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Characteristics of rock mechanics and PDC bit optimization of glutenite formation in the Pearl River Mouth Basin oilfields

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Abstract. In order to increase the Rate Of Penetration (ROP) in the glutenite formation of the Pearl River Mouth Basin (PRMB) oilfield, the mineral components of drilling detritus were tested, and laboratory tests of Uniaxial Compressive Strength (UCS), drillability and abrasivity were undertaken. Prediction models of the rock mechanical properties of the glutenite formation with logging data were established. An abrasivity test was done using a modified rock drillability tester with micro Polycrystal Diamond Compact (PDC) bits. The bits used in the glutenite formation were discussed to find out the reason for the low ROP. According to the properties of the rock mechanics and the bit applications of adjacent wells, structures, such as tooth type, crown profile, tooth assembly parameters and the hydraulic structure of selected bits, were optimized. A new tiger tooth and an anticollision tooth for the optimized PDC bit were developed to increase shock and wear resistance in glutenite formation. Compared with conventional bits used in glutenite formation, the optimized bit raised footage and ROP by 131% and 48%, respectively. The new method, combined with the properties of rock mechanics, bit application and bit structure, is simple and effective to guide the bit design for glutenite formation.

1. Introduction

Glutenite formation is usually encountered in the oil and gas drilling industry. Pebbles in glutenite formation are very hard with non-homogeneous distribution, and the interbedded strata, which are high in heterogeneity and abrasiveness, are commonly found in glutenite formation. All the aspects lead to low ROP in the drilling process. The poor shock resistance of conventional PDC bits limits their application in complex glutenite formation. Tricone bits have been used in glutenite formation for some length of time, but cannot meet the severe demands of the drilling cycle and the cost of offshore drilling. Seen from the drilling data, from 2008-2009, of the PRMB oilfield in the South China Sea, the average ROP dropped by 50% and even up to 80% in glutenite formation, and the bits were seriously damaged by tooth cracking and breakage, which caused low drilling efficiency. With the improvement in compact materials, bit structures and processing techniques, it is possible to drill glutenite formation using PDC bits with high efficiency. In recent years, domestic and foreign scholars have undertaken many studies on the interaction between PDC bits and glutenite formation [1-3]. They also designed special structures of PDC bits for glutenite formation, but studies were limited to lithology formation and

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bit structure. For glutenite formation in the PRMB oilfield, it is important to study the properties of rock mechanics and drilling practice to improve structures for selected PDC bits, such as tooth type, tooth exposure height, crown profile and hydraulic structure. The final goal is to establish a general optimization method of PDC bit structures, in order to raise efficiency and cut down the cost in time and money when PDC bits drill in glutenite formation.

2. Rock mechanical properties of glutenite formation

The PRMB is one of the main four basins of the Western South China Sea (Figure 1). It is a Cenozoic sedimentary basin in the condition of shallow sea, bathyal continental shelf and aktian. Its geographical coordinates are about 105° to 122° longitude east and 16° to 25° latitude north. From the Tertiary period, this basin has experienced rift and sag evolution stages. It has a "west-east differentiation and north-south dissimilitude" tectonic framework, and sedimentary characteristics of initial terrestrial deposition and, later, marine deposition. The northern uplift of the PRMB (Hainan uplift) was generated by a glided fracture zone during the extension of the continental shelf, and the southern sag (Zhu II depression) is a subsidence zone brought about by fracture glided activity [4].

In this paper, the drilling data of drilled wells shown in PRMB (Figure 1) were studied. The lithological column and sections related to different formations of the PRMB were obtained by seismic and logging

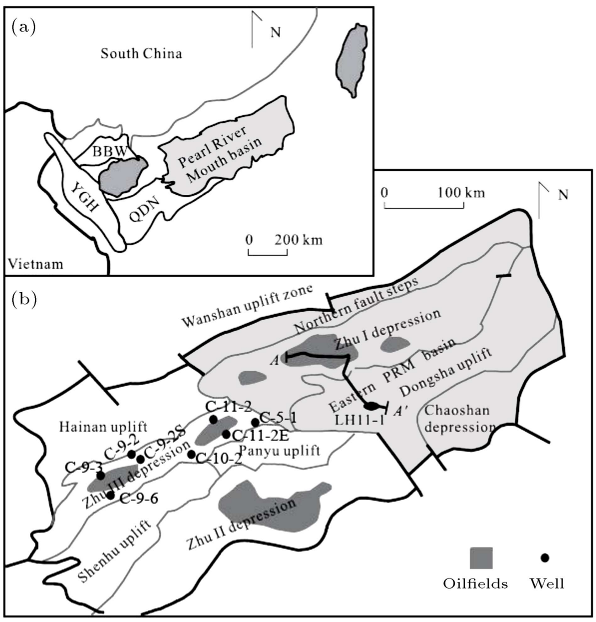

Figure 1. Geological map and locations of the PRMB, including the study oilfields.

data of 16 wells (Table 1). The ROP of Paleogene formation is, respectively, lower than Neogene formation, so, this formation is studied in this paper.

