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Controlling of Caprock on Geothermal Resource Enrichment, Take Igneous Rock Area In Southern China as an Example

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ABSTRACT <HEADING 1 STYLE>

Deep geothermal resources mainly refer to hydrothermal and dry hot rock geothermal resources buried deeper than 3000m. Based on the current exploration and development technology and cost conditions, 3000~6000m is the main development and utilization range of deep geothermal resources. In this depth range, the caprock with better heat preservation conditions is an important part of the deep geothermal system. In this paper, based on the deep geothermal geological conditions in the Fujian, Guangdong and Qiong regions of South my country, an ideal geological model of the reservoir-caprock assemblage was established to simulate the geothermal field distribution under different caprock thicknesses and caprock thermal conductivity. The simulation results show that in the raised area in the depression, the vertical geothermal distribution has a mirror reflection relationship with depth, the isotherm at the upper part of the basement elevation is a convex curve, while the isotherm at the lower part of the basement elevation is a concave curve. There is a temperature balance line between the convex and concave isotherms. Below the temperature balance line, the heat flow gathers from the concave area to the convex area; above the temperature balance line, the heat flow gathers from the convex area to the concave area. On the basis of the above simulation results, typical thin-covered areas, medium-covered areas, and thick-covered areas were selected for geothermal field inversion. The results show that in the thin-covered area represented by the Fujian coastal igneous rock belt, the depth range of 3000-6000m is mainly Develop medium and low temperature hydrothermal geothermal resources. In the mid-cover area represented by the Yuezhong Depression, the ground temperature within the buried depth range of 3000-6000m is 100-200°C, and there may be superimposed medium-high temperature hydrothermal and dry-heat geothermal resources. In the thick cover area represented by the land area of the Beibuwan Basin, the thermal storage temperature ranges from 120 to 220 °C at a depth of 3000 to 6000 m, and two types of geothermal resources are mainly developed: medium-high temperature hydrothermal type and dry-hot rock type. Site selection evaluation and resource development and utilization can be carried out according to the buried depth of the temperature balance line and in combination with specific geothermal resource requirements.

1. INTRODUCTION

Energy is the foundation of social development, vigorously developing renewable energy and establishing a clean, low-carbon energy system has become an important strategy for energy transformation in various countries (Hou J, et al., 2018). Vigorously developing and utilizing green and low-carbon geothermal resources is of great significance for reducing greenhouse gas emissions, alleviating energy shortages, achieving the "double carbon" goal, and promoting the sustainable development of the national economy.

China's geothermal resources are mainly distributed in major sedimentary basins. The total amount of geothermal resources in 15 large and medium-sized sedimentary basins is equivalent to 1.06×104 million tons of standard coal, accounting for about 89% of my country's current hydrothermal geothermal resources that can be developed and utilized. The main force of (Wang Guiling et al., 2017). To carry out exploration and development of geothermal resources in sedimentary basins, the controlling factors for the enrichment of geothermal resources should be identified first, including the characteristics of heat reservoirs and cap rocks, geothermal field and heat source conditions, the origin of geothermal fluids, and runoff channels, etc. (Homuth et al., 2012; Crooijmans et al., 2016; Wang Zaijun, 2003; Dai Mingang et al., 2020; Zhang Zhengtao, 2019). Previous geothermal research mainly focused on heat storage conditions, often ignoring or simplifying the research on caprock, and mainly made a qualitative description of the thermal insulation performance of caprock (Zhang Zhengtao, 2019; Li Tingxin et al., 2020).

This paper studies the discovery of deep geothermal drilling in the Fujian-Guangdong-Qiong area in southeast China, and analyzes the influence of caprock on the geothermal field through numerical simulation. The constituency provides direction.

