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Characteristics of Geothermal Reservoirs and Utilization Direction of Geothermal Resources in Southeast Coastal Areas of China

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ABSTRACT

Based on geological condition such as regional geological setting and stratigraphic distribution, this paper summarizes three types of thermal reservoirs in the coastal areas of Southeastern China: Paleozoic Karst fissure-type, Mesozoic granite fissure-type and Cenozoic sandstone or sandy conglomerate-type. Paleozoic carbonate rocks are widely distributed and are mostly located in the upper Paleozoic, such as Huizhou. Mesozoic granite fissure reservoir is distributed among the southeast coastal areas, such as Zhangzhou, Fuzhou, Fengshun, Yangjiang and south part of Hainan province, where its distribution is mainly controlled by NE-trending faults. Cenozoic sandstone or sandy conglomerate strata is mainly distributed in Cenozoic basins, such as Zhangzhou basin, Fuzhou basin and Leiqiong basin and so on. The geothermal systems buried depth of 0-3,000 meters are mainly of medium and low temperature convection type, the resources of which can be mainly for direct use, such as space heating, greenhouse heating, bathing and swimming, and other aspects. The geothermal systems buried depth of 3,000-6,000 meters are mainly hot dry rock type, with temperature range 150-200°C, which is conductive to the construction of enhanced geothermal system (EGS). The high-temperature resources can be used for power generation, cooling and agricultural drying, etc.

1. INTRODUCTION

The southeast coastal region of China is geographically defined as the region in the southeast of China near the Pacific Ocean. It concludes eight provincial-level administrative units in the region, including Zhejiang, Shanghai, Jiangsu, Fujian, Guangdong, Hainan, Hong Kong and Macao. This area is economically developed, densely populated and energy scarce in China. If large-scale development of geothermal resources can be realized, huge social and economic benefits will be achieved.

Surface geothermal manifestation such as hot springs and other surface heat in this area are widely distributed. Three kilometers of intermediate and low temperature geothermal resources have a long history and are mainly used for hot springs. In the north, Zhejiang, Jiangsu and other areas, there is a small amount of heating for Winter. In 1970, the first geothermal power station in China was built in Dengwu Village, Fengshun County, Guangdong Province. The preliminary study shows that the hot dry rock resources in the southeast coastal area have great potential. The 3-10 km deep geothermal resource base in southeast coastal areas is equivalent to 5.89 billion tons of standard coal, accounting for 8.2% of the country (Wang et al., 2012; 2015). If the hot dry rock geothermal resources can be developed and utilized on a large scale, it will make greater contribution to the energy structure adjustment and improve the livelihood this area.

2. GEOTHERMAL GEOLOGICAL BACKGROUND

2.1 Regional geologic setting

Geologically, the southeast coastal region of China belongs to a part of the Cathaysia block. The basement of the Cathaysia block is mainly of early-middle Proterozoic single-layer or multi-layer structure. In the Phanerozoic, the Cathaysia Block is characterized by intensive and widespread polyphase orogenesis and magmatism. The Jurassicto Cretaceous (or “Yanshanian” in Chinese literature) igneous rocks arepredominantly granites and rhyolites with subordinate mafic and rare intermediate lithologies (Li et al., 2015).

In southern China, complex structure of the tectonic evolution, different scholars and experts have different opinions and understanding, each from a different Angle discusses the tectonic evolution of south China (Li et al, 2009; Zhao et al., 2011). The area underwent deformation and transformation of Caledonian, Indo-Chinese, Yanshanian and Xishan periods. It is generally believed that the south China is controlled by the circum-Pacific tectonic domain since late Mesozoic (Meng et al., 2012; Niu, 2014).The Pacific plate subduction, strong "activation" in the eastern region of the earth's crust, and the Cenozoic marina in the western Pacific epicontinental features strong tectonic magmatic activity. Due to the subduction and collision of the Indian plate, core-mantle material transport, crust-mantle material migration, deep hot material upwelling and magmatic activity are strong.

