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Survey on Geothermal Resources in Zhangjiakou Area

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Abstract. The Zhangjiakou area is rich in geothermal resources, and many counties in the region have discovered low-temperature geothermal. Structurally, Huailai County, Zhangjiakou City is located at the intersection of Zhangjiakou-Penglai Fault Zone and Shanxi Fault Basin (or Fenwei Seismic Tectonic Zone), namely the Yanqing-Huailai Basin (Yanhuai Basin). A large amount of geothermal resource investigation and research works has preliminarily defined that the area has good geothermal resource accumulation conditions. From 2019 to 2020, the China Geological Survey has organized several investigation and research in the area for in-depth geothermal resource. As one method of the survey results verification, a parameter well for geothermal resource survey was deployed as ZK02 and completed at 3000m depth. The ZK02 well was completed at a depth of 3006.9m, drilling through the Quaternary, Neogene, and Jixian strata, and entered the Archean gneiss strata. The well successfully explored high-quality artesian heat storage in the Jixian strata, obtained deep geothermal geological data and physical data, revealed the regional stratigraphic sequence and geological structure characteristics, and provided a scientific basis for regional geothermal resource potential evaluation. Based on the engineering practice of ZK02 well, this paper systematically summarizes drilling technology and experience from well structure to drilling equipment, construction technology and key technology, analyses the complex conditions and countermeasures downhole, and provide reference for the follow-up regional geothermal resources investigation, research and development and.

1 Preface

The Zhangjiakou area is rich in geothermal resources, among which, Chicheng, Huailai, Yangyuan, Yuxian and other counties have discovered low-temperature geothermal, the current development and utilization methods are mainly wellness tourism [1]. Structurally, Huailai County, Zhangjiakou City is located at the intersection of Zhangjiakou-Penglai Fault Zone and Shanxi Fault Basin (or Fenwei Seismic Tectonic Zone), namely the Yanqing-Huailai Basin (Yanhuai Basin). A large amount of geothermal resource investigation and research work has preliminarily defined that the area has good geothermal resource accumulation conditions [2][3][4]. In order to further ascertain the accumulation conditions and resource potential of deep geothermal resources in the Yanhuai Basin, from 2019 to 2020, the China Geological Survey organized investigation and research for in-depth geothermal resources in the area, and deployed high-precision gravity and magneto telluric (MT) , Controllable source audio magneto telluric (CSAMT) and seismic surveys and other comprehensive geophysical exploration work [5]; At the same time, in order to verify the survey results, a 3000m deep geothermal resource survey parameter well “ZK02” had been deployed and completed. The ZK02 well was completed at a depth of 3006.9m, drilling through the Quaternary, Neogene, and Jixian strata successively, and entered the Archean gneiss strata. The well successfully explored high-quality artesian heat storage in the Jixian strata, obtained deep geothermal geological data and physical data, revealed the regional stratigraphic sequence and geological structure characteristics, and provided a scientific basis for regional geothermal resources potential evaluation.

This article combines the engineering practice of ZK02 well and systematically summarizes the drilling construction technology and experience, which can provide reference for the follow-up regional geothermal resource investigation, research, development and utilization.

2 Geological Profile

ZK02 Well is located in the north of Donghuayuan Town, Huailai County, adjacent to Guanting Reservoir in the north, and structurally located in the southwest of Yanfan Basin. As the depth of the peripheral known boreholes is shallow, and there are very few reference

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materials [6][7], this well is the first mid-deep geothermal parameter well in the survey area. Inferred from regional geological data analysis and geophysical prospecting results, the strata in the Donghuayuan area are mainly composed of Quaternary, Neogene, Jurassic, Jixian, Great Wall and Archean gneiss, as shown in Table 1.

Table 1. Prediction of drilling formation in ZK02 well

Stratum		Bottom depth (m)	Layer thicknes (m)	Brief description of lithology
Chronology	Symbols			
Quaternary + Neogene	Q+N	600	600	Clay, sand, gravel, Sandy gravel
Jurassic	J	1100	500	sandstone, rhyolite
Jixian System + Great Wall System	Jx+Ch	3000	1900	Dolomite

During the drilling of this well, the strata encountered were Quaternary, Neogene, Jixian and Archean from shallow to deep, no Jurassic strata were seen. As shown in Table 2.

