Heat Aggregation Mechanisms of Hot Dry Rocks Resources in the Gonghe Basin, Northeastern Tibetan Plateau

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Abstract: Hot dry rock (HDR) is an important geothermal resource and clean energy source that may play an increasingly important role in future energy management. High-temperature HDR resources were recently detected in deep regions of the Gonghe Basin on the northeastern edge of the Tibetan Plateau, which led to a significant breakthrough in HDR resource exploration in China. This research analyzes the deep temperature distribution, radiogenic heat production, heat flow, and crustal thermal structure in the Qiaboqia Valley, Guide Plain, and Zhacanggou area of the Gonghe Basin based on geothermal exploration borehole logging data, rock thermophysical properties, and regional geophysical exploration data. The results are applied to discuss the heat accumulation mechanism of the HDR resources in the Gonghe Basin. The findings suggest that a low-velocity layer in the thickened crust of the Tibetan Plateau provides the most important source of constant intracrustal heat for the formation of HDR resources in the Gonghe Basin, whereas crustal thickening redistributes the concentrated layer of radioactive elements, which compensates for the relatively low heat production of the basal granite and serves as an important supplement to the heat of the HDR resources. The negative effect is that the downward curvature of the lithospheric upper mantle caused by crustal thickening leads to a small mantle heat flow component. As a result, the heat flows in the Qiaboqia Valley and Guide Plain of the Gonghe Basin are 106.2 and 77.6 mW/m², respectively, in which the crust-mantle heat flow ratio of the former is 3.12:1, indicating a notably anomalous intracrustal thermal structure. In contrast, the crust-mantle heat flow ratio in the Guide Plain is 1.84:1, which reflects a typical hot crust-cold mantle thermal structure. The Guide Plain and Zhacanggou area show the same increasing temperature trend with depth, which reflects that their geothermal backgrounds and deep high-temperature environments are similar. These results provide important insight on the heat source mechanism of HDR resource formation in the Tibetan Plateau and useful guidance for future HDR resource exploration projects and target sites selection in similar areas.

Key words: radiogenic heat production, heat flow, crustal thermal structure, hot dry rock, heat source mechanism

1 Introduction

Hot dry rock (HDR) is a high-temperature rock body located underground (generally 3–10 km depth) that contains little to no water or steam and is an important form of geothermal energy. HDRs are widely distributed, but exploitable HDR resources presently remain mostly restricted to high-temperature rock bodies located at shallow depths due to technical and economic limitations. HDR mining research has been conducted worldwide for nearly 50 years, beginning at the Los Alamos National Laboratory in Fenton Hill, New Mexico, USA, in 1974, and the number of enhanced geothermal system (EGS) projects has continually increased since that time. A total of 39 EGS projects for HDR development have been established in various countries worldwide, including the United States, United Kingdom, Germany, France, Australia, Switzerland, Sweden, and Japan. Fourteen projects have been developed for power generation, and five remain in operation with a total installed capacity of 12.2 MW, including the Soultz project in France, which achieved commercial power generation in 2013 with 1.5 MW (Mao et al., 2019).

China is located at the intersection of the Pacific Rim and Mediterranean-Himalayan geothermal belts. Tectonic activity has led to extensive high-temperature hydrothermal activity on the Tibetan Plateau and...
surrounding areas (Qin et al., 2019; Zhao et al., 2021), as well as on the island of Taiwan. High-temperature rock formations that are either impermeable or contain a small amount of steam may form in the wings of these specific high-temperature hydrothermal systems, thus offering prospects for HDR development (Wang et al., 2016; Wang and Lin, 2020). The China Geological Survey and relevant units in Qinghai Province have carried out HDR resource exploration in Qinghai, Fujian, Guangdong, and other areas since 2012 (Lin et al., 2020, 2021), and several boreholes constructed in the Gonghe Basin have exposed HDR bodies with temperatures higher than 180°C at depths of approximately 4000 m. This confirms that the Gonghe Basin is rich in HDR resources, but its heat source remains poorly understood. Sun et al. (2011) suggested that deep granite bodies are the main cause of the high temperatures and geothermal gradient anomalies in the region and that HDR resources form under specific tectonic conditions. Yan (2015), Zhang et al. (2019, 2020a), and Tang et al. (2020) suggested that low-velocity layers with high-temperature properties in the crust may constitute a regional heat source for the HDR resources in the Gonghe Basin, but were limited to qualitative analysis based on geophysical sounding data. Lang et al. (2016) reported a heat flow of 79.5 mW/m² in Zhacanggou area, Guide County using borehole temperature data and thermal conductivity data, and suggested a mantle heat flow contribution of approximately 27 mW/m². Zhang et al. (2018, 2020b) estimated the heat production contribution of the crust and mantle in the Qiaoboqia Valley using borehole temperature data and radiogenic heat generation data, and established an approximate warm crust-warm mantle type of crustal thermal structure in the Gonghe Basin, which is considered to have a mantle heat flow contribution of 53.9 mW/m². In view of the regional influence of mantle heat flow (Francheteau et al., 1984), it remains debated whether notable mantle heat flow differences can exist in a such small area (~80 km between the two locations), and this finding is inconsistent with the traditional assessment of a hot crust-cold mantle type of crustal thermal structure in the Tibetan Plateau (Wang and Huang, 1996). Further analysis of the heat source of the HDR resources in the Gonghe Basin is therefore required to obtain a scientific basis for future HDR resource exploration, target site selection, and resource evaluation in the region.

