Deep geothermal geological conditions and optimization of strategic favorable areas in Fujian-Guangdong-Hainan Area

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ABSTRACT

Fujian-Guangdong-Hainan area (hereinafter referred to as Minyueqiong area) has outcropped various igneous rocks along the southeast coast of China. The complex geological conditions in this area are the key questions for deep geothermal resources exploration and evaluation. This paper discussed about key issues such as heat source composition, deep geothermal formation conditions, strategic area and key exploration direction of deep geothermal resources in this area. Some achievements and understandings have been obtained: heat sources in Minyueqiong area are mainly composed of heat generation from radioactive elements of granites in the crust and heat from mantle conduction, and there are also additional heat sources such as middle and lower crust melt body in some areas (such as Yangjiang, Shantou area). It is suggested that the deep high temperature geothermal resources are mainly distributed in the depression area of basins with triple heat source superposition area (including crust heat, mantle heat and additional heat source). Based on analysis of regional geothermal reservoir conditions, regional cover conditions, three strategic favorable zone of deep geothermal resources in Minyueqiong area are selected: the continental area of Beibu Gulf Basin, Yuezhong depression and Fuzhou-Zhangzhou area.

1. Introduction

Geothermal energy, as a kind of green renewable energy with great potential, wide distribution, stability and reliability, has attracted more and more attention from countries to countries (Bertani, 2012; Bertani, 2016; Lund and Boyd, 2016). The scale of geothermal development and utilization has been developed from the middle-shallow hydrothermal type to the deep high-temperature multi-type resources in recent years. Deep geothermal resources are considered as an important part of future energy supply due to their huge geothermal reserves. Most of the deep geothermal reservoirs are considered as igneous and metamorphic rocks (Brown et al., 2012; Hu et al., 2022), such as Australia Cooper basin geothermal field (Goldstein et al., 2008), Rose-manowes geothermal field in England (Richards et al., 1992), the Soultz geothermal field in France (Genter et al., 1995).

Fujian-Guangdong-Hainan area (hereinafter referred to as Minyueqiong area) is characteristic of dense population, developed economy and strong demand for clean energy, such as geothermal energy. Preliminary exploration and evaluation indicate that geothermal resources have great potential in this area (Wang et al., 2019; Wang et al., 2022). Geothermal manifestations are widely distributed, such as hot springs and other surface heat. They are mainly located in the fractures within igneous and metamorphic rocks. Previous estimates show that the potential of geothermal resources buried 3-10 kilometers deep in this region is equivalent to about 26.4 trillion tons of standard coal, which is 5,000 times of the total national energy consumption in 2021 (Wang et al., 2020). The exploration and development of deep geothermal resources in this area is expected to obtain significant social and economic benefits, which is of great strategic significance and plays an important role in adjusting the energy structure and ensuring the security of national energy supply.

2. Geological setting

Minyueqiong area belongs to the coastal zone of igneous rock zone in South China. Tectonically, it is a part of the Cathaysia block (Wang et al., 2013). These areas have experienced multiple periods of intense magmatic events since the Paleozoic, mainly manifested in Paleozoic and Mesozoic granitic rocks (Wang et al., 2013) and Cenozoic mafic magmatism (Gong and John, 2014). Since Phanerozoic, Cathaysia block has been influenced by orogenic event in various periods, especially after being strongly transformed from the Mesozoic to the present, resulting in the different structural features of the present, and the formation of the middle to high heat flow zone in the southeast (Figure 1). Since Cenozoic, the Cathaysia block has been located at the convergence and fragmentation of the Western Pacific plate, Eurasia plate and India plate (Zhang Guowei et al., 2013). It has experienced long-term and multi-stage tectonic changes, and the superposition and transformation of tectonic movements of different nature and scale in different evolutionary stages.

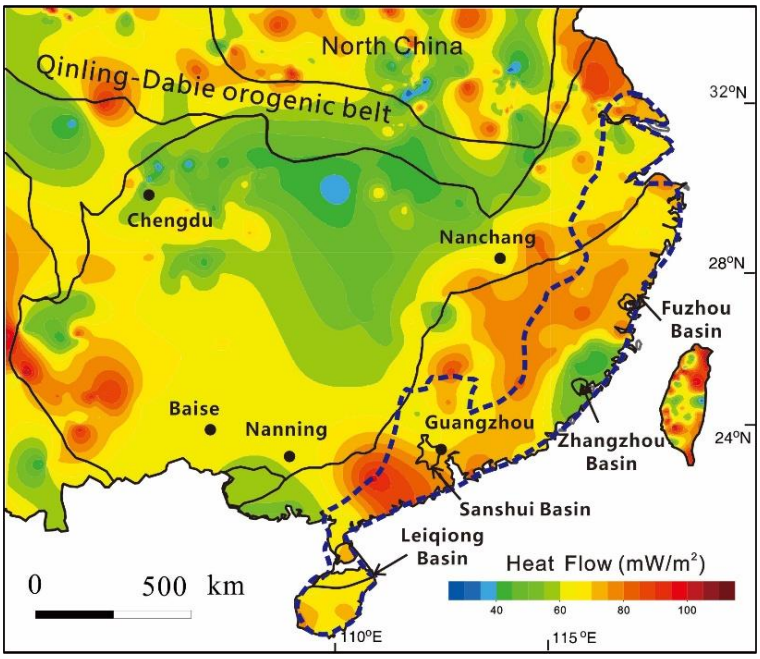

Figure 1 Geodetic heat flow distribution map in Fujian-Guangdong-Hainan Area (modified from Zhang Ying et al., 2020; Zheng Herong et al., 2021; Jiang Guangzheng et al., 2020)

MinyueQiong area has experienced multiple igneous events, mainly Mesozoic. The Mesozoic volcanic rocks are most developed in the east of Fujian Province, which are continental eruptions, and are concentrated in the Late Jurassic-Early Cretaceous. Andesitic and basaltic andesitic volcanic rocks are dominant in the Late Triassic and Early Jurassic, with a small amount of acidic pyroclastic rocks. The Middle Jurassic in eastern and central Guangdong is mainly composed of continental pyroclastic rocks with andesite and rhyolite. In the late Jurassic, dacite and rhyolite volcanic rocks are the main ones, with a small amount of basaltic and andesitic volcanic rocks. The Early Cretaceous is dominated by Anglo-rhyolite volcanic rocks. The volcanism was most intense in the late Jurassic, which was a continuous potassic calc-alkaline series of terrestrial andesite-dacite and rhyolite, dominated by rhyolite. From the east coast to the inland, the intensity of volcanic eruptions decreased.