2. REGIONAL GEOLOGICAL SETTING

The South China igneous rock region experienced multiple tectonic-thermal events such as Caledonian, Hercynian, Indosinian, Yanshanian and Himalayan, and these tectonic events provided objective conditions for the formation of heat reservoirs. Pre-Cenozoic in the area developed multiple sets of thermal reservoirs of different lithologies such as Precambrian, Cambrian, Ordovician, Devonian, Carboniferous and Permian limestones, Jurassic and Cretaceous volcanic rocks, etc. Devonian, Silurian sandstone and shale, and Triassic interbedded coal-bed sandstone constitute the main cap rocks for heat storage in different periods. In addition, the pre-Cenozoic strata may have been intruded by Yanshanian granites, and the intrusion interface between the rock mass and the strata and the weathering crust on the top of the granite, affected by weathering leaching and structural denudation, can form fractured and weathered crusts Type heat storage. The Cenozoic Paleogene, Neogene and Quaternary are mainly sandstone, conglomerate and alluvial deposits, which can be a good set of reservoir-caprock assemblages. These reservoir-cap associations exist either alone or superimposed on a regional scale, forming various types of geothermal systems. For deep layers, there are both hydrothermal geothermal systems and hot dry rock geothermal systems.

3. MODEL

A caprock is a rock formation above a thermal reservoir that prevents heat from escaping outward, and is an important part of a geothermal system, especially a sedimentary basin-type geothermal system. In order to preserve the energy in the reservoir and prevent atmospheric precipitation from infiltrating into the cooling reservoir rock, it is necessary to cover it with a low thermal conductivity caprock, which is usually mainly sedimentary rock (sediment) or volcanic rock, sometimes also May be a weathered crust of suitable thickness. Rybach et al. (1978) vividly compared the cover layer to a blanket, and called its effect the blanket effect. Widely distributed in vast sedimentary basins or depressions, regional cap rocks with large thickness, wide area and relatively stable distribution play an important role in the accumulation of heat in basins or depressions.

In order to simulate the influence of caprocks on the deep temperature field under different geological conditions, this study established a paleo-uplift geological model without considering the "thermal refraction effect" (Figure. 1). The depth H of the model is 8000m, and the width L is 16000m. λ_1 and λ_2 represent the thermal conductivity of the caprock and bedrock respectively, and D is the burial depth of the paleo-uplift. AA' belongs to the uplift area, and BB' belongs to the depressed area.

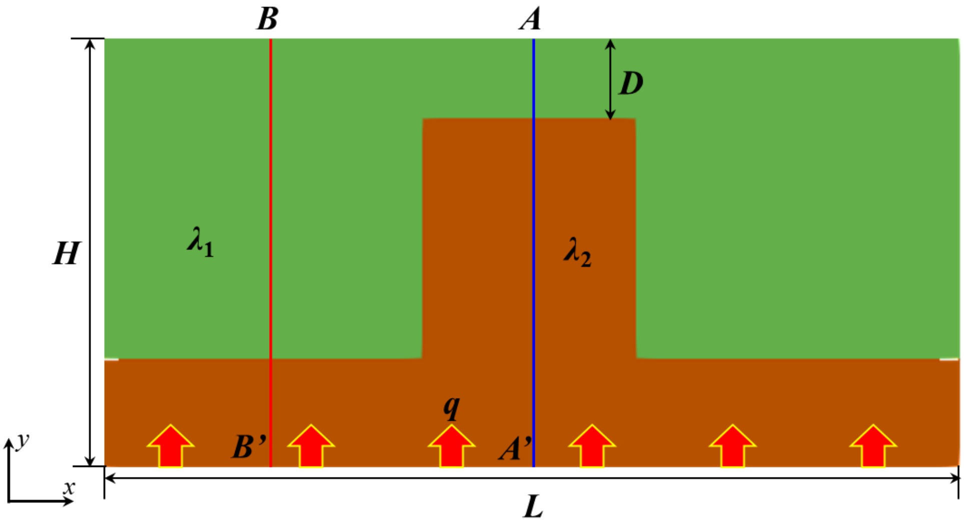


Figure 1: Uplift area model

Combined with the measured thermal conductivity data of cap rocks and thermal reservoirs in the South China igneous rock area, the cap rock thermal conductivity λ_1 = 2.56 W/(m*K), and the bedrock thermal conductivity λ_2 = 3.93 W/(m*K). Modeled using the 2D heat conduction equation:

