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Analysis of drilling resistance characteristics of Permian strata in Shapai block based on logging data

Xindong Wang[1], Ming Yi[1], Guiyi Zhang[1], Xin Zhang[1], Tao Su[1], Haitao Ren[2,*], Jintao Zhu[1], Xuebin Sun[1]

[1]*Engineering Technology Research Institute of China National Petroleum Corporation West Drilling Engineering Company Limited, Kelamayi, Xinjiang Uygur Autonomous Region, 834000, China*
[2]*College of Mechanical and Electrical Engineering, Southwest Petroleum University, Chengdu, Sichuan, 610500, China*
[*]*Corresponding author: 254440593@qq.com*

Abstract: *Logging data contain a large amount of formation information, which can better reflect the anti-drilling characteristics of the formation. By carrying out indoor unit experiments and establishing analysis models, the profile curves of single well formation compressive strength, mud content and drillability grade value are calculated. On this basis, the prediction method of the change trend of the lateral anti-drilling characteristics of the formation rock is established by using the power basis function fitting theory of the cubic surface. Taking the deep strata of Shapai block in Junggar Basin as an example, this paper calculates and analyzes the anti-drilling characteristics of single well strata and the lateral distribution of strata in the block. The range of rock anti-drilling characteristics parameters of Wuerhe Formation, Fengcheng Formation and Jiamuhe Formation in Permian strata is studied, and the overall change trend and local stage change area are obtained. The analysis method established in this paper can provide reference for subsequent drilling design, bit selection, drilling parameter optimization and other engineering operations, which is helpful to improve the efficiency of bit use, reduce drilling cost and shorten well construction period.*

Keywords: *Logging data; anti-drilling characteristics; permian strata; bit selection*

1. Introduction

Logging data contain a large amount of formation information, which can better reflect the anti-drilling characteristics of the formation. W.H.Somerton[1] proposed that the rock drillability can be predicted by acoustic time difference. At the same time, the feasibility and correlation of the method of acoustic time difference reflecting formation drillability are analyzed. It is considered that it is feasible to calculate rock drillability by logging acoustic time difference in engineering. At present, major foreign drilling companies have their own computer software, among which the more famous are Baker Hughes ' ROCKY and Smith International 's DBOS software [2-3]. In China, Professor Zou Deyong, Li Zhonghui et al. [4-5] gave the relationship model between rock drillability grade and logging data on the basis of laboratory tests. Dou Tongwei [6] et al.established an analysis model of the longitudinal variation law of formation rock mechanical strength based on multi-factor logging parameters. On this basis, the mapping relationship function was established by using the cubic surface power function fitting method, and a new method for analyzing the lateral variation law of formation rock strength was formed. Wang Kexiong and Liu Xiangjun[7-8] established a prediction model of formation anti-drilling characteristic parameters in Dongying Sag of Shengli Oilfield based on the relationship between the measured results of indoor formation anti-drilling characteristic parameters and acoustic velocity.

In oil and gas drilling engineering, due to the change of formation lithology, drilling parameters are often improperly applied, abnormal bit failure accidents occur frequently, and even serious accidents such as broken drilling tools and broken blade are caused by bit pressure holding and jumping. In order to accurately grasp the anti-drilling characteristics of formation rock in the block, improve the drilling operation efficiency and reduce the drilling safety risk, this paper carried out the analysis of anti-drilling characteristics of formation rock based on logging data. Taking Shapai block of Junggar Basin in western province as an example, the prediction model between rock anti-drilling characteristic parameters and logging data is established through analysis, and the prediction technology of lateral distribution law of formation rock anti-drilling characteristics is formed, and the analysis and evaluation of Permian

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formation rock anti-drilling characteristic parameters are completed. The research work in this paper can provide parameter basis for personalized design of drill bit, optimization of drilling parameters and optimization of BHA[9].