Table 2. Summary of drilled formations in ZK02 well

Stratum		Bottom depth (m)	Layer thickness(m)	Brief description of lithology
Chronology	Symbols			
Quaternary + Neogene	Q+N	1327.9	1327.9	Clay, sand, gravel, Sandy gravel
Jixian System + Great Wall System	Jx+Ch	2960	1632.1	Dolomite, shale, Sandy gravel, mudstone, diorite porphyry
Archaean	Ar	3006.9	46.9 Unperforated	granite gneiss

The Quaternary stratigraphic lithology from shallow to deep are: brown fine gravel, mainly composed of quartz and granite; light gray clay, medium plasticity, containing silty fine sand; light gray coarse sand, mainly composed of quartz, sub-circular, sorted Etc., partly with sandy soil and fine gravel.

From shallow to deep, the Neogene stratigraphic lithology are light gray sandy mudstone, gray claystone, light gray brown sandy gravel, sandy mudstone, and sandy gravel.

The Jixian system is composed of Tieling Formation, Hongshuizhuang Formation, Wumishan Formation, Yangzhuang Formation, and Gaozizhuang Formation from shallow to deep. The lithology is dominated by dolomite, and there are well-developed fissures in some well sections.

The lithology of Archean strata is granite gneiss, gray and off-white gneiss-like structure, and the main components are feldspar, quartz, hornblende, mica and other dark minerals, which are recrystallized.

3 Well Structure

Before the ZK02 well, the stratification and burial depth in the deep part of the region were inferred based on the existing geological data and geophysical prospecting results. Therefore, in order to ensure the smooth implementation of the drilling project to achieve the geological purpose, an extra section is reserved in the well structure design. According to the drilling engineering design, the well structure has three sections with the completion diameter is Φ215.9mm bare hole. The Φ152.4mm diameter is reserved as an alternative plan for downhole complex drilling situation. Shown in Table 3.

Table 3. Structure design of ZK02 well

Section	Chronology	Well structure			
		Drill bit size (mm)	Drilling depth (m)	Casing size (mm)	Casing depth (m)
First	Quaternary + Neogene	444.5	602	339.7	600
Second	Jurassic	311.1	1102	244.5	1100
Third	Jixian System + Great Wall System	215.9	3000	177.8 *(reserve)*	
Forth *(reserve)*		*152.4*	*3000*		

In the actual drilling process, the bottom depth of the Neogene was 1327.9m, and no Jurassic stratum was seen. The Jixian system as the main reservoir has well-developed fissures and relatively fragmented partial stratum, which will cause risk of well wall collapse during the pumping test. According to the engineering design, the well structure and casing depth have been optimized and adjusted: First is increasing depth of the first and second section casing to the top of the Jixian formation; Second is insert Φ139.7mm casing + screen pipe when the third section completed, and arranged the screen pipe according to the distribution of the hot water layer. Shown in Table 4.

Table 4. Completion structure of ZK02 well

Section	Well structure			
	Drill bit size (mm)	Drilling depth (m)	Casing size (mm)	Casing depth (m)
First	444.5	1020.2	339.7	1010.86
Second	311.1	1494	244.5	1488
Third	215.9	3006.9	139.7	3006.9

The well structure design is very important to the exploratory well drilling project especially in unknown or more complex formations [8][9], and the adjustment of well structure during the drilling process is more common [10][11]. A common practice in well structure designing in unknown or more complex formations is to reserve an extra section, or to develop an alternative well structure which can effectively prevent the implementation of the drilling project from being too passive or forced to stop due to the complexity situation downhole [12][13]. In the engineering design, The ZK02 well has reserved an extra section which provides ample room for the adjustment of the well structure, during the implementation of the project, reasonable adjustments were made to the well structure according to the stratum conditions, which provided a strong guarantee for the smooth implementation of the project.

4 Drilling equipment selection and matching

The selection of drilling engineering equipment must considering about geological purpose of drilling, regional environment, construction technology, completion depth, completion diameter and other factors [14][15][16]. In recent years, with the continuous acceleration of the exploration and development of geothermal (hot dry rock) resources, the workload of geothermal drilling has increased sharply. Existing large-diameter geothermal drilling equipment mainly includes water well drilling rigs and oil drilling rigs. The advantages of water well drilling rigs are that the equipment is relatively compact, easy to relocate, and there are few construction crews; its disadvantages are mainly that the drilling depth is limited by the lifting ability, and the installation conditions of the well control equipment and solid phase control equipment are limited by the height of the first-floor platform. The installation conditions of logging sensors are poor. The oil drilling rigs are relatively mature, with a complete range of drilling depth capabilities. The structure and design of the drilling rig meet most needs of well control equipment and solids control equipment, also the ability to handle complex accidents is relatively strong. In the process of drilling equipment selection, especially exploratory wells, new types of drilling rigs with maturity and recent age should be selected first, which can provide an effective guarantee for the smooth implementation of the project.