The most widely distributed granites in south China are crust-derived remelting granitoids, which are formed by magma intrusion from the remelting of continental crust (Fig.1). Remelting granitoids are basically equivalent to the land-crust remolded granitoids (Xu et al., 1984). Crust-derived remelted granites are widely distributed in the Sinian - Caledonian Geosynclinal fold area of south China. The material source of these granites is largely dependent on the metamorphic basement of south China continent, which is closely related to the nature and composition of the deep metamorphic basement (Shu et al., 2012).

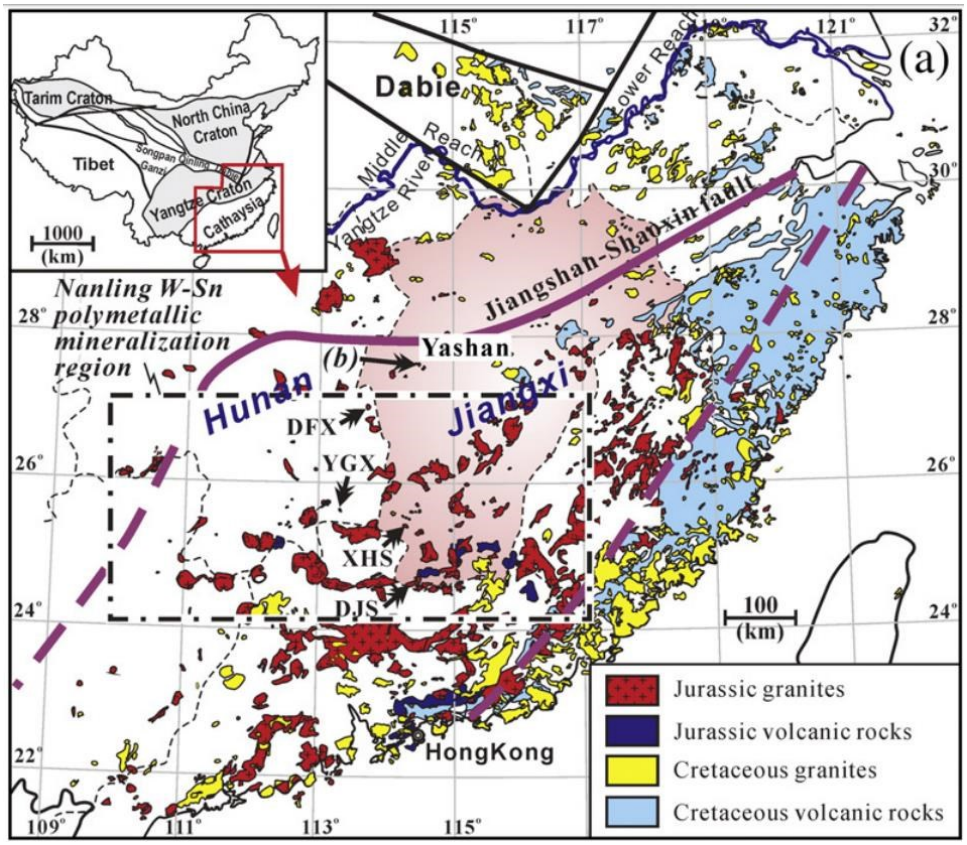

Figure 1: The distribution of igneous rocks in different periods in southeast coastal areas of China (from Li et al., 2015)

2.2 Heat flow characteristics

The distribution of terrestrial heat flow in south China is showed in Figure 2. It can be divided into 3 obvious heat-structure partition: the eastern, central and southwest region. The east region is characterized by high terrestrial heat flow. The boundary between east and central region is Tanlu-Wuling-Shiwan fault; the central and east region is of relatively low terrestrial heat flow, bounded by Jinshajiang-Ailaoshan Suture zone. The east and southwest zone is generally higher than 70 mW/m^2, while the central zone is lower than 60 mW/m^2.

