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Overview on hydrothermal and hot dry rock researches in China

Gui-ling Wang[a], Wei Zhang[a], Feng Ma[a, b,*], Wen-jing Lin[a], Ji-yun Liang[a], Xi Zhu[a]

[a] *The Institute of Hydrogeology and Environmental Geology, CAGS, Shijiazhuang* 050061, *China*
[b] *School of Water Resources and Environment, China University of Geosciences, Beijing* 100083, *China*

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A B S T R A C T

Geothermal energy is a precious resource, which is widely distributed, varied, and abundant. China has entered a period of rapid development of geothermal energy since 2010. As shallow geothermal energy promoting, the depth of hydrothermal geothermal exploration is increasing. The quality of Hot Dry Rock (HDR) and related exploratory technologies are better developed and utilized. On the basis of geothermal development, this paper reviews the geothermal progress during the "12th Five-Year Plan", and summarizes the achievements of hydrothermal geothermal and hot dry rocks from geothermal survey and evaluation aspects. Finally, the authors predict the development trend of the future geothermal research to benefit geothermal and hot dry rock research.

1. Introduction

Geothermal energy is a kind of energy generated from nuclear fission in the Earth’s interior. According to the global average terrestrial heat flow value, it ’s estimated that the dissipated heat, which transmitted from the Earth’s interior to the surface every day, is equivalent to 2.5 times of the average daily energy used by human beings nowadays (Wang JY et al., 1990). Therefore, the Earth is a huge heat reservoir. The geothermal energy is a natural heat energy extracted from the Earth’s crust. The energy comes from the lava in the Earth’s interior, and exists in the form of heat. It belongs to a clean and renewable energy, and has a broad prospect for development and utilization. Geothermal resources include geothermal energy, geothermal fluids and their useful components that can be economically utilized by humans. They are valuable and comprehensive mineral resources that can be used for power generation, heating, planting, and breeding etc. They can be divided into three types of energy resources, shallow geothermal energy resources, hydrothermal type geothermal resources and hot-dry-rock (HDR) type geothermal resources. During the "12th Five-Year Plan" period, the survey and evaluation of shallow geothermal energy in towns and cities have been completed. As for the hydrothermal geothermal resources, exploration and evaluation which are focused on typical geothermal resources also have been completed. The resource potential assessment tests have initially achieved excited results. This paper emphasizes on the discussion of hydrothermal type geothermal resources and HDR type geothermal resources.

The distribution of the geothermal resources is not balanced in the world. The obvious geothermal anomalies are mainly distributed in plate growth or cracking, ocean expansion ridges and plate collisions within decline sites. Countries with rich geothermal resources in the world include the United States, Philippines, Mexico, and Iceland. The global geothermal resources amount to about 4.9×10^{14} t of standard coal, among which China accounts for about one-sixth (Fig. 1). China's geothermal resources are characterized by wide distribution, variety of types, and abundance of resources.

After more than 40 years development, global heat flow data has accumulated to 58000. In recent years, the geothermal industry has developed obviously in China. Both the investment in scientific research on geothermal geological surveying and the enthusiasm of the market indicate that the development of geothermal energy in China enters an boom period. With the "Three deep and One soil" strategy proposed by the Ministry of Land and Resources, the expansion to the deep resource space, the development of deep geothermal resources and the development of deep geothermal detection and development technologies are important directions for

* Corresponding author: *E-mail address:*mf-1203@163.com (Feng Ma) .

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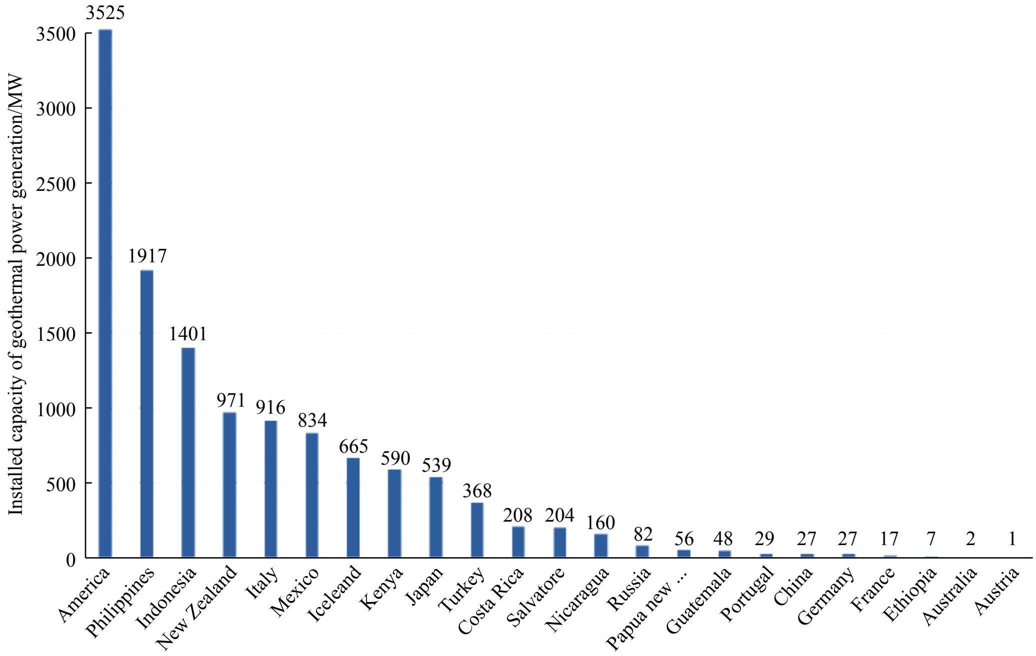

Fig. 1. Histogram of world geothermal power generation capacity in 2014.

future national geothermal support. Whether it is from the detection accuracy and depth of hydrothermal and geothermal resources, or the high efficient development technology of hot-dry-rock, there will be a qualitative leap. The detection and development of geothermal resources is an integrated technology. The detection of geothermal resources usually requires the comprehensive use of geophysics, geochemistry, drilling and other means. Geothermal development also involves reservoir construction, downhole heat exchange, reinjection and other technologies, while the use of geothermal resources also includes materials technology, power generation technology, heat transfer technology and other aspects (Fig. 2, 3).

