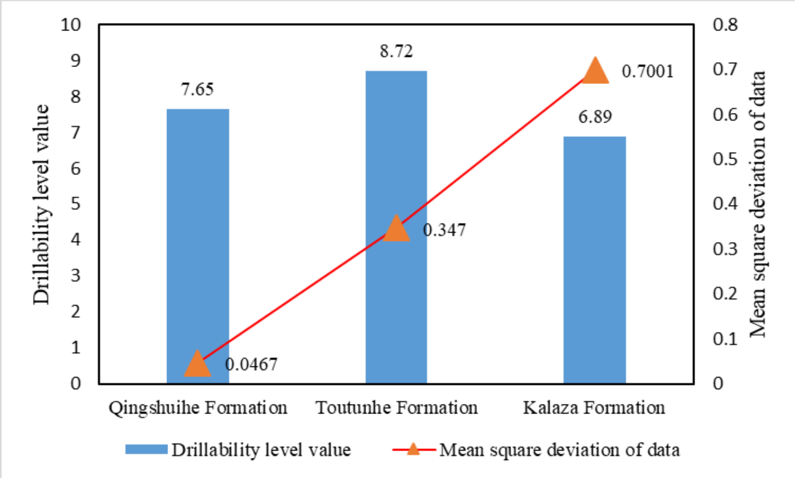

Figure 9: Comparison of drillability class data of typical strata

It can be seen from the Figure 9 that the rock homogeneity of the Qingshuihe Formation is good, and the mean drillability is 8.26, and the uniform variance of each measured data is 0.3470. The average drillability of the Toutunhe Formation is 7.53, and the uniform variance of the measured data is 0.0467, indicating that the formation uniformity is good. The mean drillability of Kalaza Formation is 6.78, and the uniformity variance of each measured data is 0.7001, indicating poor formation homogeneity.

3. Modeling of formation rock resistance characteristics based on logging interpretation

After obtaining the measured data of rock mechanical properties of the above formation, the corresponding calculation model can be established, and the section curve of rock mechanical parameters in deep formation can be analyzed and calculated through the logging data, which provides a reference for the study of the changing trend of rock mechanical properties and the recommendation of bit selection.

Well logging data contain abundant formation geological information, especially acoustic wave, gamma ray and density logging data, which can better reflect the compressive strength, shear strength, drillability grade and mud content of formation rocks. According to relevant technical data, the form of calculation model is shown in Table 3.

Table 3: Analysis of the classical model of rock resistance to drilling based on logging data

Types	Model	Notes
Compressive strength	$\delta_c = A_1 - B_1 \cdot ln(\Delta t_p) - C_1 \cdot GR$	δ_c:compressive strength,MPa A_1, B_1, C_1:undetermined coefficient $\Delta t_p, GR$:P-wave slowness;gamma
Drillability level	$K_d = D_1 + \Delta T + A_4 \exp(\lambda \Delta t_p)$	K_d:drillability level D_1:undetermined coefficient ΔT:corrected the numerical difference in drillability

According to the above classical calculation model, combined with the test results of rock drilling strength characteristics obtained above, the calculation model of rock drilling resistance is established by using the correction method and basic principles shown in the Figure below. As shown in Fig 10.

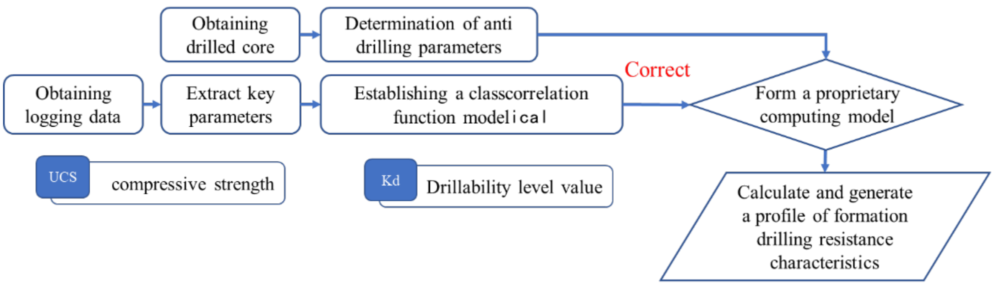

Figure 10: Principle of establishment of calculation model for drilling resistance of formation rock

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Taking well HT1 in the southern margin of Junggar Basin as an example, the original data of modeling and calculation of drilling resistance characteristics of related strata rocks are shown in Table 4.

