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Characteristics of Geothermal Reservoir and Evaluation of Geothermal Resources in Shahejie Formation of Damintun Depression

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Abstract Damintun Depression is a key experimental area for promoting geothermal energy construction in Liaohe Oilfield during the dual-carbon period, and has a good potential for geothermal resources. Ascertaining the geological conditions in this area and accurately evaluating the geothermal resources in this area can provide theoretical support for the exploitation and utilization of geothermal resources in mining areas and the transformation of energy structure. In this paper, the geological structure, distribution of geothermal reservoir, earth temperature field and water chemical characteristics of Damintun Depression were analyzed comprehensively. The occurrence characteristics of geothermal resources in this block were revealed, and the amount of the resources was estimated. The results show that the main geothermal reservoir layers in this area are the first and third members of the Paleogene Shahejie Formation, which are the main target layers for geothermal development. The gradient of earth temperature in this ares is 2.8 – 3.5 ℃/100 m, and it is high in the west and north and low in the east and south. The total amount of geothermal reservoir resources in the favorable area of the research block is 783.28×10^6 GJ, equivalent to $2\,672.69\times10^4$ tons of standard coal. The amount of recoverable geothermal reservoir resources is 195.827×10^6 GJ, equivalent to 668.17×10^4 tons of standard coal.
Key words Geothermal reservoir resources; Gradient of earth temperature; Liaohe Fault Depression
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In the 21^{st} century, mankind is faced with great challenges such as energy shortage and environmental pollution, and countries around the world have successively added "carbon peaking and carbon neutrality" to their strategic planning, which has become a new direction for green, low-carbon and sustainable development[1]. The "two-carbon" goal has accelerated the transformation of China's energy structure, and the proportion of low-carbon clean energy in China's energy consumption has gradually increased. Geothermal energy, as an important clean energy, has the characteristics of stability and continuity, and has been paid more and more attention. Geothermal energy and petroleum are two kinds of energy resources co-existing in sedimentary basins. There are a large number of geothermal resources in China's oil fields, and they have huge development potential[2].

Damintun Depression is located in the lower Liaohe Fault Depression, mantle uplift zone and Cenozoic fault depression basin. Shahejie Formation and Dongying Formation of the Tertiary system are composed of multiple sets of sand – mud interbedded sedimentary cycles, among which Shahejie Formation has large deposition thickness and many sedimentary cycles, and sand layer and mud layer can be used as heat storage and cover layer respectively, having favorable geothermal geological conditions. However, due to the lack of data of necessary formation parameters and geothermal field characteristics, the utilization rate of geothermal energy is low. In this paper, based on various hydrogeological data in Shahejie Formation in Damintun Depression, the occurrence characteristics of geothermal resources in the area were analyzed to provide the basis for the development and utilization of geothermal resources in the future.

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1 Overview of the study area

The study area (122°52′ – 123 °14′ E, 41°45′ – 41 °59′ N) is located in the middle of Damintun Depression in Xinmin City under the jurisdiction of Shenyang City. It has convenient transportation and mild climate, as well as a warm temperate sub-humid continental monsoon climate. It has developed economy, and its population density is 205 persons/km^2. It is one of the important industrial bases of Shenyang and a part of Liaohe alluvial plain. The working area has an area of 400 km^2.

1.1 Geological structure Damintun Depression, a second-order tectonic belt of Liaohe Fault Depression, is located at the northeast corner of Liaohe Fault Depression. It is a continental Tertiary sedimentary depression with complex geological structure[3] and well-developed faults.

There are more than 50 large or small faults developed in the area, including 16 major faults. There are four stages of development: 23 faults were developed in Es_4 period, and 19 faults were developed in Es_3 period, while 28 faults were developed in Es_1 period. Most of the faults are distributed in the direction of NE, NNE and near EW. Except for the eastern and western boundary faults which are reverse faults and a few translation faults in southern Dongshengbao, most faults are all normal faults. The development of basement faults and the fluctuation of faults and basement play an important role in controlling the structure of buried hills and overlying strata.

