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Geothermal Resource Evaluation of the Middle Permian Qixia-Maokou Formation in the Southern Sichuan Basin, China

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Keywords: Southern Sichuan Basin; Qixia-Maokou Formation; Thermal reservoir characteristics; Geothermal resource evaluation; Qixia-Maokou Formation

ABSTRACT

Sichuan Basin is rich in geothermal resources, ranking first among China's large and medium-sized basins. The geothermal gradients in the Southern Sichuan Basin are above 24 ℃/km, and most of the terrestrial heat flow is above 60 mW/m2, which are relatively high abnormal areas in the Sichuan Basin. In this paper, the Qixia-Maokou geothermal reservoir in the Southern Sichuan Basin with relatively shallow burial depth (mostly in 2000-3000 m), relatively high thermal reservoir temperature (46-114 ℃), and a relatively thick thermal reservoir (300-540 m) were selected, and the potential of geothermal resources was evaluated. In the study, the three-dimensional geological model was established using strata thicknesses, porosity, and lithology. Combined with the present geothermal field and rock thermal physical properties, the temperature at the top and bottom of the Qixia-Maokou Formation was calculated based on the one-dimensional steady-state heat conduction equation. Finally, the geothermal resource intensity and resource amount of the Qixia-Maokou Formation were calculated using the volume method. The results show that the temperature of the thermal reservoir of the Qixia-Maokou Formation is 46-114 ℃. The total amount of geothermal resources is 2.37 × 1021 J, equivalent to 80.89 × 108 tons of standard coal, and the exploitable geothermal resources are 4.74 × 1021 J, equivalent to 16.18 × 108 tons of standard coal. It is proposed to give priority to the development of geothermal cascade utilization demonstration projects such as mid-low temperature comprehensive geothermal power generation, geothermal drying, and geothermal agriculture in the southwest area of the Southern Sichuan Basin. The results lay a foundation for the selection and reconstruction of available abandoned drillings and the development of oilfield geothermal resources in the future.

1. INTRODUCTION

The geothermal resource is a clean, non-polluting renewable energy, with a wide distribution, and huge reservoirs (Kana et al., 2014, Li et al., 2022). The development of geothermal energy is of great significance for realizing energy structure adjustment, reducing carbon emissions, and alleviating smog (Aydin and Merey, 2021, Wang et al., 2022).

Most of the petroleum basins in China are abundant in geothermal resources. The hydrothermal geothermal resources reach 31784.45 $\times 10^{18}$ J, equivalent to 1084.8 $\times 10^{8}$ tons of standard coal (Wang et al., 2019). Meanwhile, the petroleum basins have unique advantages in the subsequent geothermal energy exploration and development, including geophysical data, and abandoned drillings. As an extremely important hydrocarbon-bearing basin in China, the Sichuan Basin has rich petroleum resources and hydrothermal resources (Wang et al., 2017). Many scholars have evaluated the geothermal resources of the Sichuan Basin in the evaluation of geothermal resources of major sedimentary basins or oilfields in China (Wang et al., 2017, Wang et al., 2019). However, in the previous evaluation of geothermal resources in the Sichuan Basin, the results of geothermal resources evaluation are quite different because of the difference in data mastery and evaluation accuracy (Wang et al., 2019). In addition, most of the studies are overall evaluations, and there is a lack of research on the geothermal resource distribution of major thermal reservoirs of the Sichuan Basin (Al-Douri et al., 2019).

With the exploration of the petroleum in the Southern Sichuan Basin, plenty of detailed drilling, geophysical and hydrochemical data was accumulated in the Southern Sichuan Basin, providing important support for geothermal resources evaluation (Templeton et al., 2014, Kurnia et al., 2022). The temperature and burial depth of thermal reservoirs are important factors for the economic benefit of geothermal resource development (Mottaghy et al., 2011, Liu et al., 2022). Considering these factors, the Qixia-Maokou Formation of the Southern Sichuan Basin was selected for geothermal resource potential and distribution evaluation. The thermal reservoir of the Qixia-Maokou Formation has the characteristics of relatively shallow burial depth (mostly 2000-3000 m), high temperature (46-114 ℃), and relatively thicker thickness (300-540 m). Then, according to the intensity of geothermal resources and thermal reservoir temperature, put forward their views on the development prospects of geothermal resources in different regions.