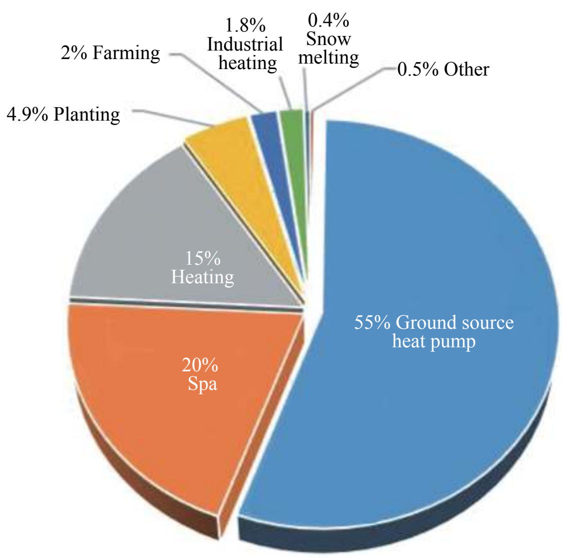

Fig. 2. Chart of world geothermal direct utilization.

2. Historical reviews

China is the earliest country in the world to use geothermal energy. According to historical records, as early as 2800 years ago, the King of the Zhou Dynasty used hot spring baths for recuperation at Huaqing Hot Springs in Mount Li. The earliest geothermal data in China was the "Summary of China Hot Springs" written by Zhang Hongzhao in 1956, which recorded 927 hot springs. The history of geothermal development in China can be summarized into the following three stages.

2.1. Initial stage

Geothermal research in China was systematically began in the 1970s. On October 15th, 1970, Li Si-guang visited the geothermal development and utilization facility in Tianjin. He

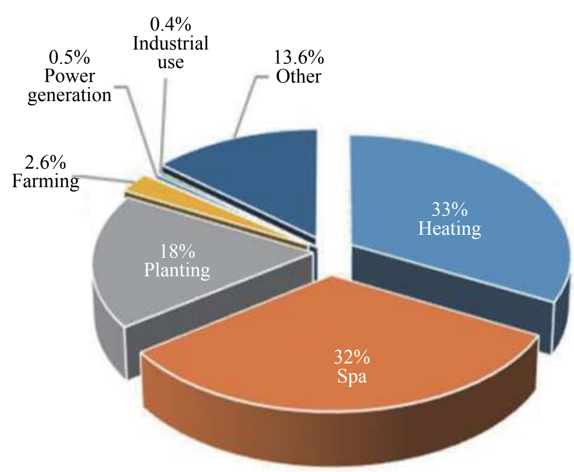

Fig. 3. Utilization methods of geothermal resources of hydrothermal type in China.

pointed out: "The Earth is a large heat reservoir, which is a new source of natural energy for humans, just as humans discovered coal and oil can be burned."(Wang M et al., 2010). The Tianjin geothermal campaign kicked off from that moment. China has gradually entered a booming development stage of geothermal energy. From 1970s to 1980s, China completed a general survey of geothermal resource in more than 20 provinces and regions, and identified the distribution and characteristics of geothermal resources in China. In addition, geothermal exploration are applied at some important geothermal fields, mainly in Tianjin, Niutuo, Zhangzhou, Yangyi, and so on.

2.2. Development and utilization stage

Since the 1990s, geothermal development entered the marketization stage, causing disorderly development in some areas, which has affected the sustainable use of geothermal resources to some extent. During this period, a lot of achievements have been made in several aspects, including geothermal fundamental research, geothermics in mines, oil and gas basins. The Chinese Academy of Sciences has published some terrestrial heat flow data (Wang JY et al., 1988, 1990; Hu SB et al., 2001), compiled and revised the national heat flow map; the former National Commission of Mineral Reserves established a database of some hot springs and water wells, and geothermal fields in the country. Thermal water and hot brine resources has been successively discovered in the oil and gas bearing basins. Geothermal resources are extensively studied in the oilfields of Beijing-Tianjin-Hebei etc., and techniques and methods are formed to restore the thermal history of a complicated multi-stage evolution of sedimentary basins in China (Qiu NS et al., 2002). Some geothermal research results have been applied to oil and gas exploration practices; mining geothermal studies have gradually been increased, and new understandings of deep ground temperature prediction and causes of heat damage have been achieved. Since the National Land Resources Survey was launched in 1999, the Chinese Geological Survey organized and implemented geothermal resources exploration and evaluation work in Yinchuan plain of Ningxia, urban areas of Beijing, Guanzhong basin in Shaanxi and Lubei region, etc., which made important contributions to the development and utilization of regional geothermal resources and local economy.

2.3. All-round development stage

The systematic evaluation of geothermal resources in China has entered a rapid period of development since 2010. It was also 'a second wind' for the development and utilization of geothermal energy in China. In terms of shallow geothermal energy, China completed the investigation and evaluation of cities at prefectural level and above. Due to the hydrothermal type of geothermal exploration, the country basically determined the present situation of national geothermal resources development and utilization (Hou ZQ et al., 2018). Initial results have been achieved in key geothermal fields from high temperature in the Southwest (western Sichuan, southern Tibet) to low temperature in the East (Pearl River Delta). In 2013, it is launched a survey, evaluation, exploration and demonstration work of HDR resource. The Ministry of science and technology has also set up two "863" high-tech research programs, specifically, "The key technology research on the development and comprehensive utilization of hot-dry-rock (HDR) thermal energy" and "The key technology research and demonstration of medium and low temperature geothermal power generation". The exploration and evaluation of HDR officially started. From the regional perspective, favorable target areas for HDR exploration and development in China were delineated, and four types of HDR resource genetic models were proposed. Certain achievements have been made in the detection of HDR at the southeastern coast, northeast margin of the Tibetan Plateau, Wudalianchi and other places.

In terms of geothermal development and utilization technologies, major breakthroughs have been made on geothermal reinjection, geothermal reservoir chemical stimulation, downhole heat exchange and geothermal comprehensive utilization technologies, which is laid the foundation for the future efficient use of geothermal energy in China (Zhu JL et al., 2015). This paper is focused on geothermal research progresses in China since the "12th Five-Year Plan".

3. Geothermal foundational measurement

As the fundamental work of geothermal research, measurements of terrestrial heat flow and thermophysical properties were greatly accumulated in this stage, especially in the acquisition of the deep rock mass thermophysical property parameters and geothermal gradient, which greatly improves the accuracy of heat flow measurement on the surface. As geothermal work being carried out in recent years, measurements of terrestrial heat flow and thermal properties have accumulated a lot at this stage, especially the quantity and quality of deep thermal parameters that has been greatly expanded the operation of temperature logging in large scale and the acquisition of thermal properties of deep rock masses.

3.1. Terrestrial heat flow

Systematic geothermal measurements and data analysis began in the 1950s. At present, there are more than 58000 terrestrial heat flow data sets (35523 of land and 23013 of sea) in the world. China began geothermal surveys in the 1970s and released geothermal flow data four times. By June 2016, the quantity of heat flow data in China had reached 1230, which is still lower than that of internationally advanced level (The actual measured heat flow data in the United States is nearly 6000). During the "12th Five-Year Plan" period, another 368 terrestrial flow data are added. The new heat flow data were mainly concentrated in some petroliferous basins. In addition, except the heat flow data blank areas in Ali of

Tibet, Guizhou, Guangxi, and Jilin provinces were filled up. The current terrestrial heat flow data covers the major tectonic units in the land, but there are still geographically variable distribution in characteristics. The terrestrial heat flow in China is high in east and south, and low in west and north (Fig. 4).