In the Eastern region, 2 high value anomaly zone with NE direction are located in Fuzhou-Zhangzhou zone along the southeast coast and Wuchuan-Sihui fault zone with NE distribution. The two anomaly zones are characterized by high heat flow value (>80 mW/m^2, locally up to 220 mW/m^2). In the lower Yangtze region, it is higher in the north and lower in the south. The average terrestrial heat flow in the northern Jiangsu basin is 71.2 mW/m^2, while that in southern Jiangsu and southern Anhui is 62.7 mW/m^2.

In the Central region, the low heat flow is distributed in NS direction, from Baise to Dabie mountain. In the Southwest region, the high heat flow is only concentrated in southwest Yunnan. the average of the terrestrial heat flow in Sichuan basin in the north is 53.6 mW/m^2, while Yunnan area in the south is 76.7 mW/m^2. Jianghan basin in the middle is also low in the north and high in the south, with the subsurface fault as the boundary. To the north of the subsurface fault, the average terrestrial heat flow is 47.8 mW/m^2, and 61.6 mW/m^2 in the south.

In South China, the eastern region, central region and southwest region are characteristics, the average heat flow value of South China with 64.2 mW/m^2 is higher than that in Chinese mainland area for 61 mW/m^2 (Wang et al., 1900), and close with the global area with 65 mW/m^2. The abnormally high value in south China is mainly located along the suture zone or deep fault zone.

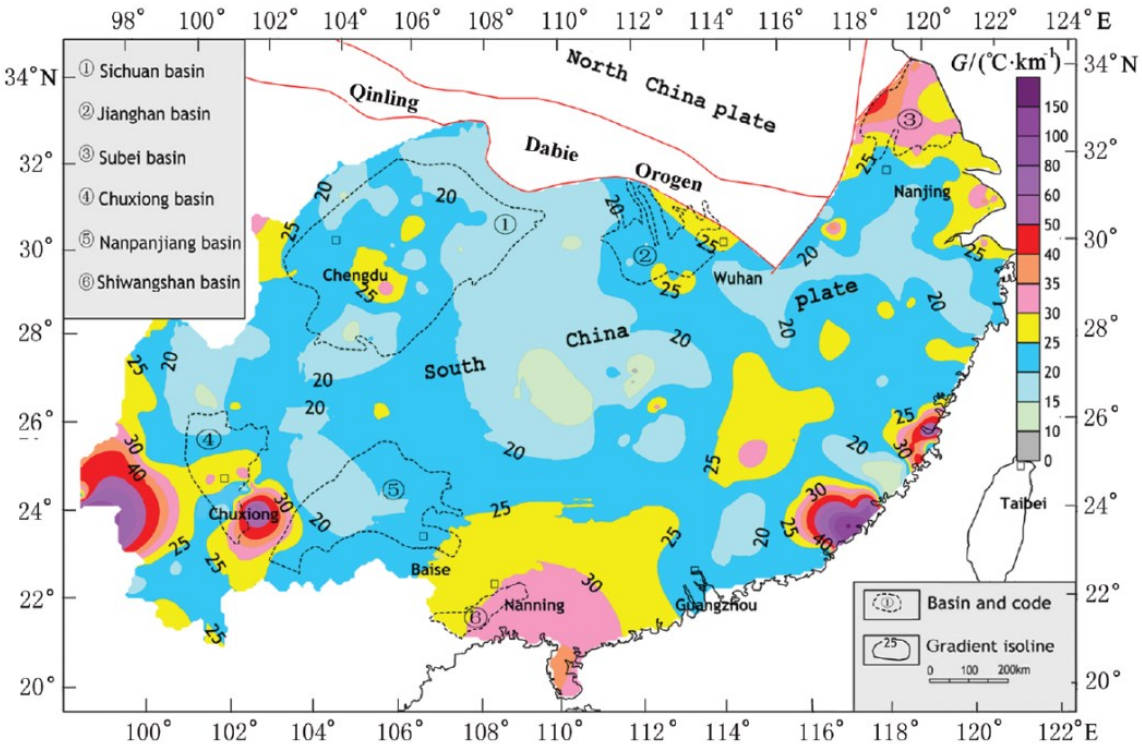

Figure 2: Geothermal gradient map of South China continent（From Yuan, 2007）

3. GEOTHERMAL RESERVOIR

3.1 Cenozoic sandstone or sandy conglomerate reservoir

Cenozoic sandstone or sandy conglomerate strata is mainly distributed in Cenozoic basins, such as Zhangzhou basin, Fuzhou basin and Leiqiong basin and so on. Those basins are mainly controlled by faults. The Tertiary sedimentary basin is controlled by NE fault, while the Quaternary sedimentary basin is controlled by NW fault.

