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Key geological factors greatly related to drilling design of karst geothermal reservoir in Xiong'an New Area

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ABSTRACT

Xiong'an New Area is a key area for the development and utilization of high-quality karst geothermal reservoirs in Bohai Bay Basin. Based on the regional geological background, 2-D seismic data and 131 well loggings, three key geological factors, including reservoir-caprock assemblage, caprock characteristics, and karst geothermal reservoir characteristics, were studied in detail, and comprehensive evaluation of favorable zones was carried out. The results showed that two reservoir-caprock assemblage patterns were identified, the Eogene-Jxw is distributed on the northern slope belt of the Niutuozhen Bulge, where the top surface burial depth of Jxw is below 1 500 m, and the Neocene-Jxw is distributed on the Niutuozhen Bulge and the Rongcheng Bulge, where the top surface burial depth of Jxw is above 1 500 m. The Neocene caprock has poor diagenesis and is unstable. As a result, borehole wall sloughing is more likely to occur in thick poorly-cemented sandstone intervals of the Niutuozhen Bulge and the Rongcheng Bulge, which is mainly developed in the depth range of 450-700 m and 800-1 000 m. The geothermal reservoir property is in the longitudinal and horizontal zonation. Burial-hill-type karstification controls the formation of high quality reservoirs of Jxw in Xiongan New Area, and first grade and second grade geothermal reservoirs mainly develope within a thickness of 350 m. The optimized thickness of production zone decreases from the Rongcheng Bulge to the northern slope belt of the Niutuozhen Bulge to the Niutuozhen Bulge, the results are 1 000 m, 880 m, and 500 m, respectively. The area of Rongcheng Bulge and Niutuozhen Bulge with top reservoir surface burial depth of 1 250~1 500 m is the most favorable exploration and development zone because of the moderate burial of the thermal reservoir, better reservoir property, stronger diagenesis, and less drilling risk. The results can provide guidance for the successful drilling of karst geothermal reservoirs and the effective development of geothermal resources in Xiongan New Area.

1. INTRODUCTION

Xiong'an New Area is a key area for the development and utilization of geothermal resources of karst geothermal reservoirs in the Bohai Bay Basin. By the end of 2020, 131 geothermal production wells and injection wells have been drilled, and the cumulative geothermal heating area has exceeded $7 \times 10^6 m^2$. The regional thermal reservoir is the karst thermal reservoir of Wumishan Formation of Mesoproterozoic Jixian System, with the individual producer water rate of 55~158 m^3/h and the wellhead temperature of 42~90 ℃. The thermal reservoir of Wumishan Formation is characterized by wide distribution, shallow burial, great physical properties, large water production rate, and high water temperature, and has a broad development prospect. In geothermal well drilling process, engineering accidents such as lost circulation, stuck drilling and borehole collapse often occur, affecting the smooth implementation of geothermal drilling. The well history data of five accident wells completed from 2017 to 2019 shows that the accidents are caused by geological risks. The reasons are summarized as follows: the combination type of thermal reservoir and thermal cap rock is not clear, resulting in inaccurate completion of the stuck layer in the site; The unclear understanding of the characteristics and distribution rules of the thermal caprock leads to insufficient prediction of drilling risks such as wellbore instability and collapse; The lack of systematic research on the internal development law of the reservoir results in the waste of drilling footage. Therefore, carrying out targeted geological research on the existing engineering problems is the key problem to be solved urgently for the large-scale development and utilization of geothermal resources in Xiong'an New Area.

In combination with 2D seismic data, and drilling data and logging data of 131 geothermal wells, types and distribution characteristics of reservoir-caprock assemblage in Xiong'an New Area were studied systematically, characteristics of caprock in different regions and characteristics of Wumishan Formation karst thermal reservoir were analyzed, main water producing zones in different zones were identified, the favorable zones were comprehensively evaluated. The paper provides guidance for the large-scale development and scientific utilization of geothermal resources in Xiong'an New Area.