This paper analyzes the geothermal field distribution, radiogenic heat production rate, heat flow, and thermal structure of the crust in the Qiaoboqia Valley, Guide Plain, and Zhacanggou area of the Gonghe Basin based on analysis of the regional geothermal geological background including geothermal exploration borehole logging data, rock thermal property data, and regional geophysical exploration results. The findings are applied to discuss the heat accumulation mechanism of the HDR resources in the Gonghe Basin. This study provides a reference for future exploration and HDR resource development in the Gonghe Basin.

2 Study Area

The Gonghe Basin is located on the northeastern edge of the Tibetan Plateau, with the South Qinghai Mountains to the north, Wahong Mountains and Heka Mountains to the west and south, West Tipping Mountains to the east, and a low-lying basin in the middle (Fig. 1). The basin is 210-km long from east to west and 50-km wide from north to south. The altitude ranges from 2600 m to 3500 m and strongly decreases from northwest to southeast.

The Gonghe Basin is a faulted basin that formed at the beginning of the Neoproterozoic. The northern and southern sides of the basin are tectonically controlled by deep northwest–west and east–west fractures, and the eastern and western ends are controlled by deep northwest–west fractures. The basin basement was extruded owing to north–south, southwest–northeast, and east–west primary stresses during the time between the end of the Proterozoic and beginning of the Cenozoic, which led to the formation of (1) northwest–west and north–west oriented folds and compressional fractures and (2) near north–south and north–east oriented tensional fractures. Deep northwest–oriented fractures are relatively developed in the basement of the Gonghe Basin. The Indosinian–Yanshanian basal and ultramafic igneous rocks are intruded in the northwest–oriented deep fractures in both the eastern and western ends of the basin, which indicates that these fractures crossed the crust and extended deep into the mantle. These fractures have thus controlled the formation of bulges and depressions in the basin basement. Since the beginning of the Neoproterozoic Era, clastic sediments have been deposited in the basin with thicknesses ranging from 3000 m to 7000 m, which determine the general outline of the modern geological and geomorphological pattern of the basin (Liu et al., 2020). The Gonghe Basin has experienced strong neotectonic activity owing to the uplift of the Tibetan Plateau since the Cenozoic, which is manifested in the revival of old fractures in and around the basin. This has further strengthened deep hydrothermal activity and created an optimal regional geological and tectonic background for the formation of geothermal resources (Zheng et al., 2020). The Gonghe Basin is therefore a prospective area for geothermal energy resources.

The geothermal anomalies in the Gonghe Basin are mainly distributed in the area between the eastern Qiaoboqia Valley (Fig. 1b) and Guide Plain (Fig. 1c). The Qiaoboqia Valley hosts two groups of fractures in the north–west and north–northwest directions, and the groundwater on both sides of the Ayihai ditch in the fracture junction area outcrops to form a swamp with spring water flow of generally less than 1 L/s, a maximum flow of 4.97 L/s, and water temperatures of 12°C–27°C. In previous hydrogeological explorations, low-temperature (25°C–45°C) geothermal reservoirs were identified in the shallow confined aquifer. These reservoirs are approximately 10°C warmer than normal water temperatures and mostly used for swimming, bathing, and medical care. Several geothermal exploration boreholes (e.g., QR1, R1, DR1, DR2) have been constructed in the Qiaoboqia Valley in recent years, which have revealed that the Neoproterozoic geothermal reservoir occurs at a burial depth of 1260.00–1497.85 m with water temperatures of 64°C–91°C, and has characteristics of both a conductive
and convective geothermal system. The geothermal anomalies in Guide area are mainly distributed along the edges of the intrusive rocks in Zhacanggou, Qunaihai, and Xinjie, with water temperatures of 75°C–93°C, 88.5°C, and 63°C, respectively. Among them, the Zhacanggou hot spring is located in a northwest gully approximately 15 km southwest of Guide County with a single spring flow rate of 0.041–0.794 L/s and total flow rate of 15.2 L/s. The water temperature is approximately 78°C (maximum = 93°C) and is mainly used for bathing by local residents. Several geothermal exploration boreholes have been constructed in recent years to explore the geothermal resources of the Guide Plain. Among these, the R2 borehole is 1709.56-m deep and exposes the Neoproterozoic geothermal reservoir at a depth of 235.20–560.7 m, yielding a maximum flow rate of 968.46–1288.22 m³/d and temperature of 36.5°C–41°C.