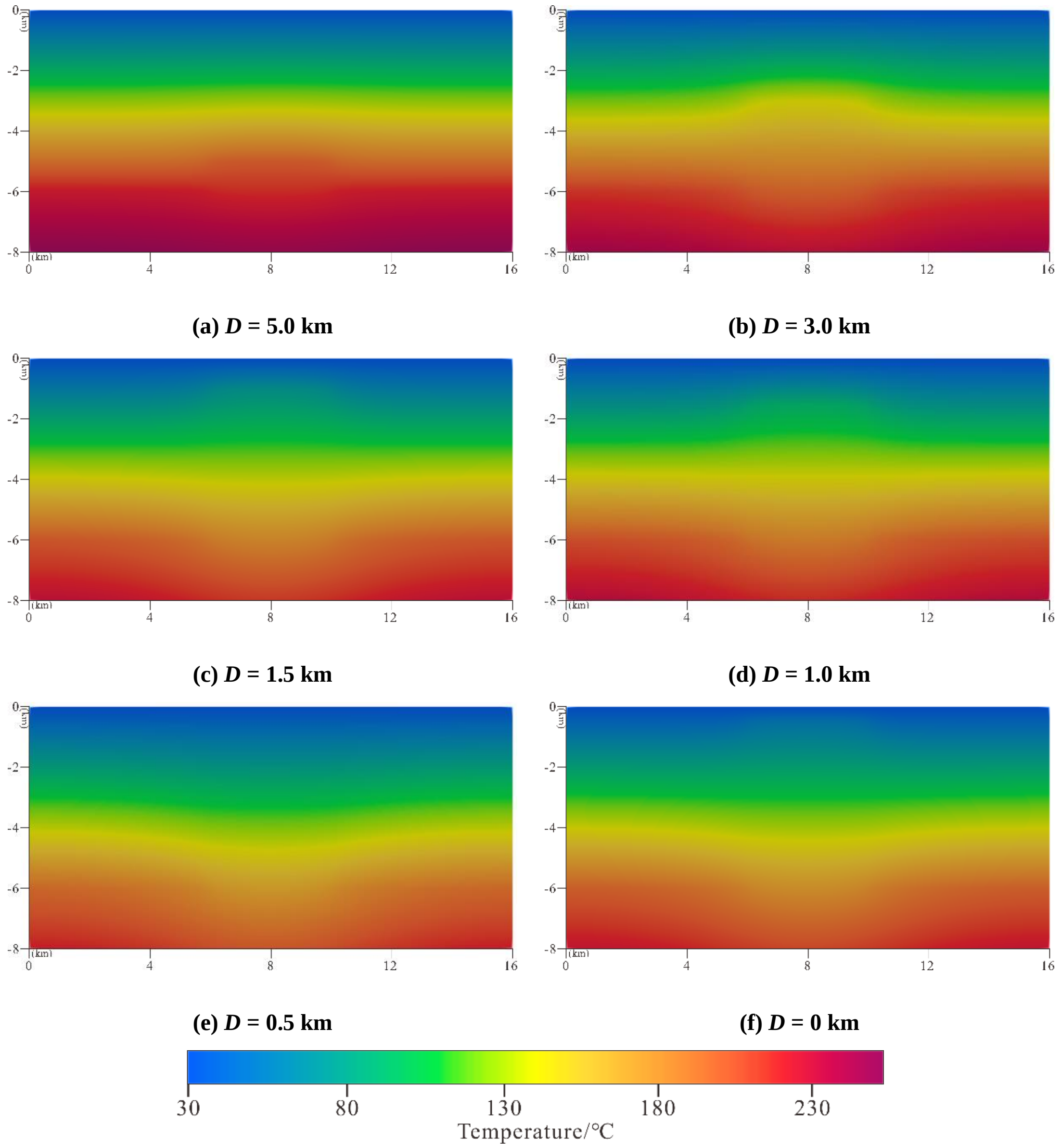
$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=\frac{\rho c}{\lambda}\frac{\partial T}{\partial t} \tag{1}$$

In the formula, T is the paleogeothermal temperature, °C; t is the time from the start of the simulation, s; ρ is the formation density, kg/m^3, and the value is 2500 in this study; c is the specific heat capacity of the rock, J/(kg*°C), the value is 860; x and y represent the horizontal and vertical directions, respectively. The boundary conditions are:

$$\begin{cases} T|_{t=0}=T_0 \\ T|_{y=0}=f(x,t) \\ \lambda \left.\dfrac{\partial T}{\partial \mathbf{n}}\right|_{y=-8000}=q(x) \end{cases} \tag{2}$$

Among them, T_0 is the initial temperature, since the steady-state simulation is carried out, the initial temperature has no effect on the simulation results; $f(x)$ is the surface temperature, which is related to the spatial position and the simulation time, in order to simplify the calculation in the simulation, it is set to is a fixed value at 27°C; $q(x)$ is the upward heat flow from the bottom of the model, which is only related to the spatial position, and is also set to a constant value here, 83.99 mW/m^2.