Table 4: Corresponding parameters between the measured drillability level and logging data of deep formation rock outcrop

Stratum	Compressive strength /MPa	Drillability level	Well section /m	The mean value of DT /Δt	Gamma /API
Qingshuihe Formation	52.58	8.26	7090-7120	62.29	16.13
Toutunhe Formation	51.45	7.53	7230-7280	66.14	36.72
Kalaza Formation	24.37	6.78	7450-7480	84.52	92.88

3.1 Revised modeling of formation compressive strength calculation model

Firstly, the current compressive strength value was calculated according to the classical calculation model, and the calculated result was 38.25MPa lower than the experimental result. Therefore, the classical model was modified on this basis, as shown in Fig 11.

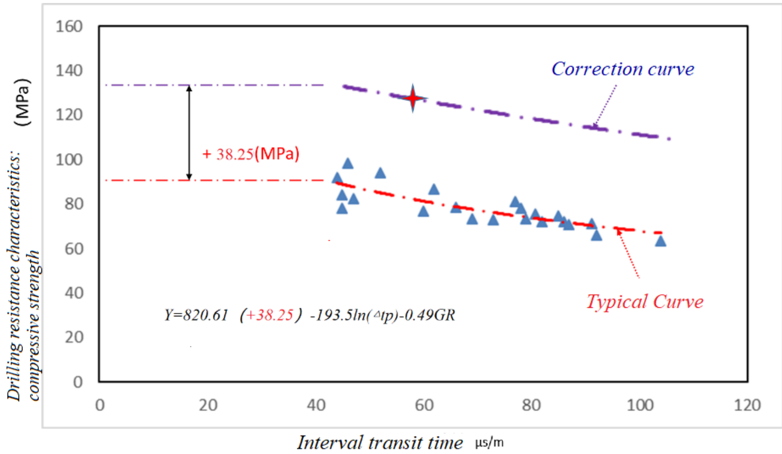

Figure 11: Modification of formation rock compressive strength model based on calculation of logging parameters

The final calculation model is as follows:

$$\delta_c = 858.86 - 193.5 \cdot \ln(\Delta t_p) - 0.49 \cdot GR \quad (1)$$

After the above calculation model is obtained, it can be used to calculate the typical rock mechanical property profile of deep strata in the southern margin of Junggar Basin.

3.2 Revised modeling of the calculation model of formation drillability level

Similarly, based on the above data and the revised curve shown in the Figure 12, the undetermined coefficient of the analysis and calculation model is finally determined. The calculation formula is as follows:

$$K_d = 5.79 + 31.81\, exp(-0.041\Delta t_p) \quad (2)$$

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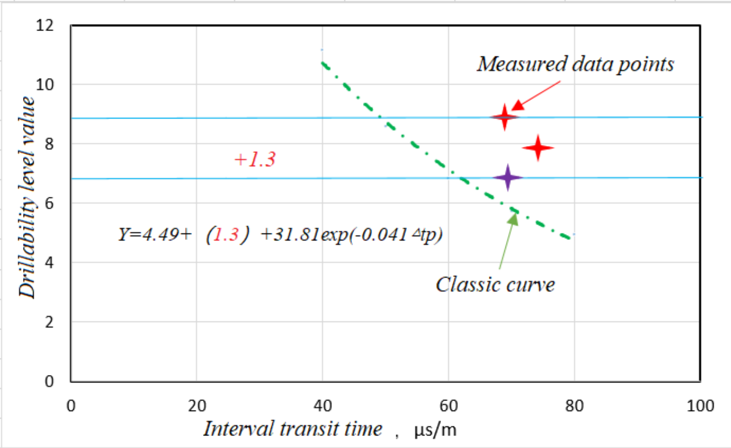

Figure 12: Correction curve of rock drillability grade and logging data of deep formation in the south margin

4. Analysis of drilling resistance profile of typical rock in south margin formation

The southern margin of Junggar Basin is affected by the strong uplift and northward extrusion of the Tianshan Mountains. The thickness of the Quaternary sediments, which are mainly gravel beds, is up to 2000 m. The long axes of anticlinal structures are nearly east-west, and most of the faults are southerly dip reverse faults, and the foreland thrust belt is rich in oil and gas resources. In recent years, the exploration in the southern margin has gradually moved to the deep middle-bottom combination, and the difficulty and risk of drilling have been increasing. The rocks in the Toutunhe Formation and the following formations in the region have high drilling strength and strong heterogeneity, and complex accidents occur frequently during drilling, which are the main bottlenecks affecting the development of oil and gas in the southern margin region.