High geothermal gradient anomalies were identified in the Gonghe Basin during the deep hot water exploration process. These include an anomaly detected in borehole R1 in the Qiaboqia Valley at a depth of 1203.48 m with a bottom temperature of 83.08°C and geothermal gradient as high as 5.80°C/100 m, which indicates the possible existence of deep HDRs in this area. HDR exploration boreholes DR3, DR4, GR1, and GR2 have since been constructed in the Qiaboqia Valley and boreholes ZR1 and ZR2 in the Zhacanggou area, all of which have shown high-temperature granite at depth. The GR1 and ZR2 boreholes obtained bottom temperatures of 207°C and 214°C at depths of 3705 and 4609.57 m, respectively, which made a breakthrough in HDR exploration in the area and laid the foundation for the implementation of HDR resource testing and development in the Gonghe Basin. The main deep hot water and HDR exploration boreholes in the Gonghe Basin are listed in Table 1.

3 Materials and Methods

3.1 Heat flow calculation

Heat flow is the movement of heat (energy) from the Earth’s interior to its surface. Under one-dimensional steady-state conditions, heat flow equals the thermal conductivity multiplied by the geothermal gradient. In practice, heat flow is mainly obtained based on borehole logging data and rock thermal conductivity measurements, and can be calculated according to a Bullard plot when the geothermal gradient of the borehole and thermal conductivity at the corresponding depth are available (Qiu...
Table 1 Major deep hot water and HDR exploration boreholes in the Gonghe Basin

<table>
<thead>
<tr>
<th>Location</th>
<th>No.</th>
<th>Geographical coordinates</th>
<th>Depth of granite (m)</th>
<th>Bottom temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qiaboqia Valley</td>
<td>QR1</td>
<td>100.61° 36.29° 976.00 2786.00 627.29</td>
<td>70.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R1</td>
<td>100.61° 36.24° 1203.48</td>
<td>Undiscovered 83.08</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DR1</td>
<td>100.61° 36.24° 1453.58 2776.00 1354.00</td>
<td>87.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DR2</td>
<td>100.60° 36.24° 1852.38 2796.00 1440.00</td>
<td>98.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DR3</td>
<td>100.62° 36.26° 2927.26 2806.00 1340.25</td>
<td>181.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DR4</td>
<td>100.62° 36.30° 3102.00 2889.00 1402.00</td>
<td>182.32</td>
<td></td>
</tr>
<tr>
<td></td>
<td>DR5</td>
<td>100.61° 36.28° 1501.60 2860.00 1490.00</td>
<td>86.70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GR1</td>
<td>100.65° 36.25° 3705.00 2863.80 1350.00</td>
<td>236.00</td>
<td></td>
</tr>
<tr>
<td>Guide Plain and</td>
<td>GR2</td>
<td>100.69° 36.23° 3003.00 2648.70 940.00</td>
<td>186.00</td>
<td></td>
</tr>
<tr>
<td>Zhacanggou</td>
<td></td>
<td>101.31° 35.97° 4721.60 2465.52 592.07</td>
<td>214.00 (4600 m)</td>
<td></td>
</tr>
</tbody>
</table>

The heat generated in the Earth’s crust mainly comes from (1) the decay of radiogenic elements (e.g., U, Th, K) in the crust and (2) deep heat flow conducted upward from the mantle. The distribution of these two components form the basis of crustal thermal structure analysis. The partitioning of crust-mantle heat flow affects the activity of the present-day crust, upper mantle, and deep temperature distribution, and can illustrate the most essential features of a geothermal system (Qiu et al., 2019). The thermal energy generated by the decay of radiogenic elements in the Earth’s crust is given by:

\[ Q_C = \sum q_a \]

where \( q_a = AD \) is the thermal energy produced by the decay of radiogenic elements in each structural layer of the crust, \( A \) is the heat production rate, \( D \) is the corresponding layer thickness, and the mantle heat flow \( q_m \) is determined by (Birch et al., 1968):

\[ q_m = q_d - q_e \]

The ratio of crustal heat flow to mantle heat flow can thus be obtained to analyze the crustal thermal structure.