2.1. Rock mechanics experiments

An X-ray diffractometer (D/MAX 2500) was used to test the mineral components of the detritus [5]. The results of 9 wells in the PRMB oilfield showed that there are 31.2% to 62.5% quartz and 18.3% to 38.6% clay minerals in the glutenite formation (Table 2). The Z-formation (including the Z-1st section, Z-2nd section and Z-3rd section) and the E-formation both belong to sandstone. The proportion of siderite in the Z-1st section is 5.7%, and is up to 18% in the Z-2nd section. From logging data of 26 wells, the formation is sandstone and mudstone-sandstone interbedded strata and the percentage of $\Phi 2-7$ mm pebble is over 6%. The formation is compacted and frequently changed in lithology:

(1) 53 rock samples from 3341 to 3986 m of the Z-formation in the PRMB oilfield were prepared in standard cylinders whose diameters were 38 mm, and whose slenderness ratios were 1.8 to 2.0 (GB/T50 266-99) [6]. Their strength was measured by UCS and triaxial tests (Table 3).

    The results show that the Z-formation is medium to hard strength formation, but its strength increases rapidly under confining pressure; every 15 MPa increase of the confining pressure caused the collapsing strength to increase by 2 to 3 times. The strength of medium sandstone is just half of fine sandstone.

(2) The $\phi 38$ mm cores are too small to test, so, they are wrapped with impermeable materials and put in the middle of the 100 mm × 100 mm cement samples. The end face of the cement is polished. Samples are tested following the industrial standard (SY/T 5426-2000) (Table 4). The drillability value of PRMB is 4.6 to 6.44, which means that the formation is soft and easy to drill.

(3) Rock abrasiveness is studied mostly by laboratory experiments that do not have a single uniform method. The test equipment usually includes a modified drill press [7], cutting rig [8], planer [9] and milling machine [10]. These pieces of equipment are huge, hard to operate, complex to modify, difficult to move and expensive. A simpler piece of equipment, modified from a rock drillability tester, is introduced. The micro PDC bit is used to break the rock while the water is applied to cool the bit and flush cuttings to simulate the actual conditions of a bottom hole. The diameter of the PDC bit is 32 mm. The diameter of the diamond compact is 13.32 mm,

Table 1. Lithological column, sections and ROP of the PRMB.

Formation age	Formation	Section	Lithology	Thickness (m)	Rop (m/h)
Neogene	Aoh	/	Mainly mudstone with minor sand appearances	70-1220	30-60
	Hanj	/	A make up of sand, mudstone and glutenite	117-628	32-58
	Zhuj	/	A make up of sand and mudstone	560-1336	30.5
Paleogene	Zhuh	Z-1st	Mainly mudstone with minor sand appearances	257-909	10.6
		Z-2nd	34% mudstone; 60% sandstone; 6% glutenite	227-418	8.2
		Z-3rd	48% mudstone; 42% sandstone; 10% glutenite	86-466	6.8
	Enp	/	Sand and mudstone of varying thickness.	53-121	5.7

Table 2. Mineral components of the detritus.

Well	Depth (m)	Section	Kinds of mineral and content (%)							Clay Mineral (%)
			Quartz	K-feldspar	Plagioclase	Calcite	Dolomite	Siderite	Noncrystalline	
C-10-2	3348	Z-1st	48.5	5.7	/	8.3	13.6	5.7	/	18.2
C-11-2	3571	Z-2nd	31.2	2.4	4	15	/	18	/	28.2
C-9-2	3986	Z-2nd	60.5	8.8	7.2	2.7	/	/	/	20.8
C-11-2	4026	Z-3rd	62.5	5.5	3.1	/	4	/	/	24.1
C-11-2	4224	Z-3rd	67	/	7.8	/	6.9	/	/	18.3
C-11-2	4374	E-formation	31	0.7	4.7	/	/	/	21.1	41.2
C-11-2	4424	E-formation	63.6	3.4	9	/	2.6	/	/	20.2
C-11-2	4474	E-formation	51.2	1.4	9.4	1.9	/	/	/	34.7
C-11-2	4524	E-formation	30.3	/	3.1	/	/	/	26.5	38.6

Table 3. Some results of rock compressive strength test.

Well	Depth (m)	Section	Confining pressure (MPa)	Collapsing strength (MPa)	Elasticity modulus (MPa)	Lithological character
C-11-2	3570.7	Z-2nd	0	33.656	14.691	Pelitic siltstone
	3570.7	Z-2nd	30	227.302	19.815	Pelitic siltstone
C-10-2	3347.8	Z-1st	0	23.019	5.212	Medium sandstone
	3347.8	Z-1st	30	178.055	15.587	Medium sandstone
C-9-2	3985.9	Z-2nd	0	58.769	10.347	Glutenite
	39859	Z-2nd	15	161.203	15.2671	Glutenite
	3985.9	Z-2nd	30	293.607	21.7358	Glutenite

Table 4. Some results of rock drillability experiment.