In order to study the influence of caprock thickness on the geothermal field, the burial depth D of the paleo-uplift is set to 5.0km, 3.0km, 1.5km, 1.0km, 0.5km and 0km. The evolution process of the geothermal field under different conditions was simulated separately, and the distribution of the geothermal field when it reaches equilibrium is shown in Figure 2. According to the results, it can be seen that there is an obvious correlation between the distribution of the geothermal field and the thickness of the caprock.



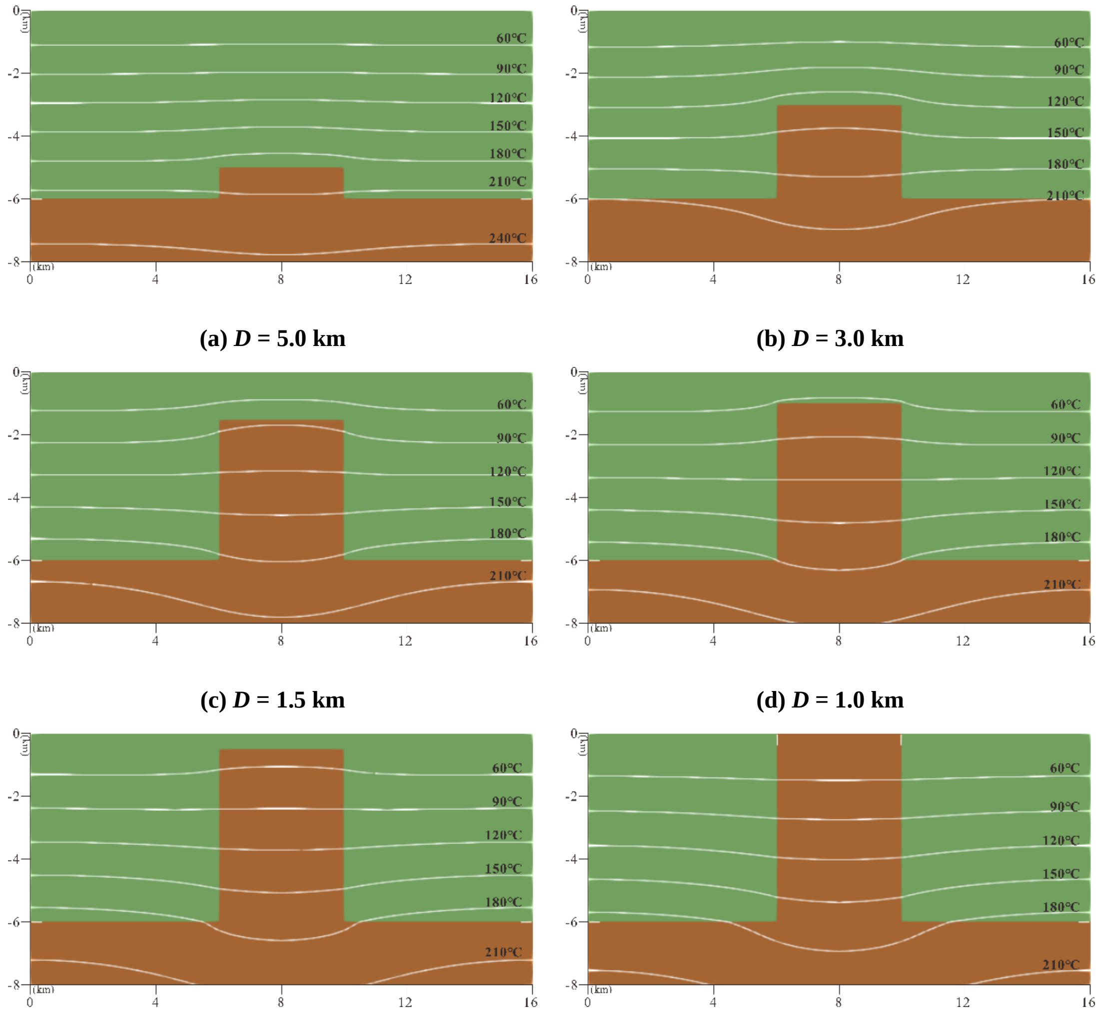
(a) *D* = 5.0 km
(b) *D* = 3.0 km
(c) *D* = 1.5 km
(d) *D* = 1.0 km
(e) *D* = 0.5 km
(f) *D* = 0 km