3.2. Thermal conductivity of the rocks

The research on the thermal conductivity of the rocks is mainly with indoor testing analysis to the combination of *in-situ* test and indoor test. The thermal conductivity data is more representative, and the terrestrial heat flow obtained data is more accurate. The study of thermal conductivity of rocks in the basin is relatively complete. The thermal conductivity of the sedimentary basin in China is controlled by the sedimentary environment and diagenesis, and generally high east to low west. The thermal conductivity of Songliao Basin in the east is relatively high, and the average thermal conductivity of sandstone and mudstone is 2.0–2.75 w/(m·K). The average thermal conductivity is 2.68 w/(m·K) based on 123 samples from the Songke-2 well around 3230–4536 m, and the horizontal thermal conductivity is higher than the vertical thermal conductivity, $K_{//}/K_{\perp}$=1.05. The higher thermal conductivity and weak anisotropy in the Songliao Basin indicates the Cretaceous rock mass in the basin undergoes a relatively high diagenesis. The rock porosity is small and the structure is dense. The thermal conductivity is high. On the other hand, the Songliao Basin is affected by sedimentary compaction, and the contribution of orientation arranged by clay minerals becomes smaller (Demongodin L et al., 1993; Midttomme K et al., 1998). The northwest basin in China is a large petroliferous and superimposed basin with a relatively low thermal conductivity. The average thermal conductivity of the Tarim Basin is 2.318 w/(m·K), and the average thermal conductivity of the Qaidam Basin is 1.914 w/(m·K). The average thermal conductivity of the Junggar Basin is 2.048 w/(m·K). The thermal conductivity increases with depth (Qiu NS et al., 2015). As the rock formations in the Sichuan Basin have generally been deep-burial, compacted, uplifted and eroded, the thermal conductivity is not changed greatly with depth. The thermal conductivity of rocks is mainly determined by their lithology, and the overall thermal conductivity is between 1.69 – 5.55 w/(m·K). The average value for mudstone is at least 2.50 w/(m·K), and the maximum value for anhydrite is 3.81 w/(m·K). (Xu M et al., 2011).

Relatively, the bedrock in the uplifted mountain area is exposed, then the rock thermal conductivity will be high, and the heat conduction effect is obvious. The thermal conductivity in the southeastern coast is relatively high with 3.41±1.22 w/(m·K) and 3.59±1.19 w/(m·K) for sandstone and mudstones respectively. The average thermal conductivity of the granites is 2.83 w/(m·K) (Wang AD et al., 2015). The lack of low thermal conductivity caprock is an important reason for the failure of heat energy aggregation in the southeastern coastal areas.

3.3. Radioactive heat generation of rocks

The radioactive heat generation of rocks is mainly caused by the decay of the radioactive elements U, Th and K. In the recent years, research mainly focused on the determination of regional crustal thermal structure through the radioactive heat generation of rocks. Especially in the assessment of HDR target areas of radioactive heat generation granite type in the southeastern coastal areas of China, the radioactive heat generation is an important index for priority selection of HDR target areas.

The granite exposed during the Mesozoic-Cenozoic era in China generally has a high rate of radioactive heat generation. The average thermal conductivity of Late Mesozoic granites in the Zhangzhou area was 3.7 μw/m^3, and the heat generation rate of rock mass in Fogang of Guangdong reached 6.77 μw/m^3. The average heat generation of Fogang rock mass in the Nanling area reached 5.18 μw/m^3. (Lin LF et al., 2017). All of them are above the global average level. Radioactive heat generation of rock mass generally has the characteristics that the younger the date, the greater the radioactive heat generation. The intrusive rocks in the Tashkurghan region of Xinjiang are Himalayan granites with an intrusion time of 11–13 Ma. The radioactive heat generation is an additional heat source in the region (Chang J et al., 2016). As the highest and youngest plateau in the world, the Qinghai-Tibet Plateau has a thickness of 20 km for radioactive concentration layer, a heat generation rate of about 3.2–5.4 μw/m^3, and a heat flow ratio for crust mantle source of q_c/q_m=2.34. It is the highest continental area in China, which belongs to the typical hot shell and cold mantle type thermal structure (Guan YW et al., 2012). Since the radioactivity of granite is 1 to 2 orders of magnitude higher than that of basalt and other basic-ultrabasic rocks, the radioactive generation of rocks is a slow process, whose heat generated during the radioactivity process is a major factor to prolong the cooling and crystallization of the granite.

4. Geothermal research and evaluation

Geothermal resources exploration in China is transfered from evaluation to assessment of sustainable development potential. More attention has been paid to the formation mechanism of geothermal water and irrigation technology; the detection and evaluation of HDR are proceeded from regional site selection to exploration. HDR trial exploration are demonstrated in places like Gonghe and Haikou. How to pick up the heat from the earth economically and efficiently is the most concerned issue. The casing heat-taking technology and deep-well heat-exchange technology have developed greatly in recent years (Yuan F et al., 2014)

There is a new understanding of potential resource and distribution of geothermal resources in China. The survey results show that there are currently 2334 exposed hot springs and 5818 geothermal wells in China (Fig 5). The capacity of hydrothermal resources is equivalent to 1.25×10^{12} t of standard coal, and the amount that can be mined is equivalent