Item	Well	Depth (m)	Section	Lithological character	Average drilling time (s)	Drillability
1	C-9-2	3784.7	Z-2nd	Glutenite	49.5	5.63
2		3785.5	Z-2nd	Glutenite	28.5	4.83
3		3785.5	Z-2nd	Glutenite	30.22	4.92
4	C-10-2	3341.5	Z-1st	Medium sandstone	27.17	4.76
5		3341.5	Z-1st	Medium sandstone	24.31	4.6
6		3348.7	Z-1st	Medium sandstone	24.18	4.65
7		3348.7	Z-1st	Medium sandstone	25.76	4.69

its thickness is 4.5 mm, its back dip and side rake angles are 20° and 15°, respectively. This new method is easy to carry out. The axis load is 1KN, rotary speed is 200 rpm and it takes 30 min for each test. Rock abrasivity is calculated by the following expression:

$$w = \frac{\Delta W}{\Delta V}, \tag{1}$$

where w is rock abrasivity, mg/cm^3; ΔW is the wear weight loss of the bit teeth, mg; ΔV is the rock breaking volume, cm^3. The rock abrasivity classification is presented in Table 5.

When the test is finished, the rock breaking volume and wear weight loss of the bit teeth are measured by a precision balance of 0.1 mg (Table 6). In Z-formation, the abrasivity of sandstone is low, but pebbled sandstone and fine sandstone are high. The abrasivity of sandstone is related to particle size and pebble content.

2.2. Prediction models of rock mechanics parameters by logging data

Experiments can only test the specific location properties of the glutenite formation. To obtain the rock mechanical parameters of the entire formation, logging data is the critical element to establish prediction models. Testing results as follows are used to calibrate the coefficients of the prediction models [11-14]:

(1) Deer and Miller tested a great number of various petrological rock types, which resulted in a relationship between the rock dynamics elastic modulus, shale content of sandstone and UCS [15]. The best-fit approximation for UCS is expressed as:

$$\sigma_c = 0.0045.E_d\,(1 - V_{cl}) + 0.008E_d.V_{cl}, \tag{2}$$

where σ_c is the UCS, E_d is the dynamic Young's modulus of sandstone, and V_{cl} is the shale content of sandstone. In this study, the coefficients, "0.0045" and "0.008", are replaced as two unknown constants, "A_1" and "A_2", respectively. According to the results of the rock compressive strength test, the two unknown constants are recalculated to minimize the prediction error of the model, which is 5.6%.

(2) The sonic travel time calculation method, which is a common method used for rock drillability prediction in recent years, is not suitable for the hard or non sand shale interbed formation [16-18]. Spaar et al. used formation compressive strength to predict the PDC bit drillability, and select the best PDC bit [19]. Laboratory experiments show that compressive strength changes frequently in glutenite formation, and the prediction error of the Spaar et al. model is above 9%. Jim and Osarumwense calculated formation strength and drillability from porosity, sonic travel time, degree of compaction, abrasiveness and hole clean requirements [20]. The Jim and Osarumwense model agrees with the complex formation well, however, it is very difficult to use for multi-variates. In this study, shale content, rock density and sonic travel time are used together to predict the drillability of glutenite formation. The multi-parameters prediction model is expressed as:

$$k_d = b_0 + b_1 \ln \Delta T + b_2 \ln \rho + b_3 \ln V_{cl}, \tag{3}$$

where k_d is the drillability, ΔT is the sonic travel time, ρ is rock density, and b_0, b_1, b_2 and b_3 are empirical coefficients. The prediction error of the model for sandstone is 3.69%, and 2.44% for mudstone, which are better than the single parameter

Table 5. Rock abrasiveness classification.

Grade	1	2	3	4	5	6	7
w	< 0.3	0.3-0.65	0.65-1.0	1.0-1.8	1.8-4.5	4.5-6.0	≥ 6.0
Classification	Low	Low-medium	Medium	Medium-high	High	Very high	Extremely high

Table 6. Some results of abrasivity test.

Item	**Well**	**Depth (m)**	**Lithological character**	**Section**	**Internal frictional angle (°)**	**Abrasivity (mg/cm^3)**
1	C-10-2	3348	Medium sandstone	Z-1st	42.51	0.94
2	C-9-2	3986	Pebbled fine sandstone	Z-2nd	50.66	2.38
3	C-11-2	4026	Medium sandstone	Z-3rd	40.80	1.83
4	C-11-2	4224	Pebbled medium sandstone	Z-3rd	36.66	2.13
5	C-11-2	4424	Fine sandstone	E-formation	36.93	2.54
6	C-11-2	4474	Pelitic siltstone	E-formation	25.13	1.00

Table 7. Rock drillability prediction models and their errors.

Item	Lithology	Average test Value	$k_d=b_0+b_1 \ln \Delta T$		$k_d=b_0+b_2 \ln \rho$		$k_d=b_0+b_3 \ln V_{cl}$		$k_d=b_0+b_1 \ln \Delta T +b_2 \ln \rho+b_3 \ln V_{cl}$	
			Prediction	Error %	Prediction	Error %	Prediction	Error %	Prediction	Error %
1	Glutenite	5.63	5.92	5.15	6.28	11.55	6.10	8.35	5.82	3.37
2-3	Glutenite	4.88	5.20	6.56	5.34	9.43	5.17	5.94	5.03	3.07
4-5	Medium sandstone	4.68	5.01	7.05	5.13	9.62	5.12	9.40	4.89	4.49
6-7	Medium sandstone	4.67	5.03	7.71	5.11	9.42	5.12	9.64	4.87	4.28

prediction model and the models discussed above (Table 7).

