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Research on Drilling and Construction Technology of Geothermal Exploration Well D03 in Xiong'an New Area, China

LI Junping[1], JIA Xiaofeng[2], WANG Guiling[3], FAN Lasheng[1], ZHANG Tongde[1]

(1. Institute of Exploration Technology, CAGS, Chengdu Sichuan 611734, China

2. Center for Hydrogeology and Environmental Geology Survey, CGS, Baoding Hebei 071051, China

3. The Institute of Hydrogeology and Environmental Geology, CAGS, Shijiazhuang Hebei 050061, China)

E-mail address: lijunping_xp@163.com, jiaxiaofengdaxia@163.com, guilingw@163.com, gysflscd@163.com, ztd8795@126.com

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ABSTRACT

To obtain the geological structure and distribution of the JiXian System carbonate rock thermal reservoir and calculate the geothermal resource potential more accurately, the drilling and construction technology of the D03 geothermal exploration well was studied. This paper introduces the drilling and construction of the D03 geothermal exploration well. The designed well depth is 2500 m, the drilling depth is 2511.10 m, and the drilling diameter is φ152.4 mm. In the process of drilling in the fourth well section, to better distinguish the dolomite from the Wumishan Formation and the Gaoyuzhuang Formation, the core drilling in the fixed well section was carried out. And the core-taking rate of the surface set core bit, the impregnated bottom jet coring bit, and the impregnated core coring bit was compared, and it was found that the impregnated bottom jet coring bit had the highest core-taking rate, reaching 75%. In the fourth well section, three drilling methods were compared during full drilling: In practice, it was proved that the drilling rate and return length of the cone bit which was driven by the screw motor were higher than those of the cone bit driven by the rotary table, increased by 64.0% and 31.4% respectively. Through the drilling construction, coring, and drilling technology of the D03 geothermal exploration well, the main lithologic characteristics of the D03 well area have been found, which provides a certain reference value for subsequent geothermal resource evaluation.

1. INTRODUCTION

To build a "zero-carbon" smart ecological city and utilize geothermal and other clean energy scientifically and rationally, Xiong'an New Area has been promoting the development and utilization of geothermal resources to achieve the goal of "carbon peaking and carbon neutrality". From 2018 to 2020, the China Geological Survey carried out systematic geothermal integrated exploration in Xiong'an New Area (Zhu Xi et al., 2022), which further revealed that there are three main geothermal reservoirs with development and utilization value. Among them, the carbonate reservoir in the Wumishan Formation is the main thermal reservoir for geothermal heating development. The karst heat reservoirs in the Gaoyuzhuang Formation are deeper, which may be the second space for geothermal exploration and development in the future (Wu Ai'min et al., 2018; Ma Feng et al., 2022; Wang Xinwei et al., 2021).

The Wumishan Formation of the Jixian System in Xiong'an New Area is the main development strata and good thermal reservoir formation, with a thermal conductivity of 5.109 W/(m·K) (Zhu Xi et al., 2021; Liu Huiying et al., 2021). However, the carbonate of the Jixian System is mainly argillaceous and siliceous dolomite, with well-developed fissures and broken structures (Li Hongmei et al., 2022). The strata of the Wumishan Formation of the Jixian System are easy to leak and difficult to be judged; And the Gaoyuzhuang Formation is complicated in geological structure and difficult to core (Ly Liqiang et al., 2019; Pan Deyuan, 2021). To solve the problems mentioned above, continuous exploration and testing are carried out to provide technical references for subsequent exploration work.

2. INTRODUCTION OF D03 GEOTHERMAL EXPLORATION WELL

2.1 Introduction of Drilling Construction

The geothermal clean energy exploration in Xiong'an New Area was carried out by the Institute of Hydrogeology and Environmental Geology of the Chinese Academy of Geological Sciences and aims at the middle-deep carbonate geothermal reservoirs. Among them, the D03 geothermal geological exploration well (referred to as well D03) was organized by the Center for Hydrogeology and Environmental Geology Survey of the China Geological Survey. The development works including drilling, logging, pumping test, cementing, and completion were carried out by the Institute of Exploration Technology of the Chinese Academy of Geological Sciences, and geophysical logging was undertaken by the Institute of Geophysical and Geochemical Exploration of the Institute of Geophysical and Geochemical Exploration (Fan Lasheng et al., 2020). According to the geological design, well D03 was deployed in Niutuo Town, Xiongxian County, Xiong'an New Area, to obtain better geothermal-hydrogeological parameters of the carbonate reservoir. The purpose of this exploration is to drill through the Wumishan Formation and reveal the carbonate of the Gaoyuzhuang Formation, verify the geological structure and distribution of the carbonate thermal reservoir of the Jixian System, and provide a basis for calculating the potential of geothermal resources.