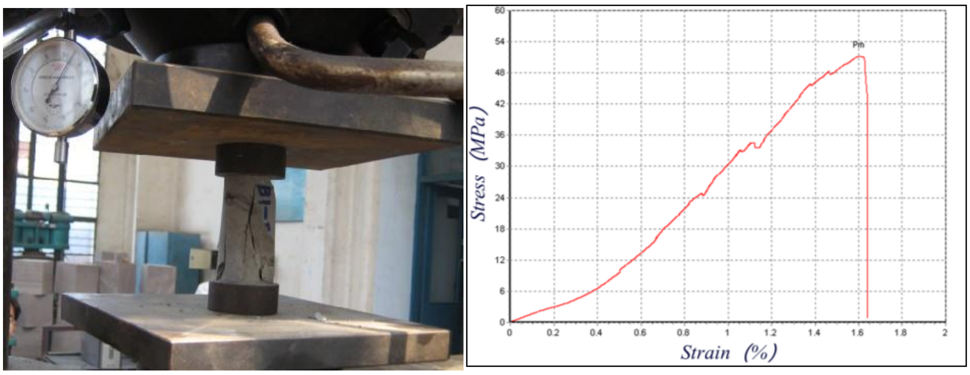
2. Calculation method of formation rock anti-drilling characteristics in block

2.1 Unit experimental test of formation rock anti-drilling characteristics

According to the formation cores of the Upper Urho Formation and Xiazijie Formation collected in the Shapai block, the parameters such as compressive strength, mud content and drillability grade were measured. Among them, the experimental determination of rock compressive strength is carried out according to the DZ/T 0276.20-2015 industry standard[10-11], and the experimental determination of rock drillability grade is carried out according to the SY/T 5426-2016 industry standard[12]. As shown in Figure 1 and Figure 2.

(a) Stratum drilling core (b) Drillability measurement

Figure 1: Experimental test of formation core and anti-drilling characteristics



(a) Determination of compressive strength (b) Compressive strength "stress-strain" curve

Figure 2: Experimental Testing of Core Compressive Strength

In the rock strength unit experiment, more than 20 actual drilling cores were collected, and more than 50 sets of experimental data were obtained. The test results are shown in Table 1.

Table 1: Experimental Results of Rock Drilling Resistance Characteristics in Shapai Block Stratum

serial number	soil sample depth (m)	longitudinal wave time difference Td (μs/m)	gamma ray (cps)	compressive strength (MPa)	Drillability level value
1	4963	69.53	41.01	107.98	7.63
2	5481	72.72	40.69	99.46	7.41
3	5003	78.48	71.84	69.45	7.06
4	5010	81.03	71.13	63.61	6.97
5	5241	77.71	60.01	77.15	7.11
…	……				

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2.2 Single well formation rock anti-drilling characteristics calculation model

According to the test results of compressive strength and drillability grade of real drilling core, the compressive strength of rock is fitted by two-factor regression of longitudinal wave time difference (Td) and natural gamma (Gr), and the calculation model listed in formula (1) can be obtained. The correlation coefficient of the model reaches 0.742, which meets the application accuracy requirements.

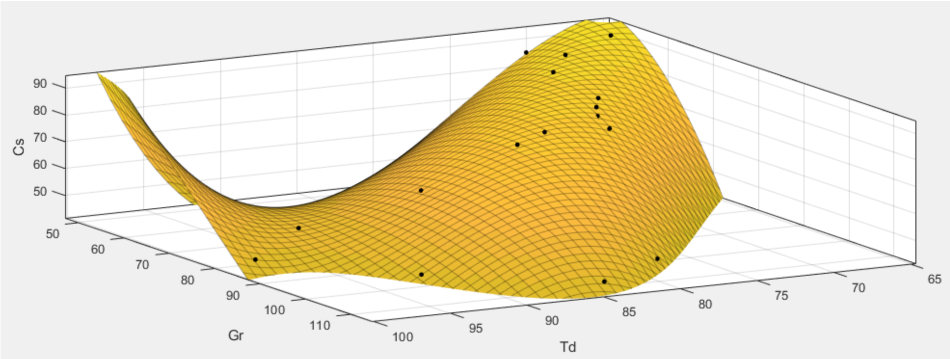

Figure 3: Regression fitting of the compressive strength of strata rocks with longitudinal wave time difference and natural gamma rays

The regression fitting function of rock drillability grade value and longitudinal wave time difference is shown in figure 4, and the calculation model listed in formula (2) can be obtained. The correlation coefficient reaches 0.876, which also meets the accuracy requirements.