(3) The abrasiveness values of many different rocks have been tested under different experimental methods in recent years [16-20]. However, these studies can only show the abrasiveness values of special rocks, the abrasiveness of the formation is still unknown. Ersoy et al. [8] used two types of circular diamond to cut a variety of ten types of rock and established a wear rate prediction model of the circular diamond saw with 19 variables, but the variables were either the energy parameters or the rock mechanics parameters, which cannot correlate with the logging data to establish the rock abrasiveness profile of the formation [8]. Considering the influences of sonic travel time, drillability, UCS and the internal frictional angle, Zhu et al. established a rock abrasiveness model [21], which can be expressed as:

$$w = ae^{b\Delta T}K_d^c\sigma_c^d\varphi^e, \tag{4}$$

where w is rock abrasiveness, φ is internal frictional angle, and a, b, c, d and e are empirical coefficients. K_d, σ_c and φ are calculated from the logging data.

Multi-variable linear regression analysis was carried out to determine the relationships between ΔT, K_d, σ_c and φ for the glutenite formation, using MATLAB software. The multivariable regression coefficient (R^2), standard deviation (S) and statistic test value (F) for the full model are calculated as shown in Table 8. The best correlation exists between ΔT and φ, with $R^2 = 0.99889$, $S = 0.02632$and $F = 7682.33$, and its empirical coefficients $a = 1.10026e-4$, $b = 1.42033$ and $e = 0.13066$. So, the prediction model can be expressed as:

$$w = 0.581e^{-0.0885\Delta T}\varphi^{0.131}. \tag{5}$$

Compared with the Kong [22] and the Shi Models [23], the prediction error of our model is the minimum, which is 3.54% (Table 9).

Table 8. Summary statistics for model.

Model	R^2	S	F
ΔT	0.99747	0.03985	6696.15
K_d	0.1012	0.7991	1.6889
σ_c	0.48567	0.60454	14.1639
φ	0.51308	0.58821	15.806
ΔT, K_d	0.99771	0.03785	3712.15
ΔT, σ_c	0.99739	0.04085	3187.11
ΔT, φ	0.99889	0.02632	7682.33
K_d, σ_c	0.50933	0.61119	7.26629
K_d, φ	0.76715	0.42103	23.0629
σ_c, φ	0.75098	0.43541	21.1111
ΔT, K_d, σ_c	0.99759	0.03885	2349.65
ΔT, K_d, φ	0.99891	0.02611	5206.85
K_d, σ_c, φ	0.87747	0.31695	71.0331
ΔT, σ_c, φ	0.99884	0.027	4867.7
ΔT, K_d, σ_c, φ	0.9989	0.02625	3863.79

2.3. Discussion

Rock mechanics property profiles in the glutenite formation of the 26 wells are established using the prediction models. The UCS of the Z- and E-formations is mainly 50 to 120 MPa (some of the interbedded glutenite is higher than 180 MPa), the drillability value is 4 to 7.3 with an average of 5.6, and their abrasiveness is 2-8 m, which is much higher than the mudstone, which shows that they are easy to drill. However, the bit is easy to damage. According to the international classification standards of the PDC bit, the PDC bit performs well in these rock characteristic formations.

Drilling data of 26 wells from 2006 to 2009 (Figure 2) are analyzed. (1) Eleven PDC bits and one cone bit were used in the Z-2nd section. The trip up for low ROP was 37%. PDC bits of 5, 6 and 7 blades with seriously worn Φ16 mm teeth, 6 blades with Φ16 mm teeth, and 5 blades with Φ19 mm teeth, performed better. Bit abrasion, teeth cracking, teeth breakage all happened seriously on the outer-row teeth, which showed that the life and shock resistance

Table 9. Rock abrasiveness prediction models and their errors.

Item	Test value	Our model	Our error (%)	Kong's model	Kong's error (%)	Shi's model	Kong's error (%)
1	0.94	0.96	1.81	1.37	45.64	0.78	-17.23
2	2.38	2.36	-0.80	2.90	21.81	3.41	43.07
3	1.83	1.80	-1.86	2.59	41.42	1.81	-0.98
4	2.13	2.10	-1.36	3.25	52.77	2.20	3.38
5	2.54	2.63	3.54	2.75	8.27	2.82	11.02
6	1.00	0.97	-3.00	1.07	7.00	1.23	23.00

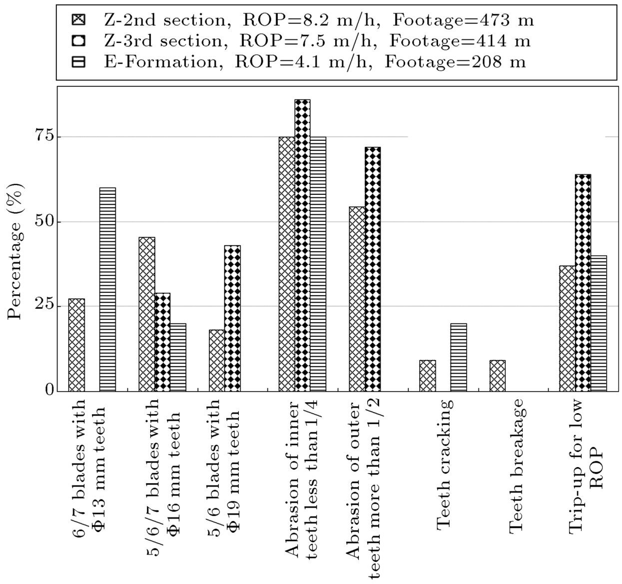

Figure 2. Practical applications of PDC bits in PRMB.

