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Survey of the Forming Mechanism of Hot Dry Rock Along the Southeastern Coast of China

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ABSTRACT

As a significant geothermal resource, hot dry rock (HDR) can be divided into four types in China according to its occurrence, namely, high radioactive heat production (HRH), modern volcano (MV), sedimentary basin (SB), and inner-plate active tectonic belt (IATB) types. Among them, the HRH type is mainly distributed along the southeastern coast of China's mainland. Combining a tectonic framework, regional geothermal flow, crust thickness, Curie interface depth, and new tectonics, this paper analyzes the occurrence background of HDR along China's southeastern coast and the existence of HDR in Fujian province. Heat control analysis was adopted to analyze the forming modal and establish the preliminary ternary heat reservoir model of HDR resources in this area. This paper also summarizes the exploration progress of HDR resources in Zhangzhou, Huizhou, and northern Hainan Island, laying a solid foundation for further relevant research.

1. INTRODUCTION

Hot dry rock (HDR) is a key form for storing geothermal resources. It refers to a dense hot rock mass without water or steam that generally exists in deep strata (generally 3–10 km underground). These widely distributed rocks will be the main direction of geothermal development in the future. According to a report by MIT in 2006, a mere 2% of HDR reserves at 3,500–7,500 m will generate 260,000 EJ, which is equal to 2,600 times the total energy consumption of the United States in 2005 (MIT, 2006). The total HDR resource at depths of 3–10 km in China's mainland amount to 2.5 × 1025 J, which is equivalent to 8.6 trillion tons of standard coal (Wenjing et al., 2012). This 2% of HDR reserves is comparable to 4,000 times China's total disposable energy consumption in 2015.

Compared with nuclear power, solar energy, or other types of renewable energy, HDR has great potential and certain commercial value, despite the current level of technology. China is not yet a strong player in terms of relevant development and studies, especially the evaluation of HDR resources, target selection, key technology research, and new demonstration projects. Hence, it is essential to narrow the gap between China and developed countries in discovering, identifying, and managing such a resource, which is well suited for China's geological conditions, and striving to be a pacesetter in the near future. Until now, high-quality HDR has only been identified in Gonghe Basin, Qinghai province (Gao et al., 2018). This paper explores the occurrence background and possible forming model of HDR along the southeastern coastal areas of China. The origin, distribution, and development of such a resource are also discussed, thus providing references for future evaluation, exploration, and development of HDR along the southeastern coastal areas of Fujian province.

2. METALLOGENIC TYPES AND DISTRIBUTION OF HDR RESOURCE IN CHINA

Different structures vary in geothermal and geological conditions, such as the burial depth of the Curie interface, the heat generated by a radioactive rock mass, the thickness of shallow overburden, and regional tectonic conditions. Therefore, more information on forming conditions and heat source characteristics of different HDR resources will help locate corresponding target areas more efficiently. Based on the distribution of geothermal flow, acid magmatic rock mass, and new heat control tectonic in China, the occurrence types of HDR resources can be divided into four types according to the forming mechanism, namely, high radioactive heat production (HRH) type, modern volcano (MV) type, sedimentary basin (SB) type and inner-plate active tectonic belt (IATB) type (Gan et al., 2015; Wang, et al., 2016).

2.1 High radioactive heat production type

Mesozoic acid granite is considered an HDR of high radioactive heat production type, with its corresponding characteristics. High-quality HDR resources are available in ideal overburden.

A key target area is along the southeastern coast of China, a vital distribution area of high geothermal flow granite. As an important area of energy consumption in China where has long seen significant shortages of coal, electricity, oil, etc., developing a local energy source is essential. Furthermore, rapid economic growth, especially numerous growing energy-intensive industries, leads to greater reductions in the energy supply. Thus, the investigation and evaluation of HDR resources could result in a significant local backup energy base.

2.2 Sedimentary basin type

Sedimentary basin (SB) type is always accompanied by large bedrock overburden, a large surface geothermal gradient, and a stable temperature increase. The low thermal conductivity of the sedimentary overburden can prevent heat loss when receiving heat from below, and so the bottom rock mass can reach more than 180 °C.

The Songliao Basin and North China Plain in East China have abundant HDR resources, which can serve as priority areas for relevant surveys and evaluation of this type.

2.3 Modern volcano type

The modern volcano (MV) type cannot be separated from volcanic activity. Hot bottom magma is the reason for obvious hydrothermal activity on the surface and generally relatively high temperatures in shallow places.

Target areas mainly are mainly found in Tengchong, northern Hainan province, Changbai Mountain, and Wudalianchi. They generally have a thermal structure of cold crust and hot mantle, and their heat source characteristics are closely related to the history of bottom magmatic activity and the characteristics of magmatic activity.

2.4 Inner-plate active tectonic belt type

Inner-plate active tectonic belt (IATB) type HDR is found in China's Qinghai–Tibet Plateau. Compressed by the Eurasian plate and the Indian plate, the plateau has gradually uplifted since the Cenozoic period. In addition, a series of large faults deep up to the upper mantle have formed in the interior of the Qinghai–Tibet Plateau and at the boundary with the Xinjiang Block, resulting in melting shallow crust and high temperatures, which is the heat source for the HDRs. Moreover, around Tashkurgan in the western Kunlun fault on Pamir Plateau, strong Holocene faults and active uplifts on both sides of the valley indicate the existence of high-temperature hot rocks, which are a potentially ideal HDR resource.

3. OCCURRENCE BACKGROUND OF HDR RESOURCES IN SOUTHEAST COASTAL AREAS

3.1 Geothermal tectonic background

Geotectonic characteristics are major contributors to geothermal energy, earthquakes, volcanoes, and fault distribution. The southeastern coastal areas of China are no exception. Located in the southern part of the Asian continent's eastern margin, a large number of Late Mesozoic volcanic-intrusive complexes are distributed throughout the area, which is an important part of the tectonic–magmatic belt along the Pacific Ocean.

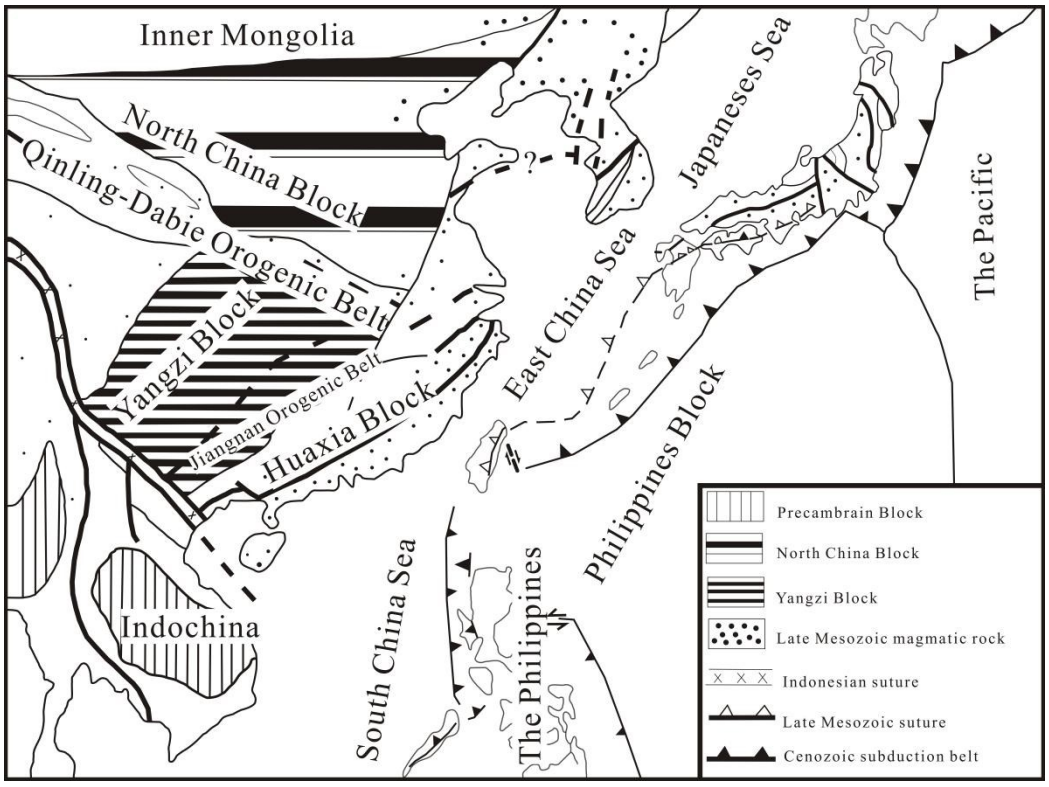

Figure 1: Tectonic framework map of eastern Asia (revised from Faure et al., 2017).

Subduction of the Pacific plate and collision of the Philippine plate since Late Mesozoic period have been crucial to Paleocene or even Quaternary magmatic–volcanic activities along the eastern Asian continent, which is directly related to whether southeastern coastal areas have high-temperature geothermal resources similar to Taiwan. There are different ideas about where the subduction zone of the Late Mesozoic Pacific plate is located; possible answers include an equi-depth area 40 km from the side of the Taiwan Strait that is opposite China's mainland, the Changle–Nanao fault zone, the Paleo-South China Sea, and the longitudinal valley zone in Taiwan. Many scholars at home and abroad believe that the Late Mesozoic subduction zone in East Asia is located in the Japan central tectonic line–Taiwan longitudinal valley zone–Mindoro–Palawan Belt (Figure 1).