2. OVERVIEW OF REGIONAL GEOLOGY

2.1 Regional structure location

Xiong'an New Area is located in the middle of Jizhong Depression in the Bohai Bay Basin, covering Xiongxian County, Rongcheng County, Anxin County and some surrounding areas in Hebei Province geographically. At present, the majority of production wells in Xiong'an New Area are drilled in Xiongxian County and Rongcheng County. Therefore, the east side of the study area is bounded by the NE-oriented Niudong fault, and the south side is bounded by the NE- oriented Niunan fault, Anxinnan fault and Xushui fault. The structural units include Rongcheng bulge, Niubei slope and Niutuozhen uplift（see Figure 1）.

2.2 Stratigraphic characteristics

Based on the interpretation of two-dimensional seismic data, the Archean metamorphic basement, carbonate buildup of shallow platform facies-dominated Mesoproterozoic, and continental clastic rocks-dominated Cenozoic are developed in the study area from bottom to top.

The Wumishan Formation of Jixian System is the main production zone of karst thermal reservoirs in the study area. The overlying caprock can be divided into regional caprock and local caprock according to attitude of stratum and degree of sealing. The Eogene is the local caprock of the karst thermal reservoirs, and the Neogene and Quaternary are the regional caprock of the karst thermal reservoirs. The thermal reservoir lithology of the Wumishan Formation is mainly argillaceous dolomite and siliceous dolomite, with a thermal conductivity of 5.109 W/(m·K), which is a good thermal conductivity layer. The Quaternary and Neogene lithology is mainly sandy clay and sandy conglomerate, and the thermal conductivity is only 1.907 W/(m·K); The local caprock is mainly composed of sandstone and mudstone, and the thermal conductivity is 2.315 W/(m·K). These two formations are good thermal barriers with poor thermal conductivity, which cover the karst thermal reservoir of the Wumishan Formation and play a good role in thermal sealing.

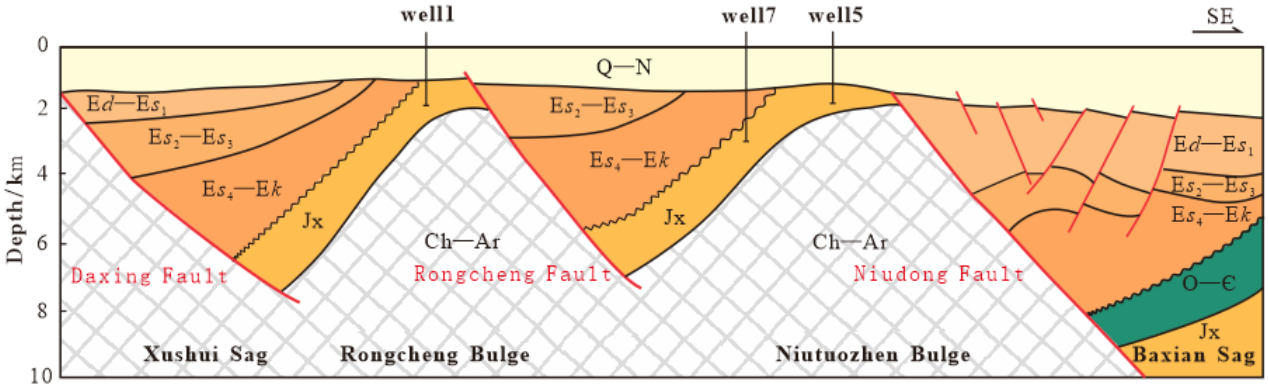

Figure 1: NW-SE trending structural geological section crossing the Rongcheng Bulge, the northern slope belt of the Niutuozhen Bulge, and the Niutuozhen Bulge

2.3 Evolution of karst thermal reservoir

The formation of the Wumishan Formation karst thermal reservoir in Xiong'an New Area is mainly controlled by the regional tectonic-sedimentary evolution process of the Bohai Bay Basin, which mainly includes three stages, namely, the marine carbonate deposition and the overall uplift type interlayer karstification stage in Lingyuan period, the Indosinian-Yanshan buried hill type karstification stage, and the early Himalayan buried hill type karstification and thermal reservoir formation stage controlled by the extension fault.

(1) Marine carbonate deposition and the overall uplift type interlayer karstification stage in Lingyuan period. In the Middle Proterozoic and Early Paleozoic, huge platform-type marine carbonate deposits were developed on the metamorphic basement. The Lingyuan movement, which occurred between the middle and late Proterozoic, uplifted and exposed the Wumishan Formation, meanwhile mainly developing interlayer karstification.