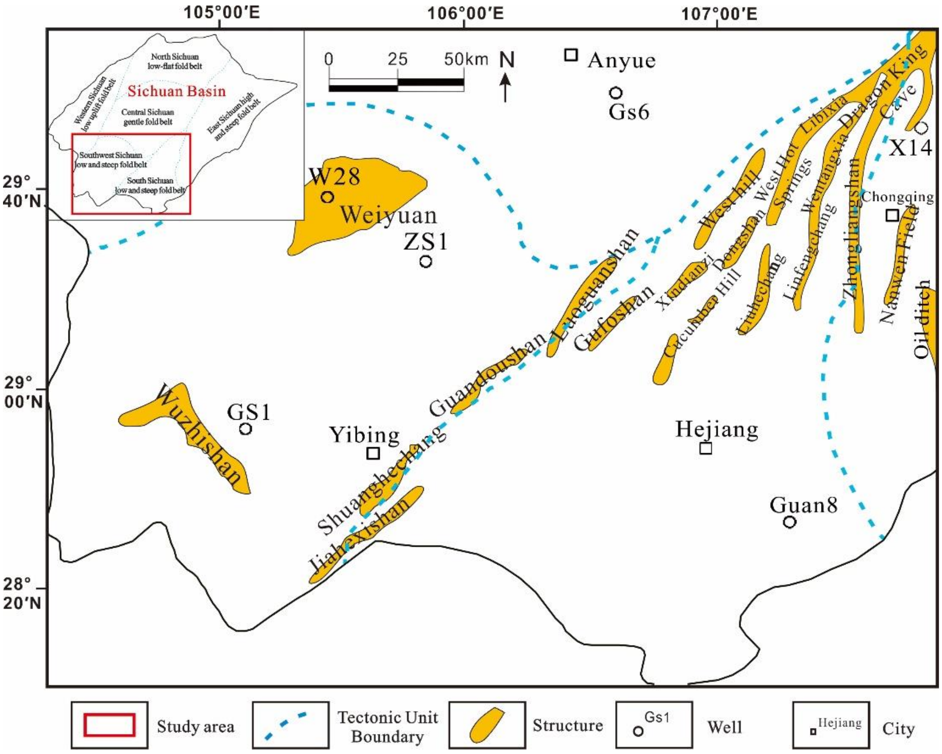

Figure 1: Structural distribution in the Southern Sichuan Basin

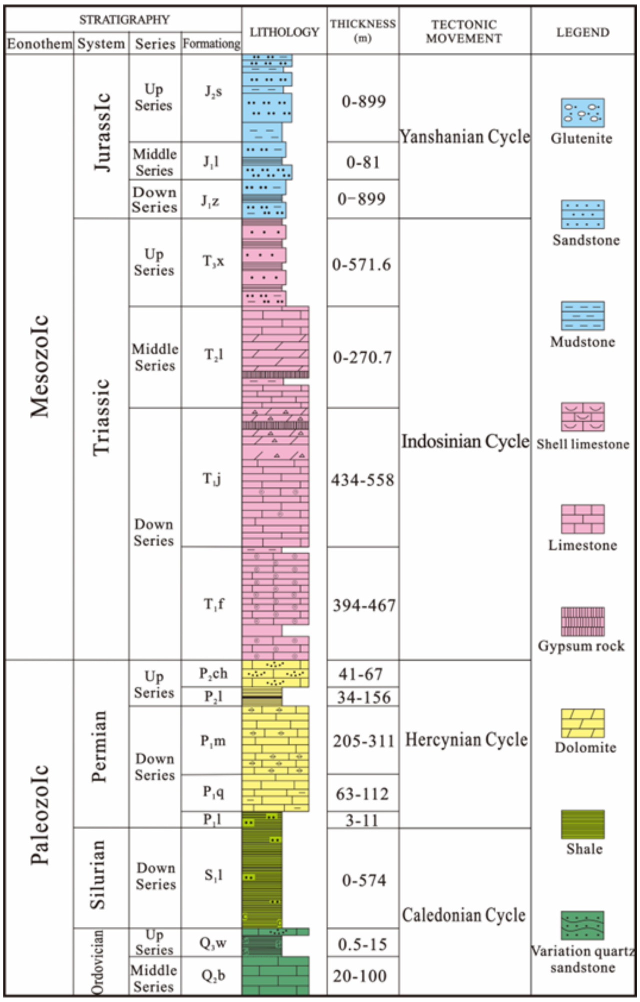

Figure 2: Stratigraphic column of the Southern Sichuan Basin

2. GEOLOGICAL SETTINGS

2.1 Geological Location and Stratigraphy

As one of the first-order tectonic units of the northwestern margin of the Yangtze Platform, the Sichuan Basin has an area of about 2.3 × 105 km2, surrounded by Longmen Mountain, Daba Mountain, Micang Mountain, and other mountains. It is a marine superimposed basin that gradually evolved from the craton basin to the foreland basin (Yang et al., 2021). The research area is located in the southern part of the Sichuan Basin and includes the low-steep fold belt in the south and the low-steep fold belt in the southwest. The east boundary is the Zhongliangshan-Shilongxia fault, the west is the Longquanshan fault, and the south is the Changning-Weixin fault-fold belt (Fig. 1). Folds and faults are relatively developed due to the superposition and transformation of multiple tectonic movements in the Southern Sichuan Basin. The stratigraphic development in the Southern Sichuan Basin is relatively complete, and there are mainly six sets of thermal reservoirs in the Middle Permian Qixia-Maokou Formation, Lower Triassic Feixianguan Formation, Lower Triassic Jialingjiang Formation, Middle Triassic Leikoupo Formation, Upper Triassic Xujiahe Formation, and Jurassic from bottom to top (Fig. 2).

2.2. Thermal Reservoir Characteristics

The Qixia-Maokou Formation in the Southern Sichuan Basin is a marine carbonate stratum composed of transgressive-regressive cycles, mainly limestone and dolomitic limestone (Xiao et al., 2016). The bottom burial depth is 2000-3500 m (Fig. 3), with a thermal reservoir thickness of 300-540 m (Fig. 4). The average rock density is 2.52×10^3 kg/m^3, and the average porosity is 4.30 %. During the late deposits of the Maokou Formation, early diagenetic weathering crust karst reservoirs were developed, which was similar to the Wumishan Formation of the Xiong'an area, under the influence of exposure and weathering leaching. The Qixia-Maokou Formation is layered monoclinic, with stable thickness, simple structure, well-developed hidden faults, and has the characteristics of a layered thermal reservoir.

The overburden cap rocks of the thermal reservoir are the Upper Permian Longtan Formation composed of mudstone, siltstone sandwiched with black shale, and coal. The thickness of cap rocks is 34-156 m, which is a relatively water-repellent layer. The underlying water-repellent layer is carbonaceous shale, sandy mudstone, and siltstone of the Lower Permian Liangshan Formation and the Silurian Hanjiadian Formation, with a thickness of 3-574 m.