According to results of P-wave tomography of the current Taiwan Strait, the collision and compression between the Eurasian and Philippine plates are dominant along the southeastern coast (Zheng et al., 2013). The NW compression of the Philippine plate played an important role in the formation of the geothermal system in the Zhangzhou area and along the southeastern coast. Based on seismic records and kinematics of the Taiwan Strait area from 1964 to 1996, collisions resulting from the downward-inserted Eurasian plate under the Philippine plate, along with the Philippine plate under the Taiwan region, can basically explain earthquakes in this region. In addition, the direction of regional principal stress is consistent with that of plate subduction and collision.

3.2 Deep thermal structure revealed by geophysics

3.2.1 Characteristics of crustal thickness

Judging from a crustal thickness map of the southeastern coast (Figure 2), characteristics there are similar to its geographic distribution, namely, a gradually thinner crust from Qinghai–Tibet Plateau to the southeastern coast, which is less than 30 km in the Fuzhou–Guangzhou area. However, the overall NE crust gains thickness from inland to coastal areas except in the Jinhua–Fuzhou area, basically following the rule of reducing thickness.

Based on the characteristics of crustal thickness and separated by Beihai–Daiyun Mountain–Hangzhou, the southeastern coastal areas can be divided into two parts: the western part exhibits an increasingly thicker zone, featuring a thicker crust in the northeast area of Jinghua–Fuzhou, and the eastern part, which exhibits a zone of steeply sloping thickness that has a sharply thinner crust toward the coast.

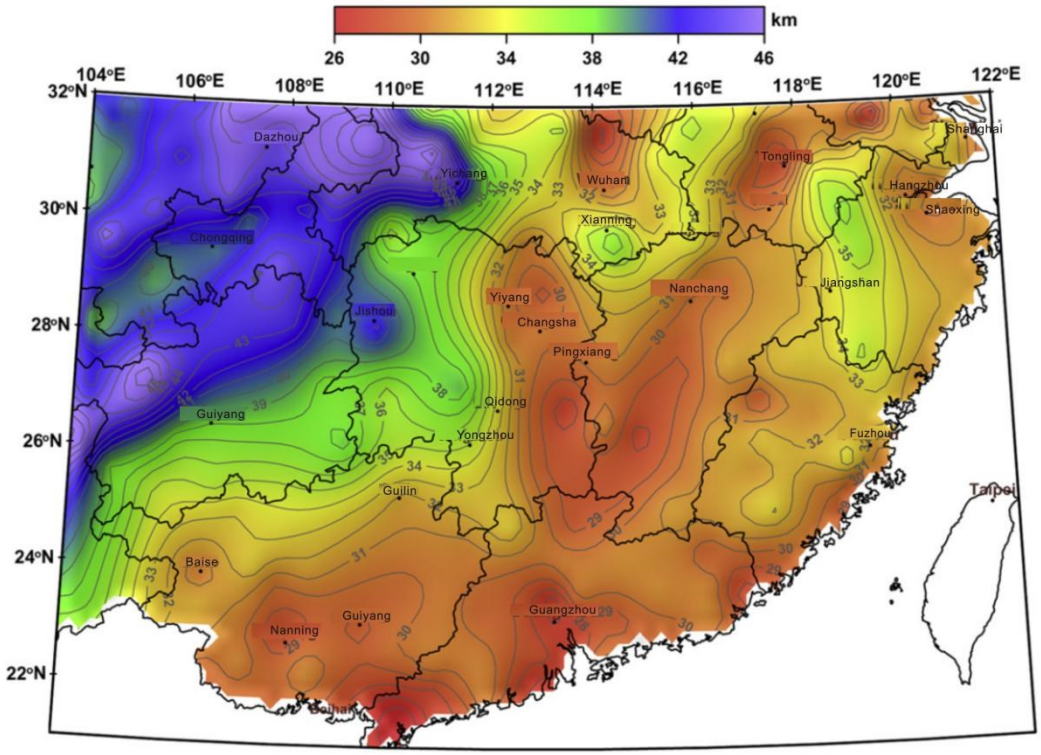

Figure 2: Crustal thickness map of southeastern coast (revised from Guo et al., 2019).

3.2.2 Seismic velocity

Various geological factors contribute to a decline of P-wave velocity, such as more fissures and wider pores in crush zone, changes of pore pressure in rocks, temperature and water content, or melting substances in the crust. As revealed by seismic refraction profiles YCA and L3, the Zhangzhou Basin in the Fujian area has an abnormally deep structure zone. Specifically, the middle-upper crust 10.2 km directly below Zhangzhou city has a low P-wave velocity of 5.8 km/s (Figure 3). One possible reason for this may be that due to a Moho discontinuity at around 29 km plus deep NW-trending tensile faults, heat can be continuously supplemented by the mantle heat source, resulting in local geothermal anomalies. Low-velocity substances at such depths can be detected from southern Jiangxi province to the coastal area in Fujian province, indicating the unity and continuity of the regional tectonic setting.

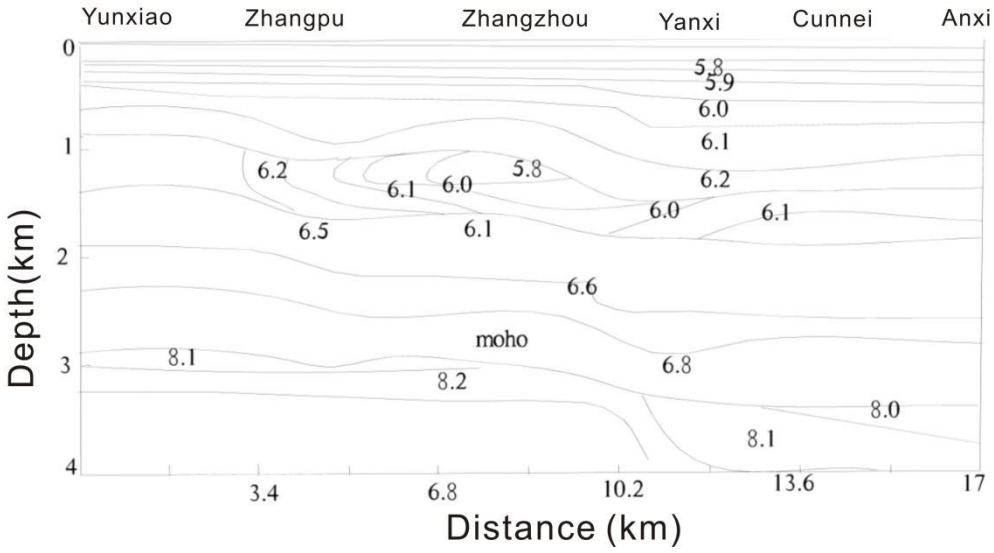

Figure 3: Contour profile of P-wave velocity through YCA lines (revised from Shaobai et al., 1991).

Considering different electrical structures, the thickness of the current lithosphere in southeastern coastal areas decreases from west to east and is extended somewhat, combined with shallow deformation (Figure 4). The flow of asthenospheric horizon promotes the extension of the lithosphere. Also, a series of crust–mantle mixed zones are present as a result of local melting at the depth of Moho discontinuity, connected to shovel-shaped extensional and detachment faults in the shallow crust, which is brittle in the upper fault as well as fragile–ductile to ductile in the lower part. Geophysical data shows that there is a low-velocity layer at approximately 15 km from middle-upper crust whose horizons are widely distributed from the southwestern Jiangsu province to the coastal Fujian province. Such horizons may represent partial melting of the magma of the middle crust or a ductile flow layer of the middle-lower crust.

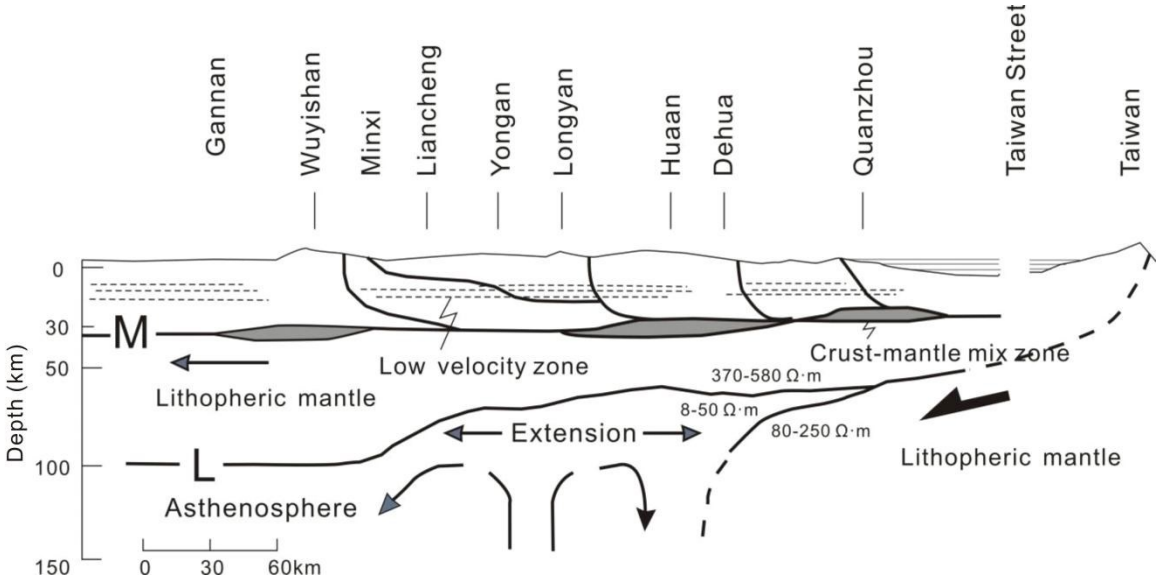

Figure 4: Comprehensive geophysical profile of southwestern Jiangxi–Fujian–Taiwan (cited from Zhou and Li, 2000).