The ZK02 well is the first exploratory well in the area. There is no reference to the well-informed well. It only has a rough estimate of the strata encountered downhole, and there is little information available for prediction of downhole conditions, and based on the principle of ensuring the safety of drilling, large capacity redundancy needs to be considered when selecting drilling rigs. Therefore, standard petroleum ZJ-30 electric drilling rigs are used, and all supporting equipment are electric, which is more friendly to the surrounding environment of the construction, and the diesel generator set is only used as an emergency backup. The main equipment list is shown in Table 5.

First, based on the drilling depth requirements, the selection of standard petroleum ZJ30 equipment can effectively ensure provide the lifting force required to drill to the designed well depth; Secondly, the supporting system according to petroleum standards can effectively ensure the compatibility of equipment, operation safety, construction efficiency and fulfil other requirements; Third, the use of all-electric equipment can greatly improve work efficiency, reduce environmental pollution, and save drilling costs. At the same time, in order to improve drilling complexity and risk response capabilities, a full set of well control equipment and blowout prevention tools are provided on site to cope with blowout risks, and diesel units are provided to cope with complex situations such as equipment failures and emergency power outages.

Table 5. List of main equipment

No.	Name	Model	Quantity
1	Drilling rig	ZJ30	1
2	Diesel unit	G12V190PZL-3/O	1
3	Auxiliary generator	CDVS-400	1
4	Mud pump	F-1000	2
5	Circulation tank	174m^3	4
6	Four-level solid control		1
7	BOP	2FZ35-35	1
8	BOP control device	FKQ-480-5	1
9	Kill manifold	PFF103-35	1
10	Choke manifold	PFF65-35	1
11	Internal Blowout Prevention Tool		1

5 VDrilling Construction and Key Technologies

5.1 First section drilling

The first section drilling encountered strata are mainly Quaternary and Neogene. Quaternary stratum is mainly brown fine gravel, light gray clay, light gray coarse sand, etc., Neogene stratum is mainly light gray sandy mudstone, gray claystone, shallow Grey-brown sandy gravel, sandy mudstone, sandy gravel, etc. The drill tool combination used is Φ444.5mm drill bit + Φ203.2mm drill collar + Φ 177.8mm drill collar + Φ127 drill rod + Kelly bar. 71.5m-1020.2m use Φ444.5mm GA115G roller bit to drill, weight on bit 10-100KN, speed 20-60rpm, displacement 30L/s, average ROP 2.9m/h, maximum ROP 9.47m/h, The longest footage of a single bit is 360.59m, of which the core drilling speed is 0.65m/h.

5.2 The second section drilling

The strata encountered in the second section drilling are mainly Tertiary sandy gravel, claystone, Jixian sandy gravel, mudstone, and dolomite. The drill tool combination used is Φ311.2mm drill bit + Φ203.2mm drill collar + Φ177.8mm drill collar + Φ127 drill rod + Kelly bar. The mud specific gravity is 1.02~1.08g/cm3, the weight on bit is 20-120kN, and the displacement is 22-30L/s.

For drilling in this section, the following points should be paid attention to:

(1) Adopt pendulum drilling tool combination to prevent deflection;

(2) In High steepness well sections with easy deviating conditions should intensify inclination

measurement, master the data and take technical measures timely, and use the MWD inclinometer to prevent inclination and maintain straightness according to the actual situation;

(3) Make a record of the drilling fluid, discover formation leakage and water inrush in time, and adjust the performance of the drilling fluid and drilling parameters accordingly;

(4) Adjust the performance of the drilling fluid in time, balance the formation pressure, prevent block dropping and collapse, connect a single root to reduce the number of strokes, minimize the number of trips, and prevent the drill bit from colliding with the well wall;

(5) Ensure that the drilling equipment is operating well;

(6) The use of screw + cone bit compound drilling can effectively increase the mechanical drilling speed. However, attention should be paid to the formation conditions, and conventional drilling tool combinations should be used as far as possible in the leak-prone formations to make preparations for leaking at any time.