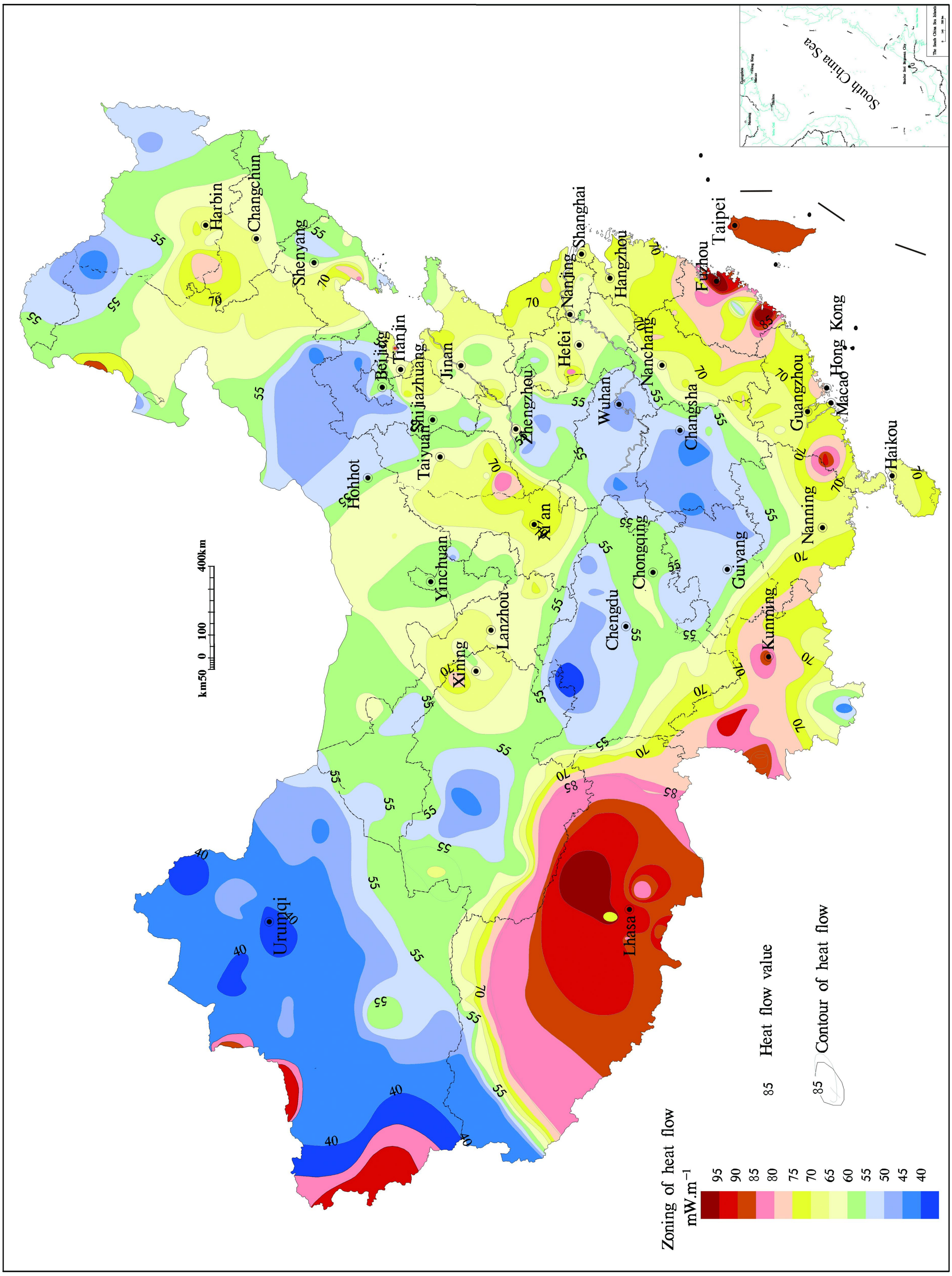

Fig. 4. Distribution of heat flow in the continental area of China.

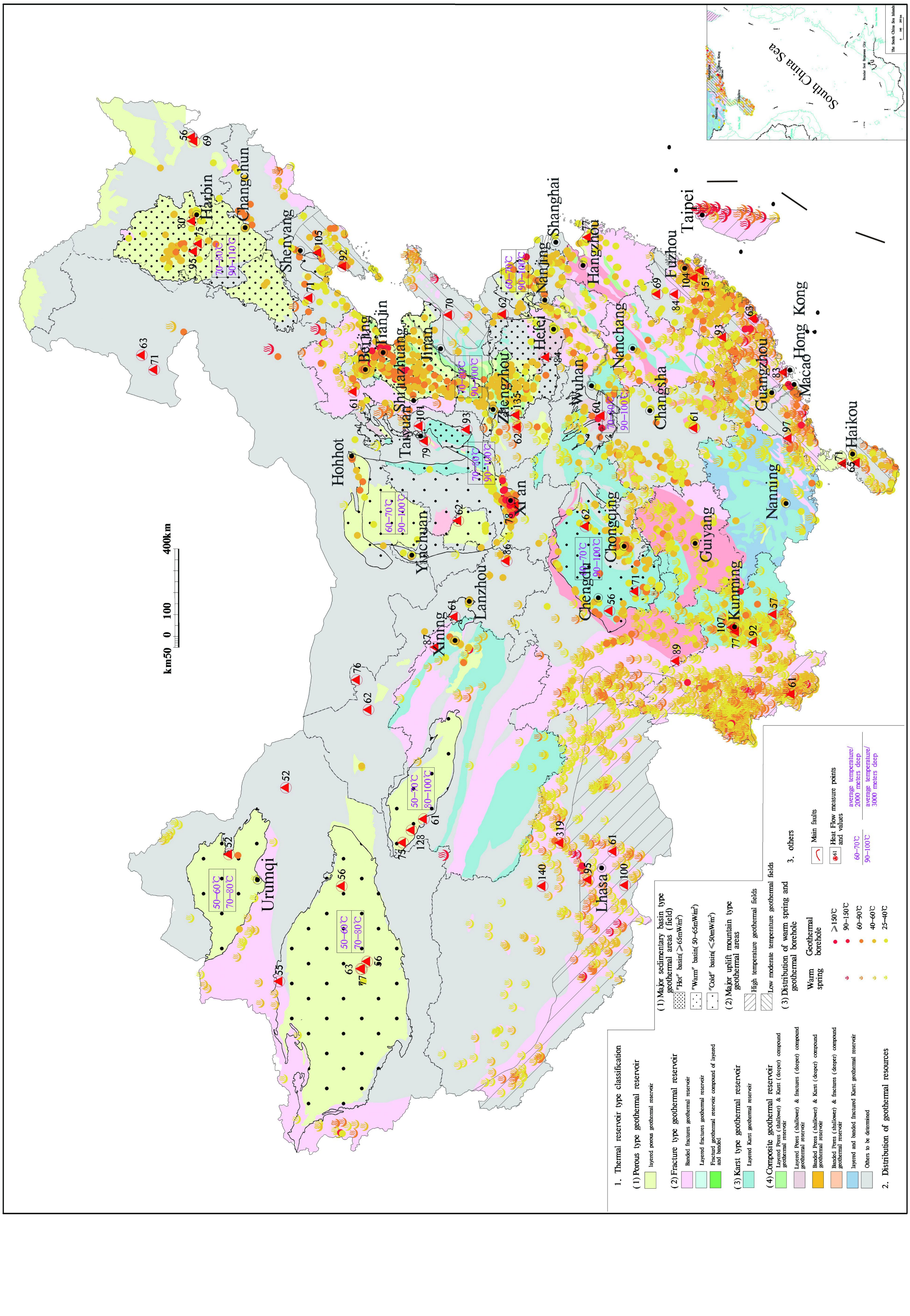

Fig. 5. Distribution of geothermal resources in China.

to 1.865×10^9 t of standard coal every year. High-temperature geothermal resources are mainly distributed in the intensive hydrothermal activity belts in southern Tibet, western Sichuan and western Yunnan, while low and medium-temperature geothermal resources are mainly distributed in the North China Plain, Hehuai Plain, Songliao Basin and the other 15 medium to large-sized sedimentary basins and mountainous fault zones (Wang GL et al., 2017). According to the preliminary estimates, the prospective resources for HDR in the continental areas of China are equivalent to 8.56×10^{14} t of standard coal (Lin WJ et al., 2012,2016).

