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Geothermal characteristics and potential evaluation of sandstone thermal storage in Kaifeng Sag

He Tingting, Wang Xinwei, and Wei Guangren

No. 263, Middle North Fourth Ring Road, Haidian District, Beijing

htt10502@163.com

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ABSTRACT

The analysis of the characteristics of the internal geological elements of the geothermal system is the basis for establishing its genetic model, and it is also the basis for the later study of the occurrence characteristics of geothermal resources and the evaluation of resources. Based on previous research results and geothermal drilling data in the area, this paper analyzes and studies the main geological factors of the geothermal system in the Kaifeng Sag, and builds a conceptual model of the genesis of the geothermal system. On this basis, the geothermal resources are finely evaluated. The results show that the sandstone thermal reservoir of Guantao Formation is the main thermal reservoir in the study area. The floor depth of the thermal reservoirs in Guantao Formation is between 1600-2200m, the average thickness of the reservoir is about 362m, the porosity is between 16%-32%, and the reservoir-thickness ratio can reach up to 67%. The water temperature of the geothermal wells is about 53-82℃. The upper Quaternary and Minghuazhen Formation strata form a good cap layer. The heat source comes from the high geothermal value background of the Cenozoic rift basin, about 56-60mW/m2. The Xinxiang-Shangqiu fault in the south is favorable channels for the upward transportation of deep heat. The geothermal system receives the atmospheric precipitation replenishment from the western mountains in the west. The evaluation results of the geothermal resources in the Kaifeng Depression show that the sandstone geothermal system resources of the Guantao Formation are more than 2647.68×108GJ, the annual geothermal resources that can be exploited are 5.29×108GJ equivalent to 180.73×104t t of standard coal. The annual exploitation of geothermal resources can meet the heating area over 6386×104 m2, and the development potential is great.

1. INTRODUCTION

With the accelerating pace of "carbon peaking" and "carbon neutrality", geothermal, as a clean and renewable resource, has attracted more and more international attention. Up to now, our country's geothermal energy development and utilization area ranks first in the world. Kaifeng, Xinxiang and Zhengzhou, which are the "2+26" cities of the Beijing-Tianjin-Hebei air pollution transmission channel, are all located in the Kaifeng depression. The development and utilization of thermal energy in the Kaifeng depression is relatively early. At present, the development and utilization of geothermal resources have been carried out in Kaifeng City, Zhengzhou City and Xinxiang City. The main mining horizons are the Cenozoic thermal reservoirs, especially the Neogene Guantao Formation sandstone thermal reservoirs. The study area has the characteristics of stable deposition, continuous distribution, medium burial depth, high permeability and geothermal gradient. Advantageous target layer for sandstone thermal storage development. The genetic mechanism analysis of the sandstone thermal reservoir of Guantao Formation in Kaifeng Sag will help to deeply evaluate the geothermal resource potential of sandstone thermal reservoir of Guantao Formation in Kaifeng Sag, and provide guidance for the exploration and development of geothermal resources in Kaifeng Sag.

2. REGIONAL GEOLOGICAL FEATURES

The Kaifeng Sag is located in the central-northern area of Henan Province. It is a superimposed basin of Mesozoic and Cenozoic sediments, and is distributed in a near east-west direction along both sides of the Yellow River. The Kaifeng sag is structurally located in the southeastern corner of the Jiyuan-Kaifeng sag in the North China Tai depression [Qi Yufeng (2007,2009), Gao Jinghong(2010), Wang Xianguo(2012)], adjacent to the Taikang Uplift in the south, Minquan Sag in the east, and adjacent to the Bohai Bay Basin by the Xinxiang-Shangqiu fault in the north. The northwestern part is adjacent to the Wuzhi uplift, and is affected by the Xinxiang-Shangqiu fault, forming a sag-shaped depression shallow in the south and deep in the north. The Kaifeng sag has strong tectonic fractures and relatively developed faults. The regional active faults are mainly NW, NW and NE trending, which control the formation of the sag and the development of the Mesozoic and Cenozoic strata. The sag is mainly controlled by 6 faults. Among them, the Pangusi fault, Xinxiang-Shangqiu fault, Yangzhuang fault and Zhongmu fault are the boundary faults of the sag, the Doumen fault is the boundary fault of the north-south part of the sag, and the Kaifeng fault is the boundary fault of the internal sub-sag.