5.3 Third section drilling

The third section drilling adopts screw drill + roller bit compound drilling speed, speed-up drilling tool combination: Φ215.9mm drill bit +172 screw +177.8 drill collar +Φ213 centralizer +178 drill collar +127 drill rod +NC501*NC460 conversion joint + 114 drill rod + NC461*NC500 conversion joint + Kelly bar. The specific gravity of the third section mud is 1.02~1.08g/cm3, the weight on bit is 20-120kN, the speed is 20-70rpm (screw), and the displacement is 22-44L/s.

5.4 Environmentally Friendly Drilling Fluid

The selection of drilling fluid formula should consider about all the aspects of pertinence, suitability, temperature resistance, security and environmental protection.

The stratum encountered in the first drilling section was the Quaternary and Neogene. The lithology is mainly light gray clay, light gray coarse sand, sandy gravel, sandy mudstone, etc. The stratum is relatively loose and broken. The higher viscosity bentonite drilling fluid is used to quickly drill through and place the casing. Using bentonite drilling fluid, the formula is as follows:

Water+6%~8% Bentonite+0.1%~0.2% Caustic Soda+0.2%~0.4% Tackifier (GZN).

The strata encountered in the second section are mainly tertiary sandy gravel and claystone, and Jixian sandy gravel, mudstone and dolomite. The formation is relatively stable, but there are problems such as mudstone hydration and swelling and gravel loss. A low-solid phase polymer drilling fluid system with good suppression and plugging performance is selected. The formula is as follows:

Clear water + 0% ~ 3% bentonite + 0.1% ~ 0.2% caustic soda + 0.1% ~ 0.5% tackifier (GZN) + 1% ~ 2% anti-collapse plugging agent + 1% ~ 1.5% fluid loss agent (GPNH)+0.1%~0.2% coating agent (GBBJ).

The stratum encountered in the third section is granite gneiss which is stable. A solid phase free polymer drilling fluid system is adopted, and polymers are added to improve the carrying capacity of the mud and ensure the cleanness of the wellbore. If the well wall is unstable, use the mud positive circulation construction instead. When the temperature exceeds 80℃, use the temperature-resistant solid phase free polymer drilling fluid system. The formula is as follows: water + 0.1%~0.2% caustic soda + 0.3%~0.6% thickener (GZN) + 1%~2% plugging agent (GFD-1) + 1%~1.5% fluid loss agent (GPNH) +0.1%~0.2% coating agent (GBBJ).

6 Pumping test

6.1 Overview of the pumping test

The ZK02 well used air compressors to clean the wells before the pumping test from January 23 to 24, 2021 in order to remove the blockages such as mud and rock cuttings in the hole especially in the thermal reservoir section to achieve clean water without sand. Combining with the geothermal resources in this area, it is defined that the pumped water is confined water, and the pumping test adopts the three-time depressurization and steady flow test method in a single well. The pumping test started at 20 o'clock on January 25, 2021 and ended at 0 o'clock on January 30, 2021. It lasted 100 hours. the duration and stabilization time of each pumping phase shown in Table 6.

Table 6. Time Statistics Table for Each Pumping Stage

Test pumping	Beginning at 20 o'clock on January 25, 2021 and ends at 20 o'clock on January 26, lasting 24 hours, the stable time is 6 hours.
Observation of water level recovery	Beginning at 20 o'clock on January 26, 2021, and ends at 4 o'clock on January 27, the observation time is 8 hours, the stable time is 6 hours.

pumping	The first drop distance	Beginning at 4 o'clock on January 27, 2021 and ends at 4 o'clock on January 29, lasting 48 hours, the stable time is 24 hours.
	The second drop distance	Beginning at 4 o'clock on January 29, 2021, and ends at 21 o'clock on the 29th, lasting 17 hours, the stable time is 9 hours.
	The third drop distance	Beginning at 21:00 on January 29, 2021 and ends at 15:00 on January 29, lasting 17 hours, the stable time is 10 hours.
Observation of water level recovery		Beginning at 15:00 on January 29, 2021 and ends at 0:00 on January 30, lasting 9 hours, the stable time is 8 hours.

