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3D Directional Drilling Technology for Hot Dry Rock of GH-03 Well in Gonghe Basin, Qinghai Province

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ABSTRACT

In order to build the first hot dry rock development demonstration project in China, China Geological Survey deployed directional well GH-03 in Gonghe basin, Qinghai Province. There are many problems, such as poor reliability of downhole tools and unstable performance of drilling fluid under high temperature, strong abrasiveness and hardness of rock, low bit footage and ROP, great possibility of sticking due to broken formation block falling, high directional difficulty under the condition of reverse formation trend in hard rock, etc. By selecting efficient bit, positive displacement motor, high temperature resistant MWD, optimizing bottom hole assembly, developing high temperature resistant drilling fluid and applying mud cooling technology, the difficulties faced by this well were overcomed. Through the application of the above techniques, the first 3D directional well GH-03 in hot dry rock has been successfully completed with high precision and a set of high temperature hard rock efficient directional technology system has been established. Compared with adjacent wells, the bit footage of GH-03 can be increased and the ROP can be increased by 103%. The successful completion of well GH-03 can accumulate valuable experience for the construction of similar high temperature hard rock directional wells.

1. INTRODUCTION

Hot dry rock (HDR) resource, as an important geothermal resource, has attracted increasing attention due to its clean, reproducible characteristics and huge potential of high temperature geothermal power generation. In recent years, some developed countries, such as the United States, Japan, France and Australia, have carried out a large number of research and experimental development work[1-3]. There are huge reserves of HDR resources in China, which are about 1 / 6 of the world's HDR resources. With the decline of traditional fossil fuels, geothermal energy represented by hot dry rock is expected to become a new strategic replacement energy source. According to the China Geothermal Energy Development Report (2018), China's HDR resources are widely distributed in the Qinghai-Tibet Plateau, Songliao Basin, Bohai Bay Basin, southeast coast and other areas. At present, a number of work have been carried out in Qinghai, Fujian, Guangdong, Hainan, and other areas. In 2017, the GR1 well was drilled in Gonghe Basin, Qinghai province. The temperature at a depth of 3705 m in the well is above 236℃, which is the highest temperature of hot dry rock in China,[4-7]. HDR is still in the experimental stage. In 2018, China Geological Survey deployed a HDR project in Qinghai Gonghe basin for the hot dry rock exploration and experimental power generation. The target is to built the first domestic hot dry rock development demonstration project. The injection well GH-01 well has been completed in 2019. GH-03 well, which is a planned production well, is the first domestic high temperature hot dry rock 3D directional well. High temperature and hard rock became the key difficulties, and there is no more experience to follow.

2.ENGINEERING DESIGN OVERVIEW

2.1 Geology

GH-03 Well is located at the transition slope zone of Tanggu depression and Yellow River uplift in Gonghe Basin, Qinghai Province. The final drilling depth is 4008.88m. The lithological characteristics of drilling from top to bottom are as follows:

(1) The Quaternary Gonghe Formation, with a buried depth of 0~564m, mainly gray clay layer and sand layer, with a general cementation degree, loose structure and good drillability.

(2) Linxia Formation and Xianshuihe Formation, with a buried depth of 564~1360m, brick red sandy mudstone, mudstone and sandstone mutual layer, local conglomerate, brittle, with good drillability, good water absorption, which is easy to make slurry.

(3) Middle and late Triassic granite, buried deep 1354~4008.88m (not worn), including: 1354~2876m mainly light flesh red granite and light gray granite diorite, both thick alternately; 2876~4008.88m mainly gray granite diorite; the granite dense, hard, poor drill ability, extremely low permeability, some layers of rock fragmentation, fissure development, cracks filled with black vein, the rest cracks filled with quartz veins..

2.2 Well track Design

GH-03 well is designed as a double target 3D directional well. According to the adjacent well drilling formation characteristics, the inclined position is planed at the depth of 3000m. Through comparing different deviation scheme, the "straight-increase-twist-stable" four-segment track is selected. After drilling to the target 2, the track is steady continue to the depth of 4000m. The stable section end closed bearing 128.08, closed distance of 287.5m.

2.3 Well structure design

After analyzing the complex situation of adjacent well, it is determined that GH-03 well adopts a three-spud well structure, and reserves a four-spud reserve scheme. The three-spud well structure is designed as follows:

(1) Using ϕ 444.5mm bit to drill 505m. ϕ339.7mm casing strings are to be cemented to the surface to seal shallow loose strata.

(2) Using ϕ 311.1mm bit to drill 1505m. ϕ244.5mm casing strings are to be cemented to the surface and the casing sits into the granite, to seal the sandstone and mudstone unstable formation.