The Kaifeng sag is affected by the regional structure, the structural high part in the Indosinian period was uplifted and denuded, the northern boundary of the sag was strongly fractured, and the northern Jurassic strata were thicker. The tectonic movement in the Yanshan period caused the stratum to be uplifted and denuded, and the Cretaceous strata were missing. The Jurassic was only partially developed and the thickness was thin, but the thicker Triassic strata were retained. During the Himalayan period, the whole area subsided into the depression period, the boundary fault activity was weak, the Neogene stratum was thick, and was in unconformable contact with the underlying Paleogene strata. The strata of Kaifeng Sag develop Cambrian-Ordovician, Carboniferous-Permian, Mesozoic, Paleogene, Neogene and Quaternary in order from old to new (Fig. 1). It is controlled by faults and has the characteristics of large lithological changes. The main thermal reservoir in Kaifeng Sag is the Neogene Guantao formation pore-type sandstone thermal reservoir. The bottom floor is buried at a depth of 1600-2000m, with moderate burial depth and well-developed thermal reservoir. The lithology is relatively coarse, and it is not easy to produce sand. The water temperature is 50-90 °C, and the deposition is stable. , which is the main thermal reservoir formation in this area.

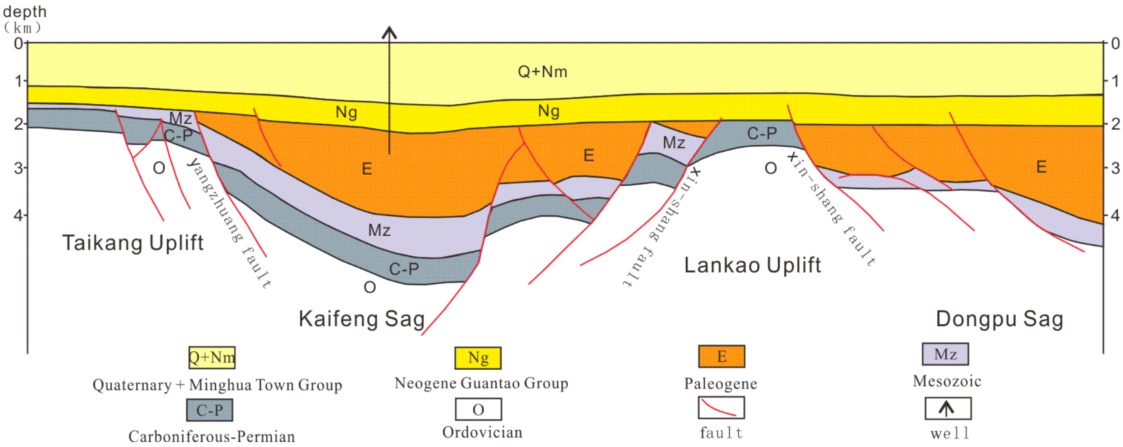

Figure 1 Geological profile of Kaifeng Sag

3. CHARACTERISTICS OF GEOTHERMAL TEMPERATURE

Geothermal heat flow is the most direct display of deep earth thermodynamics to shallow geothermal heat, and is the most important representation of the geothermal field. It reflects the thermal state and energy balance of the lithosphere, and contains rich geological and geodynamic information [Jiang Guangzheng, et al (2016), Zuo Yinhui, et al (2013)]. The distribution characteristics of heat flow are closely related to many factors, such as structure, magmatic activity, lithosphere morphology, and lithosphere physical properties [Li Zongxing, et al (2015), Wang Jiyang, et al (2012), Lei Xiaodong, et al (2018), Huang Xu, et al (2021)]. Geothermal heat flow is an important parameter in the exploration and evaluation of geothermal resources [Jacek M, et al (2014)].