The intrusive rocks in the province have a wide distribution range and a large time span, including Indosinian, Yanshanian and Himalayan. Especially, the Yanshanian intrusive rocks have the largest scale, and most of them are granites (the volume exceeds 95% of the total volume of intrusive rocks). The intrusive rocks are mainly granite, and a small amount of mafic,

ultramafic, and alkaline rocks. In western, central, and northeastern area, S-type granitoids, I-type granitoids developed. Late Paleozoic - Early Mesozoic: weak volcanic activity, Andesite - dacite - rhyolite. In Late Paleozoic - Early Mesozoic, local melting occurred in place of the in-situ mixed rocks developed in Caledonian, forming quasi-in-situ mixed granite with slight gneiss structure. In Cretaceous, there are still two types of granite emplacement, S type and I type, but the activity intensity is obviously weakened. Late Yanshanian and Himalayan rift-type magmatics: A series of intracontinental rifts developed since the Cretaceous, where bimodal volcanic rocks developed and A-type granite emplaced after volcanic eruptions. The intra-continental rifts in the Paleocene, such as the Sanshui Basin in Yuezhong, developed bimodal volcanic rocks, with each eruption cycle beginning with basalt and ending with rhyolite or trachyte. In the Leqiong intercontinental rift Valley of Neogene and Quaternary, the Neogene Marine basalts were produced in Marine clastic rocks as multilayer interlayers. Quaternary is a continental environment, the continental overflow olivine tholeiite formed thousands of square kilometers of rock bed. In addition, there are small mafic intrusions and olivine basalt tubes of the Himalayan period in eastern Guangdong.

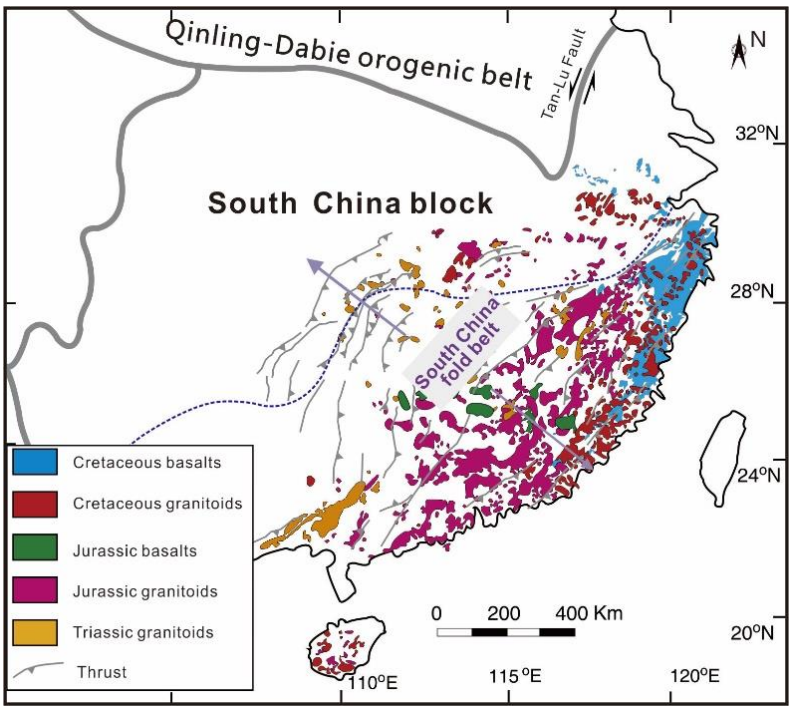

Figure. 2 Distribution of igneous rocks in South China (modified from Liu Qiongying et al., 2013)

In Hainan area, The intrusive rocks are with an exposed area of 18037 km^2, accounting for 53% of the entire island area. The intrusive rock exposed area of 13550 km^2, accounting for 75% of the area of igneous rock, intrusive rocks in granite accounted for 99%, according to the formation of granite era can be divided into three periods of Indosinian and Yanshanian granite belongs to intracontinental chasmic trough craze, subsidence, enclosed the product of the evolution process, thus formed the area of huge compound granite batholith. The geochemical composition of granite is Al poor, Ca and Fe rich. Volcanic rocks in Hainan Island are well developed and distributed from Proterozoic to Quaternary. The volcanic rocks of Himalayan periods were interbedded in the strata, and volcanic rocks were also formed in Northern Hainan area.

The middle and shallow thermal features in the South China igneous area are mainly surface hot springs (FIG. 3). Main parts in the construction of the appropriate underground thermal fluid (mostly in the two groups of fracture interchange) and proper

geomorphic conditions (piedmont plain or mountain basin and river valley) upwelling to shallow or outcropped in the earth's surface to form a hot spring, within the plate on the cause of deep circulating air convection in the low temperature (< 150 ℃) hot water system, mostly in low temperature (< 90 ℃) hot water system. Many hot springs outcropped in the granite rock mass or granite rock body in contact with the surrounding rock fracture, on the thermal field structure, most of the lack of direct coverage on the granite geothermal reservoir consists of impervious and semi permeable strata play an adiabatic effect of cap rocks, natural outcrop between the highest temperature of hot water and drilling water temperature difference is not big, Generally within 5℃. The water temperature of the well head is slightly higher than that of the spring water, mainly because the heat loss in the well during the upwelling process is less than the heat dissipation in the fracture channel. For example, a drilling at a depth of 806 m in Dengwu Thermal field, Fengshun, Guangdong, has the highest temperature of 94℃ in the well, 92℃ in the wellhead, 87℃ in the spring, and only 5℃ in the water temperature difference. In Fengshun and Yangjiang area of Guangdong province, the Wells were drilled at a depth of 620m and 309m, respectively, and the wellhead water temperature was only 1.5℃ and 5℃ higher than the spring water temperature on surface, respectively. In geothermal field with quaternary cap (even if the cover thickness is only ten meters to tens of meters) is another kind of circumstance, the quaternary clay layer insulation layer, which constitute a shallow water reservoir, sand and gravel layer is mainly due to the low temperature hot water in the process of upwelling and shallow groundwater in mixing and cooling, geothermal reservoir or in deep bedrock drilling hot water channel, For example, in the geothermal fields of Fuzhou and Zhangzhou in Fujian Province and Chao Antonshan Lake in Guangdong Province, the water temperature of wellhead is 20-40℃ higher than that of deep spring point.

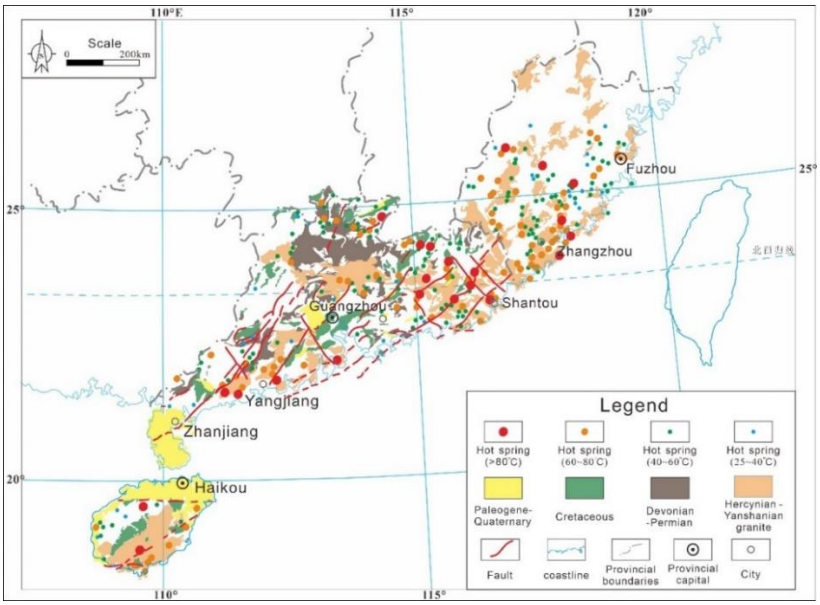

Figure 3 Distribution characteristics of surface hot springs in Fujian-Guangdong-Hainan area