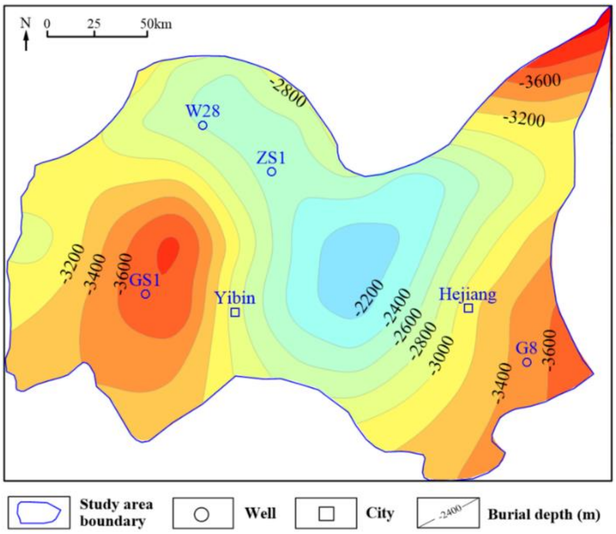

Figure 3: Bottom burial depth of the Qixia-Maokou Formation

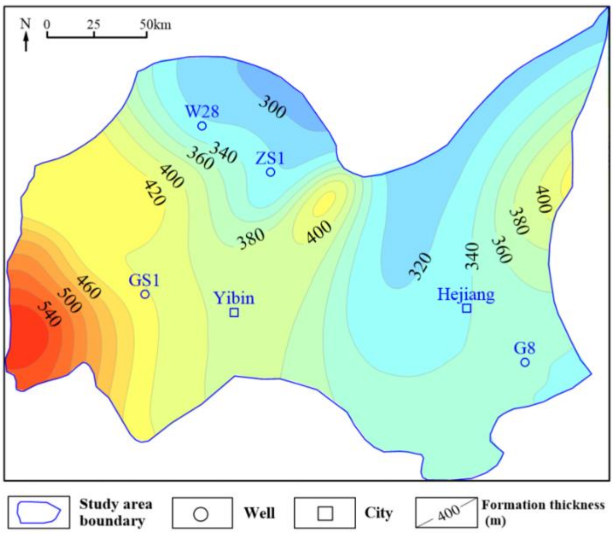

Figure 4: Thickness of the thermal reservoir of the Qixia-Maokou Formation

3. METHODS AND PARAMETERS

3.1 Geothermal Resources Evaluation Method

The three-dimensional geological model was established for geothermal resource evaluation using the BasinView software based on formation thickness, erosion thickness, porosity, lithology, etc. Then, combined with the present geothermal field and rock thermophysical parameters, the temperature distributions of the top-middle-bottom of the Qixia-Maokou Formation were simulated on the principle of a one-dimensional steady-state heat conduction equation. The geothermal resource intensity and amount of the Qixia-Maokou Formation were calculated by the Volume Method, realizing the visualization of the reservoir geological and the automation of geothermal resource evaluation.

The geothermal resource amount calculated by the Volume Method is the geothermal resources contained in the thermal reservoir and water, that is, the storage amount of geothermal energy. It is the product of the volume of the thermal reservoir, temperature, porosity, heat capacity, and density (Eq.1) (Qiu et al., 2019).

$$Q = AD(T - T_0)[\rho_r C_r (1 - \varphi) + \rho_w C_w \varphi] \quad (1)$$

where, ρ_r, ρ_w are the density of rock and water, kg/m^3; C_r, C_w are the specific heat of rock and water, J/(kg·K); A and D are the surface area of the calculation area, m^2 and the calculation depth, m; φ is the porosity of the rock, %; T is the average temperature of rock and water in the specified volume, ℃; T_0 is the reference temperature, 15 ℃.

Clarifying the temperature distribution of thermal reservoirs is significant when calculating geothermal resources. Therefore, the temperature distribution of the middle portion of the Qixia-Maokou Formation was simulated on the principle of a one-dimensional steady-state heat conduction equation (Eq.2) based on the three-dimensional geological model (Zuo et al., 2017). Then, the thermal reservoir geothermal resources were calculated.

$$T_Z = T_0 + \frac{qZ}{K} - \frac{AZ^2}{2K} \quad (2)$$

where, T_Z is the temperature at the calculated depth Z (m), ℃; T_0 is the fiducial temperature, 15 ℃; q is the surface heat flow at the calculated point, mW/m²; K is the weighted average of the thermal conductivities of rock, W/(m·K); A is heat production rates of the different rocks for the surface to the depth Z (m), μW/m³.