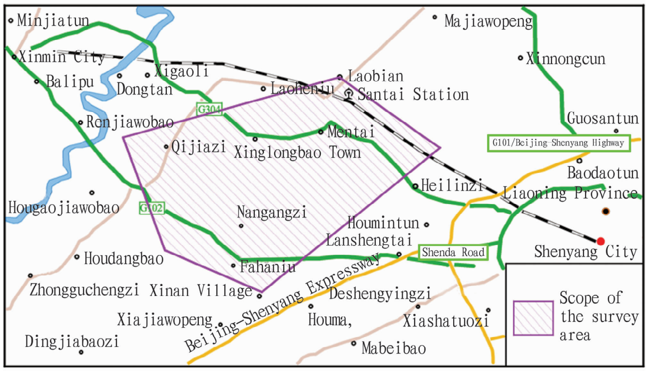

Fig. 1 Traffic location of the study area

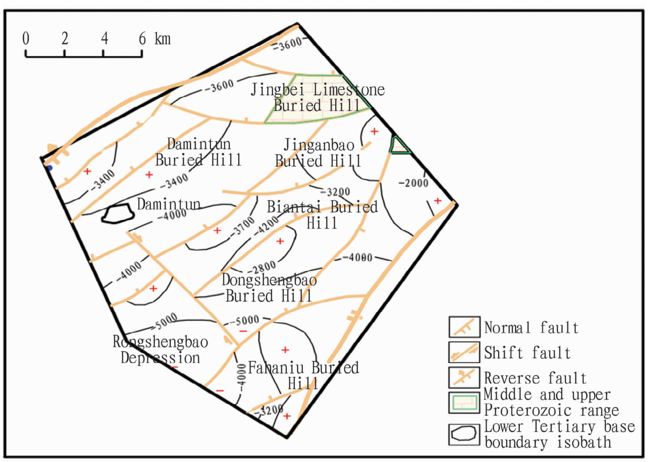

Fig. 2 Distribution of Paleogene basement structure in the working area

1.2 Stratum distribution In Damintun Depression, due to the influence and control of multi-period tectonic and block fault activities, the sedimentary environment and system of different blocks have great changes, and compared with regional strata, there is a lack of more strata, and the upper and lower interfaces are mostly in unconformity contact. Its basement is composed of a complex set of Archeozoic and lower Proterozoic metamorphic rock series. The strata from old to new type are Archeozoic, middle and upper Proterozoic and Cenozoic, among which Cenozoic is closely related to heat storage.

1.3 Hydrogeological conditions The groundwater in the study area can be divided into the pore aquifer of the Quaternary loose accumulation layer and the pore fissure aquifer of the Tertiary clital rock. The pore fissure aquifer of the Tertiary clital rock is the main thermal storage aquifer in the study area, and the water inflow of a single well is 26 – 700 t/d.

2 Characteristics of geothermal reservoir

In this study, the Paleogene geothermal water belongs to the pore water between the Cenozoic sedimentary layers, with a depth of 900 – 2 800 m. According to the strata and water-rich rock layers, it can be divided into pore thermal reservoirs in the first and third member of Shahejie Formation.

2.1 Pore thermal reservoir in the first member of Shahejie Formation The thermal reservoir overlies the third member of Shahejie Formation and is a fan delta sedimentary system. The main lithology is gray, gray green mudstone, sand conglomerate and gray white feldspar sandstone interlayer of varying thickness, and there is brown red and dark purple mudstone at the bottom and top. Its thickness ratio is generally 28% – 48%. The depth of the roof and floor is 900 – 1 300 and 1 200 – 2 000 m, respectively, and the reservoir thickness is 10 – 150 m. The permeability of the reservoir is $3.25\times10^{-3}-248.31\times10^{-3}$ μm^2, and the porosity is 8.94% – 28.24%.

2.2 Pore thermal reservoir in the third member of Shahejie Formation The stratum is widely distributed in the working area, with large thickness and great burial depth. It is a fan delta sedimentary system composed of three fan delta sedimentary systems on the plane, most of which belong to fan delta front and fan delta plain subfacies. Composite sand bodies with network channel sand as the skeleton are developed. The lithology and thickness vary greatly on the plane, and the longitudinal sedimentary cycle is obvious. The lower part is mostly fan delta front subfacies deposits, and the main lithology is gray mudstone, gray white and light gray sand conglomerate, and gravel medium sandstone interlayer. The upper section is a delta plain subfacies deposit, and lithology is gray-green and purplish red mudstone, silty mudstone and gray-white pebbly sandstone, arkose sandstone interlayer of varying thickness. Its storage thickness ratio is generally 30% – 45%. The depth of the roof and floor is 1 000 – 2 700 and 2 000 – 2 900 m, respectively, and the reservoir thickness is 36 – 227 m. The permeability of the reservoir is $4.74\times10^{-3}-192.49\times10^{-3}$ μm^2, and the porosity is 6.01% – 23.51%.

3 Characteristics of earth temperature field

3.1 Characteristics of vertical distribution The longitudinal variation of earth temperature field is closely related to formation lithology, and the longitudinal variation rate of earth temperature gradient in a certain depth rises gradually with the increase of depth. According to the changing curve of earth temperature at well Shen 640 (Fig. 3), the temperature changes little and fluctuates at a depth of 0 – 200 m, while the temperature increases in a straight line at a depth of more then 200 m, and the gradient of earth temperature tends to rise with the increase of depth.