From the perspective of geothermal resource types, the middle and low temperature hot water resources in the southeast coastal area can be divided into two categories: one is the deep circulation convection type, where the hot water temperature mainly depends on the circulation depth of groundwater, flow through, discharge and other conditions. The occurrence and distribution of hot water are strictly controlled by active faults, and the majority of hot fields belong to this type. In this type of geothermal resources, karst subtypes can also be distinguished. Hot water occurs in basins composed of Upper Paleozoic carbonate rocks, which are thick and widely distributed, and karst fissures are developed. When deep hot water relates to them through fault upwelling, a wide area of geothermal fields will be formed. The other type is conduction type, that is, geothermal resources

occurring in the sandstone layers of middle and small Mesozoic-Cenozoic sedimentary basins under the mechanism of terrestrial heat flow. Leqiong Basin across the Qiongzhou Strait, Maoming Basin, Sanshui Basin and Shiba Basin in Guangdong Province belong to this type of basins. The hot water reservoir in the basin is stratified and widely distributed. The geothermal gradient of the Cenozoic cap is generally about 3.5℃/100m. In some fault basins, such as the basement uplift of Leiqiong Basin, the amplitude of the basement uplift and the thickness of the cover layer are properly configured, and the geothermal gradient of the cover layer above the uplift area is relatively high, generally up to 4-5℃/100m, forming local thermal anomalies. When the fault controlling the boundary of the bulge area has hot water upwelling, it becomes an additional heat source, the geothermal gradient can be as high as 5-8℃/100m, and the geothermal anomaly is more significant. This is the most favorable area for geothermal development and utilization in this area. The geothermal condition of Maoming Basin is quite special. Due to the wide spread of oily mudstone with high thermal resistance and low permeability, the total thickness of 400m is about to form the cover of the underlying sandstone thermal reservoir, and the average geothermal gradient can reach 4.0-4.5℃/100m in the depth of 1000m, which makes it a low-temperature hydrothermal basin.

In Fujian Province, 187 hot springs have been identified, among which 174 have a temperature of 25℃, and the highest temperature is 89℃ (South Chengcheng of Dehua). The distribution of hot springs in Fujian Province is closely related to geological structure. Most hot springs are exposed along the intersection of faults with different directions, and about 70% of them are related to NW faults. Especially, some tension-shear faults tend to be good channels for underground hot water upwelling. The distribution of hot springs in different regions is not uniform, and different hot springs are distributed in three tectonic zones bounded by the Zhenghe-Dapu fault in NNE direction and the Ninghua-Mingxi-Shaxian fault in SE direction. The uplifted area in northwest Fujian has been uplifted for a long time after the Caledonian Movement. The pre-Sinian and Sinian metamorphic rocks are exposed to the surface in a large area, and the Paleozoic is mostly absent except in some areas. The Caledonian movement formed many NE-trending folds and compressional fractures in this area, and few hot springs were distributed. After the Caledonian movement, the southwest Fujian depression is mainly characterized by depression from Upper Paleozoic to Middle Triassic, which is the main distribution area of Marine and shallow Marine strata in Fujian Province. The Indosinian and Yanshanian tectonic movements were intense, and many NNE and EW-trending folds and compressive faults were formed. There are 34 hot springs in this district, accounting for about 20% of the total number of hot springs in the province. Most of the hot springs in this area are exposed in the intersection zone of EW compressive and SN tensile faults and NE compressive and compression torsional faults, such as the hot springs in Qingliu, Yongan, Datian and Longyan areas. Lower Jurassic volcanic rocks and Yanshanian granite intrusions are widely covered in the eastern Fujian depression. Most of the hot springs in this area are exposed along the intersection of the EW trending compressive faults and the SN trending tensile faults or along the NW trending tensile faults. There are 137 hot springs with temperatures higher than 25℃, accounting for 79% of the total number of hot springs in the province.

In Guangdong Province, 257 hot springs with spring water temperature greater than or equal to 25℃ have been identified. The distribution of hot springs is controlled by faults. Most hot springs in most areas are linear along the deep faults of Wuchuan - Sihui, Enping - Xinfeng, Zhongshan - Heyuan, Lianhuashan, Chao 'an - Puning and Shantou - Huilai in NE direction. The ones in northern Guangdong are also related to the faults of EW direction. Most of the hot springs are exposed at the compound of two or

three groups of faults in NE, NW and EW directions. There are more than 100 granites of different sizes IN the WHOLE PROVINCE, with a total area of about 1/5 of the whole province's land area. About 2/3 of the spring spots in the whole province are exposed in the granite body and its edge fault zone, so there is a close relationship between the emergence of hot springs and the distribution of granites. For example, there are 13 hot springs in Dadong rock mass in North Guangdong invaded by deep faults along the east-west direction, of which 11 are exposed at the contact boundary between rock mass and surrounding rock, and 2 are exposed inside the rock mass. Some people believe that as the age of the rock mass changes from northwest to southeast coastal zone, the spring temperature increases, and the number of hot springs greater than 80℃ tends to increase. However, it cannot be shown that the distribution of hot springs with high temperature is directly related to the age of the granite mass. The reason why hot springs with more than 80℃ in Guangdong Province are mainly exposed along the coastal zone.

Hainan Island is rich in geothermal resources, and two types of geothermal resources have been found. The distribution of hot mineral springs (hot springs) is mainly controlled by fault structures, especially the EW-trending deep faults and NE-trending and NW-trending fault zones, which play a controlling role in the generation and distribution of underground hot water in the island. The geothermal reservoirs are mainly granite fracture reservoirs. There are also low temperature geothermal resources in the Upper Neocene pore confined water aquifers in the northern and southwestern basins of Hainan. For example, there are eight confined aquifer groups distributed in the Qiongbei fault depression Basin within 1000 m depth. The 1st ~ 4th aquifer is the normal temperature aquifer, and the 5th ~ 8th aquifer is the warm and hot water aquifer. The average thickness of the aquifer is 4 ~ 98 m, the water temperature is 39.5 ~ 50℃, and the unit water inflow is 0.115 ~ 1.216 L/ s•m^{-1}. It is warm water, brackish warm water. The interior thermal fields in the Ledong Jiusuo Basin in southwest China are relatively shallow, with a depth of 50-100 m, thin thickness, and relatively low water temperature, showing discontinuous stratified distribution (Chen Yingmin, 2008).

3. Analysis of deep geothermal formation conditions

3.1 Heat conditions

In stable continental regions, terrestrial heat flow is characterized by dual components, namely crustal heat flow (radioactive heat generation from crustal rocks) and mantle heat (Hu Shengbiao and Wang Jiyang, 1994). In the tectonically active area, the terrestrial heat flow is contributed by additional heat sources in addition to the shell and mantle heat flow components.