The sedimentary basin-type geothermal resources in China are mainly distributed in the Songliao Basin, lower Liaohe Basin, North China Plain, Hehuai Basin, Subei Basin, Jianghan Plain, Fenwei Basin, Ordos Basin, Sichuan Basin, Xining Basin, Qaidam Basin, Junggar Basin, Tarim Basin, and so on. There are differences between geothermal resources in the eastern area and the western area. The upper arched crust of asthenosphere in the eastern area becomes thin with thick sedimentary deposits, where it has developed a multilayer superimposed heat storage system. The main geothermal reservoirs are the Mesozoic-Cenozoic sandstone porous type and the Paleozoic-Middle/Upper Proterozoic carbonates karst-fractured type. The basin has a high heat flow value of 60–83 mW·m^{-2} with the reservoir temperature of 35–120°C. In the central basin, the overall crust is thicker, and the terrestrial heat flow value is low, which is 40 – 60 mW·m^{-2}. The main geothermal reservoirs are the Mesozoic porous sandstone reservoir and the Paleozoic carbonate karst-fractured type reservoir. The western crust is thicker but the basin heat flow value is low (34–51 mW·m^{-2}). The main thermal reservoirs are the Tertiary porous sandy gravel and the Paleozoic carbonate karst fractured reservoir. Generally, the degree of mineralization is higher. Most are brine. In the northern basin, the crust is relatively thick, the basin heat flow is medium to high, which is 44–90 mW·m^{-2}. The average value is 62 mW·m^{-2}, which is at nearly the same level as the average (Zhao Z et al., 2015).

The uplifted mountain-type geothermal resources are mainly distributed in four intensive hydrothermal activity belts, including: (1) southern Tibet, western Sichuan and western Yunnan hydrothermal activity intensive belt; (2) Taiwan hydrothermal activity intensive belt; (3) the southeast coastal area hydrothermal activity intensive belt; (4) Shandong Peninsula hydrothermal activity intensive belt. The first two belong to the middle-high temperature geothermal activity intensive belt, and the latter two belong to the middle-low temperature geothermal activity intensive belt.

During the "12th Five-Year Plan" period, through the systematic analysis of the geophysics, geochemistry, drilling, testing, and other technical means, the thermal formation mechanism of the geothermal field throughout the country has been finely detected. For example, in the exploration of high radioactive heat generation HDR in the southeast coast, it was found that the HDR in the southeast coast can be divided into three types: overburden type, deep fracture type and shallow fracture type. The former two should be treated as the favorable target area for HDR exploration under current technical conditions. In the study of the heat accumulation mechanism of the North China Plain, the analysis of several regional deep-hole temperature measurement data shows that the geothermal field has a "double heat transfer mode" of vertical heat conduction in the deep mantle and heat accumulation in the shallow water circulation. Meanwhile, convection between layers in carbonate rock geothermal reservoirs occurs. The current status of geothermal resources in China is as follows:

4.1. Heat source mechanisms in Southwest China

The southwest region has the best geothermal conditions in China. The temperature has been reached 195°C at the depth of 230 m in the Gudui high temperature geothermal area in Cuomei of Tibet which is the highest geothermal temperature at the same depth in China. The potentials for generating electricity is up to 110 MW. A distributed geothermal electricity container is built in Yunnan Ruili geothermal field. The focal point of the geothermal exploration in the west is to coordinate high temperature and geothermal development with other clean energy sources. The equipments in high-temperature geothermal power generation are complemented with solar and wind energies, as well as the rational and efficient development and utilization of geothermal resources.

Yunnan is located in eastern branch of global Mediterranean-Himalayan geothermal belt with a regional heat flow value of 80–100 mW/m^2 and a maximum up to 364 mW/m^2 (Duo J et al., 2003; Zhou ZY et al., 2015). It is a crustal thermal structure of "hot crust and cold mantle". From the perspective of heat source mechanisms, the latent heat of magmatic intrusion, the decay heat of radioactive elements, the frictional shear heat of faults, the thermal refraction of sedimentary cover, and deep thermal effect etc., are considered as heat sources of high heat flow in southwest high-temperature regions. The radioactive isotopes in deep rocks have greater abundance and higher radioactive thermal efficiency in the earth's crust, which is significantly important to the formation of geothermal heat. Therefore, it is considered to be the steady state heat source in the region (Li BZ et al., 2011).

In the study of heat source mechanisms, the isotopes of overflow gases have shown that the heat source of Yangbajing and Yangyi is from partial crustal melting, and there is a intrusive magma derived from mantle in the shallow crust at the Tengchong-Rehai region (Guo QH, 2012). Recently, some scholars have introduced the lower continental crust ductile flow to explain the characteristics of thermal belt spreading along the north-south rift in Tibet. However, whether the lower crustal ductile flow can be widely developed or become an important source of heat and thermal control structure has not yet been finalized, which requires further research (Li LG et al., 2017). From the perspective of hydrothermal activity, the geochemical analysis results of CL and stable isotopes during the magma degassing process show that atmospheric precipitation is still the main runoff source for geothermal systems, and the chemical composition of groundwater is controlled by water-rock interaction under high temperature conditions. Meanwhile, there is also effect of mixing with shallow surface water. Generally speaking, the southwestern region has structural background and geothermal conditions with intensive hydrothermal activity. Most of the hot springs are exposed at intersections between branch faults and major faults, on the hanging wall of compression fractures, or in fractured deep gullies (Zhou ZY et al., 2015). The southwest high-temperature geothermal anomalous areas are closely related to fault strikes, granite intrusion mechanism and volcanic magmatic activity.

4.2. The high-temperature geothermal detection in the Northwest Tashkurghan region

The overall thermal resources in the northwestern China is relatively low. Research on geothermal resources in northwestern China is mainly concentrated on the oil and gas basins of the Qaidam Basin, Tarim Basin and Junggar Basin, and the Tashkurgan region in Xinjiang. The study of the northwest basins mainly combines the basin's thermal evolution with thermal history reconstruction. The average terrestrial heat flow in the Tarim Basin is 44 $mW \cdot m^{-2}$. The average terrestrial heat flow in the Junggar Basin is 42.3 $mW \cdot m^{-2}$, and the average terrestrial heat flow in the Qaidam Basin is 52.6 $mW \cdot m^{-2}$, which is significantly higher than the first two basins. The three basins belong to the thermal structure of "cold crust and cold mantle" (Rao S et al., 2013). Through the study of heat flow history, a certain breakthrough has been made in the basic theory of source rock generation and regional thermal structure evolution.