In this pumping test, the static water level is +9.8m (9.8m above the ground), and the water outlet temperature is 55°C. The dynamic water level depth of the first fall is 24.2m, the water level drop is 34.0m, and the water inflow is 160.364 m³/h. The unit water inflow is 4.717m³/hm; the depth of the dynamic water level in the second fall is 10.3m, the water level drop is 20.1m, the water inflow is 120.629m³/h, and the unit water inflow is 6.01m³/hm; the dynamic water level in the third fall is +3.6m, water level drop is 6.2m, water inflow is 53.677 m³/h, unit water inflow is 8.568m³/hm, details shown in Table 7.

Table 7. Data of pumping test

Drop distance	Still water level(m)	Buried depth of dynamic water level (m)	Water level drop (m)	Water inflow (m³/h)	Unit water inflow (m³/h.m)	Water temperature (℃)	Stable time (h)
S_3	+9.8	24.2	34.0	160.364	4.717	55	24
S_2		10.3	20.1	120.629	6.001		9
S_1		+3.6	6.2	53.677	8.568		10

6.2 Q=f(s) relation curve define

According to the results of the pumping test of the ZK02 well, combined with the field data, the basic data of the pumping test was defined.

According to the curvature method, the value of n is calculated according to the judgment formula to determine the Q=f(s) relationship curve type of the well, and n_1 and n_2 are calculated with three stable drawdowns:

$$n_1=(\lg S_2-\lg S_1)/(\lg Q_2-\lg Q_1) \quad (1)$$

$$n_2=(\lg S_3-\lg S_2)/(\lg Q_3-\lg Q_2) \quad (2)$$

In the formula, Q and S are the water volume and water level drop in the same pumping time.

When n=1, the curve is a straight line; when 1<n<2, the curve is a power curve; when n=2, the curve is a parabola; when n>2, the curve is not a logarithmic curve; When n<1, there is an error in the data.

Calculated by the above formula, n_1=1.45, n_2=1.85, the Q=f(s) relationship curve of this well is a power curve type. It means that in areas where groundwater is mainly stored and the source of replenishment is poor and the water conductivity is strong, when the water level drops, the water inflow increases greatly with the drop distance; When the water level drops beyond a certain depth, the amount of water inflow increases with the drop distance very little.

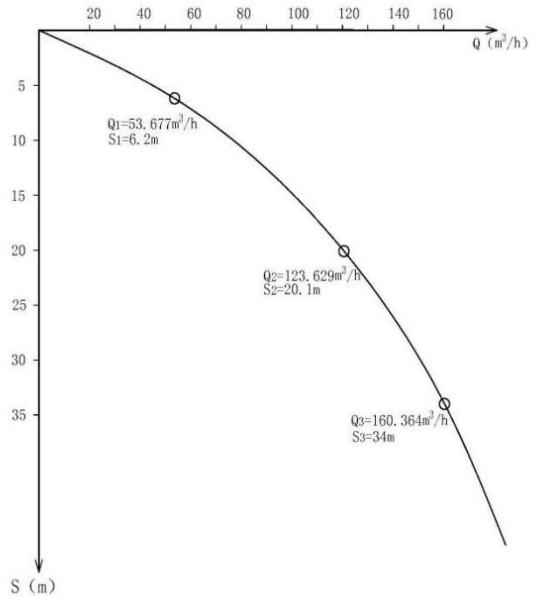

Fig. 1. Q-S curve

The change range of the pumping test when the flow rate is stable is shown in Fig. 2, where q is the fluctuation range of the water inflow relative to the average value, and S is the drop distance in the same period. The data is obtained by field measurement. It can be seen from Fig. 2 that as the drop distance increases, the water inflow gradually stabilizes.