3.2. Basic Parameters

According to the test data of drilling samples and previous research, the average density of the thermal reservoir is 2.52×10^3 kg/m³, the heat capacity is 842.3 J/(kg·K); the rock porosity is 2.83-4.6 %, with an average of 4.30 % (Wang et al., 2019), the rock thermal conductivity is 1.742-3.246 W/m·K, with an average of 2.91 W/m·K, and the rock heat production rate is 0.116-3.327 μW/m³, with an average of 0.935 μW/m³ (Xu et al., 2011). The geothermal gradient is 24-30 ℃/km, and most of the terrestrial heat flow is 60-68.8 mW/m² in the Southern Sichuan Basin (Xu et al., 2011).

4. RESULTS

4.1 Temperature Distribution

Affected by the Weiyuan structural belt and the basement uplift, the bottom burial depth of the Qixia-Maokou Formation in the research area is relatively shallow, ranging from 2000 to 3500 m. The thermal reservoir thickness is 300-540 m. The top surface temperature of thermal reservoir formation is 46-106 ℃ (Fig. 5), and the bottom surface is 50-114 ℃ (Fig. 6). According to the classification standard of geothermal resources by temperature (Wang et al, 2017), the results show that between 25 to 90 °C temperatures are a low-temperature geothermal resource zone; between 90 to 150 °C temperature is a medium-temperature geothermal resource zone; with temperatures greater than 150 °C is a high-temperature geothermal resource zone. The geothermal resources of the Middle Permian Qixia-Maokou Formation in the research area are medium-low temperature geothermal resources. The low-temperature geothermal resources are generally distributed throughout the region. and the areas of medium-temperature geothermal resources are mainly concentrated in a few areas such as the northeast and southwest.

4.2. Geothermal Resource Evaluation

The geothermal resource amount and geothermal resource intensity of the Qixia-Maokou Formation were calculated by using the temperature and thickness of the thermal reservoir (Fig. 7). Then, according to the intensity of geothermal resources, which is the number of geothermal resources per unit area, the Natural Breakpoint Classification Method was used to divide the development potential of geothermal resources in the Southern Sichuan Basin is divided into three levels using ArcGIS software (Table 1).

The intensity of geothermal resources in the middle Permian Qixia-Maokou Formation in southern Sichuan is 30-85 GJ/m², and the Level Ⅱ areas are widely distributed, and the Level Ⅲ areas are less distributed. Level Ⅰ areas are mainly concentrated in the southwest and northeast regions, and the geothermal resource development potential is the largest. The amount of geothermal fluid resources is 2.46×10^{20} J, the amount of rock skeleton resources is 2.12×10^{21} J, and the total amount of geothermal resources is 2.37×10^{21} J, which is equivalent to 80.89×10^8 tons of standard coal. Assuming the recovery rate is 20%, the exploitable geothermal resources are 4.74×10^{21} J, equivalent to 16.18×10^8 tons of standard coal.