(3) Using ϕ 215.9 mm bit to drill 4000m, and ϕ 177.8 mm tail pipe is hung at 1300m, where casing pipe is used in the section of 1300~3650m and sieve pipe is used in section of 3650~4000m. The casing strings are to be cemented during 1300~3550m section.

(4) If the granite formation in the directional section is seriously broken and the drilling process is frequently unstable, the ϕ 177.8 mm tail pipe will be cemented, and ϕ152mm drilling bit will be used to 4000m and the granite section will be an open-hole.

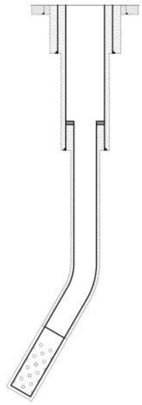

Fig1 GH-03 well structure design

3 THE DIFFICULTIES FOR HDR DRILLING

3.1 High temperature

The average ground temperature gradient of the well GH-03 is 51.4℃ / km, and the static setting temperature of the well bottom is over 200℃. The high temperature has the following effects during the drilling:

(1) High temperature poses great challenges to the life and reliability of drilling tools and measuring instruments. Under the action of high temperature, the rubber stator of PDM is easy to be damaged, the hydrulic hammer is easy to seal failure, the oil storage lubrication sealing system of the roller bit is easy to leak, and the MWD is difficult to withstand high temperature. [8].

(2) Long-term production practice shows that when the temperature exceeds 150℃, the polymer treatment agent in the water-based drilling fluid will degrade. The rheology of drilling fluid will be worse, and the cuttings removal, suspension lubricity and wall protection capacity cannot be maintained. [9-11].

3.2 High hardness and low drilling efficiency in the hard rock

There is high pressure in the deep granite formation. The rock is hard (level 7) ,abrasive, and poor drillable ability. The drilling rate is generally low, for example, the bit life in adjacent well is about 50m, and the average mechanical drilling rate is about 1.15m / h. The drilling bit had to be replaced about 48h, and weared seriously.The outer diameter of the used bit is about 206mm, which caused hole shrinkage.The drilling efficiency was seriously affected.

3.3 The risk of stick and well leakage is high

According to the analysis of accidents, rock core and debris, there are some natural fissure and crushing zone in the granite formation in Gonghe Basin. The formation erosion is serious. When well GR1 was drilled to 2800m, the hole diameter expansion rate can reach 267% . Under the combined action of ground stress and thermal stress, the formation is easy to broke, and after hydraulic fracture, the risk of stuck and well leakage is high.

3.4 The deviating force of the formations

To solve the problem of deviation control and fast drilling, besides effective controlling the side force of the drilling tools and the bit dip, enough ability should be obtained to resist the deviating force of the formations. When well GH-01 reaches 1006.97m depth, the deviation angle of the hole was increased for the complex geological structure of the formation. Furthermore, during the 2250-2450m section and 3250-3500m section, the granite formation is easily inclined. Well GH-03 should be deviated at 3000m. There is the natural reverse slope trend after 3000m against the design track, which puts forward high requirements for directional construction.

4 KEY TECHNOLOGY OF 3D DIRECTIONAL DRILLING IN HDR

4.1 High-efficiency directional drilling technology for HDR drilling

4.1.1 Bit optimization and compound drilling technology

The granodiorite is dense and hard. The compressive strength at 250℃ is up to 173.4MPa. Furthermore, the internally developing amphibole and quartz veins make the formation highly heterogeneous. The PDC bits, which are used in sedimentary rock strata, is easy to appear some problems in hard rock, such as unstable drilling speed, short tool life, and other problems, And the PDC cutter has poor thermal stability and poor impact resistance. During the HDR drilling, the PDC bit is easy to cause failure because of thermal wear and cutter collapse, which leads to reduced working life and low drilling efficiency. A PDC drill bit was tested in the well. After 3m drilling, 5 cutting teeth were found failure.

To solve the HDR directional drilling problems, such as high temperature, hardness, abrasive and strong homogeneity, an enhanced type of tricone bit was selected, which has metal seal to endure the high temperature and enhanced gauge protection with diamond to provide anti-abrasion. The roller composite bearing with high speed heavy load characteristics, can cooperate with large torque PDM for hard rock directional drilling.

In the application process, a variety of compound drilling methods were used to increase the drilling speed, such as hydraulic impactor matching roller drill bit, turbine drill matching impregnanted diamond drill bit and PDM matching PDC /roller drill bit. Compared with the conventional drilling tools， the drilling efficiency were greatly improved about 103%.