(2) Indosinian-Yanshanian buried-hill type karstification stage. The Indosinian-Yanshan movement controlled the formation of the Wumishan Formation karst thermal reservoir in Xiong'an New Area, and the strong compression caused the uplift and folding of the deeply buried huge carbonates in the study area, forming a paleogeomorphic elevation difference of more than 2000 m in the region. The bedrock in the study area was subject to intense weathering and denudation, and the Wumishan Formation was exposed to the surface. Due to the long interval, the buried hill type karstification in the Wumishan Formation was very developed.

(3) Early Himalayan buried hill type karstification and thermal reservoir formation stage controlled by the extension fault. Due to the subduction and retreat of the Paleo-Pacific plate in the late Mesozoic and Paleogene, the tectonic system has changed significantly, and the lithosphere in the eastern part of the North China craton has been thinned on a large scale, and the study area has experienced strong extensional faulting activities. The inversion of the tectonic stress field has not changed the palaeogeomorphic characteristics of the study area. Under the control of Niudong extensional fault, the fault depression in the eastern fault depression area made the western fault convex area show a relative uplift in the palaeogeomorphology. The Wumishan Formation in the study area continued to suffer from weathering, denudation and fresh water leaching, and the buried hill type karstification in the karst geothermal reservoir was further enhanced. The fault depressions were filled with relatively thick clastic deposits. The thermal reservoir of the Wumishan Formation developed organic acid karstification related to the maturity of the source rock, and the hydrothermal karstification related to volcanic activity, which developed along the fault.

3. KEY GEOLOGICAL ELEMENTS

3.1 Reservoir-caprock assemblage

The overlying caprock of the Wumishan Formation karst thermal reservoir in the study area is the Cenozoic clastic rock, which is affected by the differential denudation of strata caused by the Indosinian-Yanshan movement and the differential rise and fall of bedrock caused by the Himalayan movement during the extensional fault depression period. The residual state of the Wumishan Formation karst thermal reservoir in different structural positions in the study area is different from the development degree of the later thermal cap, and the thermal reservoir-caprock assemblage types developed in different structural positions are different. Combined with logging data and two-dimensional seismic data, the study area has identified two types of reservoir-caprock assemblages, namely, Neogene - Wumishan formation (N-Jxw) and Paleogene - Wumishan formation (E-Jxw).

The distribution of the reservoir-caprock assemblages in the study area has a certain correspondence with the buried depth of the top structure of the Wumishan Formation.

For the karst thermal reservoir of Wumishan Formation in Xiong'an New Area, the three-spud-in hole structure can meet the requirements of safe drilling. The first spud-in hole is 400~450m deep to meet the requirements of sealing off the surface loose formation and running water pump; In the second spud, drilling through the weathered crust and entering into the Wumishan Formation shall not exceed 2m, and the thermal cap layer on the Wumishan Formation shall be sealed, creating conditions for safe drilling in the third spud, with the focus on strictly controlling the buried depth of the weathered crust and the bottom of the Wumishan Formation; In the third spud-in to the design well depth, the screen completion method is often used to exploit geothermal resources in the whole water intake interval of the Wumishan Formation. At present, the thickness of water intake interval of Wumishan Formation in Xiong'an New Area is between 550 and 1400 m.

According to the buried depth of the top of the Wumishan Formation in the study area, the variation characteristics of the depth of the second spud of geothermal drilling at different structural positions can be basically determined, and the well bore structure design can be optimized to improve the drilling efficiency. On the whole, the mid-completion depth of the second spud of geothermal drilling in Niutuozhen bulge is 600~1500 m, the mid-completion depth of the second spud of geothermal drilling in Rongcheng bulge is 700~1500 m, and the mid-completion depth of the second spud of geothermal drilling in Niubei Slope is 1500~3000 m.