3.2.3 Geothermal flow value

Geothermal flow value is a comprehensive parameter for characterizing the thermal state of crust and an important geothermal geological indicator for the occurrence distribution of HDR resources. Such values in the southeastern coastal areas of China are obviously affected by tectonic settings (Figure 5). More precisely, the geothermal flow value is lower in the basin area with relatively stable tectonic activities on the southwestern side but higher along the southeastern coast near the contact zone of the plate. Under the general trend of higher values from west to east, the local deep thermal structure determines this value. According to Figure 5, the geothermal flow value is above 95 $\mu W/m^2$ in Fuzhou of Fujian province, Zhangzhou, and the Yangjiang–Maoming area of Guangdong province.



Figure5: Contour map of geothermal flow value in Southeast China.

4. DISCUSSIONS ON THE FORMING MODEL OF HDR ALONG THE SOUTHEASTERN COAST

4.1 Debate on the existence of HDR resources in the Fujian area

4.1.1 Existence of HDR resources

The EW-trending geothermal anomaly corridor from Zhangzhou Basin to the outlet of Jiulong River is caused by both a nearly SN-trending great Jiulong River deep active fault and a nearly EW-trending deeply cut Xixi active fault. This corridor, with intensive ground stress, a relatively thin crust, a high-temperature heat reservoir in the middle crust, and a potentially large magma chamber in the lower crust, covers an area of 2,000 km^2 and is a most promising area for future HDR resource development in Fujian province (Qingxiang, 2016).

Jiwen et al. (2017) held that Fuzhou Basin and Zhangzhou Basin were located precisely in the aggregation zone of collision, compression, subduction, and subtraction between the Pacific plate and the Eurasian plate. A special crust and mantle structure and a low-velocity layer in the upper crust, especially lens-shaped structures in the corresponding layer of Zhangzhou Basin, are evidence for the existence of underground heat reservoirs. Also, there is still a deep and large fault zone Zhangzhou and Changtai that runs through the crust and reaches the top part of the upper mantle, which may constitute an upward migration channel of deep material, that is, a way of supplying heat energy.

4.1.2 No HDR resources

Tianfeng et al. (1988) studied the thermal state of the lithosphere in Fujian province and concluded that it lacked the characteristics needed to develop HDR for power generation. However, in accordance with calculations, deep temperatures reach 194.6 ^oC at a depth of 5 km, even in the Zhangzhou area, and 187.6 ^oC in Dehua, whereas other areas have lower temperatures below 180 ^oC. Thus, improved technologies and lower construction cost can help us realize artificial heat storage.

In addition, Zhijie (2012) concluded that no suitable temperature conditions of magmatic heat resources existed in Fujian's upper crust because of the tectonic background of the plate located this province. Low-velocity layers (Figure 4) discovered by artificial explosions are relatively stable, which could result from fragmented rocks rather than from melting or semi-melting layers, namely, due to a shovel-like active fault system or a slip surface in Fujian province and Taiwan (Tianfeng, 1987). The burial depth of the low-angle active fault system in coastal areas is just over 10 km. Zhijie et al. (2015) believed that the large-scale hydrothermal anomaly in Fujian was caused by strong compression of the Philippine oceanic plate from the southeast since the Neogene period, which resulted in a shovel-shaped fault system in the relatively brittle and consolidated continental crust of Fujian and Taiwan, as well as fracture grids, so that abundant atmospheric water infiltrated deep underground and absorbed heat from the rocks. Owing to the pressure and density differences of water, this underground water could be discharged to the surface or stored along faults, especially in NW-trending tension-shear ones, thus forming a large number of deep circular hydrothermal convection systems. Such systems could comprise warm water storage at low and moderate temperatures or high-temperature hot water systems at greater depths. Hence,

it is difficult to exploit HDR systems under such geothermal geological conditions because high-temperature rock masses over 150 °C usually exist in granite bodies with thicker overburden (Zhijie et al., 2015).

4.2 Analysis of regional heat control system

4.2.1 Heat source mechanism

Taking Zhangzhou as an example, the southeastern coastal area of China is a typical "cold crust and hot mantle" structure, which is completely different from the "hot crust and cold mantle" heat source structure in the Himalayas (Lefu et al., 2017). Because mantle heat is a vital resource as compared to heat generated from radioactive elements, it is a major contributor to the relatively high surface heat flow in Zhangzhou (Figure 6).

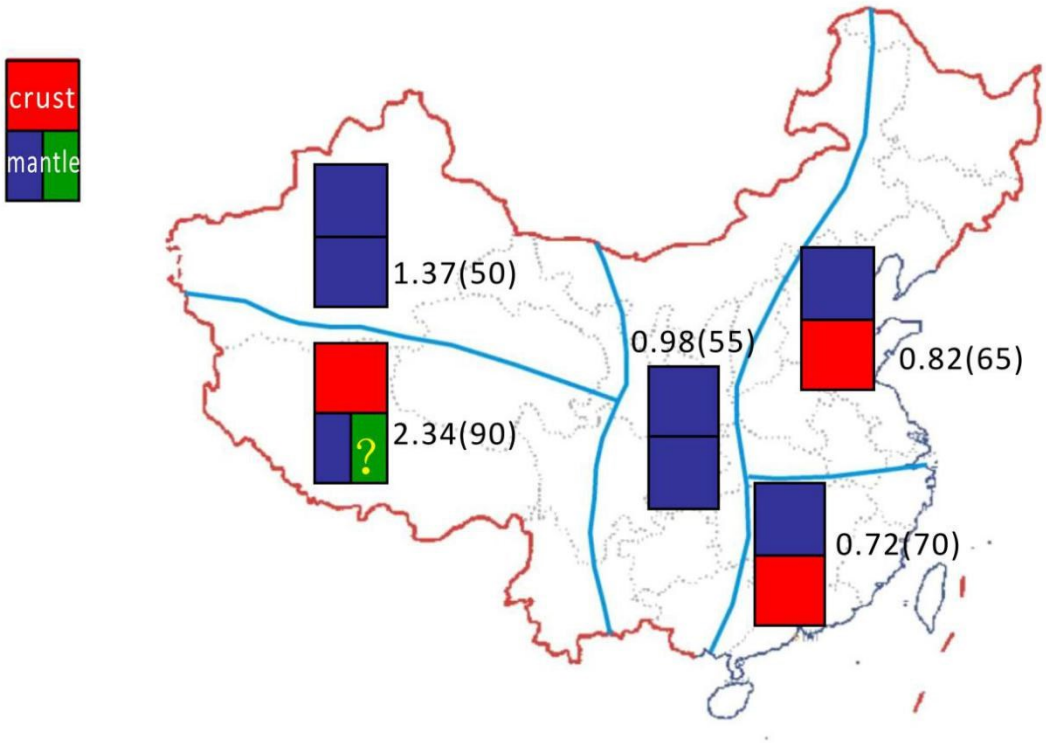

Figure 6: Ratio of crustal heat flow (qc) to mantle heat flow (qm) in China's mainland. (The values outside the brackets represent qc/qm and the values inside the brackets represent the average surface heat flow; cold crust and cold mantle in the northwest, hot crust and cold mantle in the southwest, as well as cold crust and hot mantle in the southeast.)

Surface heat flow is a direct indicator of various heat sources on the surface (including mantle heat, magma heat, tectonic heat, and heat from decay of radioactive elements). The values of surface heat flow largely reflect the comprehensive situation of deep heat sources. In China, southeastern coastal areas have higher surface heat flow than the inland Lingnan area. According to field gamma values and heat generated from the decay of radioactive elements, surface heat flow in the Zhangzhou area of the southeastern coast is lower than that of inland southern Jiangxi–northern Guangdong province, indicating that radioactive elements are relatively minor contributors in the Zhangzhou area, whereas other sources (especially the mantle) play dominant roles (Lefu et al., 2017). Based on geothermal and hydrogeochemical simulation results, Zhonghe (1987) found that mantle heat contributed about 60% of the total, whereas the decay of radioactive elements contributed around 40%. Furthermore, Xunruo et al. (1988) carried out the element and isotope geochemical simulation of a rock mass in Zhangzhou and found that the mantle also contributed more than 60% of the material found in granite. If calculated by the ratio of qc/qm in Figure 6, the heat contribution ratio for the mantle should be 1.00/1.72 = 58%, which is basically consistent withbasically in consistent with the results reported by Lefu et al. (2017). The above results show that granite bodies in the Zhangzhou area gain both heat and materials from the mantle, and thus the mantle provides important materials and energy for the formation and evolution of granite bodies.