4.1.2 Select the high-temperature deviation tools

Generally, when the well temperature exceeds 120℃, the rubber stator of the PDM will lose the original performance rapidly, and the service life will be shorter. Furthermore, it will cause many problems, such as pipe-stuck, pump pressure surge, no drill footage,etc. The drilling cost will greatly increase. At the same time, the high temperature PDM usually reduces the excess surplus, resulting in insufficient surplus and mud leakage at the normal temperature. Therefore, the different types of temperature resistance PDM are selected according to the temperature measurement of the adjacent well. Under 3000m 120℃ PDM is used, and 150℃ PDM is selected for 3000~3500m directional section, and 180℃ PDM is selected from 3500 to 4000 m .

Accurate measurement of well trajectory is the key to get the target. Two type measurements were used.

(1) Single and multi-point oblique meter.The measurement was put into the well through the drill pipe, and the data is read after drilling. It is unable to monitor the data in real-time. The research for ultra-high temperature and high pressure multi-point oblique meter was developed. Through the vacuum insulation cylinder and other technologies, it can achieve the temperature resistance of 300℃ / 4h.

(2) MWD tool. The well track parameters is collected in real time and uploaded to the ground through mud pulse. Engineers can adjust the trajectory in real time according to the acquired data. At present, the highest working temperature of domestic MWD is 175℃.

In order to ensure accuracy of the track, the plan is settled to use the 175℃ MWD track real-time tracking adjustment, when the bottom working temperature exceeds 165℃, the ultra-high temperature multi-point oblique meter will be used to measure the parameters every 50m to verify the data. According to the monitoring actual deviation rate, the engineers can adjust scheme to ensure the smooth track.

4.1.3 Optimize the BHA

The GH-03 well is designed with maximum inclination of 24° and the maximum dog-leg is only 2.88 / 30m. The radius of curvature is 600m. It is a three-dimensional curved well. The flexible requirements for drilling tools are not high. However, the target layer of lithology is hard, so a large vibration will occur during drilling and big drilling pressure will be required for the tricone bit. To ensure that the tool remains stable when applying large drilling pressure, the lower part of the drill pipe shall have a certain stiffness, Therefore, the combination of inverted drill pipe and full soft BHA is not used. Instead, a combination of conventional BHA was used. The amount of DP was reduced and the amount of HWDP increased. It is useful to reduce the difficulty of orientation and torsion direction construction. The bottom is still equipped with 1~2 column DP. In addition, due to the broken formation, it is easy to collapse. In order to avoid the jamming of the drilling pipes, it is necessary to simplify the BHA as far as possible. Therefore, the centralizer was reduced. The optimized BHA is: ϕ215.9mm bit + ϕ172mm high temperature single bending PDM + directional joint + ϕ177.8mm NMDC+ 175℃ MWD + ϕ172mm DC + ϕ140mm HWDP + ϕ127mm HWDP+ ϕ127mm DP. The optimized strength of the drill column is checked . When the drilling pressure is 140kN and the velocity in pulling pipe is 6.7m / min, the drag coefficient in the casing and the open-hole is 0.2 and 0.4 respectively. The tensile and torsion strength of the drill column meet the requirements, and the spiral flexion will not occur.

4.1.4 Well path control technology

The successful development of HDR depends on whether the product well can accurately drill the extended cracks formed after the fracturing of the injection well and establish good connection. In order to ensure that the off-target distance does not exceed 25m at target 1 and 2, the following methods were adopted to monitor and adjust the well track:

(1) Select appropriate single bending PDM according to the design track, and monitor the actual track of the drilling. If the actual slope is inconsistent with the design slope, a different bending angle PDM shall be selected, but the maximum bending angle shall not exceed 1.25.

(2) The driller must control the counter-torsion anglek to ensure the accuracy of the tool surface during slide steering drilling.

(3) The well deviation should be measured once per single drilling pipe at least. The track should be calculated and adjusted in real time.

(4) The logging was applied in the depth of 3400m to measure the parameters. After analyzing the data, the deviation plan is adjusted to ensure the accuracy of the track.

4.2 High-temperature-resistant drilling fluid technology

The main problems during the high temperature driling are mainly well wall instability, leakage , big friction and short life of drilling fluid. The granite permeability is low and the water sensitivity is not strong, As a result, the design of drilling fluid should focus on high temperature stability, wall protection, lithability and lubrication. The formula of green high temperature drilling fluid is: water + 4%~6% sodium bentonite + 0.2%~0.3 caustic soda + 0.5%~1% high temperature viscosity inhibitor (GHFV-1) + 0.3%~0.5% high temperature adhesive (GZN-240) + 1%~2% high temperature collapse inhibitor (GFT-240) + 1%~2% ~ 2% (GPNA) + 0.2%~0.3% coated agent (GBBJ) (1%~2% high temperature protector + 0. 5%~1% No fluorescent lubricant (GLUB) + barite.