The designed depth of well D03 is 2500 m, the completion depth is 2511.10 m, the completion diameter is φ152.4 mm, the incline angle of completion is 7.7° (the maximum value is 8.5°), the azimuth angle is 156°, and the temperature is 85.6°C at the bottom of the well. The whole well has completed coring drilling of 100.24 m, and the core recovery rate is 59.0%.

As shown in Table 1, the main thermal reservoirs, including Wumishan Formation and the Gaoyuzhuang Formation, were covered in the fourth section from 1350.00 m to 2511.10 m. Table 2 shows the construction technical indicators. The main procedures, such as comprehensive drilling, coring drilling, pumping test, logging, cementing, and completion, have been completed.

Table. 1 Completion well structure of well D03

Serial number	Diameter of well/mm	Drilling section/m	Diameter of casing/mm	Depth of casing/m	
				From	To
First	φ444.5	0~400.00	φ339.7	0.00	400.00
Second	φ311.1	400.00~802.33	φ244.5	345.79	802.33
Third	φ215.9	802.33~1350.00	φ177.8	747.59	1350.00
Fourth	φ152.4	1350.00~2511.10	φ114.3（water filter）	1299.60	2511.10

Table. 2 Drilling technical indicators of the fourth section of well D03 geothermal exploration

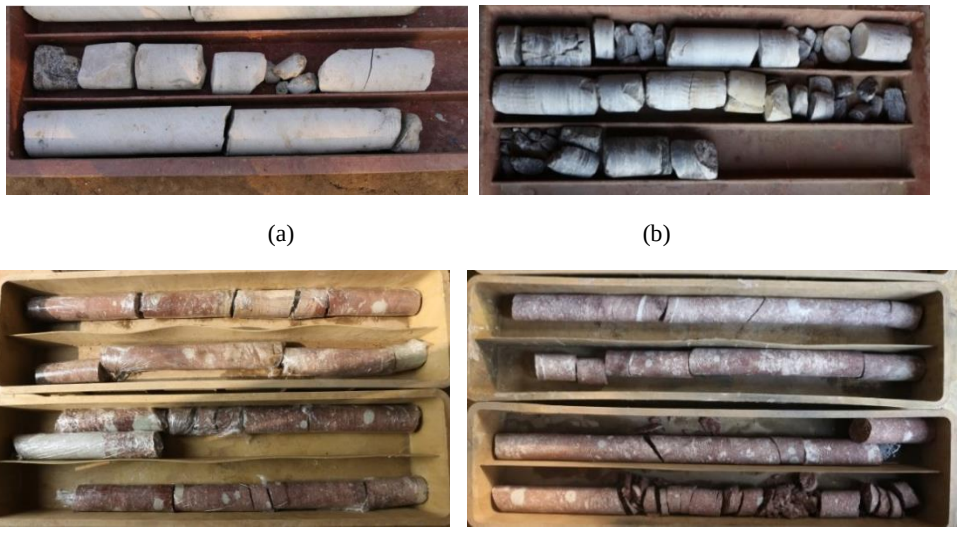
Serial number	Drilling technology	Drilling section/m		Drilling footage /m	Round trip	Drilling time /h	ROP* /（m/h）
		From	To				
Fourth	Comprehensive drilling	1350.00	2506.00	1096.90	26	1058.80	1.04
	Coring drilling	1353.76	2511.10	64.20	21	220.13	0.29

*ROP: rate of penetration

2.2 Analysis of Thermal Reservoir Formation

To support the development plans of geothermal resources in Xiong'an New Area, during the drilling of Well D03, different drilling techniques were adapted to determine the stratum distribution, lithological characteristics, burial depth, and thickness of the thermal reservoirs in the Wumishan Formation in the Jixian System providing data support for evaluating the potential of geothermal resources.

The thin-section identification was carried out with four samples, which were taken from each of the core drilling sections at well depths of 1356.60 ~ 1359.04 m, 1456.41 ~ 1459.10 m, 1714.81 ~ 1719.38 m, and 1719.38 ~ 1724.14 m (as shown in Figure.1). And the results were listed in Table 3.