The Tertiray Sedimentry basin is mainly located in Leiqiong Basin and Sanshui basin. Tertiray reservoir can be divided into Neogene and Paleogene resorvoir (Fig.3). Neogene is located on depression with Littoral facies mainly overlaps with neritic facies. The lithology is the loose sand, gravel and clay interlayer, the deep part is the semi-consolidated sandstone, the gravel sandstone, the sand conglomerate and the mudstone interlayer. The accumulated thickness of sandstones varies greatly in various areas. The thickness of the formation is 200-700 m in the north Lei area, of which the Zhanjiang depression is 200-400 m and the Jijia depression is 400-700m. Leinan area is 800-1200 m, and the maximum thickness is 1500 m in Wushi sag. The thickness of sandstone monolayer is generally 2 to 3 m, and the maximum thickness is 5 to 15 m. The Neogene reservoir is shallow and thick with abundant water, especially in the middle and upper section. It is the most valuable geothermal zone in Leizhou Basin. Paleogene located in a series of small enclosed or semi-enclosed basins. It is divided into Weizhou formation (E_3), Liushagang formation (E_2l) and Changliu formation (E_1c). They are mainly dark clastic sediments of Marine facies and the geochemical facies are reductive facies, and they are the main oil-generating rock series from Leqiong basin.

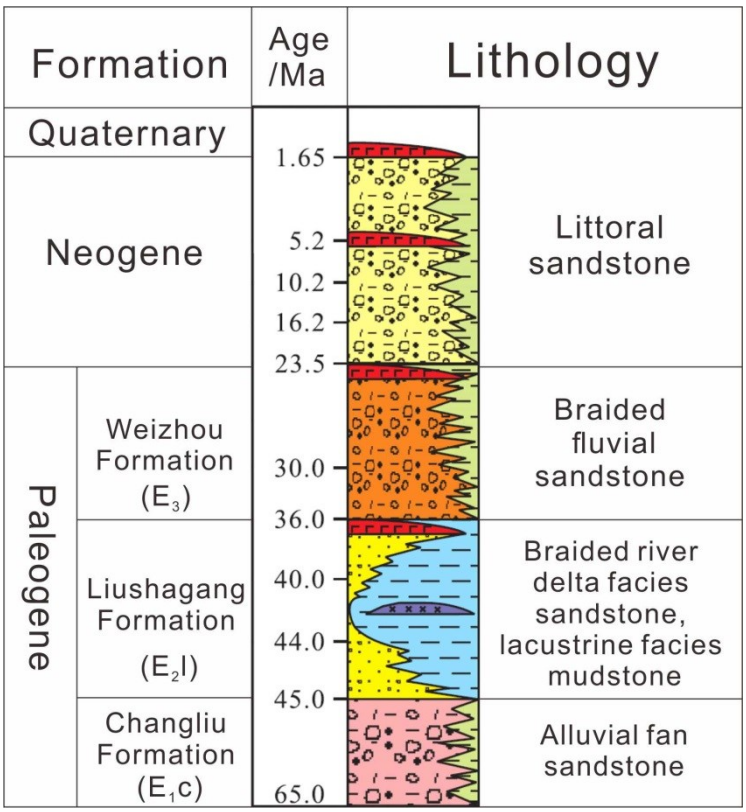

Figure 3 Stratigraphic composite histogram of Leiqiong Basin (modified after Zhao, et al., 2016)