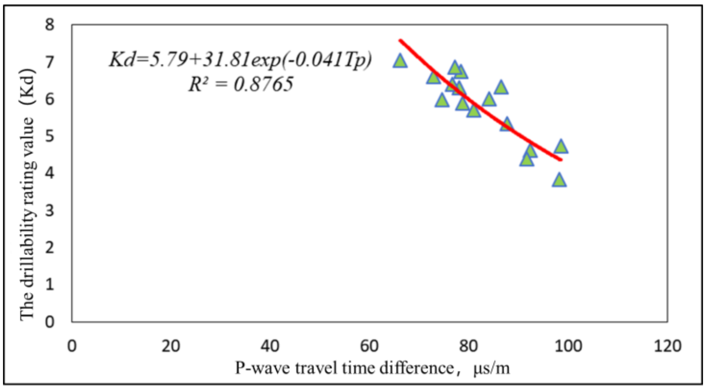

Figure 4: Regression fitting of rock drillability level values and longitudinal wave time difference in strata

In addition, the calculation model of mud content is based on the calculation model obtained in reference [12], which is listed in formula (3).

$$Cs = 948.86 - 193.5ln(Tp) - 0.49Gr \tag{1}$$

$$Kd = 5.79 + 31.8exp(-0.041Tp) \tag{2}$$

$$V_{sh} = \frac{2^{GCUR \times I} - 1}{2^{GCUR}} \tag{3}$$

$$I = \frac{Gr - Gr_{min}}{Gr_{max} - Gr_{min}} \; I = \frac{Gr - Gr_{min}}{Gr_{max} - Gr_{min}} \tag{4}$$

In the formula:

Cs ——Compressive strength, MPa;

V_{sh} ——Mud content, %;

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Kd ——Drillability level value, dimensionless;

Tp ——Longitudinal wave time difference, $\mu s / m$;

Gr ——Gamma ray, cps;

I ——Intermediate variable;

Gr_{min} ——The GR value of pure rock interval, cps;

Gr_{max} ——The GR value of pure mudstone section, cps.

$GCUR$ ——Empirical parameters. 3.7 is often taken for new strata and 2 for old strata;

2.3 Calculation model of transverse distribution of formation rock

According to the rock anti-drilling strength parameter profile of multiple reference wells in the same block and the corresponding wellbore trajectory and position coordinates, the lateral three-dimensional variation law of rock strength under different well depth conditions in the block is fitted and analyzed. Here, the cubic surface is used to realize the mathematical model of [6,10-13] by power basis function fitting method :

$$f(x,y) = a_1 + a_2 x + a_3 y + a_4 x^2 + a_5 xy + a_6 y^2 + \cdots$$
$$a_7 x^3 + a_8 x^2 y + a_9 xy^2 + a_{10} y^3$$

In the formula:

$a_1, a_2, \cdots\cdots, a_n$ ——Undetermined coefficient vector.

$a_1, a_2, \cdots\cdots, a_n$ are based on solving general linear equations. It is convenient to calculate the exact solution by using Matlab and other engineering calculation software.

The sampling data (mechanical strength value) and the fitting surface corresponding to the ' value of the difference between the square sum of the minimum ' as the general principle of equation coefficient calculation, expand into a linear transformation of linear equations, then there are:

$$\begin{cases} a_1 \sum_{i=1}^{N} b_i^1 b_i^1 + a_2 \sum_{i=1}^{N} b_i^1 b_i^2 + \cdots\cdots + a_n \sum_{i=1}^{N} b_i^1 b_i^n = \sum_{i=1}^{N} b_i^1 z_i \\ a_1 \sum_{i=1}^{N} b_i^2 b_i^1 + a_2 \sum_{i=1}^{N} b_i^2 b_i^2 + \cdots\cdots + a_n \sum_{i=1}^{N} b_i^1 b_i^n = \sum_{i=1}^{N} b_i^2 z_i \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ a_1 \sum_{i=1}^{N} b_i^n b_i^1 + a_2 \sum_{i=1}^{N} b_i^n b_i^2 + \cdots\cdots + a_n \sum_{i=1}^{N} b_i^n b_i^n = \sum_{i=1}^{N} b_i^n z_i \end{cases}$$

In the formula:

z_i ——The anti-drilling characteristic parameter value at the sampling position i ;

$b_i^1 \cdots\cdots b_i^n$ ——A set of bases of the space of polynomial of degree n.