of the bit teeth should be strengthened. (2) Seven PDC bits and one cone bit were used in the Z-3rd section. The outer- and inner-row teeth were seriously broken, especially the outer-row teeth, which caused 64% of the total trips. For PDC bits, 6 blades with Φ16 mm teeth and 5 blades with Φ19 mm teeth also worked well. (3) Four PDC bits and two cone bits were used in the Enping formation, and the trips for low ROP was 43%. The average footage of the PDC bit was 460.2 m, the average ROP was 8.68 m/h and the average drilling cost per meter was 33100 Yuan in the glutenite formation, while, for the cone bit, the average footage was 179.78 m, the average ROP was 2.66 m/h and the average drilling cost per meter was 38400 Yuan. The footage and ROP of the PDC bit were both higher than the cone bit, and the drilling cost per meter of the PDC bit was lower. It is obvious that the PDC bit worked better than the cone bit, so, the PDC bit can be used in this glutenite formation. However, in this glutenite formation, different sizes and shapes of gravel damaged the top and the nose of the PDC bit or even caused the blades to fracture. So, teeth breakage, cracking, fatigue and offset happen seriously, which leads to the early damage of the PDC bit.

Taking the 2970 m-3200 m glutenite formation of the C-9-2S-1 well, for example, its lithology is light gray gritty coarse sandstone, glutenite, oil traced fine sandstone, oil traced glutenite, fine sandstone and interbedded mudstone. The UCS, drillability and abrasiveness of this glutenite formation are calculated by its logging data (Figure 3). The UCS is 50-150 MPa, with an average of 95 MPa, which is medium to hard. Rock drillability is 4-7.2, with an average of 5.34, which is soft to be drilled. Rock abrasiveness is 0.1-4.66, with an average of 1.88, and the proportion of the formation whose abrasiveness is above 1.8 is 50.18%, that is to say, the abrasiveness of this glutenite formationis high. This formation is drilled for 34.795 hours by a single 8-1/2″ PDC bit, so, the ROP is 6.67 m/h. The bit wear evaluation is 2-4-WT-A-X-1/8-BT-PR. The abrasions of the outer and inner row teeth were 50% and 25%, respectively. The gauge row was worn out,an 8 mm bench face was created and the bit diameter was decreased by 3 mm (Figure 4). The bit wears out quickly, especially the teeth and the gauge protection part, which causes the bit trip out for low ROP.

3. PDC bit optimization of glutenite formation

The drilling cost per meter and structure parameter methods are combined to select the bit. Firstly, the drilling cost per meter method is applied to evaluate used bits [24]. Then, the structure parameter method is combined with rock mechanical properties to optimize the structure of the PDC bit [25]. Based on the rock mechanical properties, such as the compression strength, drillability and abrasiveness studied above, the selected bit IADC code is M424, whose tooth number is larger than 50. Tooth diameter is 14-24 mm and the crown profile is medium-parabola, designed by the equal wearing principle (Figure 5). The best bit structure (for example: the best blade shape and number, tooth arrangement and tooth characteristic) is further designed on the basis of the rock mechanical

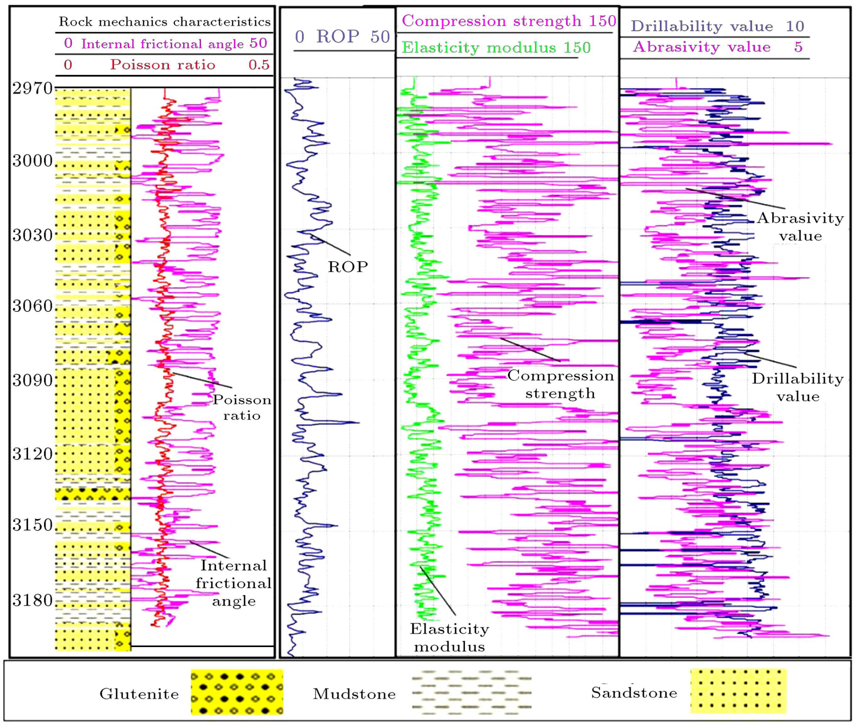

Figure 3. The rock mechanics of the C-9-2S-1 well.