Quaternary sedimentary basin is located in Zhangzhou and Fuzhou Basin. Zhangzhou basin is located in a small quaternary basin based on Mesozoic (Yanshanian) granite pluton. Fuzhou basin is located in Fuzhou city, the capital of Fujian province. Zhangzhou basin is also controlled by NE and NW faults. NW fracture mechanics to pour quality is given priority to with a shear, become the bedrock area deep runoff channels, atmospheric precipitation infiltration in the western mountain fault zone, to the deep runoff under the influence of gravity, heating by the earth's crust, upwelling of the downstream along the fault zone, the downstream downfaulted basin area is deep runoff discharge area, hot water through the deep fault belt in quaternary reservoirs in the basin, forming abnormal geothermal area, or into hot water springs overflow surface. It is a convective geothermal system distributed along the fracture zone. Fuzhou basin is mainly Quaternary alluvial and marine loose debris, the thickness ranging from several meters from the north to the south to more than 60 m. Quaternary sedimentary basin, southeast coastal big delta, two north west faults are holding block type basin, the thickness of the quaternary system more than 100 m, the Fuzhou basin is one of the largest basins, Fujian area of about 1500 km^2, Fuzhou Nanping fracture is in the southwest side of the basin, deep crust structure and tectonic Fuzhou basin and the surrounding area. According to the analysis of borehole data, Fuzhou basin began to decline from the middle of Late Pleistocene, with a relative decline of about 100 meters. Geothermal anomaly zones are formed along deep faults.

3.2 Mesozoic granite fissure reservoir

Mesozoic granite fissure reservoir is distributed among the southeast coastal areas, such as Zhangzhou, Fuzhou, Fengshun, Yangjiang and south part of Hainan province, whose distribution is mainly controlled by NE-trending faults (Fig. 4). Especially in the Yanshanian period, it may be a thermal crust. However, since the Quaternary, all the heat has been lost, which cannot constitute a heat source of water in the fault. Since the Quaternary, when the Taiwan arc pushes to the northwest and the NW-trending fissure develops, it is easy to form deep fracture zone and become the channel for hot water migration from the deep part. In southeast coastal area, 74% of hot springs are exposed in fault zone or contact zone in magmatic pluton.

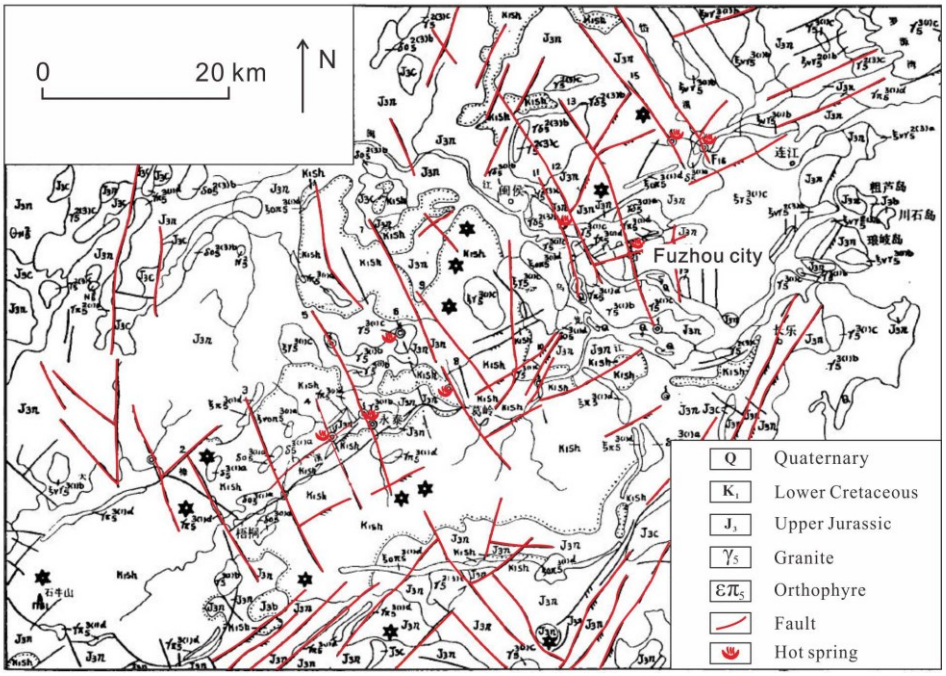

Figure 4 The fault structure in Fuzhou - Yongtai region and its control over geothermal location (modified after Lin et al., 1988)