(a) (b)

(c) (d)

Figure. 1 Core of different formations

(a: Core of the Wumishan Formation from 1356.60 ~ 1359.04 m; b: Core of the Wumishan Formation from 1456.41～1459.10 m; c: Core of the Yangzhuang Formation From 1714.81-1719.38 m; d: Core of the Yangzhuang Formation from 1719.38～1724.14 m)

Through drilling and coring, cuttings cataloging, logging, etc., as shown in Table 4, the geological structure and main lithologic characteristics of the main thermal reservoirs in the fourth section of Well D03 were identified. The strata encountered from top to bottom are gray to gray-white dolomite and flint strip dolomite (belongs to the lower part of the Wumishan Formation), the brown-red, blue-gray argillaceous-powder crystal dolomite (belongs to the Yangzhuang Formation), and gray-white siliceous dolomite, dark gray to gray-black dolomite and blue-gray argillaceous dolomite (belongs to the Gaoyuzhuang Formation) respectively.

From the pumping test, the wellhead water temperature of the Wumishan Formation in Well D03 can reach 68°C, and the water inflow was 154.10 m^3/h. While the value for the Gaoyuzhuang Formation is 80℃ and 44.10 m^3/h. According to the calculation, the

recoverable heat of geothermal fluids of the Wumishan Formation of the Jixian System in Xiong'an New Area is more than 50% of the total; The Gaoyuzhuang Formation accounts for 22% of the total, as potential thermal reservoirs in the future (Zhu Xi et al., 2022).

Table. 3 Thin-section identification results of cores

Sampling interval /m	Sample number	Conclusion				
		Name	Element/%	Secondary mineral	Rock texture	Rock structure
1356.60 ~ 1359.04	D03y-01	Dolomite with silt and micrite	Dolomite: 80%+ Terrigenous silt: 20%- Terrigenous sand: less	Dolomite, limonite	Micrite structure containing silt	Block structure
1456.41 ~ 1459.10	D03y-02	Dolomite with flint strips and micrite	Dolomite: 75% ~ 80% Silica: 20% to 25%	Limonite, dolomite, secondary quartz	Micrite structure containing silt	Ribbon structure
1714.81 ~ 1719.38	D03y-03	Dolomite with silt and micrite	Dolomite: 75%+ Terrigenous silt: 20%- Terrigenous sand:5%-	Dolomite, limonite	Micrite structure containing silt	Lamellar structure
1719.38 ~ 1724.14	D03y-04	含 Dolomite with anhydrite, silt and micrite	Dolomite: 75%+ Terrigenous silt: 15%- Terrigenous sand: 5%- Anhydrite: 5%+	Dolomite, limonite	Micrite structure containing silt	Block structure

Table. 4 Brief description of the lithology of main thermal reservoirs in Well D03

Strata				Actual drilling			Lithology
Erathem	System	Formation	Code	Roof depth /m	Bottom depth /m	Thickness /m	
Middle-Upper Proterozoic Erathem	Jixian System	Wumishan Formation	Jxw	796.00	1702.93	906.93	Dark gray to gray-black siliceous dolomite, calcic dolomite, and gray to khaki argillaceous dolomite, with flint-bearing bands.
		Yangzhuang Formation	Jxy	1702.93	1768.00	65.07	Brown-red argillaceous dolomite, with blue-gray to gray-white argillaceous dolomite agglomerates.
		Gaoyuzhuang Formation	Jxg	1768.00	2511.10	743.10	Gray-white siliceous dolomite, blue-gray argillaceous dolomite, and dark gray to gray-black dolomite alternately deposited, locally containing pyrite crystals, and most of the siliceous components appear in stripes, lenses, and tiny folds. Not penetrated.

3. ANALYSIS OF DRILLING TECHNOLOGY IN GEOTHERMAL RESERVOIRS

3.1 Significance of Coring Drilling

To distinguish better the Wumishan Formation from the Gaoyuzhuang Formation within the designed well depth, comprehensive drilling and point coring drilling (one round of coring drilling every 100m) were adopted. And the drilling parameters in the fourth section are listed in Table 5.