In sedimentary basins, the terrestrial heat flow value generally shows that the bedrock bulge area is higher than the depression area. The bedrock bulge area has high thermal conductivity and low thermal resistance, and heat is collected from both sides to the bedrock bulge area, resulting in heat flow. The average terrestrial heat flow value of Kaifeng Sag and Dongpu Sag is 58.4MW/m2, and the average terrestrial heat flow value of Neihuang Uplift and Taikang Uplift is greater than 60MW/m2. The terrestrial heat flow value in the Kaifeng sag also showed a trend of increasing from west to east sag (Fig. 2a). Zhengzhou City is about 54.5MW/m2, Yuanyang County is about 55.5MW/m2, Yanjin County is about 56mW/m2, Fengqiu County is about 57mW/m2, Kaifeng City is about 57MW/m2, and Kaifeng County is about 57MW/m2. It is 60MW/m2, and the surface heat flow value of Lankao County is about 59.5MW/m2. There are also regional differences in the distribution of strata geothermal gradients in the Kaifeng Sag (Fig. 2b). The regional geothermal gradients range from 2.8 to 3.6°C/100m. Among them, the geothermal gradient in Zhengzhou is about 2.8° C/100m, and the geothermal gradient from Yuanyang to Fengqiu is 3.1 to 3.4°C. ℃/100m, Kaifeng area has the highest geothermal gradient, which is 3.5℃/100m, and Lankao area is 3.4 ~ 3.5℃/100m[Zhang Xinyong ,et al (2009), Wang Xinyi, et al (2001)]. The distribution of the geothermal gradient value basically increases from west to east according to the extension direction of the depression, and the distribution of the geothermal field is similar to the trend of the geothermal heat flow value.

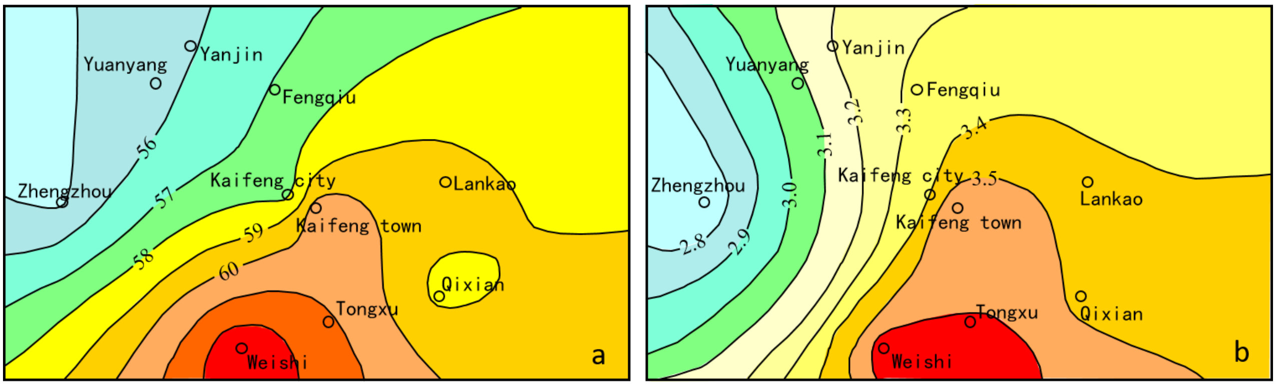

Figure 2 Distribution map of geothermal heat flow value in Kaifeng depression (a); distribution map of geothermal gradient in Kaifeng depression (b)