3.1.1 Heat from Crust - radioactive heat source

Crustal heat flow refers to the heat generated by the decay of radioactive thermogenic elements (U, Th, K) from granites in crustal rocks. Since the thermogenic elements in granites are generally more abundant than those in basic rocks (Zhao Ping et al., 1995), the crustal heat flow is mainly from the heat generated by the decay of radioactive elements in the granites of the upper crust. Artemieva et al. (2017), based on the statistical results of heat generation rate of more than 500 granitic rock samples worldwide, pointed out that the average global heat generation rate of granite is 2.05 ± 1.07μW /m^3. In addition, he also pointed out that there was a significant correlation between the radioactive heat generation rate and the age of granites, among which the Archaean-Early Proterozoic granites had the lowest heat generation rate (1.67 ± 1.49 μW/m^3 and 1.25 ± 0.83 μW/m^3, respectively). The heat generation rate of Mesoproterozoic granite is the highest (4.36 ± 2.17 μW/m^3), followed by Cenozoic granite (3.09 ± 1.62 μW/m^3).

Igneous rocks are widely developed in South China, among which the content of radioactive elements in granite is generally high, and the heat generation rate is 2-10 μW/m^3 (FIG. 4). Therefore, the radioactive heat generated by the decay of U, Th and K elements in the granites in South China may become one of the main heat sources of geothermal resources in this area. According to the existing research, high heat production rate of rock mainly the background - jiangxi region in guangdong, expands outward heat production rate of rock is on the decline, high heat rate is mainly affected by intermediate-acid magmatic rocks and south China yuan archean strata distribution control, politics and fracture on the granite - tai Po outcropped area heating rate is significantly higher than the east of the Jurassic volcanic rocks outcropped area, The heat generation rate was higher than 2.1μW/m3 in most regions of South China, and it was higher than 4.9μW/m^3 in Pearl River Delta, Shantou and Yangjiang regions. The granite in Guangdong province covers a large area and has a high weighted average of heat generation rate, followed by Fujian and Jiangxi. The heat generation rates of typical rock masses in Fujian Province and Guangdong Province. The heat generation rates of radioactive elements in rock masses in South China region range from 1.25 to 10.14μW/m3, with an average value of 3.95μW/m3. The heat generation rate of radioactive elements in granites in Fujian area is consistent, ranging from 2 to 4μW/m3, and that in Zhongteng area is up to 7.3μW/m3. The average heat generation rate of radioactive elements in granites in Zhangzhou geothermal field is 2.8 to 4.3μW/m3. The heat generation rate of radioactive elements in the Fugang pluton is the highest, with an average value of 6.77μW/m3. The heat generation rate of granite in the Huangshadong and Xinzhou km drilling areas is 5.45μW/m3 and 4.0μW/m3, respectively. According to the numerical statistical comparison of the heat generation rate of granites, it is found that the heat generation rate of radioactive elements of granites in Guangdong and Hainan areas is significantly higher than that in Fujian area, with a considerable part of granites exceeding 5 μW/m3, while the heat generation rate of radioactive elements of main granites in Fujian area is generally 3-4 μW/m3. The heat flux generated by radioactive elements heat generation of granites in Guangdong and Hainan is 6.6-13.9mW/m3. The average value is 11.1mW/m3. The heat flow generated by radioactive elements in granite in Fujian area is 2.8-12.6mW/m3. The average value is 6.63mW/m3. The heat generation rates of radioactive elements in the upper rock mass in South China range from 1.25 to 10.14μW/m3, with an average of 3.95μW/m3. The heat generation rate of radioactive elements in granites in Fujian area is consistent, ranging from 2 to 4μW/m3, and that in Zhongteng area is up to 7.3μW/m3. The average heat generation rate of radioactive elements in granites in Zhangzhou geothermal field is 2.8 to 4.3μW/m3. The heat generation rate of radioactive elements in the Fugang pluton is the highest, with an average value of 6.77μW/m3. The heat generation rate of granite in the Huangshadong and Xinzhou km drilling areas is 5.45μW/m3 and 4.0μW/m3, respectively.

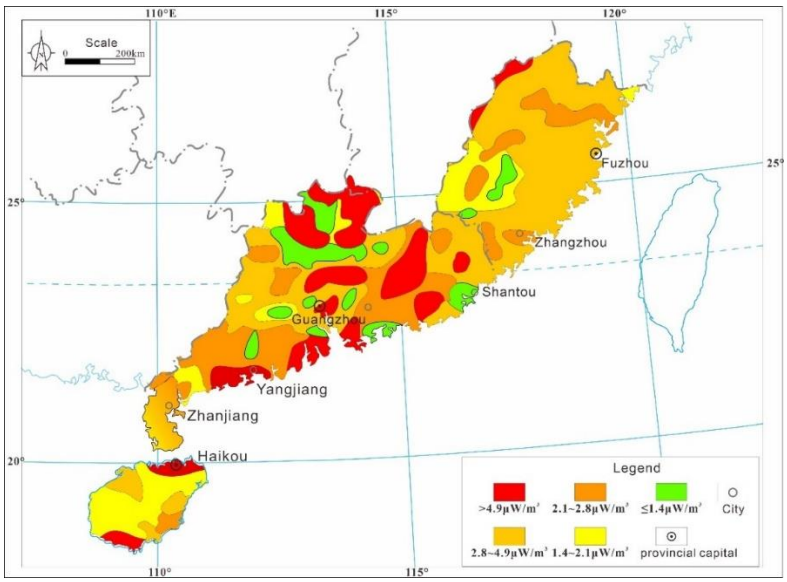

Figure 4 Distribution characteristics of granite heat generation rate in Minyueqiong Area (modified from Zhao Ping et al., 1995)

3.1.2 Additional heat source – Evidence from MT magnetotelluric data

Combined with the characteristics of geophysical field, Cheng et al (Cheng et al., 2021; Cheng et al, 2022）carried out field magnetotelluric exploration in Meizhou - Shantou area and Yangjiang area of Guangdong as thermal anomaly areas. The magnetotelluric data were mainly collected from the field MT data. A total of 83 MT measuring points were completed using the V5-2000 system produced by Phoenix Geophysical Company of Canada. Combined with 127 MT data points collected from Jiangsu Oilfield of SINOPEC in Leizhou Peninsula, Shantou-Meizhou, Yangjiang-Guigang area were selected for MT data reprocessing and inversion.

The distribution of MT measurement points in Shantou-Meizhou section (Fig. 5), which traverses the Fengshun geothermal field and main fault zones (Lianhuashan fault zone and Heyuan fault zone), is mainly used to detect whether there is a magma chamber or partial melt in the deep of the Fengshun geothermal field. All MT sites were observed for more than 20 hours, and the obtained apparent resistivity and phase curves ranged from 320 hz to 1000Hz, ensuring that the deep crustal scale structure could be obtained. According to the MT data analysis of the Shantou-Meizhou survey line, it is found that there are a series of low-resistivity abnormal bodies (C1 ~ C6) and high-resistivity bodies (R1 ~ R4) in the electrical structure of the Shantou-Meizhou profile, which is consistent with the distribution of surface fault zones and granites. The distribution depth of low-resistivity bodies ranges from 5 to 20km, and they are mainly concentrated in 5 to 10 km.