3.3 Borehole logging data

Borehole temperature logging is the first step to analyzing present-day geothermal fields and crustal thermal structures. Several geothermal exploration boreholes have been constructed in the Gonghe Basin since 2012 (Fig. 1), and systematic temperature logging was conducted after drilling to obtain high-quality steady-state well temperature data. This paper mainly uses the thermal data from boreholes DR3, DR4, GR1, and GR2 in the Qiaboqia Valley, R2 and R3 in the Guide Plain, and ZR1 and ZR2 in the Zhacanggou area for thermal conductivity and radiogenic heat rate analysis, with an emphasis on heat flow and crustal thermal structure analysis using relevant data from boreholes DR3 and R3. Boreholes DR3 and DR4 were completed on August 25, 2014, reaching drilling depths of 2927.26 m and 3085 m, respectively. Temperature logging was performed in boreholes DR3 and DR4 between October 3 and 5, 2014 using a DS2000 continuous temperature acquisition system (Laurel, USA), yielding bottom temperatures of 181°C and 178°C, respectively. Borehole GR1 was completed on November 11, 2016, reaching a depth of 3705 m. Borehole GR2 was completed on October 11, 2016, reaching a depth of 3003 m. Several temperature logs were carried out after completion to obtain bottom temperatures of 184°C and 182°C, respectively.

The R3 well is located in the Guide Plain; it was drilled on September 13, 2012 and completed on December 13, 2012, reaching a depth of 2701.20 m. A mercury thermometer was used during the drilling process to measure the temperature at a fixed depth every 100 m. On May 26, 2013, geophysical logging was conducted using a PSJ-2 digital logging instrument and 101 valid temperature data were obtained. The average well temperature was measured every 25 m, yielding 106.743°C at the bottom of the well (2650–2675 m depth). The ZR2 well is located in Zhacanggou and was completed in 2018, reaching a depth of 4721.60 m. During and after the
drilling process, the well temperature was respectively measured using a mercury thermometer with two ranges (0°C–200°C and 0°C–300°C) and a PPS71 high-temperature multiparameter meter (Pioneer Petroleum Canada Ltd.). The highest temperature of 214°C was obtained at a depth of 4633 m.

3.4 Thermal conductivity data
Rock thermal conductivity data were obtained from boreholes DR3 and DR4 in the Qiaboqia Valley and boreholes R3, R2, ZR1, and ZR2 in Guide. The ZR1 borehole data were collected and measured in the field based on 19 core samples, which were tested using an automatic thermal conductivity scanner with a measurement range of 0.2–25 W/m·K. The thermal conductivity data of the other holes were obtained from the literature (Lang, 2016; Zhang et al., 2019; Zhou, 2020). A total of 113 sets of thermal conductivity data were obtained, including 38 sets of sedimentary cover samples with lithologies of mainly mudstone and muddy siltstone, and 75 sets of basement rock samples with lithologies of mainly granite and granitic amphibolite. The data were temperature-corrected using relevant empirical equations (Sass et al., 1992). The statistical characteristics and distribution of the thermal conductivity with depth in each borehole is shown in Table 2 and Fig. 2.

3.5 Radiogenic heat production data
The radiogenic heat production (RHP) rate is a physical property that defines the amount of heat liberated in a unit time per unit volume of rock by the decay of unstable radioactive isotopes. The RHP rate is usually expressed in terms of volumetric heat production (4), which can be obtained by calculating the contents of three radioactive elements, U, Th and K, in the rocks (Rybach, 1976).

\[ A = 10^2 \times \rho \times (9.52 \times C_U + 2.56 \times C_{Th} + 3.48 \times C_K) \]

where \( A \) is the volumetric heat production (μW/m³), \( C_U \) and \( C_{Th} \) are the U and Th contents of the rock (ppm), respectively, \( C_K \) is the K content (%), and \( \rho \) is the rock density (kg/m³). The volumetric heat production data were obtained from boreholes DR3, DR4, GR1, and GR2 in the Qiaboqia Valley and boreholes ZR1 and ZR2 in Zhacanggou, of which the ZR1 data were collected and measured in the field. A total of 15 core samples were collected and measurements of \( \rho, C_U, C_{Th}, \) and \( C_K \) were carried out. U and Th are geochemically classified as trace elements, whereas K is considered a major element and generally represented by its oxide K₂O. All of the measurements were completed at the Testing Center of the Institute of Nuclear Industry 230. The other borehole data were obtained from the literature (Lang, 2016; Zhang et al., 2019, 2020a; Zhou, 2020). A total of 111 sets of rock volumetric heat production data were obtained. The sampling depths and statistical characteristics of volumetric heat production for each borehole are listed in Table 3.