4.2.2 Heat conduction channel

Exposed granite along the southeastern coast is closely related to several major fault zones such as the Pingxiang–Guilin fault zone, the Longyan–Dapu–Haifeng fault zone, the Ganjiang fault zone, the Chaling–Guangchang fault zone, the Wuzhou–Sihui hidden fault zone, and the Changle–Nanao fault zone. Granite usually exists at the intersection of fault zones. The distribution of granite, especially those formed during the Yanshan period, has a specific direction. To be more specific, early Yanshanian and Indonesian granite is mainly EW-trending, whereas late Yanshanian granite has a significant NE direction. In addition, granite that coexists closely with various types of sedimentary basins is younger from west to east and from the inland Lingnan region to the coastal area. Also, there are actually two age peaks of granite related to orogeny in each period. More precisely, older granite generally formed during the

syn-collisional orogeny period under compression, whereas younger granite usually formed during the post-orogeny period under an extensional situation. Different situations mean the possible transfer of energy and materials.

Because of deep faults in southeastern coastal areas, local melting or deep geothermal flow can transmit thermal energy to shallow places directly, resulting in isopleths of increasing geothermal temperature. Hot springs are often exposed around the intersections of deep faults and shallow extensional faults.

4.2.3 The overlying strata of thermal storage

In order to preserve the heat in basement rocks and prevent the cooling of rocks due to infiltration by atmospheric precipitation, it is necessary to cover basement rocks with an overlying strata of low thermal conductivity, which is usually sedimentary rocks (sediments) or volcanic rocks or a weathering crust of appropriate thickness. Based on standard one-dimensional, steady-state equation simulations, with other physical parameters being the same, the temperature in a granite basement covered by sedimentary overlying strata is 30–40 °C higher than that without such strata, which indicates the importance of overlying strata in preserving HDR heat.

According to statistics, the average thermal conductivity of rocks in Southeast China, especially of sedimentary rocks, is higher than that of crustal rocks. In terms of a rock's mineral composition, the calcareous, siliceous, and argillaceous mineral content predominantly determines the thermal conductivity of sandstone and mudstone. For example, the maximum thermal conductivity of quartz sandstone is 6.46 W/m·K, whereas the average thermal conductivity of calcareous sandstone is 4.58 ± 0.28 W/m·K, indicating the limited role of quartz sandstone in preventing heat loss (Liangping et al., 1994).

4.2.4 Geothermal reservoir

Highly radioactive granite bodies are major heat reservoirs of HDR, and only in the Leiqiong area are there heat reservoirs in thick sedimentary rocks. One of the main heat sources in the lithosphere is radioactive heat generation, which is basically from the elements U, Th, and the natural radioisotope potassium-40 (40K). Most of the southeastern coast has a high rate of heat generation (Ping, 1995). In particular, the large area of exposed granite throughout Guangdong, southern Jiangxi, and southern Fujian provinces has a heat generation rate of 2.8 $\mu W/m^3$, a rare case indeed in countries around the world. Estimated by borehole temperatures in southeastern coastal areas, the geothermal gradient there is 20–40 °C/km. Taking 180 °C as the minimum level of HDR resources, the preliminary conclusion is that the buried depth of heat reservoirs generally exceeds 5 km, but it's around 4–5 km in areas with higher geothermal gradients, such as Huangshadong of Huizhou in Guangdong province, Zhangzhou in Fujian province, and northern Hainan province.

5. DISCUSSIONS ON THE ACCUMULATION MODEL OF HDR RESOURCES IN SOUTHEASTERN COASTAL AREAS

Based on the above analysis of regional heat control systems along the southeastern coast, the corresponding ternary heat reservoir model there that develops HDR resource, or accumulation models featured by radioactive heat generation from acid rock mass, as well as heat conduction in faults plus heat preservation by overlying strata.

5.1 RADIOACTIVE HEAT GENERATION FROM ACID ROCK MASS

Numerous previous studies on granite have been conducted in northern Guangdong–southern Jiangxi province, which served as important assets for this project. Data on the heat generation rate per unit volume of granite without a uranium mine are shown in Table 1.

Furthermore, granite from the Yanshan period, especially late-stage granite, has the highest heat generation rate, much higher than that of granite from other periods. In other words, younger granite has a higher heat generation rate per unit volume. Hence, granite in northern Guangdong – southern Jiangxi province, particularly granite from the Yanshan period, has a far higher heat generation rate, which provides good conditions of heat generation to develop HDR resources.

Table 1: Heat generation rate of basement rocks per unit volume from different periods in southeastern coastal areas

Forming period of granite body	Heat generation rate of average unit volume ($\mu W/m^3$)
Granite from Jinning period	3.1
Granite from Caledonian period	3.3
Granite from Indonesian period	3.9
Granite from early Yanshan period	5.2
Granite from late Yanshan period	6.4

Note: The data in the table are mainly cited from Ping (1993), Xinmin (2007), Li et al. (2003), and Wang et al. (2010). A few relatively higher figures may be related to uranium mineralization, and so the statistical data are mainly based on granite that is free of uranium mines.

5.2 Heat conduction in faults

The boundaries of hot-spring zones are generally along tectonic lines. Whether hot springs are exposed has no direct relation to main faults, but it is closely related to the structures of relevant secondary faults. There are 2–4 NE-trending hot springs, namely, Gongzaiqian–Pangu, Xintang–Zhangzhou–Huangkeng–Xuemei, Dongsi–Tianli–Houxi, and Guiguan Lake–Wuyuanwan–Dongshan are located in a northeast direction, reflecting the fact that underground hot water mainly gains heat from NE-trending tectonics. Most exposed hot springs are found at the intersections of NE-trending and NW-trending structures. The NW structures are the newest ones, with better connectivity and water-bearing capacity, providing a main supply source and runoff channel for underground hot water. In conclusion, NW-trending structures control the water supply, whereas NE-trending faults control heat, indicating that faults can conduct heat.

4.3 Heat preservation by overlying strata

Sedimentary overlying strata can preserve geothermal energy and prevent heat loss. Because sedimentary strata along the southeastern coast has a higher heat conductivity than that of the mainland, the coastal sedimentary overlying strata is less able to preserve heat.

The ternary heat reservoir model of HDR resource accumulation in the distribution area of highly radioactive granite along the southeastern coast is shown in Figure 7.

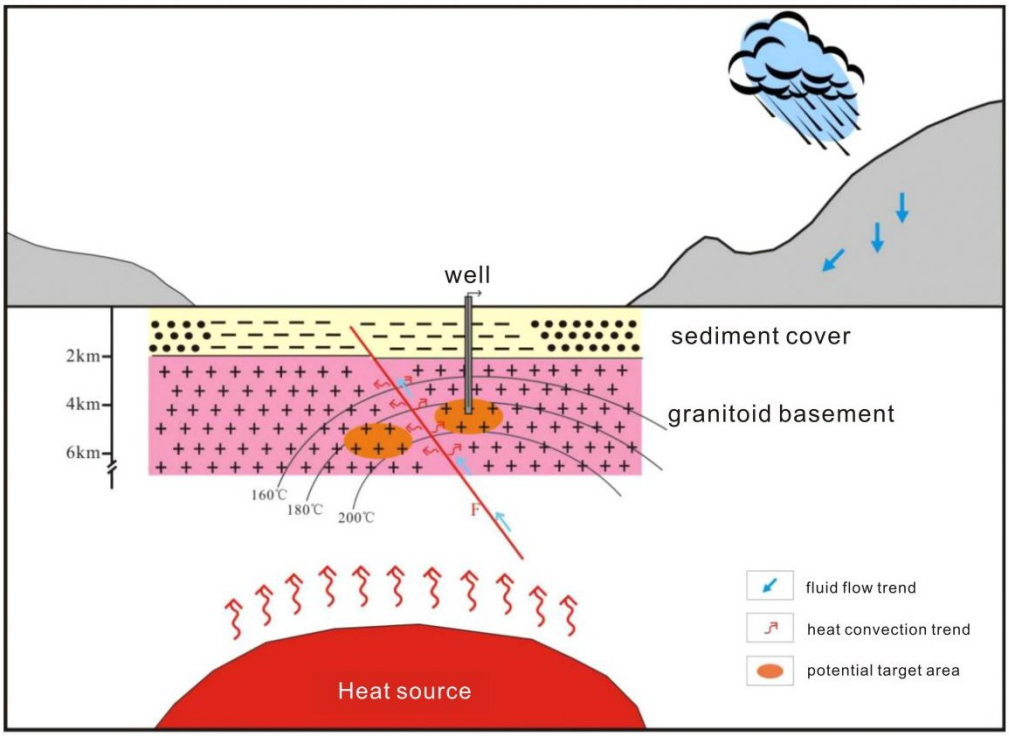

Figure 7: The ternary heat reservoir model of HDR resource accumulation along the southeastern coast.