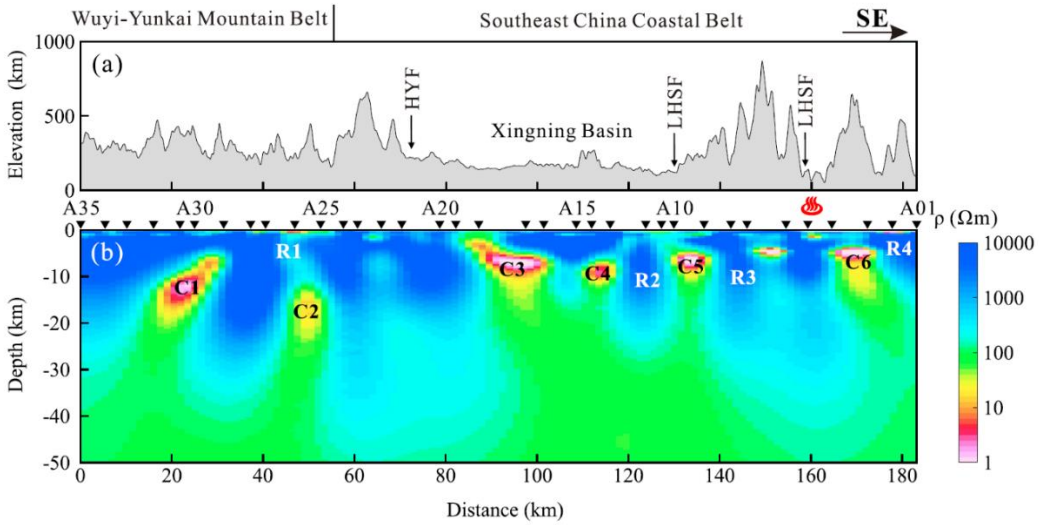

Fig.5 (a) Elevation distribution and (b) electrical resistivity cross-section along the MT profile from the final 3D inversion model. HYF, Heyuan Fault. LHSF, Lianhuashan Fault. (After Cheng et al., 2021)

Fengshun geothermal field is located at the intersection of Rongjiang fault zone and Zhenghe-Dapu fault zone. The low resistivity anomalous body C6 composed of fluid is presumed to be the deep thermal reservoir of Fengshun geothermal field. The fault zone constitutes the transmission channel of fluid and heat, and the deep fluid upwelles into the shallow reservoir of the geothermal field along the fault zone. The temperature of the geothermal fluid mainly depends on the circulation depth of the fluid, so the Fengshun geothermal field is mainly a convective geothermal system. The fluid sources of the low-resistance body are mainly composed of precipitation infiltration along the fault zone, subduction and dehydration of the Paleo-Pacific plate and upwelling asthenosphere material. The high resistivity body (0 ~ 10km) in the upper crust is mainly composed of granite, and the decay of radioactive elements in the granite forms one of the heat sources of the geothermal system. The low resistivity bodies in the middle and lower crust (20 ~ 35km) are mainly caused by the bottom invasion of the upper mantle, and the mantle-derived materials crystallize at the bottom of the crust to form the ferric magnesitic rock base.

The deep upper mantle of the Fengshun geothermal system has strong thermal erosion to the crust, so the mantle conduction heat constitutes another heat source of the geothermal system. There are 65 MT measuring points in Yangjiang-Guigang MT profile, with an average distance of 6km. In the geothermal field area, the distance between the points is encrypted to 2km, which is about 380km in total. The observation time of all measuring points is more than 20 hours to ensure the acquisition of crustal scale electrical structure. Yangjiang inversion results show that the geothermal field of the earth's crust and upper mantle low resistivity anomaly area large area, soft bottom invasion and upwelling flow spheres of phenomenon, due to the thermal erosion of magmatic rock spheres of thinning, deep fracture development and control the part of the magma intrusion and distribution, the deep source of heat and fluid can be broken up by deep and large transmission, and form the surface of the thermal field of heat source and fluid. Conghua - enping fault zone in the vicinity of new geothermal field put on the earth's crust, and connected to low resistivity zone of lower crust, appear obvious asthenosphere uplift phenomenon, show that the fault zone near the lower crust has emerged thermal disturbance, which will lead to a regional terrestrial heat flow, thermal state of the upper crust has been affected by asthenosphere lung, constitute the advantage of heat source and fluid transmission channel.

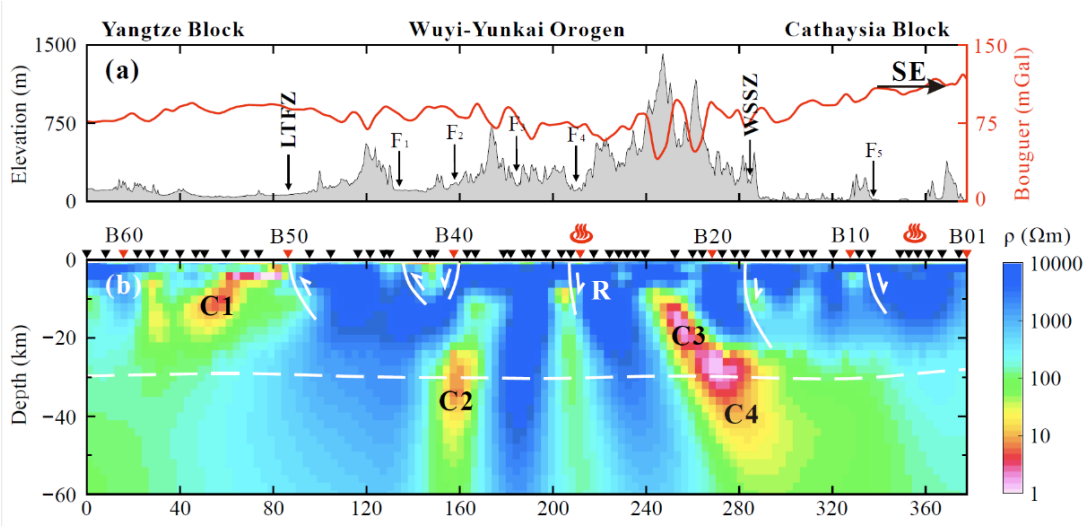

Fig.6 (a) Elevation distribution and (b) electrical resistivity cross-section along the MT profile from the final 3D inversion model. (After Cheng et al., 2022)