4 Results and Discussion

4.1 Deep temperature and geothermal gradient
The temperature logging curves and geothermal gradients of some geothermal exploration boreholes in the Gonghe Basin are shown in Fig. 3. The temperature-depth curves of boreholes DR3, GR1, and GR2 in the Qiaboqia Valley show a linear relationship in the vertical direction, which well reflects the characteristics of conductive heat transfer and indicates that they are essentially unaffected by groundwater flow. The bottom temperature of borehole

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Table 2 Statistical characteristics of thermal conductivity for the borehole cores in the Gonghe Basin

<table>
<thead>
<tr>
<th>Borehole</th>
<th>DR3</th>
<th>DR4</th>
<th>R3</th>
<th>R2</th>
<th>ZR1</th>
<th>ZR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td>2.91</td>
<td>3.17</td>
<td>2.87</td>
<td>2.35</td>
<td>3.43</td>
<td>3.74</td>
</tr>
<tr>
<td>Min.</td>
<td>3.20</td>
<td>2.27</td>
<td>2.65</td>
<td>2.00</td>
<td>1.92</td>
<td>2.58</td>
</tr>
<tr>
<td>Avg.</td>
<td>3.05</td>
<td>2.83</td>
<td>2.77</td>
<td>2.18</td>
<td>2.78</td>
<td>3.22</td>
</tr>
<tr>
<td>Granite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min.</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

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Fig. 2. Thermal conductivity of the borehole cores with depth in the Gonghe Basin.
The gray dashed lines show the depths at which the granite substrate was exposed by drilling. The hollow squares show the thermal conductivity values of the sedimentary cover samples, and the black circles show the thermal conductivity values of the basal granite samples.
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The geothermal gradient can be roughly divided into two intervals, 100–1300 and 1300–2880 m, with average geothermal gradients of 7.48 and 4.19 °C/hm, respectively. The average geothermal gradient of the entire borehole is 5.54 °C/hm. The geothermal gradient generally tends to slowly decrease with increasing depth.

The depths of boreholes R3 (Guide Plain) and ZR2 (Zhacanggou) are 2701.2 m and 4721.6 m, respectively, and their bottom temperatures are 103.7 °C and 214 °C (4600 m). The temperature-depth curves of these boreholes show notable differences owing to hydrothermal convection activity in the fracture zone. The ZR2 borehole encountered a multi-layer fracture zone at 500–3100 m depth, and its temperature-depth curve shows clear convective heat transfer characteristics due to the influence of deep circulation geothermal fluids. It is difficult for the temperature log to reflect a true change of geothermal gradient. The fracture is not developed below 3100 m and the average geothermal gradient is 4.98 °C/hm at 3100–4600 m depth.

Borehole R3 is located in the Guide Plain. The drilling data show that it is sedimentary at depths above 1400 m with mudstone and sandy mudstone as the main lithology, and granite from 1400 m to the bottom of the hole with little fracture development. Its temperature-depth curve thus shows conductive heat transfer characteristics: the temperature increases linearly with depth and the average geothermal gradient of the entire borehole is approximately 3.6 °C/hm. If the temperature-depth curve of borehole R3 is extrapolated to greater depth, it essentially coincides with the temperature-depth curve of borehole ZR2 below 3100 m, thus reflecting that the Guide Plain and Zhacanggou area have the same deep geothermal background and high-temperature environment.

4.2 Radiogenic heat production

The RHP rate is a fundamental parameter in geodynamic studies and is related to radiogenic heat sources. Granite is rich in radiogenic elements (e.g., U, Th, K), the decay of which creates an important heat source in the Earth’s crust. This is one of the main reasons why most HDR exploitation projects worldwide are presently conducted in granitic areas. Figs. 4 and 5 show the distribution of the volumetric heat production of the core samples from the main boreholes in the Gonghe Basin. It can be seen that the volumetric heat production of the granites in the Gonghe Basin generally exhibits a normal distribution, but there is no notable relationship with depth. The variation of volumetric heat production ranges from 0.63 to 7.21 μW/m³ with an average value of 3.10 μW/m³, which is slightly higher than the average global value (2.5 μW/m³; McLaren et al., 2003), but lower than the average value in Fujian and Guangdong, South China (4.2 μW/m³; Zhao et al., 1995). Another important feature of radiogenic heat production is the thermal contribution of radioactive heating elements such as U, Th, and K. The contribution of K is relatively low and does not exceed 15% in most samples; the contribution is thus mainly from Th and U. Fig. 6 shows the U to K contributions plotted against the Th to K contributions for
granite samples from different boreholes in the study area (i.e., the ratio of the radiogenic rate of K is used as a reference). The scatter of the data points deviates in the U/K direction, which indicates that the radiogenic contribution of granite in the Gonghe Basin is mainly from U. This feature is similar to that in South China, but the RHP rate of granite in the latter is significantly higher than that in the Gonghe Basin, which is also consistent with the wide occurrence of uranium mineralization in South China (Li et al., 2020).

4.3 Thermal conductivity characteristics

Fig. 3 shows that there are significant differences in the thermal conductivity of the different lithologies at depth. The average thermal conductivity of all of the samples is 2.57 W/m·K, which is close to the average thermal conductivity recommended by Smithson et al. (1974) for the middle and upper crust (2.7 W/m·K). The results further confirm that the thermal conductivity of the sedimentary cover of the Gonghe Basin is lower than that of the basal granite, which is an important condition for the heat conservation of HDRs (Rybach et al., 1978).