4.3 Mud cooling technology

Mud cooling is mainly through circulating drilling fluid. Due to the high temperature of the formation, the temperature of drilling fluid is increasing. Therefore, the downhole motor,instruments , and mud pump equipment are damaged easily. To solve the problem, the mud cooling system is designed and used successfully to cool the drilling fluid rapidly.

4.3.1 Mud cooling technology for drilling fluid

The mud cooling system is connected between the circulating tank and the mud pump suction tank. Using the principle of spray heat transfer, the sand pump extracts the purified high-temperature drilling fluid to the spray system on the top of the cooling tank. By multiple spray nozzles, drilling fluid spray down to the filling layer and form a water layer on the filler. At the same time, The axial flow fan at the top draws the cold air from outside the tank through the lower part of the tank.The cold air coming into the tank is heat-exchanged with the high-temperature drilling fluid in the filler. The exchanged hot and humid air is discharged from the tank by the fan and the cooled drilling fluid enters the water collector and flows to the mud pump suction tank.

4.3.2 Section cycle cooling during drilling process

When the well depth exceeds 3000m, the static temperature of the formation exceeds 140℃. The drilling fluid in the well is easily thickened under high temperature environment. Meanwhile, the cooling effect is greatly reduced, and the life of relevant drilling tools and instruments will be greatly reduced. Therefore, multiple section circulation method is used to cool the temperature of the drilling bit, drilling tool, measuring instrument and drilling fluid in the well. In order to require the proper cooling effect, the circulation can be perform for about 30min every 500m.

5 FIELD APPLICATION

GH-03 well has been successfully drilled by applying the above techniques. During the process of drilling, although the block occured occasionally, the well wall is relatively stable and there was no accident such as well collapse. MWD can work safely to the depth of 4000m. The off-target distance of target 1 is 1.53m, at the depth of 3552.51m and the off-target distance of target 2 is 6.85m, at the depth of 3780.51m. The track was accurately achieved. After drilling to 2950m, the deviation was started. During the subsequent directional drilling process, the tool surface was stable and the deviation effect fulfiled the requirements. The well inclination increases from 1.67 to 21.64, and the average borehole curvature is 1.03 / 30m respectively. Under the same rock and drill bit conditions, compared with conventional drilling, drill bit footage increased by 70% and ROP increased by 103% only by using composite drilling technology.

The application effect of multiple circulating cooling process and mud cooling technology was studied at different depths. The working temperature measured by MWD twice before and after the 1h working of the mud cooling system. The results are shown in Table 1. Analysis shows that the multiple section circulation cooling method and mud cooling technology can effectively reduce the working temperature. The multiple section circulation cooling method can reduce the temperature about 25℃. Furthermore, the mud cooling equipment can reduce at least 25℃ more, which can effectively guarantee the safety of drilling.

Tab 1 Application effect of mud cooling technology

TD(m)	Temperature of the Formation (℃)	Mud Temperature during cycle (℃)	Mud Temperature with the Mud Cooler (℃)
3179	171.9	143.2	113.9
3546	185.9	154.6	124.3
3865	198.6	166.3	132.8

6 CONCLUSION

(1) A set of HDR efficient directional drilling technology has been studied and successfully used in Qinghai Gonghe basin GH-03 well. The technology included high temperature resistant downhole motor , high temperature resistant MWD, long-life drill bit for hard rock, high temperature resistant drilling fluid and mud cooling system. It can effectively ensure high precision deviation and improve ROP in HDR drilling.

(2) When high temperature hard rock formation was broken, the BHA should simplify and the centralizer should be reduced to avoid "steps". The drilling fluid’s density, viscosity and shear force should increase , and the test of drilling fluid under high temperature conditions should perform frequently to maintain the good carrying and wall protection abilities.

(3) The main problem of HDR drilling is the temperature resistance of tools. The highest working temperature of domestic MWD is 175℃ and PDM is 180℃. At present, the working temperature of MWD produced by Baker Hughes has reached 205℃ and all metal PDM's temperature resistance is 300℃.The development of higher temperature-resistant MWD and all-metal downhole motor has become an urgent problem to achieve the efficient drilling of HDR.

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