3. Analysis of rock anti-drilling characteristics of Permian strata in Shapai block

3.1 Analysis of anti-drilling characteristics of single well formation rock

According to the prediction model of Permian rock anti-drilling parameters in Shapai block, combined with the drilling data and logging data[14-16], the anti-drilling characteristics of Permian formation rocks were analyzed for the specific well Shapai Ep well, and the formation anti-drilling

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characteristics profile was established, as shown in Figure.5 and Table 2.

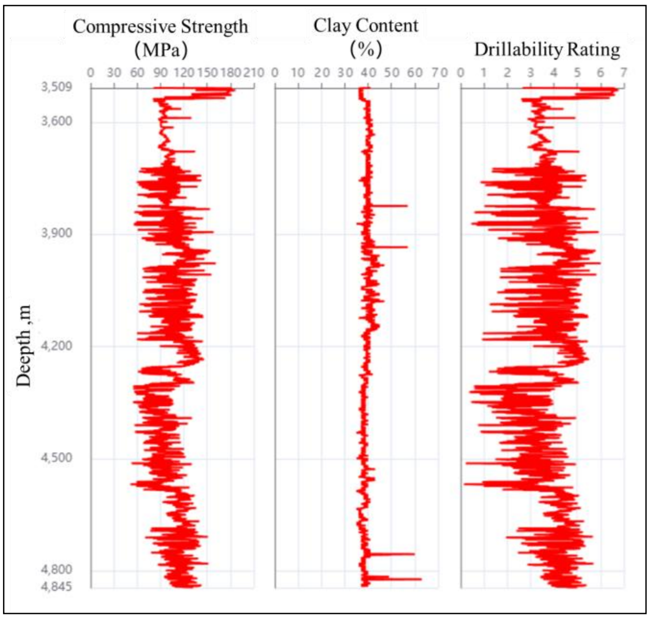

Figure 5: The anti-drilling characteristic profile of Permian formation rock in Shapai Ep well

Table 2: Statistical table of rock anti-drilling characteristics of Permian strata in Well Shapai 12, Qinshan Oilfield

section /m	horizon	Anti-drilling characteristics / minimum to maximum (mean)		
		Cs (MPa)	V_{sh}	Kd
4358~4552	upper-wuhehegroup	51.93~130.39 (90.37)	0.35~0.43 (0.38)	3.2~7.07 (4.45)
		lithological description		
		It is interbedded with mudstone, fine sandstone and glutenite, and the color is mainly brown and gray.		
4552~4687	Wind City Group	51.3~139.67 (108.92)	0.35~0.43 (0.38)	4.5~7.55 (5.73)
		It is mainly mudstone and fine sandstone, and the color is mainly brown gray and gray.		
4687~4848	Jiamuhe Formation	70.18~152.75 (114.6)	0.36~0.63 (0.39)	2.78~8.19 (6.19)
		It is mainly mudstone and fine sandstone, and the color is mainly brown gray and gray.		

In general, the Permian strata of Shapai Ep well belong to medium-hard strata, which have the characteristics of strong heterogeneity, significant soft-hard interlacing, high rock strength and poor drillability[17-19].

3.2 Prediction of lateral distribution of Permian strata

In order to further explore the lateral distribution law of anti-drilling characteristics of formation rock, each reference well in Shapai block of western Oilfield was selected as the analysis object. According to the rock strength parameter profile of multiple reference wells and their corresponding well depth trajectory and position coordinates, the lateral three-dimensional variation law of rock strength under Permian formation conditions in this block was fitted, analyzed and predicted, and then the lateral distribution trend of formation rock mechanical strength was obtained.

Taking Shapai Ep well as a reference, the upper strata of the Upper Wuerhe Formation (well depth of about 4500 m) are mainly mudstone and sandy mudstone, with gravelly argillaceous fine sandstone and medium-coarse sandstone. The lithology is complex and the soft and hard alternation is frequent. The wellhead coordinate data in Table 3 and the rock mechanical strength data of the reference well under the condition of 4500 m well depth are brought into the established analysis model of the lateral distribution law of rock strength, and the variation trend of the lateral distribution of rock strength in the Permian strata can be predicted.