Figure 2: Distribution of geothermal field under different cover thickness

4. RESULTS AND DISCUSSIONS

Variations in cap thickness correspond to basement relief. Many scholars have done statistical research and believed that basement fluctuations will have a greater impact on the geothermal field. During the conduction process, the subsurface heat flow always shifts to the parts with high thermal conductivity and low thermal resistance, and it is easy to form thermal anomalies, and it is proposed that the uplift belt has high temperature anomalies, and the level of the geothermal field has a positive correlation with the basement fluctuation.

In order to study the influence of caprock thickness on the geothermal field, the burial depth D of the paleo-uplift is set to 5.0km, 3.0km, 1.5km, 1.0km, 0.5km and 0km. The results of simulating the characteristics of the geothermal field under different caprock conditions show that the geothermal distribution is affected by the ups and downs of the paleo-uplift, and shows obvious stratification. In order to further clarify the influence of the shape of the paleo-uplift on the geothermal distribution, the isotherm distribution map under different cover layer thicknesses was drawn (Figure 3).



(a) *D* = 5.0 km

(b) *D* = 3.0 km

(c) *D* = 1.5 km

(d) *D* = 1.0 km

(e) *D* = 0.5 km

(f) *D* = 0 km

Figure 3: Distribution of isotherms under different cover thicknesses

It can be seen from Figure 3 that when there is a certain thickness of cover layer, the temperature field of the paleo-uplift can be divided into two parts in the vertical direction. The concave shape, in contrast to the basal shape, presents a symmetrical "mirror image" structure. There is a heat flow balance line between the two isotherms of different shapes, and the upper and lower parts of this line have a convex and concave shape on the isotherm, which shows that below this line, the heat flow gathers from the depression to the uplift. Above this line, the heat flow diverges outward near the vertical interface. In addition, the cap rock with an appropriate thickness can cause geothermal anomalies in the upper part of the uplift area. If the cap rock is too thin, or even the bedrock is completely exposed, the temperature contour of the upper part of the uplift area will become concave. Therefore, when there is cap rocks of appropriate thickness and bedrock bulges of a certain depth are conducive to the formation of geothermal anomalies.

The temperature-depth curves of the uplift area and the depression area are shown in Figure 4 and Figure 5. It can be found that no matter in the uplift area or the depression area, at the same depth, the ground temperature without cover is always lower than that with cover, which shows that the cover can play a good role in heat preservation and is conducive to heat accumulation. For the uplift area, the temperature-depth curves under different cover thicknesses show different trends. When the formation depth is less than 500m, the ground temperature at the same depth is $T_{0.5} > T_{1.0} > T_{1.5} > T_{3.0} > T_{5.0}$ (T_d represents the ground temperature when the burial depth of the paleohigh is *d* km). As the depth increases, when the depth is between 500 and 1000m, the ground temperature at the same depth becomes $T_{1.0} > T_{1.5} > T_{0.5} > T_{3.0} > T_{5.0}$. And when the buried depth reaches 3000m, the ground temperature is $T_{3.0} > T_{5.0} > T_{1.5} > T_{1.0} > T_{0.5}$. This is caused by the difference in thermal conductivity between caprock and bedrock. The thermal conductivity of the cap rock is low, which can prevent heat loss to the surface; the thermal conductivity of the bedrock is high, and it can transfer a large amount of heat from the deep formation to the upper formation. When the thickness of the formation is constant, the thicker the cover layer, the less heat loss, but the less heat conduction from the deep. Therefore, formation temperature is a function of caprock thickness and caprock thermal conductivity. In the depression area, because the thickness of the caprock is relatively stable, the trend of temperature change under different thicknesses of the caprock remains consistent. The thicker the caprock, the higher the corresponding ground temperature.