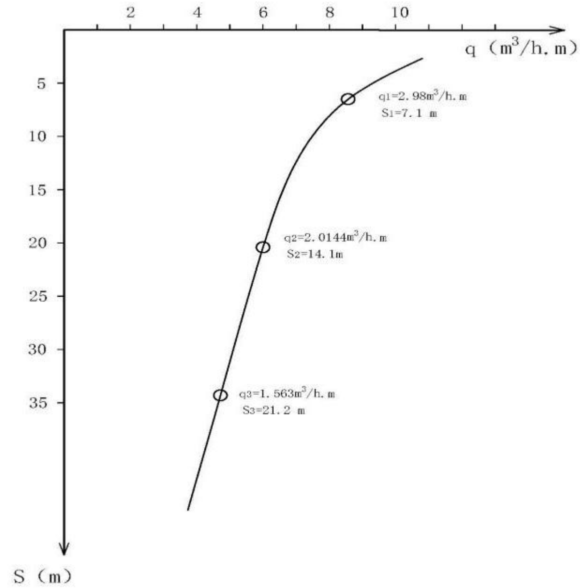

Fig. 2. q-S curve

The entire change process of the pumping test can be intuitively understood Through Fig. 3. The vertical axis is marked with a one-way dual axis Q (pumping volume) and S (pumping depth), the horizontal axis is t (pumping time). It can be seen from Fig. 3 that when the pump is stopped after pumping, the water level can be quickly restored.

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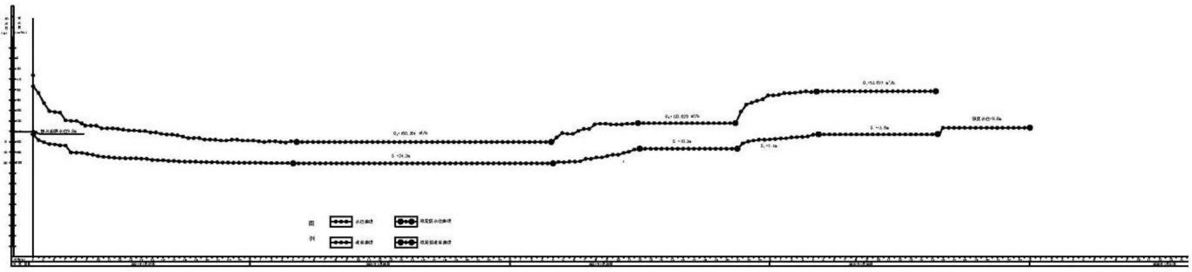

Fig. 3. Q·S-t duration curve

6.3 Calculation of hydrogeological parameters

Calculate the permeability coefficient k and the influence radius R by combining the Dupuit formula and the empirical formula of the influence radius.

Calculation formula of steady flow:

$$K = \frac{0.366Q}{MS} \lg \frac{R}{r} \tag{3}$$

$$R = 10 \cdot S \cdot \sqrt{K} \tag{4}$$

In the formula: K is the permeability coefficient (m/d)

Q is the wellbore water inflow (m³/d)

M is the effective thickness of the thermal reservoir (m)

S is the water level drop (m)

R is influence radius (m)

r is the radius of the well (m)

$$T=KM \tag{5}$$

In the formula: T is the coefficient of hydraulic conductivity (m²/d)

K is coefficient of permeability (m/d)

M is the effective thickness of the thermal reservoir (m)

According to the results of the pumping test of the ZK02 well, the hydrogeological parameters of the well are shown in Table 8.

The geothermal productivity test of The ZK02 well include three pumping tests with depressurization and steady flow in single well. Comprehensive analysis is carried out based on the results of this pumping test. The Q=f(s) relationship curve of this well is a power curve (exponential curve) type, and the pumping duration is analyzed at the same time. It can be seen from the curve that the water level of this well quickly stabilizes during pumping, and can recover quickly after stopping the pump, indicating that the well's thermal reservoir has good permeability and medium water richness, which is basically consistent with the hydrogeological characteristics of this area. It also proves that the pumping test is successful and the hydrogeological parameters obtained are true and reliable.

Table 8. Calculation table of hydrogeological parameters

Water inflow m^3/h	Drop down m	Influence radius m	Permeability coefficient m/d	coefficient of hydraulic conductivity m^2/d	Radius of pumping section m	effective thickness of thermal reservoir m
160.364	34.0	340	0.955	144.568	0.208	151.38
120.629	20.1	215	1.149	173.936		
53.677	6.2	74	1.425	215.717		

7 Conclusion

The ZK02 Well is an exploratory well deployed in Huailai County for deep geothermal resource exploration in Zhangjiakou area. By carefully designing the well structure, optimizing drilling equipment and technology, and controlling key parameters, the mission of 3006 meters footage was successfully completed. The geothermal productivity test through pumping test proved that the thermal reservoir of this well has good permeability and medium water richness, laying the foundation for the future development of geothermal resources in this area. Through the practice of the construction process, the systematic summary of drilling technology and experience can provide reference and support for the follow-up regional geothermal resource investigation, research, development and utilization.

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