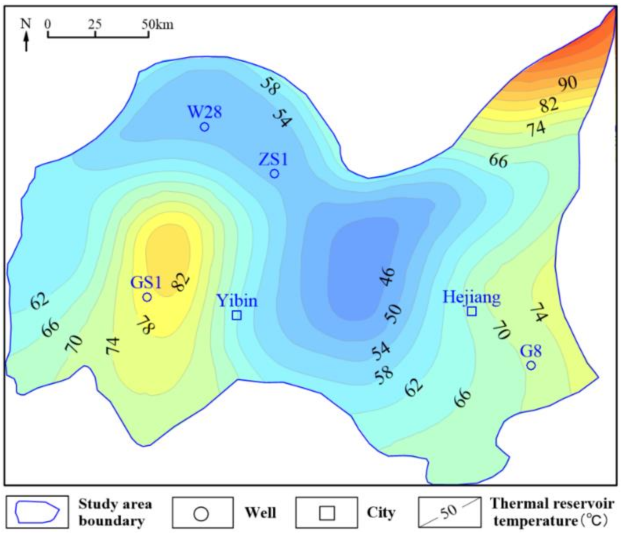

Figure 5: Top surface temperature distribution for the Qixia-Maokou Formation

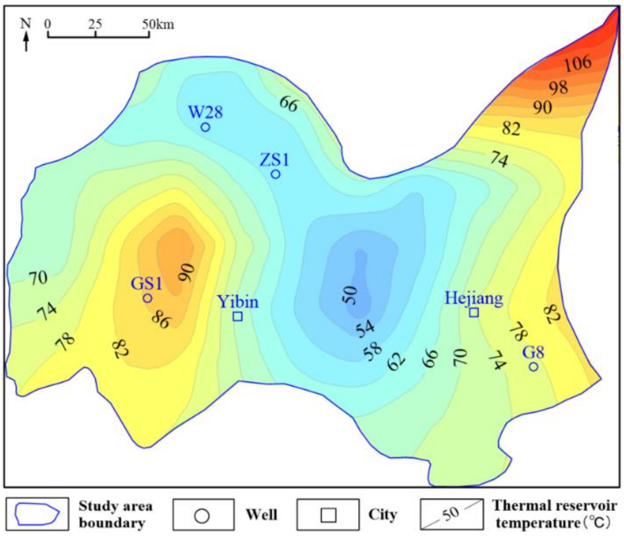

Figure 6: Bottom surface temperature distribution for the Qixia-Maokou Formation

Table 1. Grading table of geothermal resource potential

Graded area	Intensity of geothermal resources (GJ/m2)	Geothermal gradient (°C/km)	Terrestrial heat flow (mW/m^2)	Thermal reservoir temperature (°C)	Thermal reservoir thickness (m)	Geothermal resources (J)
Level I	>68	22-29	63-67	70-114	340-540	5.92×10^{20}
Level II	36-68	21-30	59-66	50-85	340-460	1.56×10^{21}
Level III	<36	22-30	59-65	46-65	280-340	2.18×10^{20}