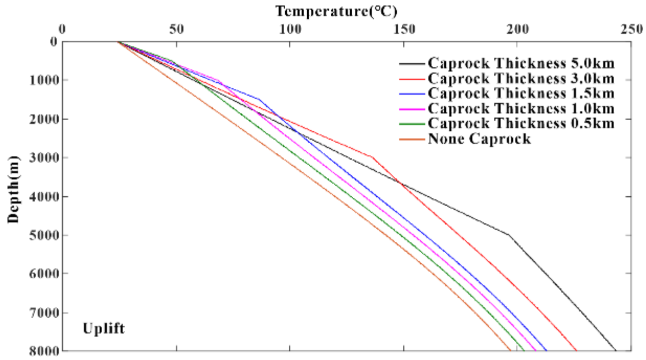


Figure 4: Temperature depth curve of uplift region

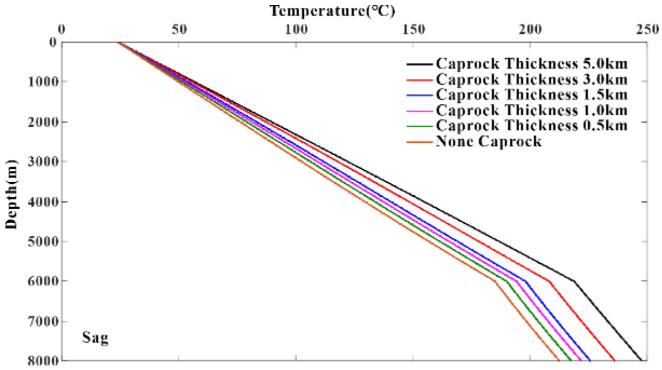


Figure 5: Temperature depth curve of depression

5. REFERENCE SIGNIFICANCE FOR DEEP GEOTHERMAL CONSTITUENCY IN IGNEOUS ROCK AREA OF SOUTH CHINA

According to previous studies, the distribution of deep geothermal resources in the igneous rock area in South China is mainly controlled by fault structure and cap thickness, which can be divided into no cap zone with a cap thickness of less than 1000m, thin cap zone with a cap thickness of 1000-3000m and thick cap zone with a cap thickness of more than 3000m.

The above numerical simulation results show that the cap thickness has a certain degree of control over the deep geothermal field. Based on the simulation of temperature fields in tectonic zones with different cap thickness in the igneous rock area of South China, it can be found that the deep geothermal fields also show different characteristics. For example, the igneous rock belt along the coast of Fujian belongs to the thin cover area, and its buried temperature of 3000~6000m is about 90 ~ 150℃. The geothermal resources of medium and low warm water type are mainly developed. The Yuezhong Depression belongs to the middle cover area, and the interior temperature is 100~200℃ in the depth range of 3000~6000m. The geothermal resources of middle and high warm water and dry heat type are superplaced up and down. The Beibuwan Basin is a thick cap area with the maximum cap thickness of 8000m. The temperature range of the heat storage at the depth of 3000~6000m is 120~220℃. Two types of geothermal resources are developed in the depression area and the dry hot rock type, while the geothermal resources are developed in the raised area (Figure 6). Deep drilling in igneous rock area of South China has proved that the simulation results are consistent with the actual situation. Under the same burial depth condition, the temperature in the thick cover area is high, the temperature in the medium cover area is high, and the temperature in the thin cover area is low, which respectively correspond to the Fujian coastal igneous rock belt where Zhangzhou Dry heat 1 well is located, the Yuezhong depression area where Huige 1 well is located, and the Beibuwan Basin land area where Huadong 1R well and Xuwen X3 well are located. The typical cap thickness in the three areas is less than 1000m, 1000-3000m and more than 3000m respectively.