a) Minhou Granite fissure reservoir, Fuzhou, Trending 30°

b) Tadou Granite fissure reservoir, Dehua, Trending conjugate 35°and 130°

c) Granite fissure reservoir from core, 10 m deep, conjugate fissure, Yangjiang

d) Longhai Granite fissure reservoir, Zhangzhou, Trending conjugate 5°and 75°

Figure 5 Granite fissure reservoir in different locations along the southeast region

The hot water of granite fracture-type reservoir is controlled by NNW-trending fault and mainly occurs in the fracture zone with good permeability (Fig. 5a, 5b), even in the core with depth of 0-50 m (Fig. 5c). Locally, some pluton is intruded by diabase dikes (Fig.

5d). In Zhangzhou and Fuzhou basin, fracture water is supplied by atmospheric precipitation in the northern, eastern and western mountains of the basin through NNW direction and NEE direction faults, and then upwelling to the shallow part along the intersection of these two groups of faults. Therefore, hot water temperature and water level is also by tectonic belt controlled water heat to gradually reduce, on both sides of her isotherm in profile is presented for the center with water transmitting fault on a bunch of convex curve.

3.3 Paleozoic karst reservoir

Carbonate rocks are widely distributed in China, with the total surface area of 1200000 km^2, accounting for 13% of China. In the North China platform, carbonate rocks are mainly distributed in the lower Paleozoic, while in South China are most located in the upper Paleozoic, such as Huizhou. Karst reservoir can form fissures and cut by late calcite veins (Fig. 6) with the depth of 400-500 m. The heat in the carbonate reservoir storage is mainly in the multiphase karst unconformity surface which can be development with depth of 1,000-3,000 m in the carbonate strata. The modern active faults formed strong runoff karst conduit flow. The buried deep carbonate rocks can also dissolve organic matter, so the hot water dissolution ability is greatly increased. 40-80 °C is the favorable temperature for organic dissolution pore formation and development. In the fault-bounded uplift area, the uplift carbonate mountains are all favorable areas for precipitation infiltration recharge. A large number of infiltration cooling formed the piedmont "cold basin" zone in the uplift, and the buried carbonate rocks in depression continue to heat up. With the help of hot water and the dissolution of organic matter, the development of deep karst reservoir is accelerated. Especially, dolomite is easier to dissolve than limestone, forming the deep-buried layered karst reservoir. For example, in north China, the dolomites buried in the 3,000-4,000 m Mifanshan Formation have formed pore, cave and fracture thermal reservoirs with porosity of 1%-5%, developed karst cave network along fault zones, and formed strong runoff zone, which has become the main channel for hot water runoff and discharge.

a) Karstic-reservoir from core, 300-400 m Longmen, Huizhou

b) Fissure in Karst-reservoir from core, Longmen, Huizhou

Figure 6 Karst reservoir in Longmen County, Huizhou, Guangdong province

4. THE DEVELOPMENT AND UTILIZATION DIRECTION OF GEOTHERMAL RESOURCES IN SOUTH CHINA

Although geothermal resources in southeast coastal areas are widely distributed, they are mainly used for bathing, while others are used for aquaculture. The overall utilization scale of resources is small, and the utilization efficiency is not high. In December 1970, China's first geothermal generator successfully generated electricity at the Dengwu geothermal experimental power station in Fengshun, Guangdong province, making China the seventh country in the world to utilize geothermal power successfully. In the past 50 years, no more power stations have been added, except for a slight increase in the installed capacity of Dengwu power station to 300 kW. In the future, large-scale exploration, development and utilization of hot dry rock resources based on deep heat storage description, heat storage transformation, recharge technology and cascade utilization technology will become the focus. The favorable areas for development and utilization of hot dry rock resources can be selected by superposition of high temperature and high-quality heat storage and geothermal market demand.