4.4 Heat flow

Fig. 2 shows that the temperature-depth curves of boreholes DR3, GR1, GR2, and R3 exhibit a good linear relationship. This indicates a very small effect of
groundwater flow and that the heat flow value can be calculated using the thermal resistance method. Boreholes DR3 (Qiaboqia Valley) and R3 (Guide Plain) were selected for the heat flow calculations based on the lithology of the strata revealed by the boreholes and the available thermal conductivity data at the same depth. The thermal conductivity of each layer was temperature-corrected using the correlation equation proposed by Mottaghy et al. (2008). The temperature-thermal resistance variation curve (Bullard plot) of each borehole was obtained based on the temperature logging data and thermal conductivity of these two boreholes (Fig. 7) and was fitted using the least squares method, yielding a good fit ($R^2 > 0.98$) and reasonable heat flow value.

From the slope of the fitted curves in Fig. 7, it can be seen that the heat flows in the Qiaboqia Valley and Guide Plain calculated by the DR3 and R3 boreholes are 106.2 and 77.6 mW/m$^2$, respectively, which are higher than the average heat flow in mainland China (60.4 ± 12.3 mW/m$^2$; Jiang et al., 2016) and the global mainland average value (65.5 mW/m$^2$; Davies, 2013). Fig. 2 shows that the temperature logging curve of borehole R3 exhibits typical conductive characteristics. This indicates that it is only weakly influenced by groundwater flow, which is consistent with the distribution and characteristics of the geothermal reservoir revealed during drilling. The drilling of borehole R3 shows that the depth of the Neoproterozoic low-temperature geothermal reservoir in the Guide Plain is 235.20–560.70 m, and the lithology of the aquifer is mainly medium to fine sand with a thickness of 27.35 m. $^{14}$C data show that the age of the hot water is approximately 20,000 years, indicating that the hot water formed from the recharge of atmospheric precipitation at lower temperatures in the Late Pleistocene under nearly static-state conditions. The depth of the Paleocene low-temperature geothermal reservoir in the Guide Plain is 608.50–1490 m. The lithology is mainly Paleocene brown-red mudstone, sandy mudstone interspersed with medium-fine sandstone, and siltstone. This geothermal reservoir has heat but little water, thus there is no prospect for development or use. The surface temperature of 8.33°C obtained from the Bullard plot is essentially consistent with the local average annual temperature (7.3°C), which indicates that the obtained heat flow represents the actual heat flux upward from depth beneath the Guide Plain. The temperature-depth curve of borehole DR3 is slightly convex, which indicates that the higher heat flow at the surface contains part of the heat flux transferred by the subsurface hot water flow. This is consistent with the fact that DR3 exposes a water-rich shallow Pleistocene geothermal reservoir at 301.1–607.55 m depth and a Neoproterozoic geothermal reservoir with conduction and convection properties at 607.55–1340.25 m depth. The surface temperature of 6.06°C obtained by the Bullard plot is similar to the average annual temperature of the Qiaboqia Valley (3.4°C), which indicates that the obtained heat flux values well represent the actual heat flux below the Qiaboqia Valley via deep conduction.

4.5 Crustal thermal structure

A layer-by-layer heat flow calculation was carried out using the back-stripping method to obtain the thermal structure of the crust in the study area. The volumetric heat production of the rocks up to a depth range of 4.6 km was taken from laboratory test results (Fig. 4), for which the relationship between the seismic wave velocity and heat generation rate proposed by Rybach and Buntebarth (1984) was used for the calculation:

$$\ln A = 16.5 - 2.47V_p$$

where $V_p$ is the P-wave velocity (km/s). The S-wave velocity of the Qiaboqia Valley was obtained from the natural seismic observation profile of Gonghe-Yushu (Qian et al., 2001) and multiplied by the wave velocity ratio of 1.709 (Liu et al., 2014) to obtain $V_p$ (Fig. 8a), whereas the $V_p$ of the Guide Plain was obtained directly from the active source seismic profile between Moba and Guide (Fig. 8b; Zhang et al., 2011). The depth of the Moho in the Gonghe Basin is between 50–60 km. Depths of 55 and 52.1 km were selected for the Qiaboqia Valley