According to geochemical analysis, Cainozoic intrusive rocks from both crust and mantle in Tashqurghan region are mixed with magma during the late period of collisional orogeny. In addition, radon is detected in the soil, which indicates higher radon is seen in talus accumulation of granite as well as the mixture of syenite and granite rather than metamorphic rocks that means geothermal anomaly in tectonic mobile belts. The Himalayan granite and syenite were developed at the vast mountain areas in the northwestern side of the region. They were excreted in the shape of batholiths and rock columns with an intrusive age between 11 Ma–13 Ma. The heat source mechanism is mainly influenced by the Cenozoic North-South fault activity and the cap rock heat preservation effect for the low thermal conductivity of Neogene mudstone and sandstone. Secondly, the radioactive heat generation of the rock mass also makes a certain contribution as an additional heat source. At present, four boreholes with higher than 150°C have been detected, of which the maximum temperature is 162°C. The HDR resources in the deep have a value for development, which will be the China's key target areas for the exploration and research of HDR in the future.

4.3. Preliminary detection of HDR in Wudalianchi and Songliao Basin in Northeast China

The northeastern region is represented by the Changbai Mountain of medium-high temperature convective geothermal resources, the Songliao Basin and Erlian Basin of medium-low temperature conductive geothermal resources, rift basins such as Yitong-Yishu of middle-low convective geothermal resources, and uplift belts in the northern margin of China of fractured fissure low temperature geothermal resources. During the "12th Five-Year Plan" period, HDR resources detection was conducted at the Weishan area in northern Wudalianchi. The natural ambient seismic noise tomography interpretation is showing a developed volcanic magma pocket at 6.5 km–8 km depth. Magnetotelluric soundings indicated that the burial depth of high-temperature rock masses is 3 km–5 km, and the temperature at drilling depth 2500 m is only 43°C. The reason is that the basic basalt is rapidly cooled after it is poured out. The magma cooling time is generally less than one million years, so the deep thermal anomaly is likely to be negative. The existence of a cooling magma pocket at depth is still arguable (Zhang SQ et al., 2017). Remote sensing images and thermal infrared data were used to analyze geothermal anomalies in the Changbai Mountain area. By selecting the four factors of surface temperature field, the distribution characteristics of hot springs and geothermal wells, Bouguer gravity field and magnetic field interpreted by remote sensing, the discriminant function was established for comprehensive analysis. The effective identification of the geothermal anomalies zone was completed (Yan BZ et al., 2017). The preliminary discovery of the HDR detection in the Songliao Basin is found that the deep basin is dominated by heat conduction and the hydrothermal activity is poor with an average geothermal gradient of 38–43$°C \cdot km^{-1}$. At the same time, the existence of high concentration radioactive layers was found at two depths of 1700 m and 3200 m, which is a favorable target area for the exploration of sedimentary basin HDR in China.

4.4. First HDR scientific drilling in the southeast coastal areas

The southeast coastal area is the main granite distributed area in China, and the area is regionally dominated by medium-low temperature geothermal resources. Due to the effects of radioactive heat generation, there is possibly occurrence of HDR in the deep. In 2014, the exploration of deep geothermal resources in the southeastern coastal areas was begun, and a systematic summary of geothermal geology indexes for selecting HDR was completed (Lin WJ et al., 2016). Priority selection of the target area for HDR was implemented in southeast coastal areas of China, including Fujian, Guangdong, Hainan and Hunan. Nine favorable target areas for exploration and development of HDR were initially delineated, such as: Fujian: Zhangzhou-Xiamen and Fuzhou; Guangdong: Huizhou, Leizhou Peninsula, Yangjiang and Meizhou; Hainan: Lingshui and Qixianling; Hunan: Ruheng.

The temperature field model of the southeast coast in China has been systematically established. It was predicted that at 4 km depth in the Zhangzhou region, the maximum temperature that can be reached is 160°C. Based on the comprehensive discussion of the distribution of acidic rock mass, distribution of terrestrial heat flow, radioactive heat generation rate of rocks, and deep temperature field in the southeast coast of China, several key regions, such as Xinzhou in Yangjiang of Guangdong Province, Huangshadong in Huizhou of Guangdong Province, Leiqiong fault Basin and Lingshui of Hainan Province, were selected as key potential target areas for the HDR development in the southeast coastal areas of China. In 2014, the first HDR drilling in China was constructed in Zhangzhou, Fujian Province. The temperature at a depth of 4002 m was 109°C, and the temperature has not reached expectations, indicating that the fault zone in the southeastern coastal area plays an important role in controlling heat and conducting water. The depth effect may exceed 4000 m.

4.5. Increasing depth of carbonate rock geothermal reservoirs in North China with the large-scaled and sustainable geothermal utilization

The average value of terrestrial heat flow in the entire North China region is 50.6 $mW \cdot m^{-2}$, 62 $mW \cdot m^{-2}$ in the plain area, and lower in the mountainous area, where the average is 42.5 $mW \cdot m^{-2}$. The terrestrial heat flow value in the plain area is close to the global average (62 $mW \cdot m^{-2}$). As a result, geothermal fields or geothermal anomalies are widely distributed, which is one of the unique advantages to develop geothermal energy in the region. During the "12th Five-Year Plan" period, the detection depth of carbonate geothermal reservoirs is gradually increasing in the North China, from the first sandstone geothermal reservoirs at Minghua town, Guantao, Dongying group, and the upper carbonate geothermal reservoir at the Wumishan group, gradually to the structure detection of the carbonate rock geothermal reservoir at the entire Wuweishan group and the detection of a geothermal reservoir in the Gaoyu Zhuang group of the Changcheng system (Chang J et al., 2016).

The North China area is the largest area of geothermal development and utilization in China. By the end of 2015, the heating and cooling area of geothermal resource buildings in the Beijing-Tianjin-Hebei region was 1.56×10^8 m^2, taking up to 5% of the total construction area. The annual exploitation of geothermal water was 1.59×10^8 m^3, which is equivalent to about 1.15×10^6 t of standard coal. The building heating area is 7.1×10^7 m^2; the annual development and utilization of shallow geothermal energy is equivalent to 2.55×10^6 t of standard coal, achieving the heating and cooling area of 8.5×10^7 m^2 for buildings.