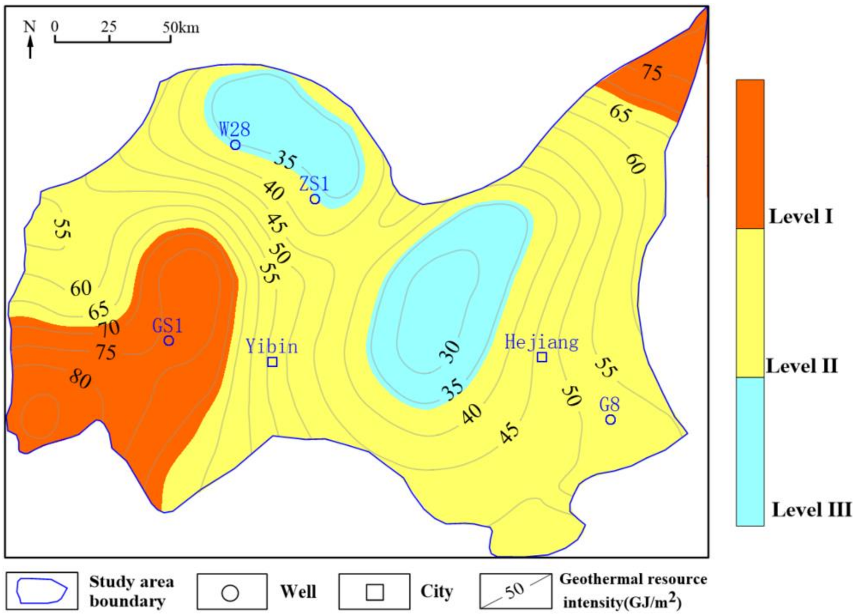

Figure 7: Geothermal Resources Intensity Distribution and grading plan

5. DISCUSSIONS

5.1 Thermal Reservoir Genesis Model

In the late sedimentary period of the Maokou Formation, affected by the Dongwu Movement, the Sichuan Basin was uplifted as a whole, and Maokou Formation was strongly leached and eroded by atmospheric freshwater. The Southern Sichuan Basin has formed a unique continental-type early diagenetic stratigraphic-controlled karst system with abundant karst water (Yang et al., 2021).

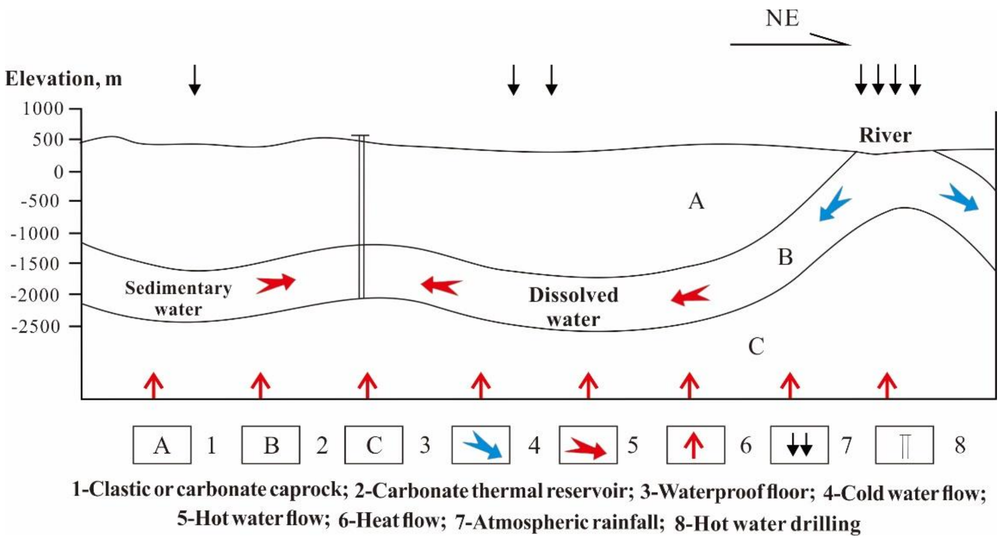

Figure 8: Genetic model of sedimentary basin-type geothermal resources

In high-altitude areas, such as the Huayingshan, the Gongchang, and the Gulin anticlines, the karst water is mainly supplied by atmospheric precipitation and migrates to the interior of the basin under the action of hydrostatic pressure. Meantime, the karst water is also mixed with sedimentary water from Sichuan Basin due to the low permeability of the pure limestone, the deep buried thermal reservoir, and the far recharge area. Therefore, the karst water is characteristic of the Cl-Na type with some HCO_3·Cl-Na·Ca type. The underground water continuously absorbed the temperature of surrounding rocks during the long-distance migration and the temperature is above 50 ℃. Then, the thermal reservoirs with medium-low temperature geothermal resources are formed (Fig. 8).

5.2. Grading of Geothermal Resources Potential

Level Ⅰ areas are mainly concentrated in the southwest and northeast of the research area. The geothermal resource intensity is 68-80 GJ/m^2, the geothermal gradient is 22-29 ℃/km, the terrestrial heat flow is 63-67 mW/m^2, the thermal reservoir temperature is 70-114 ℃, the thermal reservoir thickness is 340-540 m, and the geothermal resource is 5.92×10^{20} J. The temperature of the groundwater is mostly higher than 80 ℃, mainly medium temperature geothermal resources, geothermal resources have great development potential. Demonstration projects such as medium-low temperature geothermal power generation and geothermal cascade utilization can be prioritized.