3.2 Characteristics of planar distribution The depth of the constant temperature zone in this area is determined to be 38 m according to the changing curve of actual temperature (Fig. 4). Based on the research data of Yu Hengchang *et al.*, it is determined that the temperature of the constant temperature zone is 9.7 ℃.

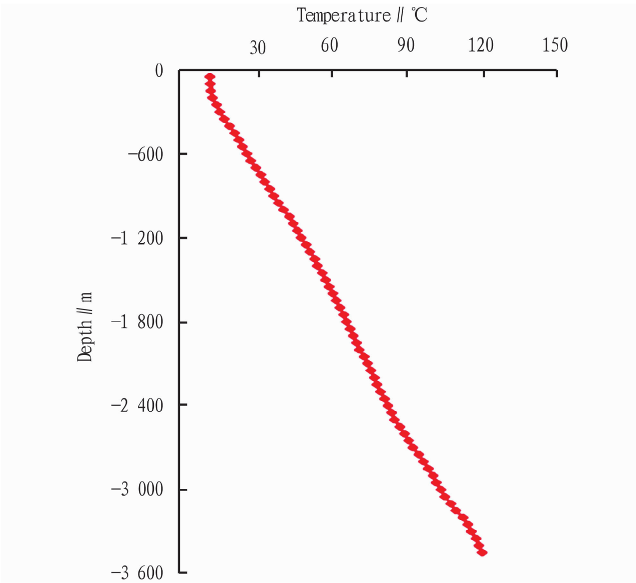

Fig. 3 Changing curve of earth temperature at well Shen 640 in the study area

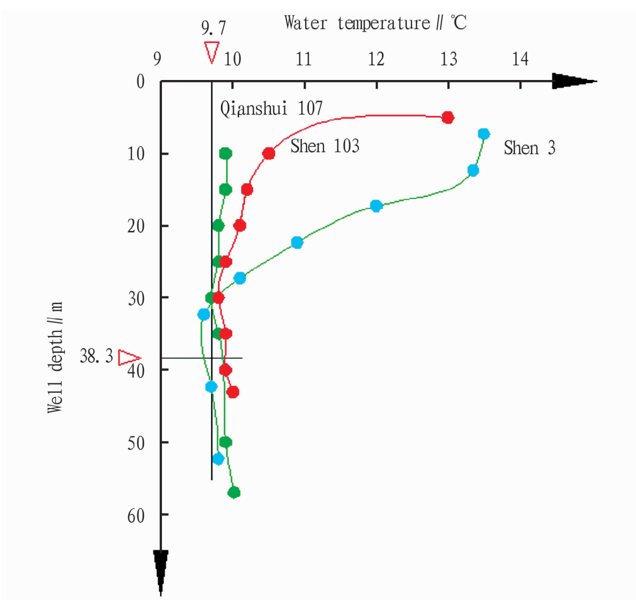

Fig. 4 Changing curve of water temperature at Shen 3, Shen 103 and Qianshui 107 in the study area

According to the static temperature/depth values of 174 intervals of 175 wells in this area, the gradient of earth temperature in this area is distributed in a band along the direction of NE, varying from 2.8 to 3.5 ℃/100 m (Fig. 5). The gradient of earth temperature is low near well Fa 26, only 2.8 ℃/100 m, and rises to 3.5 ℃/100 m near well An 89. In general, the gradient of earth temperature in the area is normal, and it is high in the west and north and low in the east and south.