Table 5 Drilling parameters and drilling fluid parameters in the fourth section

Drilling technology	WOB*/kN	RPM*/ (r/min)	Displacement / (L/s)	Funnel viscosity/s	Mud weight / (g/cm^3)	Filter loss / (mL/30min)	pH
φ152.4 mm comprehensive drilling	30 ~ 40	84	18	17 ~ 38	1.05 ~ 1.10	8 ~ 10	8.5 ~ 9.0
φ152.4 mm compound drilling	30 ~ 40	43 + Screw motor	18				
Coring drilling	30 ~ 40	43、84	15				

*WOB: weight on bit, RPM: rotation per minute

When drilling to the depth of 1700.00~1714.81 m, the drilling efficiency slowed down significantly, and the shaker returned maroon-red argillaceous dolomite and light red dolomitic mudstone cuttings (as shown in Figure. 2), then the position of point coring was adjusted. Core drilling was performed two times at the well depth of 1714.81~1724.14 m, with total drilling footage of 9.33m and a core length of 8.24 m.

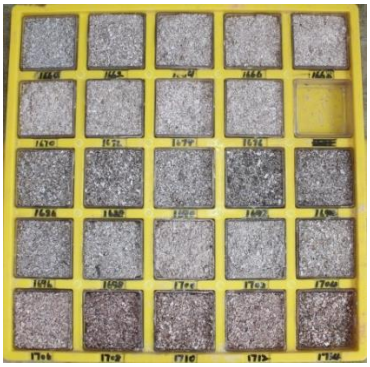


Figure. 2 Cuttings from 1660 ~ 1702 m in the Wumishan Formation and 1704 ~ 1714 m in the Yangzhuang Formation

Through thin-section identification and logging interpretation, it was confirmed that the well section 1702.93 ~ 1768.00 m is the dolomite of the Yangzhuang Formation, and the cuttings and cores marking the Yangzhuang Formation have been obtained successfully. It can distinguish the boundary of dolomite between the Wumishan Formation and the Gaoyugzhuang Formation effectively, playing a key role in completing the exploration purpose of well D03 successfully.

3.2 Analysis of Coring Drilling Technology

In the well section from 1350.00 m to 2511.10 m, the Chuan 6-4 coring tool was used to perform 21 rounds in total, with drilling footage of 64.20 m, core length of 39.74m, and an average core recovery rate of 61.9%. Three kinds of coring bits were used (as shown in Figure. 3) including surface set polycrystalline coring bit, impregnated bottom-jet coring bit, and impregnated coring bit. The coring drilling technical indicators are shown in Table 6.

(a) (b) (c)

Figure. 3 Three kinds of bits used in Well D03

(a: Surface set polycrystalline coring bit; b: Impregnated bottom-jet coring bit; c: Impregnated coring bit)

Table 6 Technical indicators of thermal reservoir coring drilling in the fourth well section

Bit type	Well depth		Footage /m	Core length /m	Drilling time /h	ROP/ (m/h)	Core recovery /%	Formation
	From	To						
Surface set polycrystalline coring bits	1353.76	1359.04	34.34	19.19	125.13	0.27	55.9	Dolomites of the Wumishan Formation, the Yangzhuang Formation, and the Gaoyuzhuang Formation
	1454.28	1459.1						
	1551.82	1553.85						
	1569.28	1573.08						
	1677.15	1684.37						
	1714.81	1724.14						
	2018.57	2020.43						
Impregnated bottom-jet coring bits	1836.23	1842.18	20.21	14.95	64.58	0.31	74.0	Dolomite of the Gaoyuzhuang Formation
	1919.00	1922.77						

	2017.81	2018.57						
	2156.05	2160.66						
	2225.68	2230.8						
Impregnated coring bits	2386.92	2391.47	9.65	5.6	30.42	0.32	58.0	Dolomite of the Gaoyuzhuang Formation
	2506.00	2511.10						
Total			64.20	39.74	220.13	0.29	61.9	

The impregnated bottom-jet coring bit drilled into the dolomite of the Gaoyuzhuang Formation, with total footage of 20.21 m and a core recovery rate of 74.0%, is the highest core recovery rate among the three kinds of bits. As for the other two kinds of bits, they have a similar core recovery of 55.9% and 58.0%. In terms of total footage, polycrystalline coring bit drilled the Wumishan Formation, the Yangzhuang Formation, and the Gaoyuzhuang Formation, with total footage of 34.34 m. And the impregnated coring bit was drilled into the dolomite of the Gaoyuzhuang Formation, with total footage of 9.65 m, as shown in Figure. 4.