Level Ⅱ is widely distributed and generally distributed in the research area, and geothermal resource potential is weaker than level Ⅰ. The intensity of geothermal resources is 36-68 GJ/m^2, the geothermal gradient is 21-30 ℃/km, the terrestrial heat flow is 59-66 mW/m^2, the thermal reservoir temperature is 50-85℃, the thermal reservoir thickness is 340-460m, and the geothermal resource is 1.56×10^{21} J. The comprehensive utilization of geothermal drying, agriculture, and breeding can be given priority.

The level Ⅲ areas are mainly concentrated in the central and northwest parts of the research area. The geothermal resource intensity is 30-36 GJ/m^2, the geothermal gradient is 22-30 ℃/km, the terrestrial heat flow is 59-65 mW/m^2, the thermal reservoir temperature is 46-65 ℃, the thermal reservoir thickness is 280-340 m, and the geothermal resource is 2.18×10^{20} J. The thermal reservoir temperature is much lower than levels Ⅰ and Ⅱ, and the thermal reservoir thickness is relatively thin. However, the bottom burial depth of the thermal reservoir is relatively shallow (2000-2400 m), and it is relatively close to urban areas such as Hejiang City. The geothermal resources of level Ⅲ can be used for healthcare projects, including spa physiotherapy, swimming pools, and agricultural applications.

5.3. Geothermal Resource Prospect

The geothermal resources in the Southern Sichuan Basin are thermally conductive geothermal resources, which are mainly controlled by a large amount of thermal upwelling from the deep mantle in the context of a relatively thin crust (Qiu et al., 2022). Therefore, the Southern Sichuan Basin should aim to find thermally conductive geothermal resources. The bottom plate depth of the Qixia-Maokou Formation is less than 3500 m, with developed karst and high porosity, forming a good geothermal reservoir, which is a favorable layer for the exploration of low-medium temperature geothermal resources. Affected by the basement uplift in the central Sichuan Basin and the Huayingshan structure, the depth of the thermal reservoir in the southwest and northeast of the research area is relatively shallow, the temperature of the thermal reservoir is relatively high, and the geothermal resources are the most abundant. The southwest region, with a relatively thick thermal reservoir (420-540 m) and high temperature (> 75 ℃), should be selected first to maximize its economic benefits. The comprehensive development and utilization of medium-low temperature geothermal power generation, geothermal drying, geothermal agriculture, and geothermal cascade utilization demonstration projects can be prioritized in favorable areas. To occupy the highlands of oilfield geothermal resources development and utilization in Sichuan Province, and help the Sichuan province win the battle of "carbon neutralization and carbon peak". In the following work, according to the distribution of geothermal resources, we will cooperate with oil and gas companies to select suitable abandoned drillings in the Southern Sichuan Basin to carry out demonstration projects such as medium-low temperature geothermal power generation and geothermal drying.

6. CONCLUSION

(1) Southern Sichuan Basin mainly has sedimentary geothermal resources with the characteristics of layered reservoirs. The Qixia-Maokou Formation is a favorable reservoir, with high temperature, shallow burial depth, and widespread karst fractures.

(2) Based on the three-dimensional geological model, we evaluated the geothermal resources of the Qixia-Maokou Formation in the research area by volume method. The total amount of geothermal resources in the Qixia-Maokou Formation is 2.37×10^{21} J, equivalent to 80.89×10^8 tons of standard coal. The exploitable geothermal resources are 4.74×10^{20} J, equivalent to 16.18 × 108 tons of standard coal.

(3) The geothermal resource potential of the Southern Sichuan Basin was divided into three levels according to the geothermal resource intensity. The suggestion of geothermal cascade utilization was proposed to give priority to the southwestern region of the Southern Sichuan Basin for comprehensive medium-low temperature geothermal power generation, geothermal drying, geothermal agriculture, etc.

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