6. EXPLORATION PROGRESS OF KEY TARGET HDR RESOURCE AREAS ALONG SOUTHEASTERN COAST

6.1 Zhangzhou area

Zhangzhou exhibits a geothermal anomaly, where most exposed hot springs are at 40–80 °C. Thirteen (13) hot springs have water temperatures of 60 °C, and the highest temperature is 121.5 °C. Considering this hydrothermal anomaly, geothermal investigations, geophysical exploration, and geothermal drilling have been used to study the occurrence characteristics of deep HDR. Strata from the Jurassic to the pre-Quaternary period are generally absent in this area. The lower part is intruded by granite from the Yanshan period, and the surface is covered by Quaternary Pleistocene alluvial–pluvial strata with a thickness of more than 20 m (Figure 8).

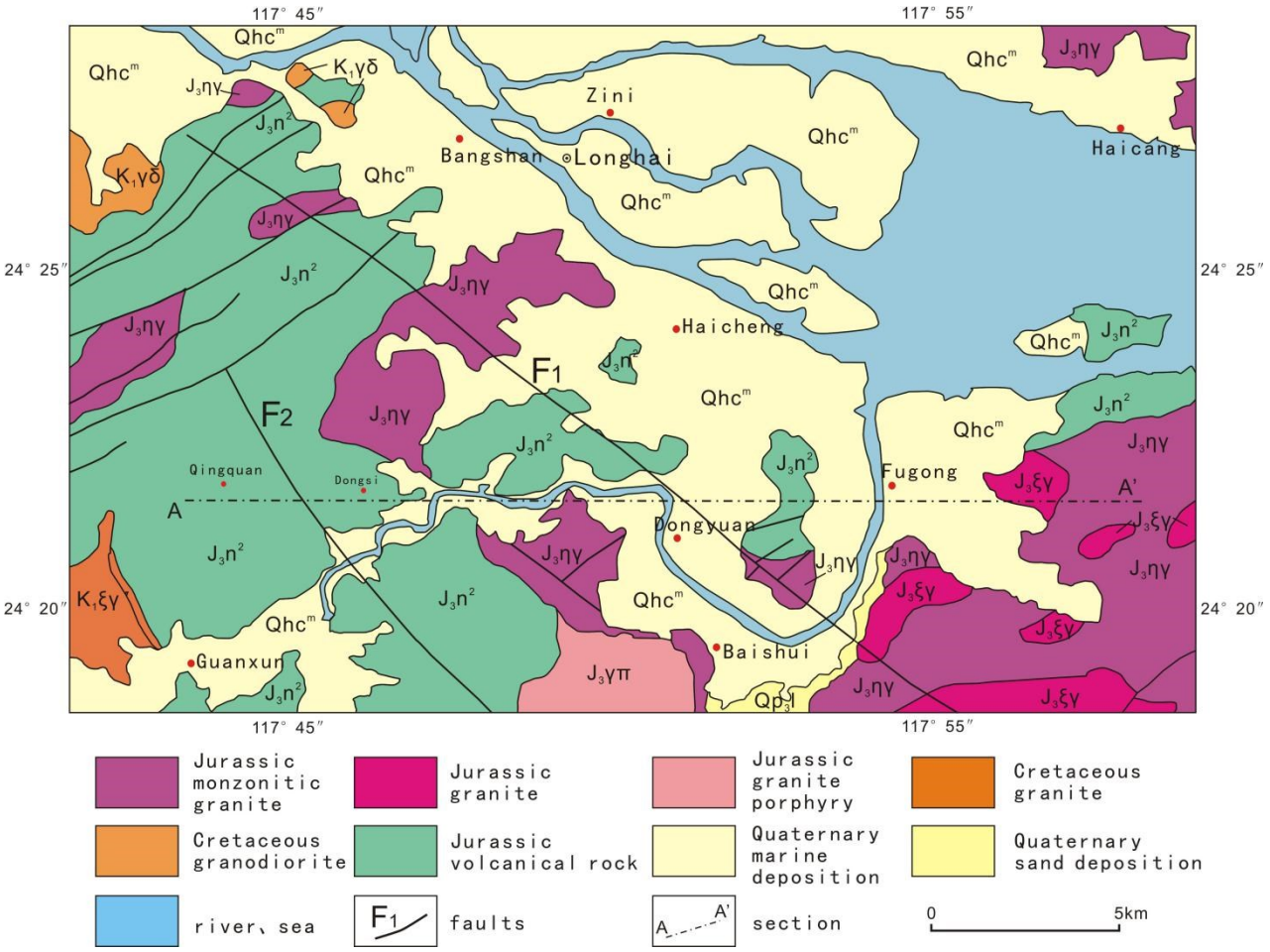

Figure 8: Geological sketch of Zhangzhou area (in which the A–A' section is a comprehensive geophysical section).

Judging from the comprehensive interpretation results of geophysical prospecting (Figure 9), granite intrusions exist throughout this area. To be more precise, No. 4, 9, and 19 rock masses all belong to stage-III γ 52 (3) c rock; the other granite comes from earlier times. In addition, No. 13, 15, and 17 rock masses are all granodiorite. Large areas of low-resistivity bodies (No. 7 and 11 rock masses) that are inferred to be semi-melting rock masses exist below 7 km in the east/ west direction of the section.

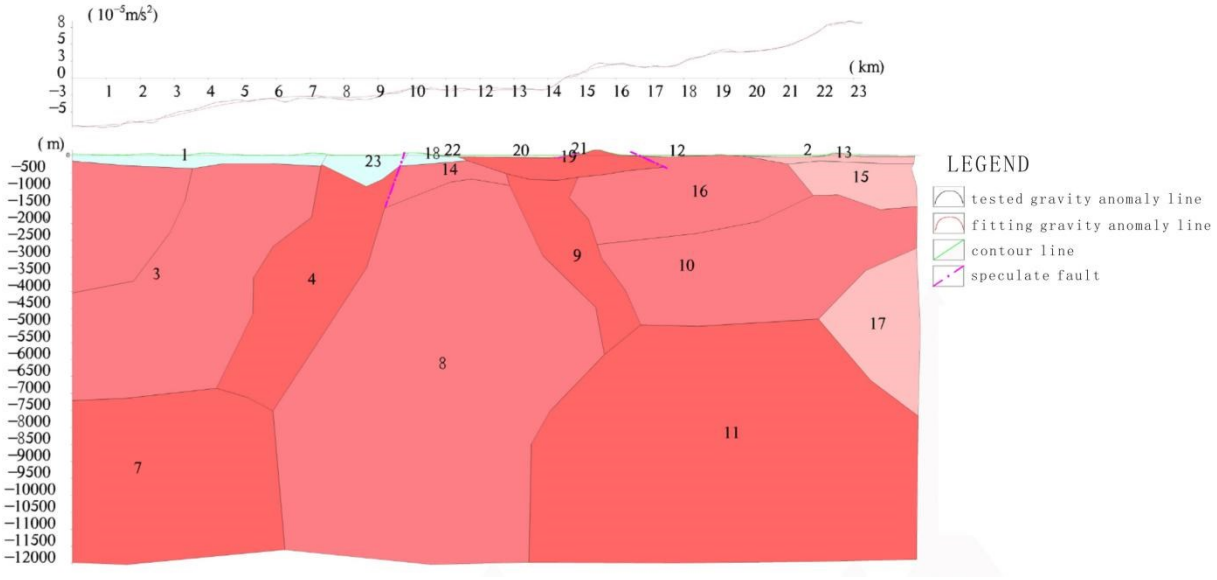

Figure 9: Illustration of inverse inference of both gravity and magnetotellurics in the Longhai District of Zhangzhou city, Fujian province (see Figure 8 for locations of sections).

On the basis of geophysical interpretation, a complete granite body was selected for geothermal drilling with a depth of 4,000 m in Dongsi Township, Longhai city. A total of three tests were conducted after drilling, and the corresponding results are shown in Figure 10. Clearly, the temperature increased because the first test was about 3 °C lower than the other two tests. Temperature curves of the second and the third tests are quite similar, indicating that the tested well temperature was the actual formation temperature. There were greater deviations in the temperature results of the first test. Also, the results of the tested well were quite similar results to those of test wells at 3,500 m. The highest temperature at 4,000 m was 109 °C, which is within the predicted temperature range.

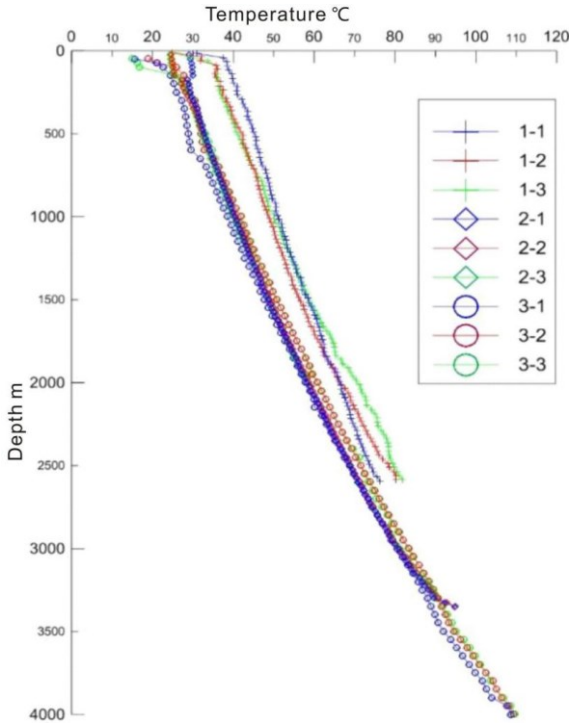

Figure 10: Temperature curves of test well at 4,000 m. (Temperature was measured three times using three groups per time; the first time reached 0–2,500 m, the second 0–3,350 m, and the third 0–4,000 m).