![Fig. 7. Bullard plots for the DR3 (a) and R3 (b) boreholes.](image-url)
and Guide Plain, respectively, based on the seismic wave velocity profile. The crustal thermal structure models of the study area are shown in Fig. 9. Among them, the crustal heat flow is 80.4 mW/m², the mantle heat flow is 25.8 mW/m², and the heat production ratio of the crust and mantle is 3.12:1. The total heat energy generated by the decay of radioactive elements in the Guide Plain is approximately 50.3 mW/m²; that is, the crustal heat flow is 50.3 mW/m², the mantle heat flow is 27.3 mW/m², and the ratio of crust and mantle heat production is 1.84:1. Both regions belong to the hot crust-cold mantle type of crustal thermal structure. Shen et al. (1990) proposed that the crustal thermal structure of the northern margin of the Tibetan Plateau is characterized by the tiny mantle heat flow component of the ancient stable massif, and Qiu (1998) obtained the mantle heat flow in the Tarim Basin (Moho depth 50–58 km) and the Qaidam Basin (Moho depth 50–58 km) in western China, which are 20 mW/m² and 25 mW/m², respectively. Therefore, the mantle heat flow in the Gonghe Basin obtained in this study is consistent with these conclusions. The Guide Plain shows a normal crust-mantle thermal structure with increasing temperature with depth, whereas the Qiaboqia Valley shows a clearly abnormal intracrustal heating type of crustal thermal structure. Fig. 8a shows that high- and low-velocity bodies are arranged in the crust of the Gonghe Basin (Jiang et al., 2009), in which a large range of the low-velocity block (only the vertical distribution of this low-velocity body can be seen at station 199) is apparently present in the Qiaboqia Valley (station 199) at a depth of approximately 22–41 km. The heat flow is notably influenced by the low-velocity layer in the crust and its heat generation contribution is approximately 38.5 mW/m², accounting for 36% of the total heat flow at the surface.

4.6 Mechanisms of heat aggregation

A low-velocity layer in the thickened crust provides the most important source of constant intracrustal heat for the formation of HDR resources. The uplift of the Tibetan Plateau due to the collision of the Indian and Asian plates was one of the most spectacular events of the Cenozoic, creating a vast plateau landscape with a chain of high, steep, and strongly undulating mountains, as well as crustal thicknesses twice as large as normal. The crustal structure of the Tibetan Plateau has thus become a hot topic in geoscience over the past century, with the occurrence of low-velocity layers in the crust as one of the focal points (Jiang et al., 2009). The presence of low-velocity layers in the crust of the Tibetan Plateau is a characteristic feature of its crustal structure. Although no definitive consensus has been reached, potential explanations regarding its genesis include intracrustal partial melting (Hacker et al., 2014), crustal ductile shear zones (Tapponnier, 2001), ongoing metamorphism (Shapiro et al., 2004), and tectonic superposition (Jiang et al., 2009). Regardless of the genesis, partial melting or shear heating will cause the low-velocity layer to also be a relatively high-temperature layer. The good correspondence between the heat flow anomaly and distribution of the low-velocity layer in the crust of the Tibetan Plateau (Li et al., 2005) also confirms the high-temperature properties of the low-velocity layer to some extent. The occurrence of the low-velocity layer at the right depth within the crust may also become a constant intracrustal heat source for the HDR resources. The Gonghe-Yushu natural seismic observation profile (Fig. 7) shows that a low-velocity layer exists in the depth range of 22–41 km in the Qiaboqia Valley. Yan (2015) and Zhang et al. (2021) suggested that this low-velocity layer is an intracrustal partially molten layer with high-temperature properties, which may constitute a regional deep heat source for the HDR resources in the Gonghe Basin. The crustal thermal structure based on the wave velocity distribution of this natural seismic observation profile shows that the thermal contribution of this low-velocity layer is approximately 38.5 mW/m², which accounts for 36% of the total surface heat flow of 106.2 mW/m² and constitutes the most important source of constant intracrustal heat of the HDR resources in the Gonghe Basin (Fig. 10).
The heat enrichment from the redistribution of radioactive elements in the thickened crust serves as an important supplement to the heat produced by HDR resources. There are many radioactive elements in crustal rocks and the heat energy released by their decay is one of the main heat sources of the Earth’s internal heat. U, Th, and K are the most dominant radioactive heat-generating elements in the Earth’s crust because of their high abundance, high heat generation, and long half-lives.

Geothermal studies have shown that the concentration of radioactive heat sources on Earth decays exponentially with depth, and that radioactive elements are mainly concentrated in the surface layer of the Earth’s crust within a certain depth, which is on average 10 km worldwide. The crustal thickening on the Tibetan Plateau due to the Indian/Asian plate collision resulted in the relative enrichment of radioactive element concentrations within the extruded thickened crust by means of thickening the radioactive thermogenic layer, which enhanced the intracrustal radioactive autothermal effect (Shen et al., 1990), thus providing an important source of heat enrichment for HDR resources. The tested RHP rates of the relevant exploration boreholes in the Gonghe Basin show that the average volumetric heat production of the basal granite is 3.10 μW/m³, which is lower than the average heat generation rate of 4.2 μW/m² of the granite in Fujian and Guangdong provinces in South China. However, in the absence of intracrustal heating of the low-velocity layer, its intracrustal heat generation contribution is higher than that in the coastal area of South China. The crustal thickness of the R3 well in Guide is approximately 52.1 km and its crustal source heat production contribution is 50.3 mW/m², whereas the crustal thickness of the HR1 well in Huizhou, Guangdong is approximately 30 km and its crustal source heat production contribution is 39.2 mW/m². This demonstrates the notable autothermal effect of crustal thickening and thus thickening of the radioactive heat generation layer.