Hot dry rock resources refer to geothermal energy contained in high temperature (greater than 180°C) rocks without water (or less water), which is a huge renewable and clean energy. Enhanced Geothermal systems, namely the EGS (Enhanced Geothermal System) may be an effective way to hot dry rock resource development (Tester, 2006; Genter, 2010; Günter, 2013; Olasolo, 2016), namely through the establishment of artificial hydrothermal type hot dry rock Geothermal System, stable and sustainable development of resources.

4.1 Cenozoic sandstone or sandy conglomerate reservoir

Southeast coastal area economy is developed, densely populated, energy shortage. Zhejiang, Shanghai, Jiangsu, Fujian and other areas have heating demand in winter and cooling demand in summer, and there are electricity and industrial drying energy demand all year round. Therefore, the development and utilization of hot dry rocks should be scientifically designed to achieve efficient and economical utilization of resources.

There are abundant hydrothermal geothermal resources in the shallow Cenozoic sandstone beds, and the geothermal resources in the shallow part of the Zhangzhou geothermal field in Fujian province, the northern part of Hainan province and the southwest part of Hainan province are all the geothermal resources in the pore heat storage of this kind of sandstone. They are not only thermal reservoirs, but also can be used as the cover of Mesozoic granite thermal reservoirs. In the main sedimentary basin areas, such as northern Jiangsu basin and Leiqiong basin, it is also a set of potential hot dry rock heat storage. The target heat storage of Well

Huadong 1R drilled in Hainan is a Paleogene sand conglomerate. Based on the analysis of geological evolution history and geothermal field characteristics, located in Fushan depression, Maichen depression and Jijia depression in Leiqiong basin are favorable areas for hot dry rock resources and exploration targets.

4.2 Utilization direction of high temperature and deep geothermal resources

There is a set of potential hot dry rock Paleozoic carbonate heat storage in the southeast coastal area. Upper Paleozoic carbonate rocks are mainly limestone, which is located in Jiangsu province, controlled by multiphase tectonic movement occurred relatively strong karstification, the occurrence of hot water type geothermal resources, has been developed for heating and hot spring bath. In Sanshui, Huizhou and other areas of Guangdong province, water-heat geothermal resources in this set of heat storage have also been found. In the future, with the deepening of exploration, the geothermal resources of water-heat type and dry-heat rock in the karst heat storage of carbonate rocks in the Paleozoic will be gradually discovered and widely used, and it is expected to become the main enrichment strata of geothermal resources in the southeast coast.

In recent years, the research on hot dry rocks in the southeast coastal areas has been continuously deepened, and two exploration Wells have been completed. In 2016, the China geological survey completed the drilling of well HDR-ZK01 in Zhangzhou, Fujian, with a depth of 4000 m and a temperature of 109°C. Hengtaiaipu company completed the drilling of well Huandong 1R in 2018 in Chengmai, Hainan, with a depth of 4387 m and a temperature of 185°C, reaching the temperature range of hot dry rocks.

Southeast coastal region is China's main area of Mesozoic granite, the discovery and development in the area with deep geothermal resources, mainly occurs in Mesozoic (mainly Cretaceous) deep faults control the granite fracture zone, the thermal fracture type, to break the location of the intersection of water is best, Fujian, Guangdong and Hainan development and utilization of larger scale. This set of heat storage is located in the shallow part of water-heat geothermal resources. In places with large buried depth and high geothermal gradient, hot dry rock geothermal resources can be formed if there is no storage space or not filled by geothermal water. In the early stage, the well HDR-ZK 01 drilled in Zhangzhou, Fujian province encountered hydrothermal geothermal resources at 4,000 m, and no hot dry rock geothermal resources were found. However, there must be dry and hot rock geothermal resources in suitable areas. The dry and hot rock resources in the areas covered by a certain cap layer have better preservation conditions and are more conducive to resource enrichment.