4. THERMAL RESERVOIR CHARACTERISTICS

4.1 Deposition Characteristics of Thermal Reservoir

The Neogene Guantao Formation in Kaifeng Sag was a continental sedimentary background, and a set of fluvial sand-mudstone deposits developed, which were evenly distributed in the whole area. The burial depth of the bottom plate is generally greater than 2000 m, and the overall features are high in the south and low in the north, high in the west and low in the east (Fig. 3). The deposition center is located in the deepest part of the depression, the burial depth can reach more than 2800m, and the deposition thickness is large. The data of drilled geothermal wells show that the Neogene Guantao Formation sandstone in Kaifeng Sag has the characteristics of stable deposition, continuous distribution, medium burial depth, high permeability and geothermal gradient, and has good heat and water storage characteristics. The Quaternary Pingyuan Formation and Neogene Minghuazhen Formation have a total thickness of about 1000-1400 m, which evenly cover the sandstone thermal reservoir of the Guantao Formation, with stable deposition and fine lithology, serving as the caprock for the sandstone thermal reservoir of the Guantao Formation.

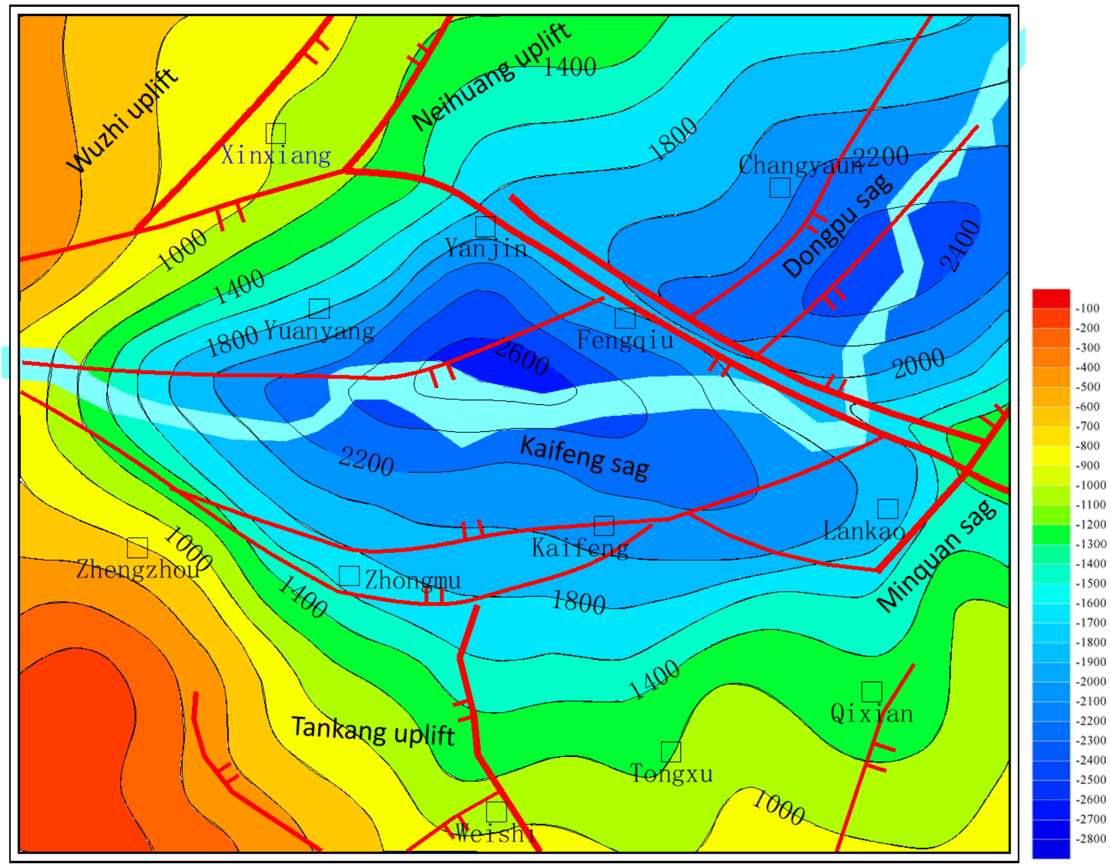

Figure 3 Distribution map of buried depth contour at the bottom of Guantao Formation in Kaifeng Sag and adjacent areas