Table 3: Reference well information of Shapai block

serial number	well number	Wellhead relative coordinates/m			Analysis of well section /m
		Abscissa X	Ordinate Y	Wellhead altitude /m	
1	Shapai 3			440	12~4983
2	Shapai 5			39.4	37~4641
3	Shapai 6			56	10~5416
4	Shapai 7			440	471~4985
5	Shapai 8	/	/	440	458~5958
6	Shapai 9			80	261~5600
7	Shapai 11			440	490~5446
8	Shapai 14			440	26~4529
9	Shapai Ep			440	10~4848

Figure.6, Figure.7 and Figure.8 represent the three-dimensional distribution trend map of Permian strata under the condition of 4500 m well depth. In the figure, the X coordinate is in the east-west direction, the Y coordinate is in the north-south direction, and the longitudinal coordinates are the variation trends of compressive strength (MPa), shale content and PDC bit drillability grade.

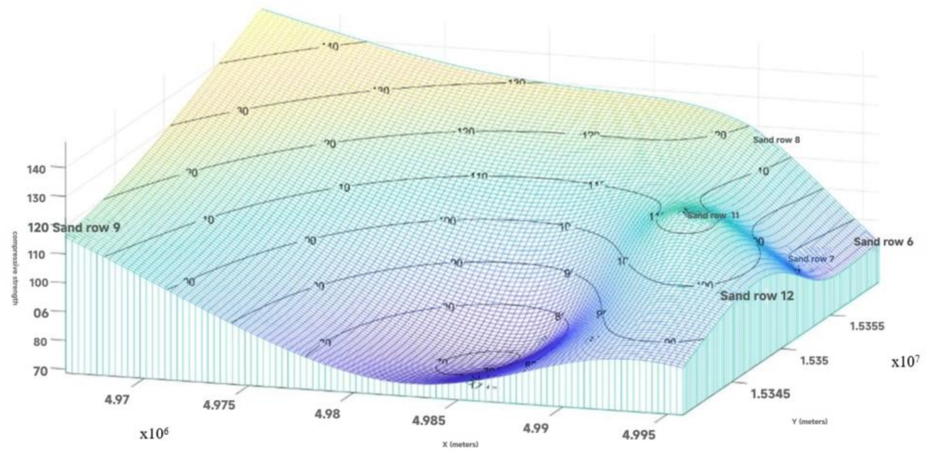

Figure 6: Horizontal gradient distribution of compressive strength of target layer

It can be seen from the above figure that the overall trend is that the deep strata gradually increase from southeast to northwest, but the values in the vicinity of Shapai 5 well and Shapai 7 well show a local downward trend, and the values in the vicinity of Shapai 11 well show a local upward trend. The minimum value of compressive strength in Shapai 5 well area is about 73 MPa, and the maximum value in the northwest direction can reach 135 MPa.

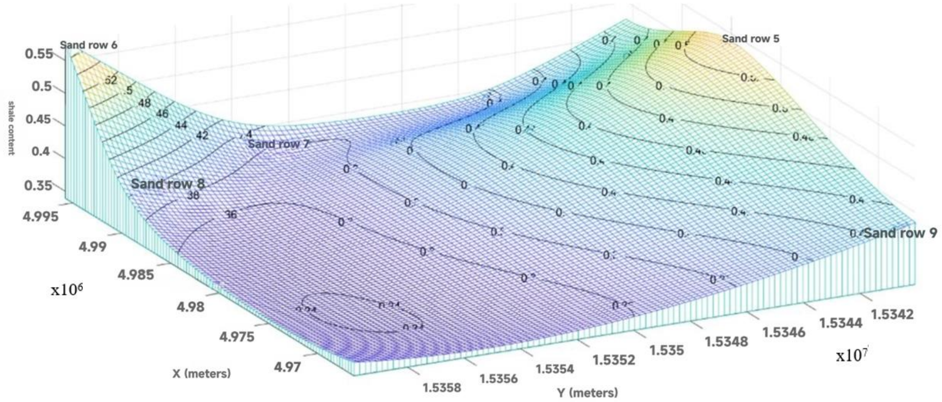

Figure 7: Horizontal gradient distribution of shale content in target horizon

The overall trend of the shale content in the above figure is gradually increasing from north to south, but the grade point is located in the Shapai 6 well area in the northwest corner, and the maximum value is about 0.56. In addition, there is also a local maximum value of about 0.45 near Shapai 5 well, which shows a downward trend from Shapai 5 well to the east and west, and the minimum value in the region can reach 0.36.