3.1.3 Mantle heat source

Based on characteristics of geophysical exploration and geochemistry from rocks, researchers thought that there are mantle plumes in and around Hainan. The geophysical detection mainly includes the imaging of MT and P /S waves in dense platform positions and the study of the receiving function. The results show that the Cathayxia block has strong transverse inhomogeneity at 150-450km, and the low-velocity anomaly only exists in the area near the Leiqiong volcano, which is integrated with the connection below the Leiqiong volcano. These low-velocity anomalies are interpreted as Hainan mantle plume (Huang, 2014; Lv Zuoyong et al., 2017; Yang et al., 2021). Petrographic analysis shows that the Cenozoic basalts widely distributed in the Leiqiong area have the geochemical characteristics of oceanic island basalts, containing magnesium-rich olivine phenocrysts, forming less than 16 Ma, mainly tholeiitic basalts, and mainly alkaline basalts between 6~4 Ma and 1 Ma, which originate from deep mantle. On the whole, the mantle source region presents the characteristics of MORB-OIB transition (Wang et al., 2012; Xu Yigang et al., 2012; Yang Wenjian, 2020). Based on the Cenozoic alkaline rocks exposed on the surface, the influence area of the Hainan mantle plume is delineated as the South China Sea, the Leiqiong Peninsula and the Indo-China Peninsula. The influence area is roughly centered on the intersection point of the Honghe fault zone and the Yuedong fault. The Middle East and southeast boundaries of the Hainan mantle plume are the Manila Trench and Nansha Trough, which are characterized by extrusion properties, respectively. Covering an area of more than 4 million km2 (Yan Quanshu et al., 2007; Xu Yigang et al., 2012).

3.2 Reservoir development conditions

Various types of geothermal reservoirs are developed in Minyueqiong area. A bar chart of the main reservoir and cap assemblages in the deep layer has been compiled based on the characteristics of regional rocks and strata, hot springs, middle shallow and deep geothermal displays. In addition to the Neogene and Quaternary, which are shallow buried and basically do not have the conditions for the formation of deep geothermal resources, other rock strata with good reservoir conditions are likely to become deep geothermal reservoirs. The preliminary study shows that there are eight sets of deep geothermal reservoirs in the area, including multiple sets of sedimentary rocks, metamorphic rocks and multi-stage igneous rocks from Precambrian to Paleogene, covering various lithologies such as granite, carbonate, sandstone and metamorphic rocks (Ke et al., 2022). The superimposed rock

strata with low thermal conductivity become the effective cap rock. Granite fissure reservoir is the most potential deep geothermal reservoir in Pre-Cenozoic. The South China igneous area experienced Caledonian, Hercynian, Indochinese, Yanshan and Himalayan tectonic-thermal events, which provided objective conditions for the formation of thermal reservoirs. Fracture type and weathering crust type heat reservoirs can be formed at the intrusion interface of rock mass and stratum and the weathering crust on the top surface of granite. With appropriate burial depth and temperature field, deep geothermal resources are expected to be enriched. The areas with Cenozoic buried depth of more than 3000 m are mainly located in Beibu Gulf Basin.

The Paleogene, Neogene and Quaternary are mainly sandstone, conglomerate and alluvial deposits, which can be a good reservoir-cap combination. Igneous rock area of south China, and the result of the study in the paper, from a new development in turn old former Cambrian granite gneiss and lower palaeozoic group sand rocks and carbonate rocks, carbonate rocks and hercynian, upper palaeozoic - yanshan period granite, the Mesozoic volcanic clastic rocks and Cenozoic clastic rock and so on more than heat reservoir types, each set of thermal storage of overlying shale interlayer can serve as a good cover, And the adjacent thermal reservoir to form a set of storage cap assembly. These reservoir-cap assemblies exist alone or superimposed in the region, forming various types of geothermal systems. For the deep layer, there are both hydrothermal geothermal system and dry hot rock geothermal system.

Table 4 Histogram of main reservoir cap assemblages in deep igneous rock area of South China

Stratigraphy		Reservoir-cap configuration	Lithology	Distribution
Cz	Q	cap	Qhpal	widely distributed
	N	cap	Sandstone, mudstone	widely distributed
	E	Reservoir-cap	Sandstone, conglomerate	Yuezhong depression, Beibuwan Basin
Mz	K	Reservoir-cap	tuff	Coastal igneous area of Fujian Province
	J	Reservoir-cap	Tuff, sandstone	Coastal igneous area of Fujian Province
	T	cap	Sandstone inbedded with coal bedding	Coastal igneous area of Fujian Province
Pz_2	P	Reservoir	limestone	Yuezhong depression
	C	Reservoir-cap	Limestone, sandstone	Yuezhong depression、Beibuwan Basin
	D	Reservoir-cap	Sandstone, limestone	Yuezhong depression、Beibuwan Basin
Pz_1	S	cap	shale	Yuezhong depression
	∈	Reservoir	sandstone, slate	Yuezhong depression、Beibuwan Basin
Pt	Pt_2-Z	Reservoir	Gneiss, sandstone, slate	Yuezhong depression、Beibuwan Basin

3.2.1 Granite fissure reservoir

Mesozoic granite fissure reservoirs are distributed among the southeastern coastal areas, such as Zhangzhou, Fuzhou, Fengshun, Yangjiang and southern Hainan Province. In these areas, the distribution of reservoir is mainly controlled by NE-trending faults, for instance, in the area around Fuzhou Basin (Fig. 7a, b). Most of these granites were formed during the Yanshanian period. There are two types of heat source: Crust source originating from radiogenic heat from K-, Th- and U-bearing minerals of granites and mantle source connecting to the nearby ground by the deep faults. In the Quaternary, most of the radiogenic heat of granite was lost along the fault zone and could not constitute a source of geothermal heat in the fault. The NE-

trending faults were developed because of the west dipping subduction of Western Pacific Ocean Plate (ZHANG Lu, 2008). Therefore, it is easy to form deep fracture zone and become the channel for hot water to migrate from the deep mantle. In southeast coastal area, 74% of hot springs are located in fault zone or lithological contact zone in magmatic plutons.

The hot water distributed in the fractured granite reservoir is limited by NNW-trending fault and mainly occurs in the fracture zone with higher permeability, even in the core with depth of 0~50 m. Some local granitic plutons were intruded by diabase dikes. The fissure water in Zhangzhou Basin and Fuzhou Basin was recharged by atmospheric precipitation in the northern, eastern and western mountainous areas through NNW-trending and NEE-trending faults, and then upwelled to the shallow part along the intersection of these two groups of faults.

3.2.3 Paleozoic karst reservoir

Carbonate rocks are widely distributed in China, with the total surface area of 1 200 000 km2, accounting for 13% of rock in China. In the North China Craton, carbonate rocks are mainly distributed in the lower Paleozoic strata, while in South China regions, they are most located in the upper Paleozoic strata, such as those in Huizhou area, Guangdong Province. Karst reservoir can form fissures and be easily cut by later intruded calcite veins (Fig. 7c, d). The karst reservoir is mainly located in the multiphase karst unconformity interfaces, and the depth of the reservoirs is 1 000-3 000 m. The modern active faults formed the conduit heat flow for strong runoff karst. The carbonate rocks buried in depth can also dissolve organic matter, which enables them to form pores easily. 40-80 °C is the favorable temperature for formation and development of dissolution pores. In the uplift zone of the fault area, the uplift carbonate buried hills are all favorable areas for precipitation infiltration recharge. Hot water and the dissolution of organic matter accelerated the development of deep karst reservoir. Especially, dolomite was easier to dissolve than limestone to form the deep-buried layered karst reservoir. For example, in North China, the dolomites buried under the 3 000~4 000 m of the Wumishan Formation formed pore, cave and fracture thermal reservoirs with porosity of 1%~5%. The karst cave network was formed along fault zones. Also, it formed strong runoff zone, which has become the main channel for runoff and discharge of hot water.