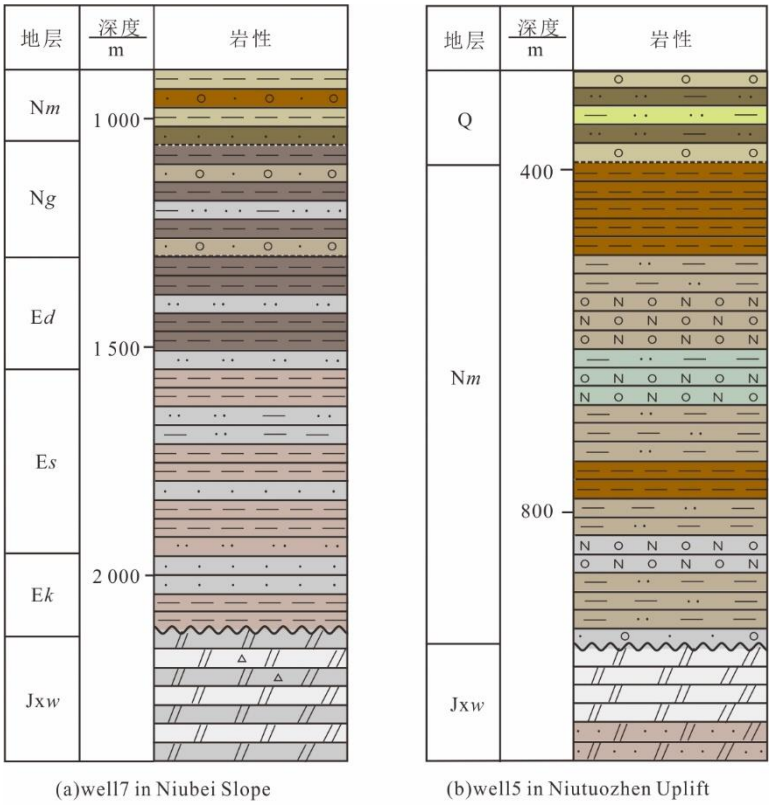

Figure 2: Lithological columns of the reservoir-caprock assemblage in typical wells

3.2 Caprock characteristics

(1) The Neocene caprock

Two sets of strata of Minghuazhen Formation and Guantao Formation are developed in Neogene in the study area.

A set of stable brown mudstone is developed at the top of Minghuazhen Formation, and the upper segment develops the interbedding of light grayish brown and grayish green pebbly medium and coarse sandstone and variegated silty mudstone. The sandstone particles are relatively coarse, diagenesis is weak, the degree of cementation is very low, and there are few cements, which are in the form of loose sand. The gravel is mainly composed of feldspar, followed by quartz; The lower section mainly develops brownish red mudstone, silty mudstone, light gray coarse sandstone and pebbly sandstone with different thickness interbedding, which are pure mudstone, poorly sorted sandstone, argillaceous filling, extremely low cementation, and loose sand. According to the division and comparison results of the regional geothermal well thick sand layer, the Minghuazhen Formation in the study area develops six stably distributed thick sand layers. The thickness of the main sand body from the bottom to the top is 30~40, 10~15, 20~28, 10~15, 40~55, 12~20 m, mainly distributed in 450~700 and 800~1000 m (mainly because the buried depth of the floor of the existing geothermal well drilling in Minghuazhen Formation is mostly 800~1000 m).

The Guantao Formation mainly develops purplish red mudstone mixed with light gray coarse sandstone, pebbly sandstone and glutenite, and a relatively stable set of variegated glutenite is developed at the bottom. Sandstone, pebbly sandstone and glutenite are poorly sorted, with argillaceous cementation and low cementation degree. The conglomerate is mainly composed of quartz and flint. The conglomerate is hard, poorly sorted and loosely cemented.

(2) The Eogene caprock

Dongying Formation, Shahejie Formation and Kongdian Formation are developed in Paleogene. The Dongying Formation develops purplish red mudstone mixed with gray sandstone and siltstone deposits, with certain cementation. The Shahejie Formation is divided into four sections. The upper part of Shahejie Formation is dark red mudstone with sandstone, the middle part is mudstone with oil shale, limestone, etc., and the bottom part is sandy conglomerate; The upper part of the second member of Shahejie Formation develops greyish red mudstone and gypsum mudstone, and the lower part is mostly sandy conglomerate; The third member of Shahejie Formation is characterized by a set of dark mudstone deposits rich in organic matter; The bottom of Es4 is characterized by a set of gravelly sandstone with stable distribution. The lithology of Kongdian Formation is mainly purplish red mudstone and red sandstone, mixed with igneous rocks, with a small amount of dark mudstone in the middle and upper part. The sandstone cementation is strong and relatively dense.