The thermal storage of the Guantao Formation in the Kaifeng Sag is a porous layered sandstone thermal storage, and the reservoir lithology has obvious vertical segmentation (Fig. 6). The boundary marks of the upper Guanshang Member and the upper Minghuazhen Formation are not obvious. The lithology is mainly interbedded deposition of fine sandstone and mudstone with unequal thickness. The logging curve is toothed bell-shaped, finger-shaped and funnel-shaped. The natural gamma shows a high value, and the "dual structure" of meandering river sediments is obvious. The toothed bell-shaped curve corresponds to the beach deposition in the riverbed subfacies, the finger-shaped curve corresponds to the natural levee deposition in the bank subfacies, and the funnel-shaped curve corresponds to the breach fan deposition in the bank subfacies. The lower section of Guan is in unconformity contact with the lower Paleogene Dongying Formation, and the lithology is dominated by sandstone and gravel-bearing sandstone intercalated with thin mudstone. The logging curve shows thick layer and high amplitude box-shaped, micro-dentate box-shaped and bell-shaped, and the natural gamma shows a low value. Braided river deposits are developed. The thick box curve corresponds to the vertical superimposed multi-stage braided channel deposits. At the bottom of the Guantao Formation, there is variegated conglomerate with poor drillability and a thickness of 20-30m, which can be used as a bottom marker layer and is a sedimentary sediment at the bottom of the channel.

4.2 Physical Properties ofThermal Reservoirs

According to the statistical analysis of geothermal wells in Kaifeng City and Lankao County in the central and eastern Kaifeng Sag, the thickness of the Guantao Formation thermal reservoir is 300-420 m, the average thermal storage thickness is 362 m, and the sand-to-ground ratio is between 47-67%. The physical properties of thermal reservoirs in the Guantao Formation are vertically affected by the depositional environment. The physical properties of the thermal reservoirs in the lower part of the Guantao Formation are better than those in the upper part. Therefore, the lower section of the Guantao Formation is the main water-producing section of the thermal reservoir of the Guantao Formation. The thermal sand storage ratio in the upper section of the Guan is 36-62%, the porosity is mainly concentrated in 15-26.5%, and the permeability is 55-528mD. The thermal sand storage ratio in the lower section of the Guan is 61-90%, the porosity is mainly concentrated in 18.8-28.6%, and the permeability is 123-614mD. Geothermal wells in the new area of Xinxiang Plain in the west show that the thermal reservoir thickness of the Guantao Formation is about 130m, the average porosity is about 16%, and the sand-to-ground ratio is about 29%, resulting in poor water-rich thermal reservoirs. This is because the sediment transport distance in the intermountain basin and piedmont area is short, the particle size is mixed, and the sediment sorting is poor, resulting in poor thermal storage and water richness. On the other hand, in the plain area far from the front of the mountain, the sorting performance is better, and the thermal storage and water richness are relatively good.

5. WATER CHEMICAL CHARACTERISTICS

According to the chemical composition analysis results of geothermal well water in the Kaifeng sag (Table 1), there are differences in the chemical types of water in the east and west of the Kaifeng sag. The chemical type of geothermal water in the Guantao

Formation in the Kaifeng-Lankao area in the east of the sag is mainly Cl-Na type (Fig. 8a), the pH value is generally 6.5~7.6, it is weakly alkaline water, and the TDS value of the geothermal water is 10000-20000 mg/l Among them, the salinity is high, the cations are mainly Na^+ and Ca^{2+}, and the anions are mainly Cl^- and SO_4^{2-}. In the Zhengzhou-Xinxiang Plain New Area of the west of the depression, the hydrochemical type is mainly HCO-Na, the pH value is about 7.96, the TDS value is less than 1000mg/l, the salinity is low, the cation is mainly Na^+, and the anion is mainly HCO^{3-}. It shows that the western part of the sag is closely related to atmospheric precipitation and receives recharge from atmospheric precipitation at a close distance, while the eastern part of the sag is far away from the recharge area.