Based on the above calculation model and the deep formation logging data of HT1 well in Junggar Basin, the drilling resistance profile of formation rocks is calculated, as shown in Fig 13.

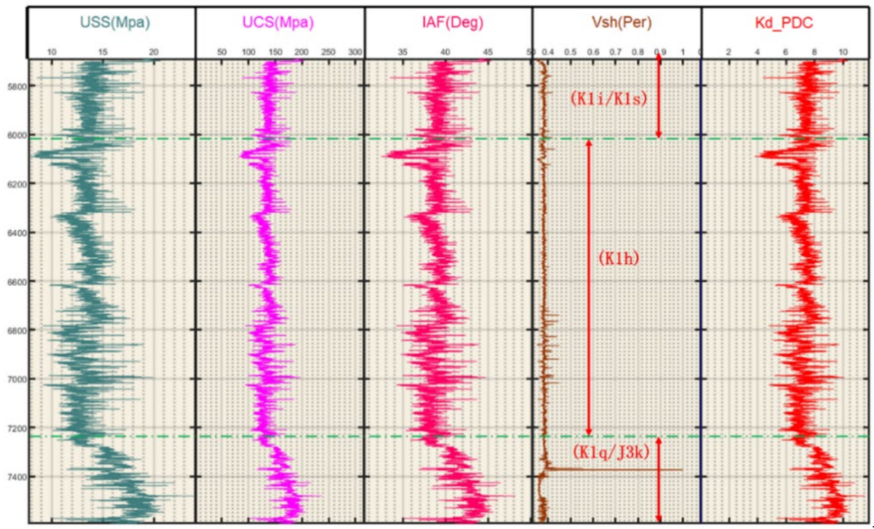

Figure 13: Section curve of rock resistance to drilling in well Hutanyi 1

It can be seen from the above Figureure that there are three groups of typical drilling resistance characteristics: First, the formation uniformity of Lianmuqin and Jinkou Formation above 6000 meters is good, the compressive strength distribution is between 130Mpa and 150Mpa, and the drillability level is between 7 and 8. The second is the formation dominated by Hutubihe Formation up to 7250 m, which has poor homogeneity and fluctuates from class 4.5 to class 8.5. The third is that the Qingshuihe and Karaza Formation is the main formation at the bottom of the well, the compressive strength gradually increases from 135Mpa to 200Mpa, and the drillability level gradually increases from 7 to 10. The lower stratum is mainly composed of mudstone, argillaceous siltstone and silty mudstone. The lithology is

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relatively dense and the plasticity is strong, which makes it difficult for the cutting intrusion ability of drill bit.

5. Summary

(1) The drilling strength parameter of formation rock is an important reference for drilling engineering design, bit selection and drilling parameter optimization. By carrying out the unit experiment test of rock resistance to drilling, the correlation calculation function of logging data and drillability level value is established, and the rule profile of rock resistance to drilling with the change of well depth is obtained, which can provide reference for drilling engineering design, bit selection and drilling parameter optimization.

(2) According to the limited experimental data and the classical model of rock drilling resistance in the target block, the calculation model of formation compressive strength and drillability level based on logging data is established by using the "modified coefficient method" regression fitting. This method breaks through the limit of experimental core quantity and has good engineering application value and potential.

(3) According to the calculation results, the stratigraphic homogeneity of Shenlian- Muqin Formation and Jinkou Formation at 6000 m in the southern margin of Junggar Basin is good, and the drillability grade is between grade 7 and grade 8. The 7250 m formation, dominated by the Shenhu-Tubihe Formation, has poor homogeneity and fluctuates from class 4.5 to class 8.5. The drillability of the Qingshuihe and Kalaza Formation has gradually increased from grade 7 to above grade 10.

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