(3) Drilling geological risk tips

The study of the lithological change characteristics of the overlying thermal caprock of the Wumishan Formation can not only guide the completion of the stuck layer on the site, but also predict the geological risks in the drilling process in different areas in advance, and take preventive and response technical measures for possible emergencies.

Paleogene sandstone has strong diagenesis, relatively dense cementation, and stable contact between thermal reservoir and thermal cap; Neogene sandstone has weak diagenesis, less and mostly argillaceous cementation, loose cementation, and unstable contact between thermal reservoir and thermal cap. In the study area, 80% of the borehole collapse drilling accidents occurred in the Neogene loose thermal cap in the structural uplift area (the remaining 20% of the borehole collapse drilling accidents occurred in the thermal reservoir of the Wumishan Formation with karst fractures), and no similar drilling accidents have occurred in the structural slope with the development of the Paleogene thermal cap. Compared with Niubei slope, Niutuozhen uplift and Rongcheng bulge are more prone to drilling engineering accidents. The two depths of 450~700 m and 800~1000 m mainly develop thick loose sandstone deposits, which are prone to wellbore collapse; Large sets of mudstone deposits are developed in other depth sections, which are prone to shrinkage and sticking accidents.

In addition, after the preliminary determination of the mid-completion depth of the second spud based on the characteristics of the top buried depth of the Wumishan Formation, it is necessary to pay close attention to the site cuttings logging during the drilling of geothermal wells, and according to the characteristics of the Neogene thermal cap marker layer, block the target layer, avoid the second spud drilling of the Wumishan Formation, and reduce the risk of thermal cap instability collapse, sticking and other accidents caused by the loss of return and the sudden drop of wellbore pressure.

Bu et al. carried out simulation and experimental studies on building heating using DBHE in Qingdao, China, and indicated that the extracted thermal output per meter well depth increases with depth, as shown in, e.g. X.B. Bu et al (2019) and X.B. Bu et al (2019). In the oil and gas industry, the technology of drilling directional well is mature, e.g. E. Tuna et al (2020) and P. Andrés et al (2021). Enlightened by this, a multi-directional wells deep borehole heat exchanger (MDWDBHE) system is proposed in this study, which is implemented by drilling directional wells at the middle and lower part of vertical well with high q_L in order to reduce the costs of drilling and completion by sharing the vertical well with low q_L and improve the thermal output as well as shorten the payback period.

3.3 Reservoir characteristics

The Wumishan Formation has experienced multiple stages of tectonic uplift, such as Indosinian, Yanshanian and early Himalayan, and has been subjected to weathering and denudation for a long time. Buried hill karst is sufficient, forming a set of weathered crust reservoirs with stable development and good reservoir property on its top. Among them, the vertical seepage zone develops vertical dissolution holes and high angle dissolution fractures with poor connectivity, and the horizontal subsurface flow zone develops horizontal dissolution caves and fractures with strong connectivity. Therefore, the karst thermal reservoir at the top of the target interval has better reservoir performance.

The lateral distribution of karst heat reservoir in the study area has obvious differences, which is determined by the different genetic models of karst heat reservoirs in different structural parts.

Taking well 2 and well 3 of Rongcheng bulge as an example, there are two types of genetic models of buried hill karst and fault karst in the class I karst fracture interval. Among them, the class I thermal reservoirs of buried hill karst genesis are mainly distributed within the upper depth of 300 m of the target layer, and the class I thermal reservoirs of fault karst genesis are relatively limited, mainly distributed in the depth of 1100~1400 m of Well 2. class II thermal reservoir is characterized by bedding distribution and obvious stratification, which is caused by interlayer karstification. Among them, the lateral connectivity of interlayer karst thermal reservoir in the second and first member of the fog is medium, while the connectivity of the third member of the fog is relatively poor. Niutuozhen bulge, taking Well 4 and Well 6 as examples, class I and II thermal reservoirs are mainly distributed in the depth of 350m above the target layer, which is caused by buried hill karst, and other karst processes are relatively undeveloped.