Table 1 Water chemical analysis data of Kaifeng sag

depth/m	PH	TDS（mg·L^{-1}）	geothermal water chemical types	anion /（mg·L^{-1}）				
				Na^+	Ca^{2+}	Cl^-	SO_4^{2-}	HCO_3^-
2342	6.57	2.71×10^4	Cl-Na	6295.57	1877.61	14535.83	361.34	105.91
2310	6.56	2.53×10^4	Cl-Na	6178.76	1745.58	13102.75	346.49	105.04
2200	6.90	1.43×10^4	Cl-Na	4248.75	586.42	8001.65	661.96	152.73
2240	6.73	1.50×10^4	Cl-Na	4506.1	642.69	8121.19	563.57	151.01
2240	7.56	1.55×10^4	Cl-Na	3871.84	564.47	8361.98	592.19	123.24
2218	6.68	1.64×10^4	Cl-Na	4376.24	695.79	9011.61	562.59	148.8
1782	7.96	0.89×10^3	HCO_3^--Na^+	329	10.17	132.94	119.93	580.01

6. GENESIS MODE AND POTENTIAL

Porous layered thermal storage in Guantao Formation sandstone in Kaifeng Sag can form a set of geothermal system. Combined with the analysis of its geological characteristics of "source, storage, communication and cover", the genetic model of the geothermal system is established. The heat source of this geothermal system comes from the high geothermal flow value in the Cenozoic rifted basin background, about 52-57 mW/m2, and the Jiyuan-Jiaozuo-Shangqiu deep fault in the north constitutes a favorable channel for the upward transport of deep heat flow. The sandstone thermal storage is supplied by atmospheric precipitation from the western and southwestern mountainous areas, enters the destination layer along the fault, migrates along the reservoir section for a long distance, and is enriched in the thermal storage after deep circulation and heating by the surrounding rock. The finer sedimentary strata of the upper Quaternary and Minghuazhen Formation constitute a good caprock, thus forming a water-rich geothermal system with bidirectional recharge, long-distance migration, and pressure preservation (Fig. 4).