The downward bending of the upper lithospheric mantle caused by crustal thickening forms a small partial mantle heat flow component. Another effect of crustal thickening is the downward curvature of the lower crust and lithospheric upper mantle, which disrupts the thermal equilibrium at the lithosphere-asthenosphere boundary (Houseman et al., 1981). This may trigger local convection in the tectonically active zone, thus enhancing the mantle heat flux component while creating a small mantle heat flux component in the tectonically stable zone (Qiu et al., 2019). Previous studies (e.g., Qiu, 1998) have shown that the mantle heat flow from deep in the eastern rift basins of China is very large. For example, the mantle heat flow in the Liaohe Basin is 40.2 mW/m² and 38 mW/m² in the North China Basin, which account for 61% and 65% of the surface heat flow of the basins, respectively. In contrast, the mantle heat flows in the Qaidam Basin and Tarim Basin, which are located in the tectonically stable area in the west, are only 25.4 and 20 mW/m², respectively, accounting for only 47.9% and 45.5% of the surface heat flow of the basins, respectively. In addition to the increased heat production from crustal sources due to the presence of low-velocity layers in the crust, the reduction of the mantle heat flow fraction caused by crustal thickening is also an important component.
5 Conclusion

This paper analyzes the deep temperature distribution, rock radiogenic heat rate characteristics, heat flow, and crustal thermal structure of the Qiaboqia Valley, Guide Plain, and Zhacanggou area in the Gonghe Basin based on the results of relevant geothermal exploration borehole logging data, rock thermophysical properties, and regional geophysical exploration. The heat source mechanism of the HDR resources in the Gonghe Basin is explored and the following conclusions are obtained.

(1) The deep geothermal fields in the Qiaboqia Valley, Guide Plain, and Zhacanggou area in the Gonghe Basin are generally characterized by conductive heat transfer. The temperature-depth curves of the Qiaboqia Valley and Guide Plain show typical conductive heat transfer characteristics, due to their thick sedimentary cover and undeveloped fractures, with average geothermal gradients of 5.54 and 3.6°C/m, respectively. In contrast, the temperature-depth curves of Zhacanggou are characterized by convective heat transfer at a depth of 3100 m due to the development of fracture zones within the deep circulation of geothermal fluid. The well temperatures below 3100 m generally increase linearly with depth and show the same deep temperature increasing trend as the Guide Plain, which reflects their similar geothermal background and deep high-temperature environment.

(2) The thermal conductivity of the different lithologies at different depths in the Gonghe Basin show notable differences, with 1.34 W/m·K for sedimentary non-granite samples (mainly mudstone and muddy siltstone), 3.06 W/m·K for basal granite samples, and a mean value of 2.57 W/m·K. The lower thermal conductivity of the cover provides important conditions for the preservation of heat in the deep HDRs.

(3) The volumetric heat production of granites in the Gonghe Basin varies from 0.63 to 7.21 μW/m³, with a mean value of 3.10 μW/m³. This is slightly higher than the global average and lower than the average value in the coastal area of South China. However, the heat enrichment after the redistribution of radioactive elements caused by crustal thickening makes it an important source of heat for the HDRs in the Gonghe Basin.

(4) The heat flow in the Qiaboqia Valley is 106.2 mW/m², including 80.4 mW/m² of crustal heat flow and 25.8 mW/m² of mantle heat flow, with a crustal to mantle heat flow ratio of 3.12:1. This indicates a normal hot crust type of intracrustal heating and crustal thermal structure. In contrast, the heat flow in the Guide Plain is 77.6 mW/m², including 50.3 mW/m² of crustal heat flow and 27.3 mW/m² of mantle heat flow, with a crustal to mantle heat flow ratio of 1.84:1. This indicates a normal hot crust-cold mantle type of crustal thermal structure.

(5) The low-velocity layer in the thickened crust of the Tibetan Plateau provides the most important source of constant intracrustal heat for the formation of the HDR resources in the Gonghe Basin, whereas crustal thickening redistributes the concentrated layer of radioactive elements. This compensates for the relatively low volumetric heat production of the basal granite and serves as an important heat supplement for the HDR resources in the Gonghe Basin. The negative effect is that the mantle downward curvature of the lithosphere caused by crustal thickening results in a small mantle heat flow component. The mantle heat fluxes in the Qiaboqia Valley and Guide Plain of the Gonghe Basin are 25.8 and 27.3 mW/m², respectively, which are lower than the average global mantle heat flux values.

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geological characteristics and exploration direction of hot dry rocks in the southeastern Tibet Plateau, northeastern Qinghai Province.


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