Based on the above reservoir evaluation results of Well 7 in Niubei Slope, the lateral comparison results of the reservoir show that the formation of high-quality thermal reservoirs in Wumishan Formation in Xiong'an New Area is controlled by buried hill karst, and the buried hill karst thermal reservoirs developed in the study area are mainly developed within the range of 350 m from the unconformity surface of Wumishan Formation, which is determined by the palaeogeomorphic characteristics of the study area which has been in the karst highland during the tectonic movement of Mesozoic and Cenozoic, The development of thermal reservoir is characterized by layer-penetrating property and excellent horizontal connectivity, which is a good horizontal migration channel for groundwater; Fault karstification mostly forms class I and class II thermal reservoirs. The distribution of thermal reservoirs is controlled by faults. The study area can be developed, and the lateral connectivity of thermal reservoirs is poor. However, the thermal reservoirs near the fault zone are good, and they are good vertical migration channels for groundwater; Interlayer karstification mostly forms class II and class III thermal reservoirs. The development of thermal reservoirs is controlled by sedimentary microfacies and diagenetic facies, which are distributed along the layer with medium horizontal connectivity, mainly distributed in Niubei slope and Rongcheng bulge.

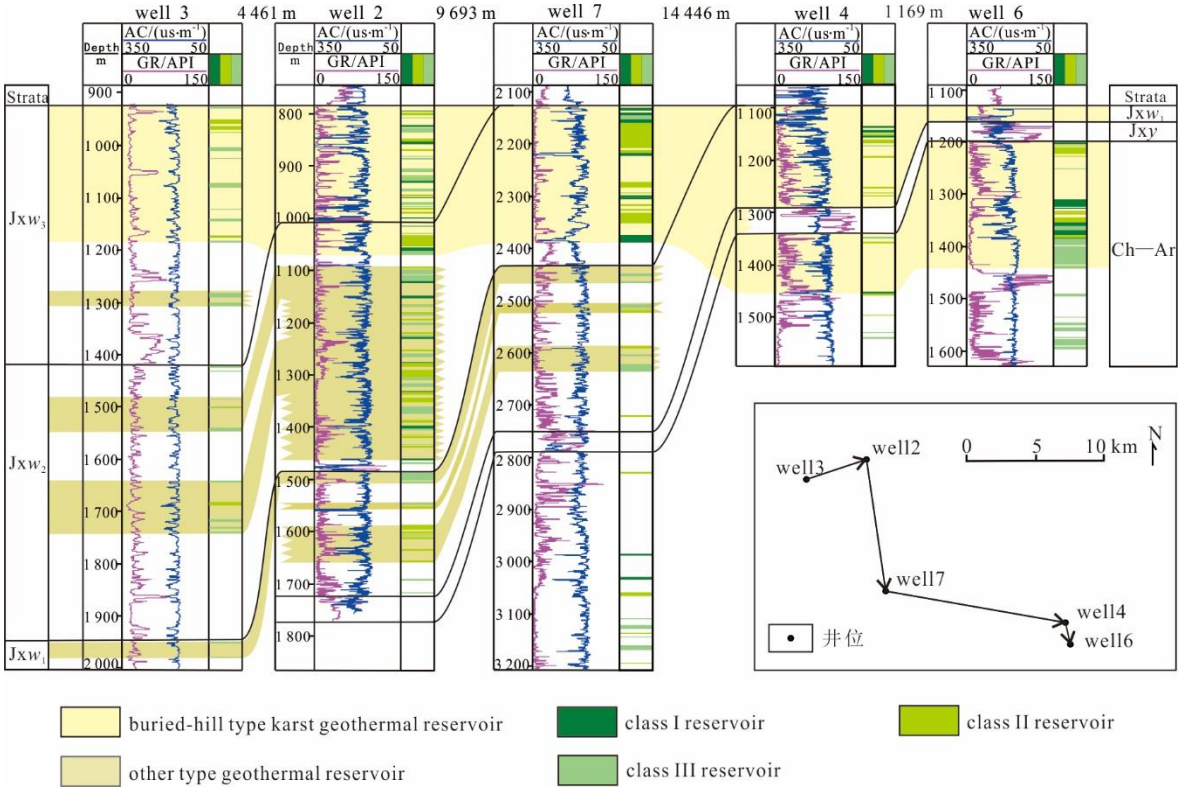

Figure 3: NW-SE oriented geothermal reservoir correlation profile in the study area