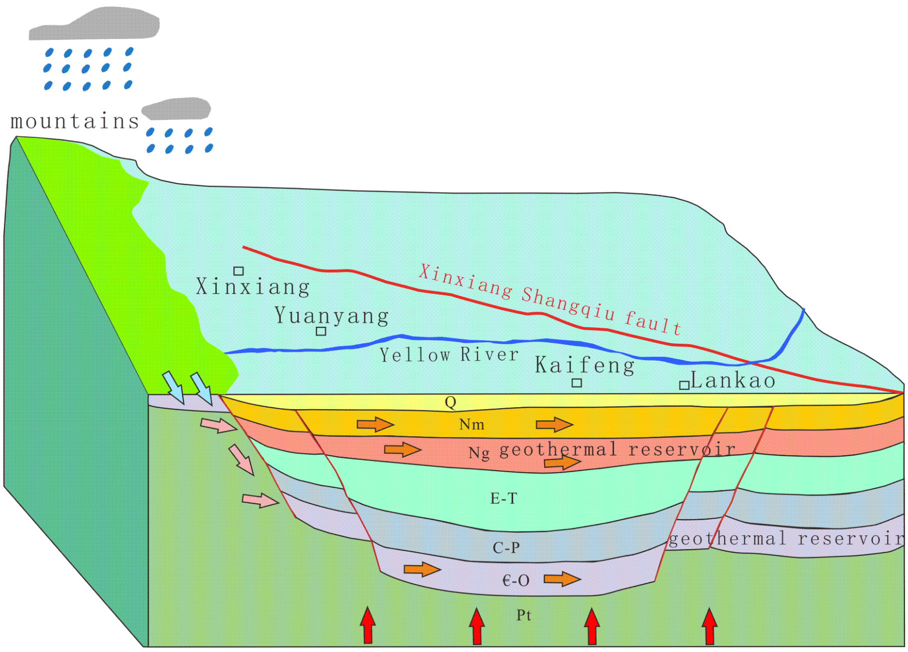

Figure 4 Genesis model of geothermal system in Kaifeng Sag

The geothermal system of Kaifeng Sag is a sedimentary basin-type layered thermal storage. On the basis of the above-mentioned analysis of the genetic mechanism of the geothermal field, combined with the existing drilling data in the study area, the thermal storage volume method was used to evaluate the resources of the sandstone thermal storage in the Guantao Formation. The thermal storage area of Kaifeng Sag is about 5528km2. The effective thickness of thermal storage is calculated according to the storage thickness ratio of existing geothermal wells combined with the average formation thickness, and the average effective thickness of thermal storage is 362m. The thermal storage temperature is calculated to be about 65°C based on the temperature of the thermal storage roof and bottom plate in the area. According to the logging interpretation data, the average porosity of the Guantao Formation is calculated to be 22%. The temperature of the constant temperature layer is 16℃ with reference to the annual average temperature. The density of sandstone is 2600kg/m3, the specific heat of sandstone is 878J/(kg·℃), the density of water is 1000kg/m3, and the specific heat of water is 4180J/(kg·℃).

The total amount of geothermal resources in Kaifeng Sag is 2647.68×108GJ, equivalent to about 9.0364×108t of standard coal. The recoverable geothermal resources are 529.54×108GJ, equivalent to about 1.8073×108t of standard coal. According to the calculation that the heat required for heating per square meter per year is equivalent to 0.0283t standard coal, the geothermal resources of the advantageous thermal storage section of the Guantao Formation in the Kaifeng Sag can meet the heating area of 63.86 million m2. The geothermal resources are superior and the development potential is huge.

7. SUMMARY

(1) The heat source of Kaifeng sag comes from the high geothermal heat flow value under the background of Cenozoic rifted basin, which is about 58.4mW/m2, and the geothermal gradient is distributed at 2.8-3.6℃/100m, showing an overall trend of increasing from west to east sag.

(2) The sandstone thermal storage floor of the Guantao Formation in the Kaifeng Sag is buried at a depth of 1600-2200 m. Influenced by the depositional environment, the physical properties of the thermal reservoir in the lower section of Guantao are better than those of the upper section of the Guan. The sand-to-formation ratio of the upper part of the Guan is about 36%-62%, and the porosity is about 15%-26.5%; the sand-to-formation ratio of the lower part of the Guan is about 61-90%, and the porosity is about 18.8%-28.8%.

(3) The chemical type of geothermal water in the Guantao Formation in the central and eastern Kaifeng sag is mainly Cl-Na type, and the western part is HCO-Na type. The geothermal water comes from the atmospheric precipitation in the western and southwestern mountainous areas.

(4) The porosity layered sandstone thermal reservoir of Guantao Formation in Kaifeng Sag is formed in a relatively high geothermal flow background, and is a water-rich geothermal system with lateral recharge and long-distance migration along faults. The total amount of sandstone thermal storage geothermal resources in the Guantao Formation is 2647.68×108GJ, and the recoverable geothermal resources are 529.57×108GJ, equivalent to about 1.8073×108t of standard coal. The annual exploitable geothermal resource is 5.29×108GJ, equivalent to 180.73×104t of standard coal, which can meet the heating area of about 6386×104m2, and has great development potential.

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