5. Research on hot dry rock (HDR)

In the early 1970s, the United States started the HDR drilling program in Fenton hill. So far, the United States, Japan, France, Germany, Australia, Switzerland and other countries have conducted HDR detection and demonstration. United States, Japan, France, Germany and Australia have all achieved enhanced geothermal power generation. However, no commercialization has been achieved at present. Currently, the largest project for the development of HDR in the world is the FORGE (Frontier Observatory for Research in Geothermal Energy) implemented by the United States Department of Energy. FORGE is divided into three phases: the first phase, by the end of June 2016, consisted of the United States Department of Energy (DOE) successively building FORGE in five regions, including Milford in Utah, Newberry Volcano in Oregon, Fallon in Nevada, Snake River Plain, Coso in Eastern California, and actively promoting the fundamental research, technology development and EGS utilization of geothermal resources, especially HDR; the second phase, from the late summer of 2016 to the beginning of 2018, focused on the characterization of geothermal reservoirs and initially carrying out microseismic monitoring as well as the mitigation of induced earthquake activity, improving the geological model and optimizing favorable target areas; the third phase, the full operation of FORGE from 2018 to 2022 is planned to start reservoir stimulation and testing, on-site monitoring, optimization of favorable zoning assessment results, improvement of resource potential and assessment of economic impacts, etc.

China began a nationwide HDR potential evaluation and demonstration target area research work in 2013 with the China terrestrial heat flow map, the map of Curie-point surface, the map of neotectonic movement, and the distribution map of acidic rock mass. Based on the profile analysis, the Chinese EGS target area is divided into four types of plate tectonic activity, modern volcano, sedimentary basins, and acidic rock mass (Gan HN et al., 2015). The characteristics of heat generation for various types of HDR target areas was analyzed (Ma F et al., 2015). Nine target areas were selected to analyze the siting index of the EGS demonstration project by establishing the index system. It is believed that Yangbajing, Yangjiang and Zhangzhou are favorable sites for preparatory work of HDR in China.

In 2014, HDR detection was carried out in Zhangzhou of Fujian Province, Wudalianchi and Qinghai Gonghe basins. On May 21st, 2015, the first HDR scientific drilling well in China was started in Qingquan forest farm, Dongsi town, Longhai city, Fujian Province, which was organized and implemented by the Chinese Geological Survey. The drilling depth will ultimately reached 4000 m. In April 2014, the Qinhai Institute of Hydrogeology and Engineering finally drilled 153°C HDR at a depth of 2230 m from borehole DR3 at Gonghe Basin of Hainan Tibetan Autonomous Prefecture in Qinghai Province after test drilling for 2 years. In June of the same year, HDR of above 168 °C was successfully drilled at a depth of 2735 m. The rock mass is widely distributed at the bottom of the Gonghe Basin, where the area of HDR mass controlled by drilling alone has reached 150 km^2. On October 6^{th}, 2014, Well ZKD23 in Gonghe county of Qinghai had achieved a drilling depth of 2886 m and a bottom temperature of 181 °C.

In August 2017, a HDR mass of 236 °C was measured at 3705 m in the GR1 well of Gonghe Basin, which meets the requirements for high quality HDR with a huge potential (Zheng KY et al., 2017).

6. Outlook

With the detection of geothermal resources from shallow to deep, the use of geothermal energy is extensively promoted, and production of geothermal energy nationally is into a new phase. Going beyond that, the technology of deep geothermal detection, development and utilization will be the key part of future geothermal project in China, focusing on how to find heat, how to exchange heat and how to use heat. It involves geothermal geophysics, geochemistry, high-temperature drilling downhole for heat exchange, reinjection technology and reservoir construction, and so on.

6.1. High-temperature and high-precision geophysical probing techniques

The exploration of geothermal resources is the basis for the development and utilization of geothermal resources. It is also an important application of geophysical methods. Geophysical exploration in the geothermal field is mainly an indirect method of exploration. By observing the geophysical response at the surface or in the borehole, the petrophysical parameters are inverted. The relationship with temperature is studied to determine the temperature and distribution range of the geothermal reservoir. Most of the geophysical methods can be used for geothermal exploration. The comprehensive geophysical prospecting method was used to detect thermal anomalies in the Xiaoyangkou area of Nantong city, which forms an effective method to determine geothermal well locations using geophysical response characteristics (Zuo LQ et al., 2016). In the exploration of the Qinghai Gonghe Guide Basin, it is believed that basin-based depression reflected by gravity may be affected by the low density lateral inhomogeneity of the granite, while aeromagnetic analysis can avoid this error (Xue JQ et al., 2013).

The accuracy of thermal anomaly area interpretation by geophysical methods needs to be improved.To obtain information related to deep geothermal and HDR through geophysics has the advantage of cheap and efficient. Integrated planar geophysics with borehole logging, studying deep geothermal resources based on the analysis of thermal properties of geophysical fields will be the future direction of geophysical development.

Overall, although China has achieved a lot in the field of geophysical exploration of geothermal resources in recent years, it still falls behind the international advanced level in terms of method and technology and application level. The future geophysical exploration trends are as follows: (1) The target of geothermal reservoirs for exploration changes from shallow to deep, and exploration becomes more difficult. It is necessary to further improve the theoretical foundation of geophysical exploration of geothermal resources and to make innovation in geophysical exploration methods and technologies so as to adapt new needs. (2) The geophysical exploration methods of geothermal resources gradually develop from the traditional two-dimensional profile measurement to three-dimensional array measurement. The accuracy of detection has also been greatly improved. (3) Data denoising techniques, deep geophysical anomaly information extraction techniques, constraint and joint inversion techniques for different types of geophysical data, and comprehensive interpretation technique, etc. need further development. (4) The application of geophysical methods is extended from the traditional exploration of geothermal resources in the early stage to the real-time monitoring of the development and application of geothermal resources in the later stage (Zeng ZF et al., 2012).

6.2. The national geochemical data-sharing platform urgently needs to be established

The application of geochemical technology in geothermal energy exploration and development has a long history. Geothermal system information played a particularly important role and received more and more extensive attention due to its low cost. Geochemical technologies involve many methods such as water chemistry, isotope geochemistry, gas geochemistry, radioactivity, and trace element geochemistry. Many years practices have proved that geochemical methods are very effective in delineating geothermal anomalies, estimating the deep geothermal reservoir temperature and depth of thermal water circulation, inferring the origin of thermal water and its components, discriminating and eliminating the influence of the mixing effect, clarifying water-rock-gas interaction processes and mechanisms in deep geothermal systems, determining the geothermal water runoff direction, velocity and age, predicting scaling and corrosion (Sun et al., 2014). For the detection of HDR, the application of geochemical technology still has some limitations. The main reason is that there is almost no water and rock interaction in deep thermal reservoir, so it is difficult to obtain deep information by water and gas samples. In the future, HDR geochemistry would focuses on rock geochemistry and geochemical parameters acquired through logging.