4. FAVORABLE ZONE OPTIMIZATION

Based on the research results of three key geological factors, the optimization of favorable zones in the study area was carried out. N-Jxw combination is preferred for the combination type of thermal reservoir and thermal cap. Compared with E-Jxw combination, N-Jxw combination has a longer sedimentary gap between the thermal cap and the thermal reservoir. The karst thermal reservoir of Wumishan Formation experienced stronger weathering and denudation. The buried hill karst in the thermal reservoir is extremely developed, and the reservoir physical properties are good. In terms of caprock, Neogene caprock with a buried depth of 1250~1500 m is preferred. 80% of wellbore collapse drilling accidents in the study area occurred in the Neogene loose thermal caprock in the structural uplift area, and the accidents occurred in the loose sandstone section above 1250m. The burial depth of the lower part of the Neogene system is relatively moderate (1250~1500 m), with strong diagenesis and dense cementation, which is not prone to drilling engineering accidents. Therefore, the lower part of the Neogene system is a high-quality cap rock in the study area.

Three types of favorable zones are divided in the study area. class I favorable zones are distributed in the bulge area with the buried depth of 1250~1500 m on the top surface of the thermal reservoir, and the thermal reservoir-heat cap rock combination of the Neogene-Jixian Wumishan Formation is developed. The thermal caprock in class I favorable area has strong diagenesis, low drilling risk, relatively shallow thermal reservoir, good physical properties, and good overall development potential. It is the most favorable exploration and development area. class II favorable zones are distributed in the bulge area with the buried depth of the top surface of the thermal reservoir less than 1250m, and the thermal reservoir-heat cap rock combination of the Neogene-Jixian Wumishan Formation is developed. The thermal caprock in the class II favorable area has general diagenesis and certain drilling risks, but the thermal reservoir is shallow buried, good physical properties, large distribution area and rich geothermal resources. It is a high-quality geothermal resource development area for geothermal heating and utilization. class III favorable zones are distributed in the slope area where the buried depth of the top surface of the thermal reservoir is more than 1500 m and the total footage of the optimized water intake interval is less than 3000 m, and the combination of the thermal reservoir and caprock of the Paleogene-Jixian Wumishan Formation is developed. The thermal caprock in class III favorable area has strong diagenesis, low drilling risk, relatively deep thermal reservoir and medium physical properties, and is not considered as a short-term exploration and development target.

5. CONCLUSIONS

(1) Two types of reservoir-caprock assemblage are developed in Xiong'an New Area. The Neogene-Wumishan Formation reservoir-caprock assemblage is developed in the Niutuozhen uplift and Rongcheng bulge with the buried depth of less than 1500 m on the top of the Wumishan Formation, and the mid-completion depth of the second geothermal drilling is 600~1500 m and 700~1500 m respectively; Niubei slope with buried depth of more than 1500m at the top of the Wumishan Formation is developed in the Paleogene-Jixian Wumishan Formation combination, and the middle and final depth of the second spud of geothermal drilling is 1500~3000 m.

(2) The contact between Niutuozhen uplift and Rongcheng bulge in Xiong'an New Area is unstable, which is more prone to drilling engineering accidents than Niubei slope. Among them, thick loose sandstone is mainly developed at the depth of 450~700 m and 800~1000 m, which is prone to wellbore instability and collapse, and large sets of mudstone are developed at the other depth sections, which is prone to sticking.

(3) The karst thermal reservoir of Wumishan Formation in Xiong'an New Area has obvious vertical stratification and plane zoning. Buried hill karst controls the formation of high-quality thermal reservoir in Xiong'an New Area, which is mainly developed within 350 m from the unconformity surface of Wumishan Formation.

(4) The zone with a buried depth of 1250~1500 m on the top surface of the thermal reservoir around the Rongcheng and Niutuozhen bulges is the most favorable exploration and development area in Xiong'an New Area due to its moderate thermal reservoir burial, good reservoir physical properties, strong diagenesis of the thermal cap and low drilling risk.

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