The buried depth of this area is 4,000-6,000 m, and the storage temperature of dry and hot rocks is generally 150-200°C. EGS technology is adopted to develop and produce geothermal fluid wellhead temperature of about 130-180 °C. Therefore, it is advisable to develop and utilize dry hot rock geothermal resources by using adjustable cascade utilization method according to the differences of energy demand in different regions and seasons.

The geothermal fluid produced by EGS system is probably firstly used for power generation(Figure 7), then the power generation tail water may be used for direct use such as space heating, greenhouse heating, aquaculture pond heating, agricultural drying, industrial uses, cooling, bathing and swimming. The tail water enters the EGS system and continues to be heated underground for recycling. As the demand varies greatly in different seasons and different regions, Britain has established a dynamic regulation system to order production and maintain the efficient and stable operation of EGS system.

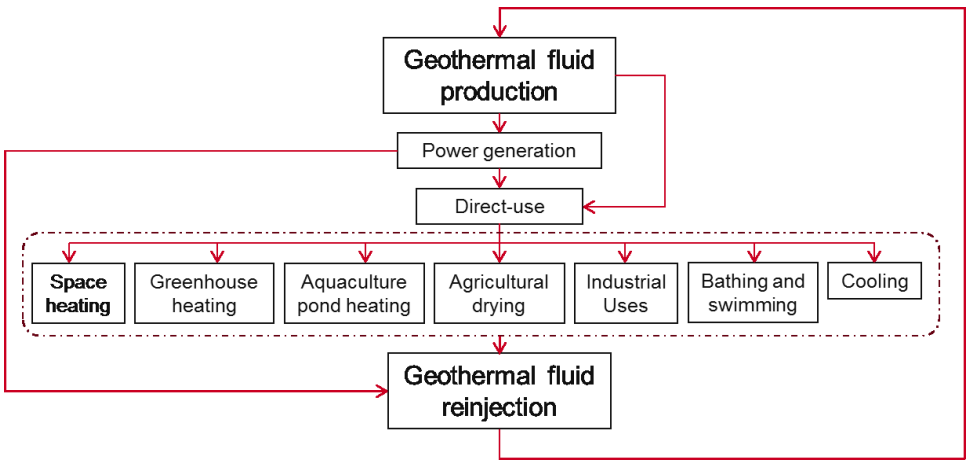

Figure 7 Flow chart illustrating utilization of geothermal resources (modified from Lund et al., 2015)

5. CONCLUSIONS

The southeast coastal region of China belongs to a part of the Cathaysia block with widely distributed granites. Based on its Heat flow characteristics, it can be divided into 3 obvious heat-structure partition: the eastern, central and southwest region. The east region is characterized by high terrestrial heat flow. The central and east region is of relatively low terrestrial heat flow, bounded by Jinshajiang-Ailaoshan Suture zone. The east and southwest zone is generally higher than 70 mW/m^2, while the central zone is lower than 60 mW/m^2.

According to the geological condition, this area contains three types of thermal reservoirs: Paleozoic Karst fissure-type, Mesozoic granite fissure-type and Cenozoic sandstone or sandy conglomerate-type. Paleozoic carbonate rocks are mainly distributed in the upper Paleozoic, such as Huizhou. Mesozoic granite fissure reservoir is distributed among the southeast coastal areas, such as

Zhangzhou, Fuzhou, Fengshun, Yangjiang and south part of Hainan province. Cenozoic sandstone or sandy conglomerate strata is mainly distributed in Cenozoic basins, such as Zhangzhou basin, Fuzhou basin and Leiqiong basin and so on.

Southeast coastal area in China is characteristic of developed, densely populated and energy shortage. Therefore, the development and utilization of geothermal energy such as hot dry rocks should be scientifically designed to achieve efficient and economical utilization of resources. The geothermal fluid produced by EGS system is probably used step by step, such as using for power generation firsy, then used for direct use such as space heating, greenhouse heating, aquaculture pond heating, agricultural drying, industrial uses, cooling, bathing and swimming.

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