3.2.1 Cenozoic sandstone or sandy conglomerate reservoir

Cenozoic sandstone or sandy conglomerate reservoirs are mainly distributed in Cenozoic basins, such as Zhangzhou Basin, Fuzhou Basin and Leiqiong Basin, etc. These basins are mainly bounded by faults tectonically. The Tertiary sedimentary basins such as Leiqiong Basin and Sanshui Basin, are controlled by NE-trending faults, while the Quaternary sedimentary such as Zhangzhou and Fuzhou basins are controlled by NW-trending faults.

Tertiary sedimentary basins mainly include Leiqiong Basin and Sanshui Basin. Tertiary reservoir is composed of Neogene and Paleogene reservoirs. Neogene strata is located in the depressions of littoral facies, mainly overlapping with the neritic facies. The lithology is composed of the semi-consolidated sandstone, the gravel sandstone, the sand conglomerate and the mudstone interlayer (Figure 7e, f). The accumulated thickness of sandstones varies greatly from one area to another. For instance, the thickness of the formation in the northern part of Leiqiong Basin is 200~700 m, including 200~400 m in Zhanjiang depression, 400~700 m in Jijia depression, and the maximum thickness of 1 500 m in Wushi sag. The thickness of a single layer of sandstone is generally 2 m to 3

m, and 5 m to 15 m at maximum. The Neogene reservoir is shallow and thick and has abundant water, especially in the middle and upper section. Therefore, it is the most valuable geothermal zone in the northern part of Leiqiong Basin. Paleogene is located in a series of small enclosed or semi-enclosed basins. It can be divided into Weizhou Formation (E3), Liushagang Formation (E2l) and Changliu Formation (E1c).



Figure 7 Field photos of different types of geothermal reservoir rocks（a. granites from huangshadong, Huizhou; b. granites from Foshan; c, carbonates from Longmen county, Huizhou; d, carbonates from Well Huire 2, Huizhou; e, Sandstone from well X3, Xuwen; volcanic rocks from Fengshun area）

3.3 Cover and preservation conditions

Cap rock is a rock layer above the thermal reservoir that can prevent heat from dissipating outward, and it is an important geological structure in geothermal systems (especially in the interior of sedimentary basins). In order to preserve the basement energy and prevent atmospheric precipitation from infiltrating the cooling reservoir rock mass, the basement is covered with a low thermal conductivity cap, usually mainly sedimentary (sediment) or volcanic rock, and sometimes weathering crust of appropriate thickness. Rybach et al. (1978) figuratively compared the cover layer to a blanket and called its effect the blanket effect. Regional cap rocks with large thickness, wide area and relatively stable distribution all over the vast sedimentary basins or depressions play an important role in heat accumulation in basins or depressions.

4. Strategic area and key exploration direction of deep geothermal resources in Fujian-Guangdong-Hainan Area

4.1 Present situation of deep geothermal exploration in Minyueqiong Area

The utilization of geothermal resources in Fujian-Guangdong-Hainan area has a long history. Before 1970, it was mainly used for hot spring bathing and so on. In 1970, the first geothermal power station was built in fengshun, guangdong province, with a power of 300kWe, marking the industrialization of geothermal utilization. With the increasing attention to the deep geothermal resources in South China, since 2016, the Geological Survey Bureau and enterprises have drilled three deep geothermal Wells in the area, namely, Dry heat Well 1 located in Zhangzhou, Fujian Province, Huige Well 1 located in Huizhou, Guangdong Province, and Huadongheat Well 1R located in Hainan, in an attempt to explore and develop dry hot rock resources. In addition, a high

temperature of 211℃ was measured in well Xwen X3, an oil and gas exploration well located in Xuwen, Guangdong Province, in 2010, indicating the existence of high temperature conditions in the deep layer of the area.

Zhangzhou Dry Heat Well 1 is the first dry hot rock scientific drilling well in Fujian Province organized and implemented by China Geological Survey. It is located in Qingquan Forest Farm, Dongsi Township, Longhai City, Zhangzhou, Fujian. The deep part of the well is granite. The well was spudded on May 21, 2015 and completed in December 2016 at a depth of 4,000 m. The temperature measured at the bottom of the well at 4000 m is 109℃, which is significantly lower than the predicted temperature (>150℃), and also lower than the temperature of other shallow drilling Wells in Zhangzhou City (the highest temperature at 100m is 122℃). The analysis shows that the location of well Dry Heat 1 is too close to the fault zone, and the drilling location is still in the fracture zone. The drilling depth of 4000m is connected with the shallow geothermal water, resulting in the temperature in the deep is close to the shallow temperature (110-120℃).

Huizhou Dry heat Well 1 is the first dry hot rock scientific parameter well organized and implemented by China Geological Survey in Guangdong Province. It is located in Huangshadong geothermal field, Huizhou City, and was implemented from 2017 to 2019. Drill the Wells in the 1565 m event of concealed granite rock mass and its overlying sedimentary cover lithology from shallow to deep, in turn, is thousand pieces of shale and fine sandstone and siltstone and quartz sandstone interbed, carbonaceous SLATE, tectonic breccia and silicified quartz sandstone layer, a metamorphic grade metamorphic sequences from shallow to deep, show granite magma thermal emplacement cause thermal contact metamorphism of sedimentary cover. According to the stratigraphic distribution of the profile, 20 m shallower is quaternary, 20 ~ 1109 m is Cambrian, 1109 ~ 1565 m is Sinian, 1565 ~ 3009 m is Yanshanian monzogranite, occasionally sandwiched with Sinian thin stratum hornstone

Huadongrei Well 1R, drilled by Hengtai Aipu (Hainan) Clean Resources Development Co., LTD., is located about 600 meters southeast of Guoshe Village, the old town of Chengmai County, Hainan Province. It was started on December 28, 2017 and completed on March 23, 2018 with a depth of 4550m and vertical depth of 4387m. It was announced that 185℃ (unsteady) high temperature dry hot rock resources were drilled (Li Dewei, 2018). The strata drilled in this well from top to bottom are the Fourth system, the Neogene Wanglougang Formation, Dengloujiao Formation, Jiaowei Formation and Xianyang Formation, the Paleogene Weizhou Formation, Liushagang Formation and Changliu Formation (not exposed). The main reservoirs are Liushagang Formation and Changliu Formation. The Liushagang Formation is interbedded with fine sandstone and siltstone of lacustrine and delta facies, and contains asphaltene interbedded. Changliu Formation is alluvial facies conglomerate. The thermal reservoir with temperature greater than 150℃ starts from the bottom of Liushagang Formation, and the thermal reservoir with temperature greater than 180℃ starts from the upper part of Changliu Formation.