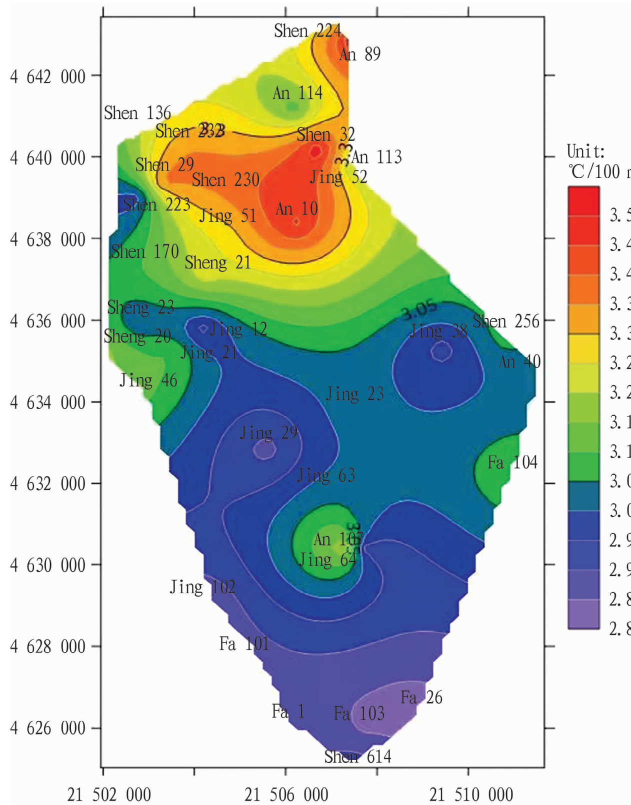

Fig. 5 Surface isolines of gradient of earth temperature in the study area

4 Characteristics of hydrochemical field

In this study, samples collected from two geothermal wells of Shahejie Formation in the area were tested, the main ionic component of the geothermal water is HCO_3^-, and the content is 488 – 530.87 mg/L. The cation is mainly Na^+, and the content is 212.8 – 231.2 mg/L. The content of Ca^{2+} and Mg^{2+} is very low, namely 2 and 1.2 mg/L, respectively (Table 1). The chemical type of the groundwater is classified as $NaHCO_3$ water according to Shukarev classification. The salinity is 778.7 – 800.93 mg/L, so it is low mineralized water.

Table 1 Water quality of geothermal fluid in Paleogene thermal reservoir in the study area

Well No.	Position	Content of the main ions // mg/L						Total salinity // mg/L	Total hardness // mg/L	Water type
		$Na^+ + K^+$	Mg^{2+}	Ca^{2+}	HCO_3^-	Cl^-	SO_4^{2-}			
Shenshui 501	S	212.8	1.2	2.0	530.9	12.0	19.9	778.7	10.0	$NaHCO_3$
Shenshui 502	S	231.2	1.2	2.0	488.0	12.0	24.6	800.9	10.0	$NaHCO_3$

5 Calculation of geothermal resources

The "geothermal reservoir method" in the *Geologic Exploration Standard of Geothermal Resources* (GB/T 11615 – 2010) was used to calculate geothermal resources. The total amount of geothermal reservoir resources in the favorable area of the research block is 783.28×10^6 GJ, equivalent to $2\,672.69 \times 10^4$ tons of standard coal. The amount of recoverable geothermal reservoir resources is 195.827×10^6 GJ, equivalent to 668.17×10^4 tons of standard coal (Table 2).

5.1 Geothermal reservoir in the first member of Shahejie Formation (S1) The amount of geothermal reservoir resources is 178.32×10^6 GJ, equivalent to 608.66×10^4 tons of standard coal. Geothermal fluid storage capacity is 2.8×10^8 m^3. The amount of recoverable geothermal reservoir resources is 44.6×10^6 GJ, equivalent to 152.17×10^4 tons of standard coal. The amount of recoverable water resources is 0.56×10^8 m^3.

5.2 Geothermal reservoir in the third member of Shahejie Formation (S3) The amount of geothermal reservoir resources is 604.9×10^6 GJ, equivalent to $2\,064.03 \times 10^4$ tons of standard coal. Geothermal fluid storage capacity is 4.01×10^8 m^3. The amount of recoverable geothermal reservoir resources is 151.23×10^6 GJ, equivalent to 516.01×10^4 tons of standard coal. The amount of recoverable water resources is 0.8×10^8 m^3.

Table 2 Geothermal resources of Paleogene Shahejie Formation in the study area

Stratum	Geothermal resources		Recoverable geothermal resources		Total amount of hot water resources	Amount of recoverable hot water resources
	Total amount $\times 10^6$ GJ	Standard coal $\times 10^4$ t	Amount $\times 10^6$ GJ	Standard coal $\times 10^4$ t	$\times 10^8$ m^3	$\times 10^8$ m^3
S1	178.38	608.66	44.60	152.17	2.80	0.56
S3	604.90	2 064.03	151.23	516.01	4.01	0.80
Total	783.28	2 672.69	195.82	668.17	6.81	1.36

6 Conclusions

(1) The structure of the study area is complex, and the gradient of earth temperature is distributed in a band along the direction of NE, ranging from 2.8 to 3.5 ℃/100 m. In general, the gradient of earth temperature in the area is normal, and it is high in the west and north and low in the east and south.

(2) The total amount of geothermal reservoir resources in the favorable area of the research block is 783.28×10^6 GJ, equivalent to $2\,672.69 \times 10^4$ tons of standard coal. The amount of recoverable geothermal reservoir resources is 195.827×10^6 GJ, equivalent to 668.17×10^4 tons of standard coal. The storage capacity of geothermal fluid is 6.81×10^8 m^3, and the recoverable capacity of geothermal fluid is 1.36×10^8 m^3.

(3) The study area is rich in geothermal resources, so it is suggested to strengthen the development of medium and deep geothermal reservoir, carry out geothermal development according to local conditions, and improve the utilization rate of geothermal resources.

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