Figure 4. The worn PDC bit.

properties and the bit practical applications of adjacent wells.

The drilling cost per meter method combined with the rock mechanical properties are used to determine the best structure of each section: the Z-2nd and Z-3rd sections choose 6 blades with Φ19 mm teeth to keep aggressiveness. At the same time, shock resistance and fatigue levels should be improved. The E-formation chooses 5 more powerful blades with Φ19 mm teeth. The main reason for low ROP in the PRMB oilfield is the early damage of the PDC bit. The critical way to solve this problem is to improve the shock and wear resistance of the bit, especially its heel cone. The following parts need to be considered:

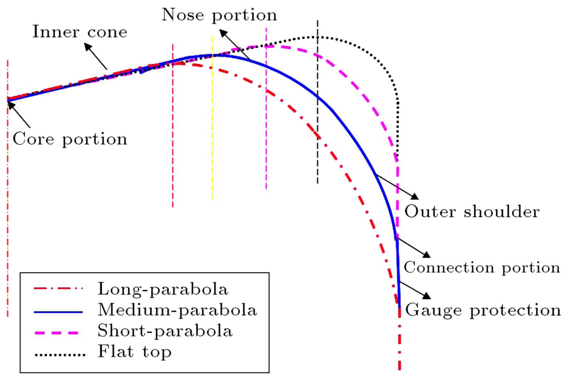

Figure 5. The crown profiles.

(1) Improve the shock and wear resistance of the tooth to fit the interbedded strata and glutenite formation;

(2) Optimize the crown profile to increase the tooth density of the heel cone;

(3) Design reasonable tooth assembly parameters and double row teeth to increase bit life;

(4) Use anticollision teeth for gauge protection and shock resistance;

(5) Optimize the hydraulic structure to avoid bit balling.

3.1. Development of a new Tiger tooth

For hard, abrasive and heterogeneous formation, Mensa-Wilmot et al. designed a specialized non-circular PDC cutter to enhance limestone pre-fracturing, so as to improve PDC bit performance [26]. However, when this kind of non-circular PDC cutter is used in glutenite formation, it could be easily crushed. Mensa-Wilmot et al. developed a new generation cutter to minimize its deterioration rate and avoid impact damage [27], and Clayton et al. used the Thermal Mechanical Integrity (TMI) technique to develop an advanced Z3 PDC cutter [28]. These cutters perform well in hard formation, however, for glutenite formation, their performance is still unknown. So, a new Tiger tooth for the PDC bit is developed for the glutenite formation (Figure 6). The latest pressure system raises the sintering pressure of the diamond powder to get more D-D chemical bonds, which switch the physical bond of the diamond powder to a chemical bond. This new method obviously improves the shock resistance and fatigue level of the Tiger PDC compact. The new formula of the compact and sintering process reduces the metal residue in the Tiger tooth, which is 20% less than the standard tooth, and which, therefore, improves its thermostability. The wear resistance of the two types of teeth was tested on ab abrasion tester (Figure 7). Alkaloid soap lye was used to cool the teeth. After testing 50 times, we found that:

(1) The wear loss of the Tiger tooth is 50% less than the standard tooth, while they all broke the same volume of rock (Figure 8).

(2) In order to get the same cutting speed in the later period of tests, the WOB on the Tiger tooth is 50% less than the standard tooth, which shows that the Tiger tooth could keep sharp for a longer time (Figure 9). The wear resistance of the Tiger tooth is equal to or better than the standard tooth after 50 passes on the wet test.

The impact strength of the teeth is tested by a drop weight impact tester. Each cutter receives a maximum of 10 hits. After each hit, the cutter is inspected for spalling. If the spallation area is greater than 30% on the cutter, the test is stopped (Figure 10). The breaking rate of the Tiger teeth is 27% lower than for standard teeth. The wearlessness (life) of the Tiger tooth is increased by 50% without a decrease in shock resistance.

Figure 6. The Tiger tooth and the standard tooth.

Figure 7. Abrasion tester of octagon granite.

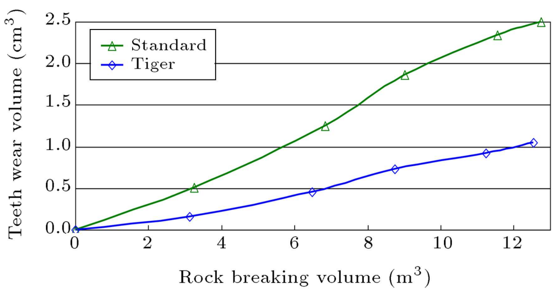

Figure 8. The teeth wear volume and rock breaking volume.