In order to reduce the errors caused by numerical calculation, TOUGH2 software was used to divide the Tyson polygon in the horizontal direction and to limit the largest single grid to within 10,000 m^2, whereas the equidistant subdivision method was applied in the vertical direction so as to divide the Tyson polygon into 40 layers of 200 m each, for a total of 39,680 grids. The relevant parameters of the model are shown in Table 2. As shown in this table, granite was the major heat reservoir. Information from the test wells, the heat conductivity test of the drill core, and empirical values were used to determine that the heat conductivity was 3.4 W/m·K, porosity was 0.01, and permeability was 1×10^{-17} m^2. Silicification in the faults can explain the higher heat conductivity of 5.5 W/m·K. The thermal storage of the fracture was 5.5 W/m·K higher than conventional thermal storage.

Table 2: Main parameters of the model

Model part	Porosity	Permeability (m^2)	Heat conductivity W/m·K
Geoheat reservoir	0.01	1×10^{-17}	3.4
Shallow fault	0.05	1×10^{-12}	5.5
Deep fault	0.02	1×10^{-17}	5.5

The initial pressure of the model was calculated using the hydrostatic pressure, $P = P_0 + \rho_{water} \times g \times h$. In this equation, P is the pressure of the target grid, P_0 is atmospheric pressure measured in Pa, g is the gravitational acceleration (N/kg), and h is the depth of the grid center (meters/m). Through linear fitting of temperature data at less than 2,500 m, the equation T= 23.403 + 0.0186.Z can be made, in which T is the temperature (°C), and Z is the depth (m). These were the initial temperature conditions of the model.

Following the above conditions, the evolution of the geothermal field was simulated and corresponding simulation results of the deep geothermal distribution in the study area are shown in Figure 11. The figure shows that deep heat is mainly transmitted through faults to shallow parts according to the apparent bulging geothermal isoline. This model predicts that the formation temperature at 5,100 m can reach 140 °C.

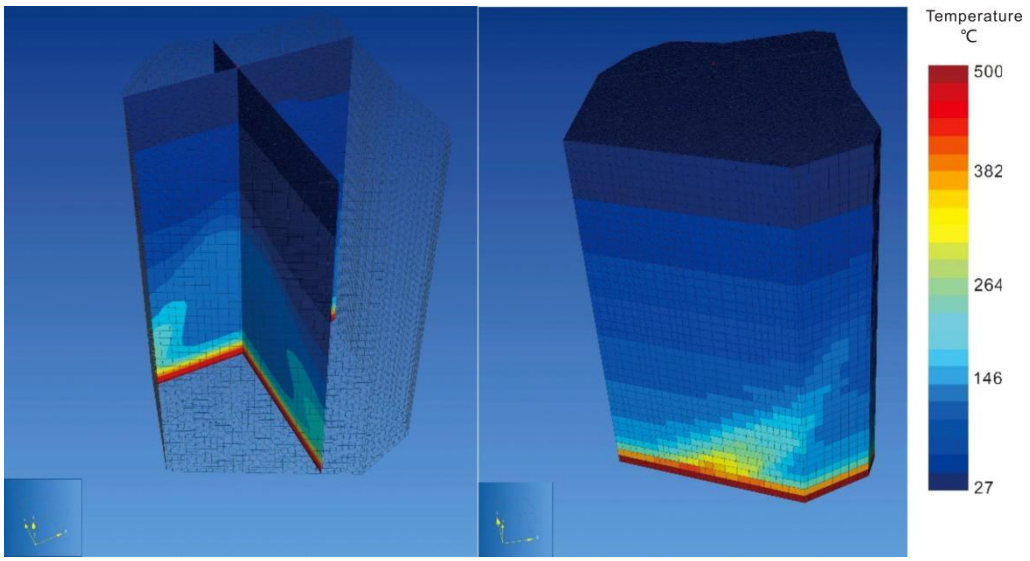

Figure 11: Distribution map of deep geothermal temperature in study area.

6.2 Huangshadong area in Huizhou city

The Huangshadong area in Huizhou city belongs to the South China plate and the southern part of the Cathaysian block. It is about 30 km southeast of the deep Heyuan fault zone, about 12 km southeast of the deep Zijin–Boluo fault zone, and 40 km northwest of the deep Lianhuashan fault zone. The exposed strata in the study area includes the Sinian Laohutang Formation (Z2lh), the Cambrian Niujiaohe Formation (Єn), the Devonian Laohutou Formation (D1-2l), the Maozifeng Formation (D3C1m), the Carboniferous Ceshui Formation (C1c), and the Quaternary Huanggang Formation (Qp3hg). The northwestern study area is the Dadianding rock mass (J1D) and its lithology is fine–medium-grained biotite adamellite (Figure 12).

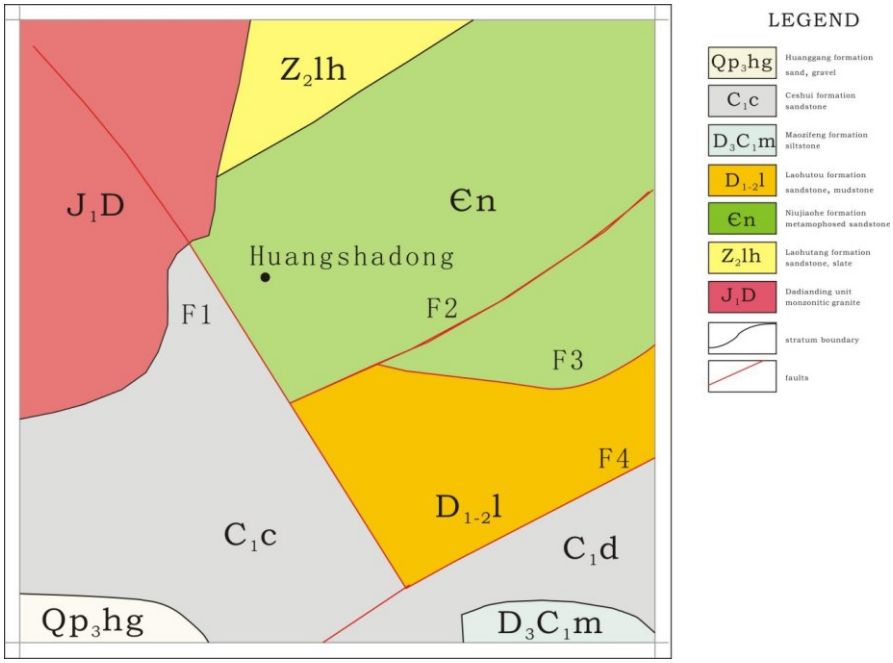

Figure 12: Geological sketch of Huangshadong area.

According to the gravity inversion profile (Figure 13), the burial depth of the basement ranges from 4 to 9 km. Well-developed basement structures in the study area cross in the NE and NW directions. These great faults control rock intrusion and stratum deposition, and the rock mass on low mountain slopes intrudes along the intersections of faults. The basement in this area is composed of the crystalline bedrock of early Paleozoic Sinian metamorphic rocks.

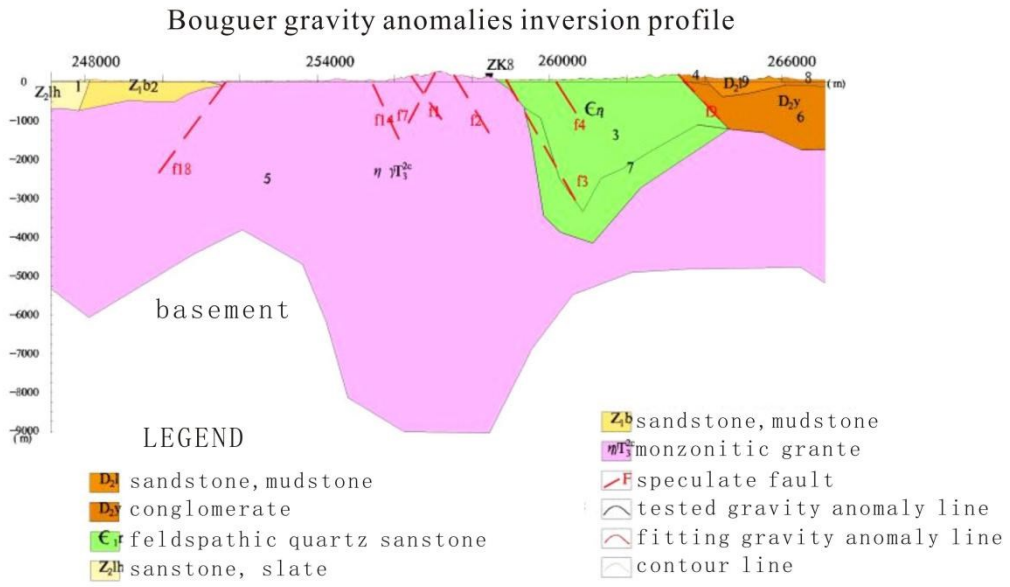

Figure 13: Gravity inversion profile in study area.