Xuwen X3 well is an oil and gas exploration well completed by Sinopec Jiangsu Oilfield in December 2010. It is located about 150m east of Tigu Village, Maichen Town, Xuwen County, Guangdong Province, and is located in the high structural position of Mai10 block in the southern stepfault zone of Maichen Sag, Beibu Gulf Basin. The stratigraphic sequence of well Xwen X3 drilling is normal, from top to bottom: The fourth system (Q), Wanglougang Formation (N2w), Denglougang Formation (N1d), Jiaowei Formation (N1j) and Xianyang Formation (N1x) of the Recent system, Weizhou First Section (E3w1), Weizhou Second section (E3w2) and Weizhou Third Section (E3w3) of the Paleogene System, and Weishagang First section (E2l1) of the Paleogene system.

The well depth is 6010.00m (vertical depth 5413.28m). The temperature measurement data at 5397m vertical depth obtained a high temperature of 211℃, which is the highest deep temperature revealed by drilling in the area.

4.2 Strategic selection of deep geothermal in Minyueqiong Area

According to the existing geothermal display and recent deep geothermal drilling results, the distribution of deep geothermal resources in the South China igneous area is mainly controlled by the thickness of the cap layer and the fault structure. Generally speaking, the thickness of the cover layer controls the temperature of the geothermal resources. The deep geothermal temperature is higher in the thick cover area, higher in the medium cover area, and lower in the thin cover area. These three scenarios correspond to the terrestrial geothermal system in the Beibu Bay Basin where Huadong 1R well and Xuwen X3 well are located, the geothermal system in the Yuezhong depression where Huige 1 well is located, and the geothermal system in the coastal igneous zone of Fujian where Zhangzhou Dry Heat 1 well is located. Therefore, it can be divided into thick cap zone with cap thickness greater than 3000m, middle cap zone with cap thickness between 1000 and 3000m, and thin cap zone with cap thickness less than 1000m. The type of deep geothermal resources is controlled by the development of high quality reservoirs. If there are high permeability reservoirs, the hydrothermal geothermal system will be formed. Otherwise, the dry hot rock geothermal system can only be formed in deeper locations.

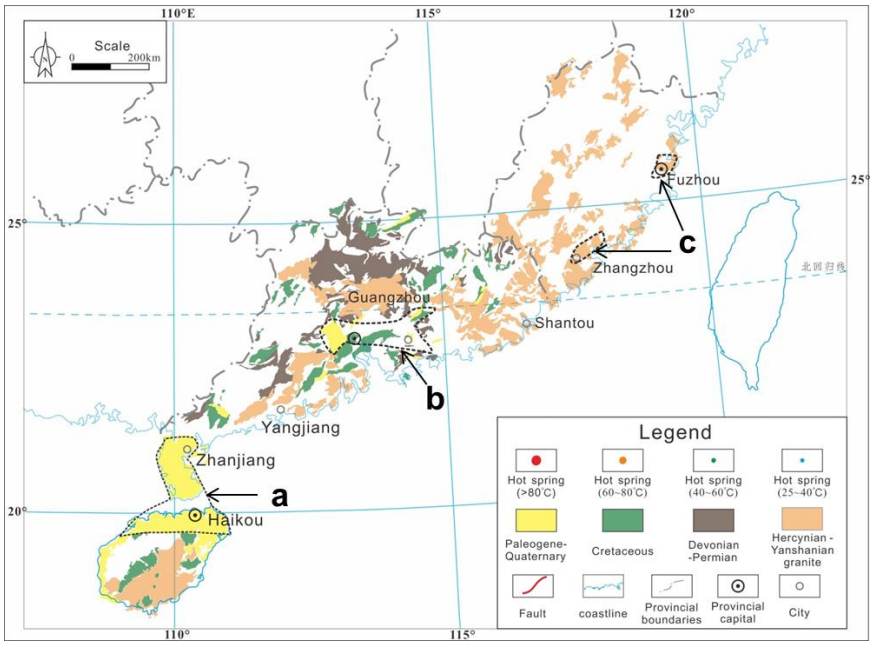

Figure 8. Strategic favorable zone of deep geothermal resources in Minyueqiong area: a, the continental area of Beibu Gulf Basin; b, Yuezhong depression; c, Fuzhou and Zhangzhou area

There is a slight difference in the distribution of geothermal resources between warm water type and dry hot rock type. Among them, the water hot type geothermal resources are mainly distributed in the bulge basin area, small basins and uplift area, zhangzhou basin, fuzhou basin, such as sand dong area, such as high temperature hot water type geothermal resources are mainly distributed in the sag area of the great basin and attached to the heating source area, and the great basin bulge zone and the deep of small basin area, such as the beibu gulf basin in fushan sag, Michael Chen sag of concave. In Wushi Sag and the deep part of Sanshui Basin, dry hot rock geothermal resources are widely distributed, and the thermal reservoir depth varies greatly according to the difference of structural location, and is widely distributed below the buried depth of 4000 ~ 6000m

Combined early geothermal resource exploration and development and drilling in deep geothermal resources, have the potential to develop scale in igneous rock area of south China in the deep geothermal resources are mainly distributed in the Cenozoic basin and surrounding areas, land area, of which the Beibuwan basin depression in guangdong and fujian southeast coastal igneous rock band for the typical representative area, respectively corresponding to the thick cover layer in the area, cover area and thin layer cover area. The distribution of rock strata in the three regions is different, and the characteristics of reservoir and cap assemblages are also different. The deep geothermal resources in the continental area of Beibuwan Basin are the best, followed by Yuezhong depression, and then the coastal igneous belt of Fujian Province. The moderate and high warm water thermal geothermal system and dry hot rock resources with suitable bedrock depth (3000 ~ 5000m) in the continental area of Beibuwan basin are favorable directions for recent exploration.

5. Conclusion

（1） In terms of the genetic mechanism and resource distribution of deep geothermal, it is clear that the heat sources in Minyueqiong areas are mainly composed of heat generation from radioactive elements in the crust and mantle conduction heat, and there are additional heat sources such as middle and lower crust melt in some areas (such as the Shantou, Yangjiang area). It is suggested that the deep high temperature geothermal resources are mainly distributed in the depression area of the great basin with triple heat source superposition area.

（2） According to the geological conditions, these areas contain three types of geothermal reservoirs. Cenozoic sandstone or sandy conglomerate reservoirs are mainly distributed in Cenozoic basins, such as Zhangzhou Basin, Fuzhou Basin and Leiqiong Basin. Mesozoic granite fissure reservoirs are distributed along the southeastern coastal areas, such as Zhangzhou, Fuzhou, Fengshun, Yangjiang areas and southern part of Hainan Province. Paleozoic Karst reservoirs are mainly distributed in the upper Paleozoic strata, such as the limestone in Huizhou area.

（3） In terms of resource and selection evaluation, Based on analysis of regional gethermal reservoir conditions, regional cover conditions, three strategic favorable zone of deep geothermal resources in Minyueqiong area are selected: the continental area of Beibu Gulf Basin, Yuezhong depression and the southeastern coastal igneous zone of Fujian.

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