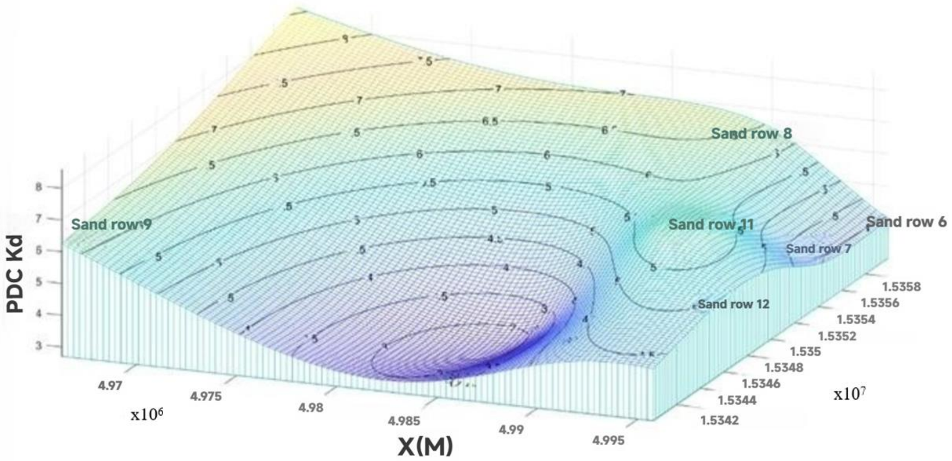

Figure 8: Horizontal gradient distribution of target layer drillability grade value

The change trend of drillability grade value in the above diagram is generally equivalent to that of compressive strength. There are local minimum values in the area near Shapai 5 well and Shapai 7 well, which are 3.2 and 4.5 respectively. In Shapai 11 well, the local maximum value is about 6.3, and the global maximum value in the northwest direction can reach more than 8 levels.

4. Conclusions

(1) Logging data contains abundant parameters of formation rock anti-drilling characteristics. The analysis model is established by carrying out indoor unit experiments, and the equal section curves of single well formation compressive strength, shale content and drillability grade are calculated. Based on this, a technical means for analyzing the variation trend of lateral rock anti-drilling characteristics in deep formation based on reference wells in the region is formed, which can provide an intuitive reference for drilling engineering operations such as bit selection and drilling parameter optimization.

(2) With the increase of well depth, the compressive strength parameters of the Permian strata in the Shapai area of the Junggar Basin change sharply, fluctuating frequently from 51 MPa to 153 MPa, and the change trend of interlayer strength is very obvious. The argillaceous content is mainly distributed between 35 % and 40 %. Two groups of high argillaceous strata appear in the well section below 5000 meters, and the content can reach more than 60 %. The change of drillability grade is also very sharp, and the overall trend is on the rise with the increase of well depth. In the shallow strata below 4400 meters, the overall fluctuation is between grade 2 and grade 4, and in the deep strata below 4400 meters, the overall fluctuation is between grade 4 and grade 8, especially the fluctuation trend of the strata below 4760 is very obvious.

(3) In the analysis of the lateral variation trend of formation anti-drilling characteristics at a depth of 4500 meters, it can be seen that the overall trend of compressive strength is that the deep formation gradually increases from southeast to northwest, but the value in the Shapai 11 well area shows a local increase trend, and the maximum value in the northwest direction can climb to 135 MPa. The overall trend of mud content is gradually increasing from north to south, and the local maximum value in Shapai 6 well area is about 0.56, and it shows a downward trend from Shapai 5 well to the east and west. The change trend of drillability grade is generally equivalent to that of compressive strength. The local maximum value in Shapai 11 well is about 6.3, and the global maximum value in the northwest direction can reach more than 8.

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