The CSAMT method was adopted to detect shallow faults. Four survey lines were arranged: NW-trending L1 and L3, along with NE-trending L2 and L4. From the joint interpretation of L2 and L4 through audio-frequency magnetotellurics, there was a corresponding channel for low-resistivity substances east of L3 (Figure 14). When projected onto Figure 12, the channels in the NW direction and the channel reflected by L2 are smaller than that reflected by L4. Therefore, it can be concluded that this channel gradually decreases from south to north, which is defined as T1.

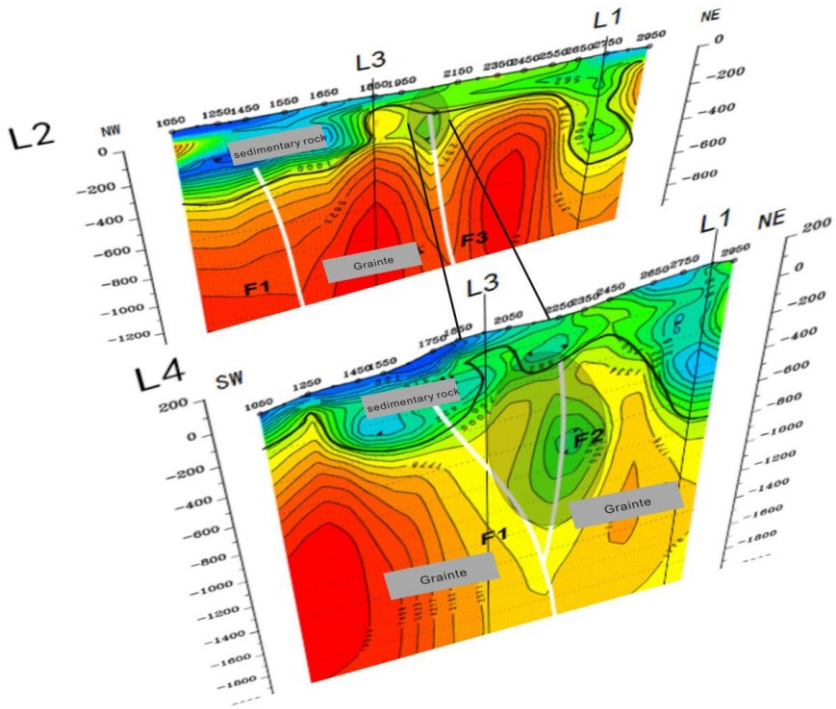

Figure 14: Joint interpretation of survey lines L2 and L4.

Another joint interpretation of L1 and L3 through audio-frequency magnetotellurics indicates that there is a boundary between corresponding low-resistivity and high-resistivity substances (T2), which is approximately consistent with L4 (Figure 15). Such a channel NE-trending when projected to Figure 12, which is in line with the NE-trending fault zones (F2–F4) on the surface, that is,

between the Maerzhai fault (F3) and the Chuanlongwa fault (F4). These results mean that F3 and F4 are the reflections of this boundary on the surface.

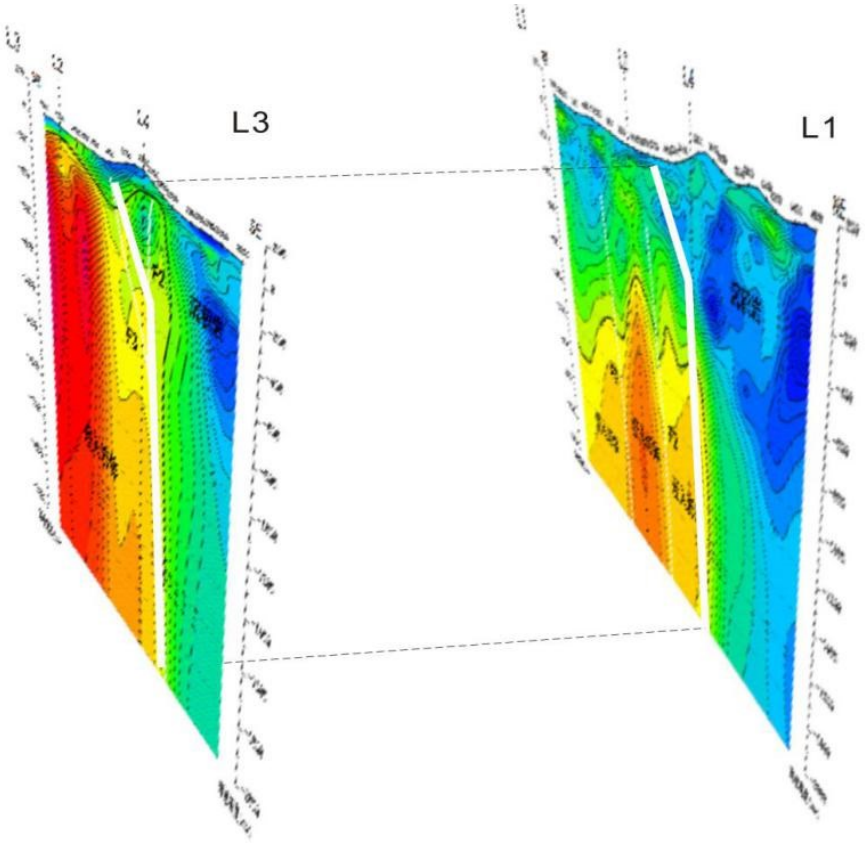

Figure 15: Joint interpretation of survey lines L1 and L3.

According to the interpretation of geophysical prospecting, in addition to corresponding geological conditions between T1 and T2 in Figure 16, NW-trending exposed hot springs/geothermal wells are basically located in the low-resistivity channel T1, and so T1 is supposed to be the heat control and water conduction structure for hot springs/geothermal wells. Also, the tectonic geological survey shows that NW-trending faults with high dip angles are present in the strata within T1, which can serve as evidence for the existence of faults. In terms of regional stress, the main stress direction σ1 is NW–SE compression (anticline folds with an axial direction of 245° in hot-spring areas) and the smallest NW-trending stress direction σ3 is tensile, which also confirms T1's role as a water conduction channel.

In view of the above conclusions, the boundary line T2 between high resistivity and low resistivity is formed by compression and extends downwards widely, which is the deep reflection of NE-trending faults. As a result, T2 is presumed to be the heat control and heat conductivity structure of hot springs/geothermal wells.

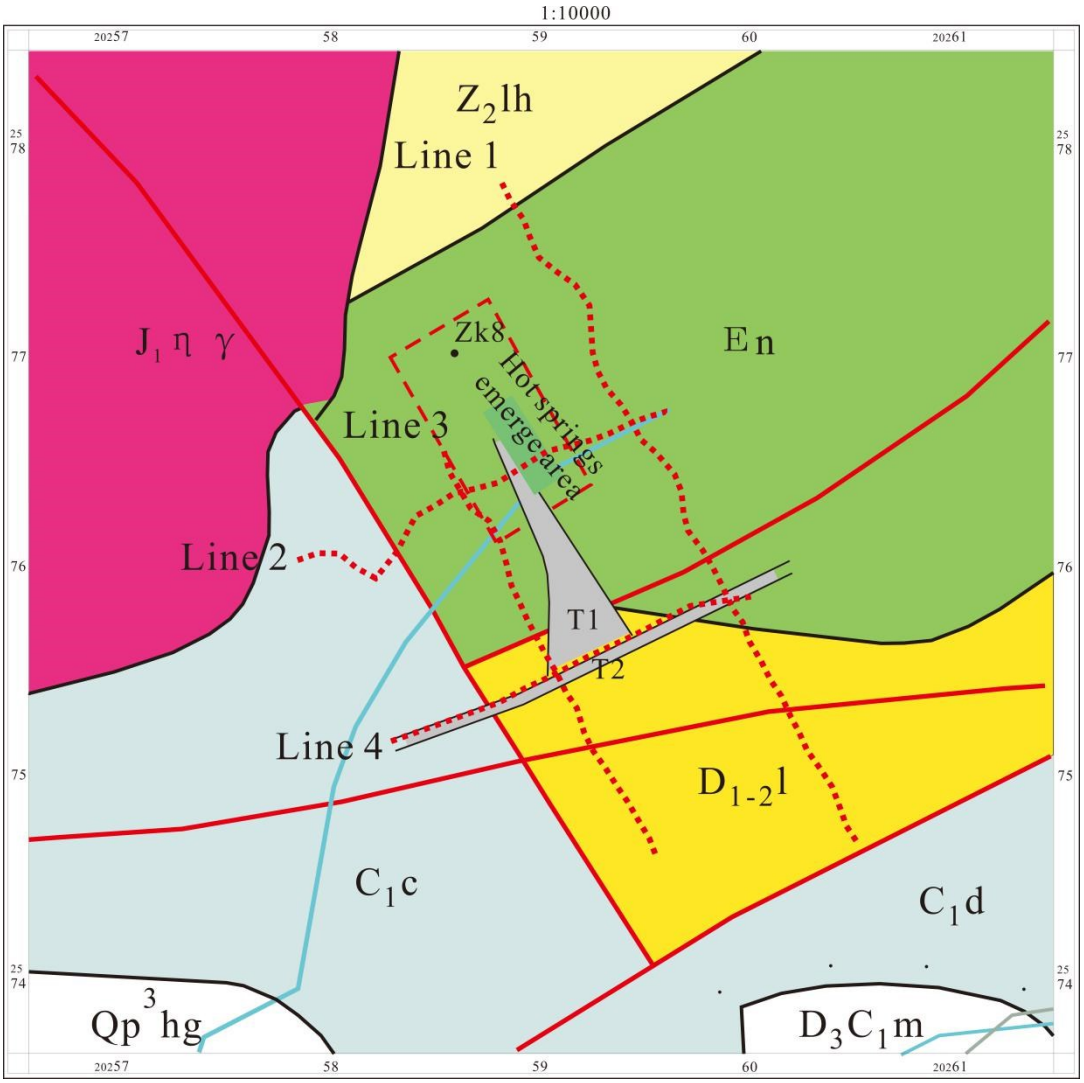

Figure 16: Map corresponding to the interpretation of geophysical prospecting and geological conditions (for lithologic symbols, see Figure 12).