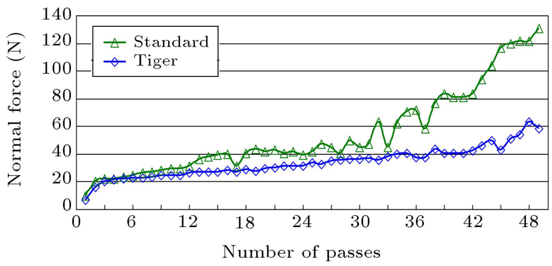

Figure 9. Normal force at the same cutting speed.

3.2. Crown profile and tooth assembly parameters

For hard and high abrasivity glutenite formation, the crown curve is designed by the equal wearing principle:

$$h = \int \sqrt{\left(\frac{r}{r_s}\right)^2 - 1} dr + C, \qquad r \geq r_s, \tag{6}$$

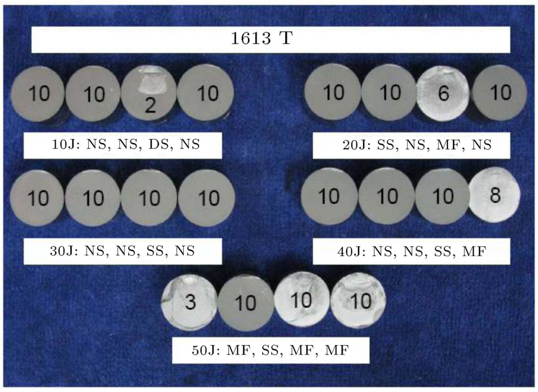

Figure 10. Results of the drop weight impact test.

where h is the axial distance of the cutter at r_s, r is the bit radius, r_s is the radial distance of the number of the cutter and C is the integral constant. The more the bit is suitable for hard formation, the bigger the r_s is, and that much shorter the crown heel cone is. Considering the complex formation characteristics in the PRMB oilfield, three long blades and three short blades are designed. The parabola length of the crown is 5% longer than the original. The Φ16 mm Tiger teeth are used to strengthen the wear resistance of the PDC bit. The strength of braze welding is increased by 19% and shear force is raised from 170 MPa to more than 200 MPa, using QAg-N welding material and special flux. At the same time, welding temperature is decreased from 710° to 680°. The lower temperature strengthens the fixing force of the tooth and the matrix structure, and reduces the risk of tooth loss. For the same welding strength, the welding area is decreased by 12%, and the tooth exposure height is increased by 15% to 65%. The back dip angle of the teeth on the bit shoulder is 3° bigger than the original, which strengthens the shock resistance of the bit shoulder. A two inch length of gauge protection surface is used to protect the bit diameter. Double row teeth are used to increase the teeth number of the bit and to decrease the rock breaking volume of a single tooth, in order to decrease the shock and wear of the teeth, and prolong the bit life. According to the equally cutting principle [29], the teeth radial distributing formula is:

$$R_{ci+1} = \frac{R_{ci}}{2} + \frac{1}{2}\sqrt{R_{ci}^2 + \frac{8r_0r_c}{f_d}},$$
$$(i = 1, 2, \cdots, N-1), \tag{7}$$

$$f_d \approx \frac{2(N-1)r_c}{L_c}, \tag{8}$$

$$\theta_{ci} = \frac{R_{ci} - R_{cl}}{R_{cN} - R_{cl}}\theta_s + \theta_m, \qquad i \in [1, N], \quad m \in [1, M], \tag{9}$$

where R_{ci}, R_{ci+1} are the radius of the No. i, $i+1$ the cutter center on the bit; r_0 is the radius of the bit crown; r_c is the radius of the cutter; f_d is the coefficient of the distributing density of the cutter; N is the number of cutters; L_c is the length of the crown circular arc; θ_{ci} is the circumferential angle of No. i cutter in No. m spiral line; θ_s is the polar angle remainder between the gauge cutter and the center cutter; θ_m is the starting polar angle of No. m spiral line; R_{cl}, R_{ci} and R_{cN} are the radius of the cutter center, No. i cutter and gauge cutter, respectively, on the surface of the bit; N is the number of cutters on the bit; M is the number of the spiral line for cutter distribution. The outer-rows of the long blade and the short blade are located with 11 and 7 Tiger teeth, respectively, and all the inner-rows are located with 4 Tiger teeth (Figure 11). PDC bit safety was checked under these conditions by finite element analysis.

3.3. Anticollision teeth

The anticollision teeth are sphere teeth made by impregnated diamond. Three anticollision teeth are located on the inner-row end of each long blade, and restrict the cutting depth of the Tiger teeth, decrease vibration and resist the whirl of the bit (Figure 12). An anticollision tooth is arranged on each blade of the gauge protection surface to protect the bit diameter.

3.4. Hydraulic structure

There is a nozzle at the front of each blade and a nozzle between the adjacent long and short blades. With the

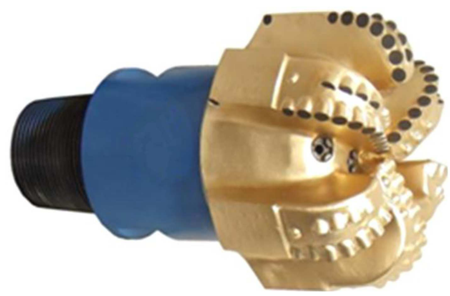

Figure 11. The new PDC bit.