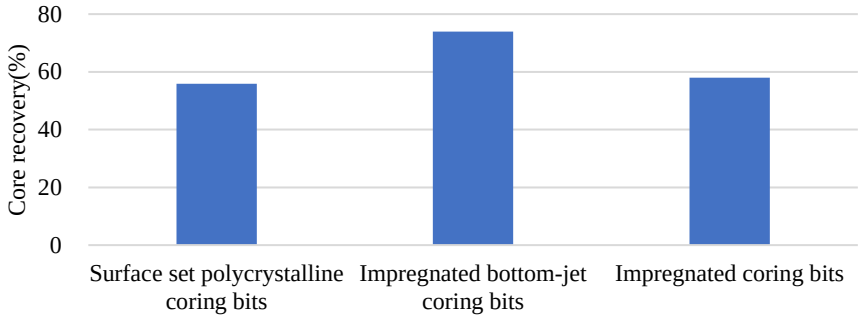


Figure. 4 Core recovery of three kinds of bits drilling the Gaoyuzhuang Formation

The thermal reservoir has developed fissures and karsts, with a high degree of weathering and broken cores in local formation (Guo Sasa et al., 2020; Liao Yuansu et al., 2021), resulting in a low core recovery. To increase the coring rate during drilling, it is usually necessary to reduce the excessive erosion of the drilling fluid and the disturbance of the drilling tools to the core, further reducing the degree of core breakage and avoiding the core plugging.

Compared with the other two drill bits, the impregnated bottom-jet coring bit adopts the design with water eyes at the end of t the bit lip, where there are 6 groups of 9 mm water eyes. Compared with the common bit nozzle structure, the bit provides both water-resisting properties and the water flow channel of the drilling fluid, avoiding the direct erosion and disturbance of the core by the drilling fluid and improving the integrity of the core.

3.3 Analysis of Comprehensive Drilling Technology

The technical indicators of comprehensive drilling in the fourth section are listed in Table 7. The comprehensive drilling footage of the roller bit driven by the rotary table is 575.10 m, the average ROP is 0.86 m/h, and the average return length is 38.34 m. The comprehensive drilling footage of the roller bit driven by the screw motor is 503.58 m, the average ROP is 1.41 m/h, and the average return length is 50.36 m. The average ROP and rounds length of screw motor compound drilling are higher than these of rotary drilling, which are increased by 64.0% and 31.4%, respectively.

Table 7 Technical indicators of comprehensive drilling in thermal reservoirs in the fourth section

Drilling technology		Well depth /m		Footage/m	Round trip	ROP/ (m/h)	Average of rounds length /m	Formation
		From	To					
Comprehensive drilling	Roller bit drilling driven by the rotary table	1350.00	1353.76	3.76	15	0.86	38.34	Dolomite of the Wumishan Formation
		1359.04	1454.28	95.24				
		1459.10	1551.82	92.72				
		1553.85	1569.28	15.43				
		1573.08	1677.15	104.07				
		1684.37	1714.81	30.44				
		1724.14	1739.65	15.51				Dolomite of the Yangzhuang Formation
		1825.00	1836.23	11.23				Dolomite of the

		1842.18	1919.00	76.82				Gaoyuzhuang Formation
		1922.77	2017.81	95.04				
		2083.98	2100.30	16.32				
		2154.13	2156.05	1.92				
		2230.80	2243.43	12.63				
		2358.00	2361.97	3.97				
		Subtotal		**575.10**				
	PDC bit drilling driven by the rotary table	1739.65	1757.87	18.22	1	0.53	18.22	Dolomite of the Yangzhuang Formation
		Subtotal		**18.22**				
	Roller bit drilling driven by the screw motor	1757.87	1768.00	10.13	10	1.41	50.36	
		1768.00	1825.00	57.00				Dolomite of the Gaoyuzhuang Formation
		2020.43	2083.98	63.55				
		2100.30	2154.13	53.83				
		2160.66	2225.68	65.02				
		2243.43	2358.00	114.57				
		2361.97	2386.92	24.95				
		2391.47	2472.01	80.54				
		2472.01	2506.00	33.99				
		Subtotal		**503.58**				
Total				**1096.90**	26	1.04	42.19	

Well depth of 1825.95~2361.97 m and 1768.00~2506.00 m in the fourth section both are dolomite formations of the Gaoyuzhuang Formation. The same drilling fluid parameters and drilling parameters were used, but different drilling methods including rotary table rotary drilling and screw motor compound drilling were adopted respectively. Figure.5 shows the comparison of ROP in each round with the two different drilling methods. The screw motor compound drilling efficiency is significantly higher than that of the rotary table drilling when drilling in the same type of formation. According to statistics, the ROP of screw motor compound drilling and rotary table drilling are 1.37 m/s and 0.85 m/s, respectively.