6.3 Position selection of drilling holes

Considering the aforementioned conclusions, the heat formation model of geothermal fields in Huangshadong area is mainly that a deep heat source transmits heat along the NE-trending compressive–torsional fault zone T2 (F2–F4) to shallow places. When encountering NW-trending tensile low-resistivity channel T1, the fluid becomes the medium that further transmits heat to the surface, forming hot springs. In light of this model, drilling holes should be set under northwestern T2 and in T1 (Figure 16). As the heat transmission in faults gradually weakens due to smaller T1 from SE to NW, it is better to locate drilling holes near T2's heat conduction fault zone.

The planned advanced depths have been 3,009 m and 2,537 m since November 29, 2017, which are the deepest depths in Guangdong province. The drilling well has a three-hole deep structure. Safe and efficient drilling should comprise advanced high-temperature geothermal energy (HDR), including a direct permanent magnet, a top-drive drilling rig, and a high-speed turbodrill that is resistant to high temperatures and has a long life, together with a high-temperature, high-speed rotary blowout preventer.

The drilling hole successfully punches through overlying strata at 1,560 m and enters into underlying embedded granite bodies. The lithology of the overlying sedimentary strata from shallow to deep is sandstone, phyllite shale, carbonaceous slate, tectonic breccia, and silicified quartz sandstone, a typical sequence of metamorphic degree. According to the geothermal curve of the Huizhou No. 1 geothermal well, the drilling hole reaches 127.5 °C (Figure 17) at 2,900 m, which is the highest temperature at the same depth in the Huizhou area. Apart from that, sharp changes can be seen between 2,400 m and 2,500 m, as well as between 2,750 m and 2,800 m. Combined with the analysis of water leakage from drilling, these two sharp changes are the result of rising temperature due to high-temperature hot water from corresponding aquifers in these two sections. Moreover, the geothermal characteristics at 0–3,000 m are good evidence to predict that further drilling into hot-temperature areas that without water can provide promising HDR resources.

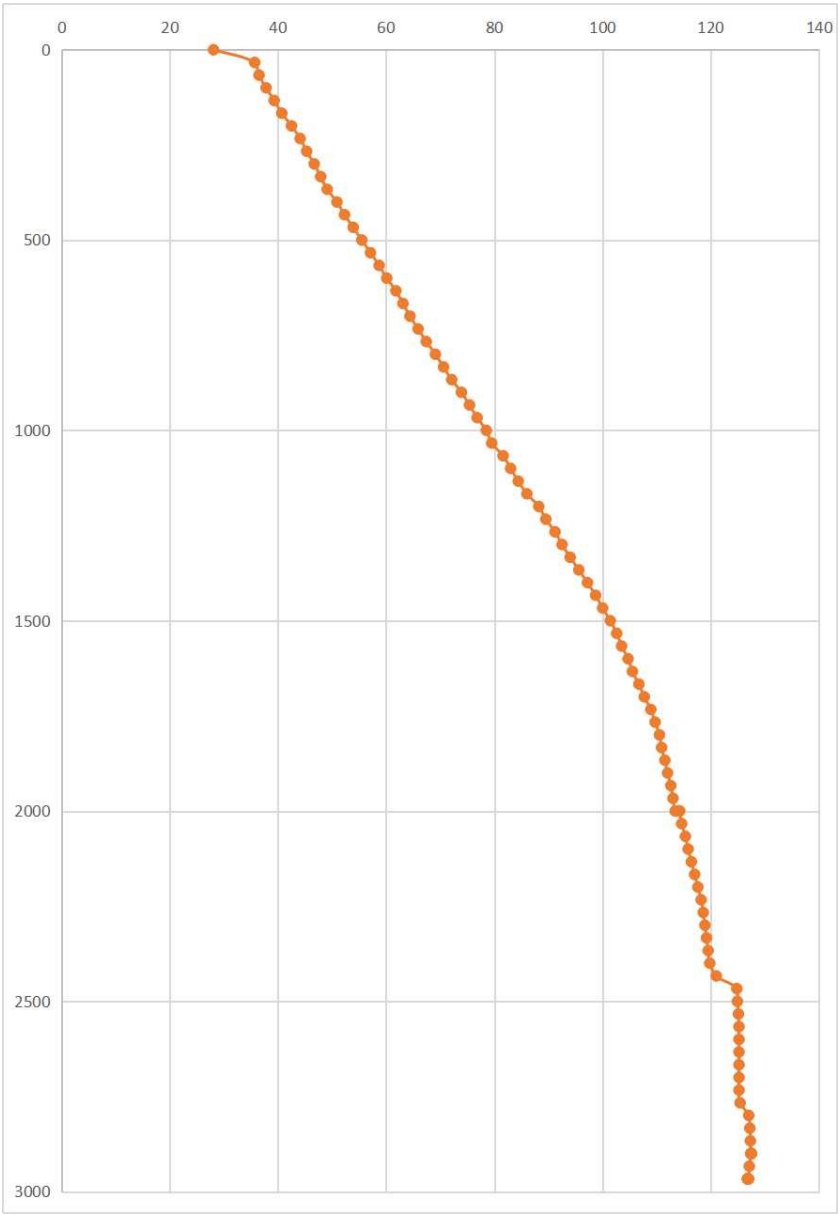

Figure 17: Geothermal curve of Huizhou No. 1 geothermal well.

7. CONCLUSIONS AND SUGGESTIONS

7.1 Conclusions

1) The geothermal flow values in China's southeastern coastal areas are obviously affected by their tectonic background. Those near the contact zones of the Pacific plates have especially higher geothermal flow rates. The NW-trending compression of the Philippine plate plays an important role in forming the geothermal system in these areas. In the middle-upper crust from southwestern Jiangxi province to coastal areas in Fujian province are low-velocity layers about 15 km from the surface, which may represent partial melting magma or ductile flow layers from the middle-lower crust.

2) At present, there are still debates about the existence of HDR in Fujian province, but it is generally believed that Fujian has a geothermal anomaly, and an HDR resource is possible in granite bodies with thicker overlying strata at 5 km or deeper.

3) Taking Zhangzhou as an example, the southeastern coastal areas have typical "cold crust and hot mantle" structures, so that the mantle heat is dominant in heat sources. As heat conduction channels, regional deep faults can directly transmit geothermal energy of partial melting or deep heat flow from deep to shallow regions, increasing the geothermal isoline. Also, overlying strata that preserve heat there are mainly sandstone and mudstone. Because of their mineral content, the heat conductivity of the rocks is higher than that of the average level of the crustal rocks. Heat reservoirs mainly consist of granite from the Yanshan period, with a general burial depth of over 5 km and a specific burial depth of about 4–5 km in some areas with relatively higher geothermal gradients.

4) HDR in southeastern coastal areas mainly gains heat from the ternary heat reservoir model, which features radioactive heat generation from acid rock mass as well as heat conduction in faults plus heat preservation by overlying strata. The heat generation

rate of granite from the Yanshan period can reach 6.4 μW/m^3, a major part of crustal heat source. Regional fault structures act as heat conduction channels to connect deep heat sources with the shallow surface and transmit deep heat to shallow parts. Besides, the overlying sedimentary strata radiate heat to the acid rock mass and heat conduction in faults can preserve heat and prevent heat loss to a certain extent.

5) The key target HDR areas along the southeastern coast include Zhangzhou city and the Huangshadong area of Huizhou in Fujian province, where the temperature is 109 °C at 4,000 m due to the lack of necessary overlying strata. In addition, the sedimentary overlying strata in Huangshadong area is about 1,500 m deep, where the NE-trending deep fault acts as the heat conduction channel and the drilling hole reaches 127.5 °C at 2,900 m, the highest temperature at the same depth in Huizhou area by far. The geothermal gradient after entering granite is 31°C/km, which means 180 °C at 4,000 m calculated by this gradient.

7.2 Suggestions

A preliminary ternary heat reservoir model is established through discussions of HDR's forming reasons and accumulation model in southeastern coastal areas. However, the contributions of radioactive heat generation from acid rock mass and heat conduction in faults remain to be further studied. In addition, the sedimentary overlying strata there is generally less able to preserve heat. Therefore, the suggestion is that more studies on the contributions of each thermal accumulation factor in the ternary heat reservoir model should be conducted and a more precise model indicators should be set up based on regional geological tectonic characteristics.

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