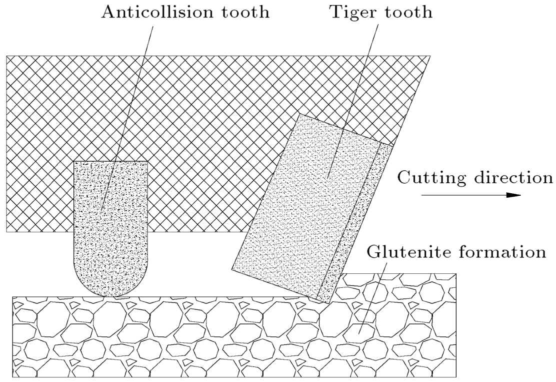

Figure 12. Working principle of the anticollision teeth.

help of CFD simulation software, the flow field of the bottom hole is improved in two ways:

(1) The redundant sectional area of the junk slot is decreased; flow speed is raised by 36%, which improves its cutting transportation and cooling capability.

(2) A certainty is achieved in making sure that the flow speed and direction on the front side of the blade are helpful in transporting cuttings and cooling the teeth.

4. New PDC bit application

The new PDC bit was used in Z-formation of a C-14-2 well on Feb 2nd, 2011, which was driven by the top driver system with the suggested drilling parameter. The rotary speed was 97.2 rpm, the WOB was 4.03 ton and the displacement of the mud pump was 3182 liters per minute (l pm). The bit drilled the entire Z-formation from 1911 m to 2386 m. The footage was 495 m, the average ROP was 11.37 m/h, and drilling time was 42.87 hours. The 2139 to 2297 m interval is glutenite formation, whose pebble diameter is 2-7 mm (Figure 13). The interval of 2312 to 2386 m is also glutenite formation and the pebble diameter is 1-4 mm. The footage of a single bit rose by 131%, ROP rose by 82% and cost per meter was reduced by 28% compared with the adjacent C-14-3 well. The bit IADC wear evaluation was 1-2-WT-A-X-I-BU-TD. The new PDC bit performed very well in the C-14-2 well (Figure 14), and it can continue to do so.

Another new PDC bit was used in Z-2nd and Z-3rd glutenite formation of a C-9-3 well on Oct 19th, 2010. The pebble average diameter is 2-5 mm. The debris in these sections is subangular, poorly graded and well cemented. The average rotary speed was 108.7 rpm, the WOB was 5.2 ton, the displacement of the mud pump was 2156 lpm and the mud density was 1.294 g/cm^3. The bit drilled from 2832 m to 3259.5 m, with footage of 427.5 m, drilling time of 34.62 hours and average ROP of 13.9 m/h. The footage of C-9-3 rose by 166%, ROP rose by 68% and cost per meter was reduced by 33% compared with the adjacent C-9-1 well. The bit IADC wear evaluation was 1-3-WT-A-X-I-NO-TD. The new bit performs well and a single one could penetrate this glutenite formation.

Figure 13. Rock debris and pebbles.

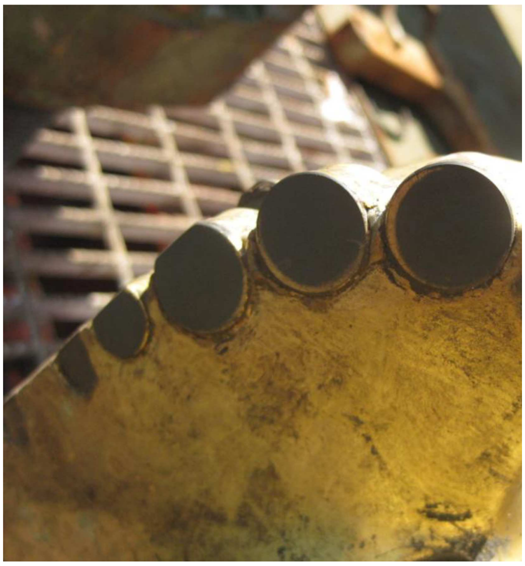

Figure 14. The used new PDC bit.

5. Conclusion

In glutenite formation, the UCS is 50-180MPa with an average of 93 MPa, rock drillability is 4-7.3 with an average of 5.6, and rock abrasiveness is 0.1-8 with an average of 2.2, which show that the formation is hard and brittle, easy to drill, and highly abrasive. A new PDC bit was developed especially for drilling in glutenite formation, and a new bit design theory was presented considering the properties of the rock mechanics, bit applications and bit structure optimization. The shock resistance and wearlessness of the new Tiger tooth are both increased by 50%, and the tooth exposure height of the new bit is increased to 65%, which ensure bit life and bring about the greater aggressiveness of the new PDC bit for a longer time. The anticollision tooth can improve the shock resistance and wearlessness of the bit, and also helps to drill the glutenite formation smoothly. The new PDC bit performed very well in glutenite formation in the PRMB oilfield. The footage of the new bit rose by over 131%, the ROP rose by over 48% and the cost per meter was reduced by over 28% compared with the conventional bit, which shortened the well construction cycle and reduced drilling costs. This new PDC bit and design theory is useful for glutenite formation, and can be used for other oilfields with similar formations.

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