The current geothermal geochemistry challenges are as follows: (1) The geochemical comprehensive prediction and evaluation system for hydrothermal type geothermal energy needs to be constructed; (2) High-quality geothermal geochemical data needs to be accumulated, and a data-sharing visualization platform needs to be created; (3) Geochemical exploration techniques for HDR type geothermal energy should be urgently developed; (4) The scale inhibition in development of geothermal energy, corrosion prevention and reservoir stimulation in geochemical techniques needs to be improved; (5) National geothermal energy geochemical exploration and demonstration bases urgently need to be established.

6.3. The high-temperature drilling technology is the keypoint for deep detection in the future

With the development of deep geothermal and HDR, high-temperature drilling technology in deeper formations will be the most critical technology, which will affect geothermal exploration and development in the future. Deep geothermal resource rock masses are difficult to be drilling, an extremely slow drilling rate, of long duration and high costs. It is urgent to develop key technologies for efficient and safe drilling processes that meet the development of deep geothermal resources (Xu ZQ et al., 2016).

The current high-temperature drilling in China is mainly concentrated in the southwest region, but there is few drilling wells for scientific research. The temperature at 230 m depth in Gudui of Tibet reached 205°C, and the maximum temperature at 2000 m in Ganzi of Sichuan Province was 205°C. Secondly, the temperature at a depth of 4815 m in the main hole of the China Continental Scientific Drilling (CCSD) at the Sulu UHP Metamorphic Belt in Donghai of Jiangsu Province was 133.5°C. The borehole temperature at the depth of 6400 m in the Cretaceous Scientific Drilling in Songliao Basin exceeds 200°C (Xu ZQ et al., 2016). In addition, the main difficulty of high-temperature deep drilling is currently material issue. Furthermore, with the introduction of the enhanced geothermal system, the development of geothermal resource drilling engineering technology trend is toward higher temperature and deeper research fields. Research and development of tools and instruments, borehole working fluid and special well structures with stronger temperature resistance, these shall be urgently needed for the large-scale development of geothermal resources in the future. Geothermal drilling technology will focus on the following aspects: high-power laser well completion technology, ultra-high temperature capacitor, downhole electronics, downhole television, impact hammer drilling technology, directional drilling systems, seismic measurement tools, high-temperature multi-functional optical fiber technology, crack identification technology and new refrigerant heat exchange fluids, etc.

6.4. The downhole heat exchange technology is gradually maturing and in application

In the 1970s, Li Si-guang mentioned that "We are going to think of a way to take heat without water and protect the geological environment in the future" (Wangming, 2010). The downhole heat exchange technology is intended for the sustainable utilization of heat energy in the condition of taking heat without water, which has been attracted much attention in recent years. The closed downhole heat exchange technology refers not directly extracting underground thermal water, but through the heat exchange of refrigerant within the closed system with geothermal fluids or high-temperature rock, transferring the heat from the underground to the surface. Closed downhole heat exchange technology has been widely applied in shallow ground source heat pumps, but its application in the development of medium-depth geothermal energy is still in the preliminary experimental stage. At present, Xi'an, Tianjin, Harbin and other places in China have all tested downhole heat exchangers in deep formations, which are in good operation. The application of this technology can greatly reduce costs and improve the efficiency of resource utilization in the reconstruction of abandoned wells. In addition, gravity heat pipes based on material technology may be the most disruptive new generation of geothermal energy development technology. At present, research on the direction of kilometer super-long or multi-stage heat pipes is carried out in the world, which shall make it possible to further scale and economize the downhole heat exchange technology.

6.5. Sandstone geothermal reinjection and bedrock fissure reinjection technology

For geothermal resources, an alternative green energy, reinjection is the key to ensure its large-scale sustainable development and utilization. According to the difference of geothermal reservoir medium and recharge performance, geothermal resources can be divided into three types: geothermal reservoir of bedrock fissures, geothermal reservoir of karst fissures, and geothermal reservoir of sandstone pores. Geothermal recharge in China mainly belongs to the recharge of karst fissure geothermal reservoirs. A larger pattern has been established for geothermal heating and recharging in North China, which plays a certain role in protecting the sustainable development of geothermal fields. The geothermal resources development and utilization technology forming a balance between heat mining and recharging in the Beijing-Tianjin-Hebei region will be the main goal of geothermal exertions in the future. In the field of sandstone geothermal reinjection, geothermal reinjection guidelines have already been preliminarily established. The bedrock fissure geothermal reinjection is mainly in the three geothermal fields of Yangbajing, Naqu and Langjiu in Tibet, where China has carried out a large number of research and production practices in reinjection, and made some achievements. Except for experiments, there is currently no productive reinjection in China. In the future, the high-temperature geothermal development in western China will be a major research topic (Kang FX, 2015).

6.6. The reservoir construction and monitoring technology

The core technology in the development of HDR is the construction of the reservoir. The ideal and economic EGS system shall stimulate a reservoir volume of 0.1 km^3 and an effective heat exchange area of 10^6 m^2. At present, the stimulation area for many reservoirs of EGS projects in the world has been achieved the goal of far exceeding 0.1 km^3, while there is a certain gap between the effective heat exchange area of a geothermal reservoir and its commercialization (Wang GL, 2015). The key of EGS is to effectively stimulate the geothermal reservoir. Currently, the international EGS reservoir stimulation experience shows that it is almost impossible to produce new fractures in rock mass by water injection into the reservoir. The initial fissures, which are relatively closed in those rock masses and perpendicular to the minimum principal stress, play a decisive role in the later heat exchange of the reservoirs. Therefore, understanding the original geostress conditions of the geothermal reservoir and the spatial distribution pattern of the existing fractures is the primary task of establishing an enhanced geothermal system and is also the direction of key research on reservoir construction in the future (Dou J et al., 2014; Xu TF et al., 2016 ;Yuan F et al., 2014).

7. Conclusions

In 2017, the government work report puts forward the requirement of "We will make our skies blue again". As a clean and renewable energy source, geothermal energy will play an important role in the energy saving and environmental protection, prevention and control of haze, etc. At the same time, the exploration and development of geothermal and HDR in China has entered a critical stage. Despite the great potential of geothermal resources in China, there are still many problems in the development and utilization. China is the country with the largest scale of shallow geothermal energy development and utilization in the world. However, there is still problems of shallow geothermal energy development and coupling the use of urban underground space in development and utilization. There is still a problem of unknown geothermal reservoir mechanisms in hydrothermal type geothermal exploration and development. The technology for sustainable development of geothermal resources under the balanced condition of mining and reinjection needs to be further improved. The exploration of HDR resources just started in China. A single relevant testing of HDR development has not yet been completed. The main work remains in resource evaluation, indoor simulation and theoretical research. Through the formation of a scientific research collaboration and exchange platform, we should be able to tackle the key technical problems in the sustainable development of geothermal resources, especially in the detection and development of HDR resources.

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