Combined with the previous exploration and development of geothermal resources and the drilling of deep geothermal resources, the deep geothermal resources with large-scale development potential in the igneous rocks in South China are mainly distributed in the meso-Cenozoic basins and their surrounding areas, among which the continental area of the Beibuwan Basin, the Yuezhong Depression and the igneous rock belt along the southeast coast of Fujian are the typical representative areas, corresponding to the thick cover area, middle cover area and thin cover area respectively. There are differences in the distribution of rock strata and the characteristics of reservoir-cap assemblages in the three regions. The Northern Gulf Basin has the best geothermal resources, followed by the Yuezhong depression and the Fujian coastal igneous rock belt. In the Beibuwan Basin, the geothermal system with moderate and high warm water and hot dry rock resources with suitable depth of bedrock (3000 ~ 5000m) is a favorable direction for recent exploration.

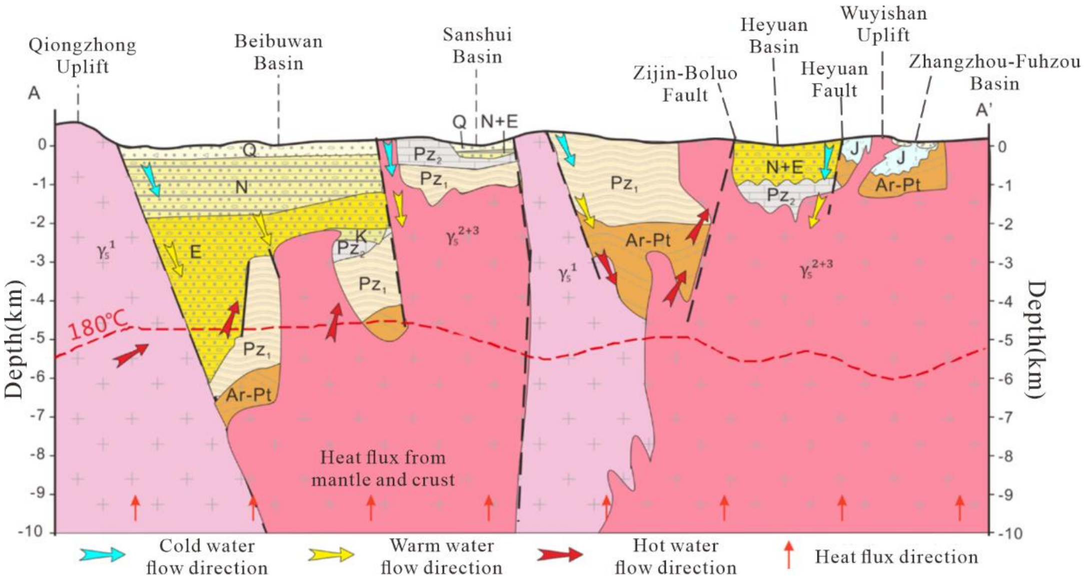


Figure 6: Distribution profile of deep geothermal resources in South China

6. CONCLUSION

(1) The sedimentary cover dominated by Cenozoic mudstone in the upper part of igneous rock area in South China has low thermal conductivity, which is very different from the bedrock heat reservoir dominated by granite, and can form an effective geothermal reservoir combination, which is conducive to the enrichment of geothermal resources in the bedrock heat reservoir.

(2) As the main thermal reservoir segment, the upper isotherm of the bedrock uplift is an upconvex curve, while the lower isotherm is a concave isotherm, and there is a temperature balance line between the convex isotherm and the concave isotherm. Under the temperature equilibrium line, heat flow accumulates from the depression area to the uplift area. Above the temperature equilibrium line, the heat flow accumulates from the bulge to the depression.

(3) There are some differences in geothermal resource types in the depth range of 3000~6000m in the igneous rock area of South China according to different cap thickness. The igneous rock belt along the coast of Fujian Province belongs to the thin cover area and mainly develops geothermal resources of medium and low warm water type. The middle depression of Yuezhong belongs to the middle cover area, which may develop two types of geothermal resources, namely middle-high warm water hot type and dry hot type, superposed up and down. The Beibuwan Basin is a thick-covered area, and there are two kinds of geothermal resources, namely medium-high warm water hot type and dry hot type, and the temperature is higher than that of the Yuezhong Depression.

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