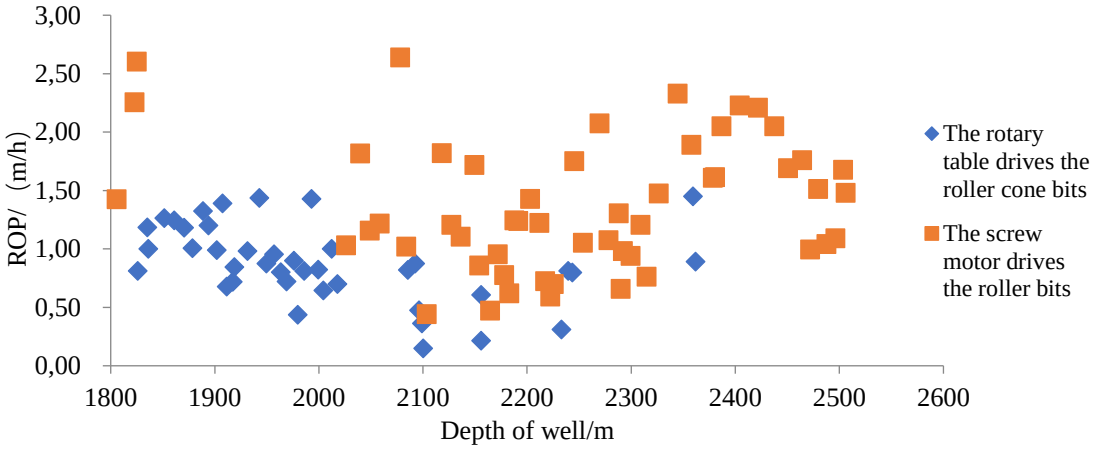


Figure. 5 ROP of comprehensive drilling in the Gaoyuzhuang Formation

Increasing the ROP can be achieved by increasing the WOB or RPM, according to the literature (Tan Fenglin, 2017). However, by limiting formation, drilling tools, and other factors in actual drilling, excessive WOB may cause downhole safety accidents. So, it is more scientific to increase the ROP by increasing the rotational speed. The rotary table rotates the drill string to transmit torque to drive the cone bit. Due to the length of the drill string being more than serval kilometers, there is a great input power loss in the transfer process, resulting in a certain decrease in the ROP with the increase of well depth.

The screw drilling tool is a volumetric downhole power drilling tool that uses drilling fluid as power and converts liquid pressure energy into mechanical energy (Tan Xianfeng et al., 2021). Compared with the low rotational speed of the rotary table, the screw drilling tool provides high rotational speed, near-bit driving force, and effective power for the drill bit to break the rocks quickly, by converting the liquid pressures energy into mechanical energy, while effectively reducing the friction and the power loss between the well wall and the drilling tool. Compound drilling is the combination of a rotary table and a screw motor. The rotational speed of the roller cone bit comes from the superposition of the rotational speed of the rotary table and the screw motor, which can achieve low

drilling pressure and high rotational speed drilling, playing a key role in improving the ROP. Therefore, the ROP of the screw motor compound drilling is 61.2% higher than that of the rotary drilling in dolomite stratum of the Gaoyuzhuang Formation.

4. CONCLUSION

(1) The cuttings and cores of the Yangzhuang Formation were successfully obtained by coring drilling, effectively distinguishing the dolomite boundary between the thermal reservoirs of the Wumishan Formation and the Gaoyuzhuang Formation. The buried depth of the Wumishan Formation is 796.00~1702.93 m, and its lithology is mainly dolomite and argillaceous dolomite; The buried depth of the Gaoyuzhuang Formation is 1768.00~2511.10 m (not penetrated), and its lithology is mainly dolomite, siliceous dolomite, argillaceous dolomite, and flint strip dolomite.

(2) The core recovery rates of surface set polycrystalline coring bits, impregnated bottom-jet coring bits, and impregnated coring bits were compared during the coring drilling in the fourth well section. It can be concluded that the core recovery rate of the impregnated bottom-jet coring bit is the highest, reaching 74.0%.

(3) During the comprehensive drilling of the fourth well section, the ROP and the rounds length of the compound drilling with roller cone bit driven by screw motor were both higher than these of the rotary table drilling, which were increased by 64.0% and 31.4%, respectively, ROP increased was achieved in this exploration.

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