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Estimation of Deep Temperature and Geothermal Resource Potential Assessment in the Lower Yangtze Area, East China

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ABSTRACT

Geothermal energy is now becoming an increasingly important new energy and has attracted much attention, owing to its friendly environment and renewability. The Lower Yangtze area (LYA) that locates at east China, is one of the most developed regions in China, with many mega-cities, dense population and huge demand for energy. Geothermal energy is considered as a better solution for energy issue in the LYA in future; however, the resource potential of this area has not yet been assessed well, due to a lack of understanding its accurate geothermal condition. Here we integrate newly retrieved temperature data and rock thermal properties, to estimate the temperatures-at-depth of 1000-4000 meters, and accordingly suggest the potential targets for geothermal energy exploration. Our results show that the present-day geothermal gradient of the LYA vary from 16 ℃/km to 41℃/km, with a mean of 30 ℃/km; the heat flow values for the LYA fall within 48-80 mW/m^2, with a mean of 60 mW/m^2. The estimated temperature-at-depth of 1000 meters ranges from 30 to 54 ℃, and that of 2000 meters is between 50 and 95 ℃; at the depth of 3000 meters, the temperatures vary from 65 to 130 ℃, while for the 4000 meters, the temperatures range from 80 to 170 ℃. Since the temperature presented here are estimated from conduction method, it should keep in mind that such temperatures in the geothermal reservoir could be reduced because of the heat convection process commonly dominant in the geothermal reservoirs. Our results indicates that the LYA is of relatively high geothermal regime and has a great geothermal energy potential. In addition, the spatial pattern of the estimated deep subsurface temperature for the LYA shows strongly lateral variation, featured by high in the north and low in the south, as a result of differential magmatism, faulting and local tectonics. The high temperature anomalies in the northern LYA would be the feasible targets for geothermal energy exploration.

1. INTRODUCTION

Thermal regime of sedimentary basins is closely related to hydrocarbon generation and preservation, and also holds key for geothermal energy potential assessment (Wang et al, 1989; Barker, 1996; Welte et al., 1997; Forster and Merrian, 1999; White et al., 2003; Qiu et al., 2004; Wang et al., 2015). Geothermal energy, as a new type of energies, has attracted worldwide attention. In particular, the emerging demand for geothermal energy resources in recent years have prompted the research of thermal regime to a new phase (Renner, 2006; Huenger and Patrick, 2011; Stober and Bucher, 2013). The Lower Yangtze Area (LYA), here means the middle-lower reach of the Yangtze River, located in eastern China, is one of the regions with well-developed economy, highly concentrated population and complete infrastructure. With the initiative of developing the Yangtze economic belt, proposed by China government, the LYA definitely would call for a big demand on energies. Understanding the regional geothermal characteristics and outlining the deep temperature pattern are the prerequisites for the assessment and development of geothermal energy resources.

Previous studies have been carried out on the geothermal field in south China. Among them, the coastal area in the southeast and southwestern Yunnan are the high geothermal gradient areas of the South China, and the Yangtze area is a middle-low geothermal gradient area. The geothermal gradient in the whole south China is 20-25 ℃/km, averaging 24 ℃/km, which is lower than that in the North China Basin (33-35 ℃/km) and the Songliao Basin (38 ℃/km), and is slightly higher than the Tarim Basin (20℃/km) and Junggar Basin (23 ℃/km) in northwest China (Wang et al., 1986; Yuan et al., 2006). Generally, the heat flow distribution of the south China is characterized by high in the east and southwest, and low in the middle, with obvious zoning; the average value is 64 mW/m^2, slightly higher than that of the mainland of China (61 mW/m^2), approaching the global average heat flow of 65 mW/m^2, in which the plate boundaries and the deep fault zones are with high anomalies of heat flow (Yuan et al., 2006).

Specifically, the geothermal gradient in the Upper Yangtze area (Sichuan Basin) ranges from 18 to 33 ℃/km, with an average of 23 ℃/km, and the heat flow of the Sichuan Basin is between 35 and 69 mW/m^2, averaging 53 mW/m^2. It is a typical craton basin with medium and low heat flow value. The distribution pattern of the heat flow is controlled by the base structure (Xu et al., 2011; Lu et al., 2005). In terms of the Middle Yangtze area, the heat flow in the middle Yangtze area (Jianghan Basin) was stable and mediate (50-55 mW/m^2) before the Indosinian (240 Ma), and then began to increase. The peak heat flow value of the Jianghan Basin was 72 mW/m^2 during the middle Yanshanian period (155 Ma). After the Late Yanshanian, the heat flow in the whole basin declined rapidly (Li et al., 2010). While the lower Yangtze area presents a medium-high geothermal state with the gradient of 18-25 ℃/km, and the heat flow is 48-80 mW/m^2, with a mean of 60 mW/m^2 (Wang et al., 1995, 2013).

On the whole, the previous studies of geothermal field in south China focus more on large scale but poor data coverage, so details of regional geothermal field are not clear. In addition, less attention was paid to the estimation of regional deep temperature in early works, restraining the evaluation of regional geothermal energy resources. In recent years, with the progress of hydrocarbon exploration in this region, a number of new geothermal data have been accumulated. In this paper, on the basis of new geothermal data and measured rock thermal properties, the geothermal field in the Lower Yangtze area has been studied in detail. The temperatures at the depth of 1000 m to 4000 m within the Lower Yangtze area have been estimated in order to provide new clues for the assessment of geothermal energy resources in the region.

2. GEOLOGICAL SETTING

Geographically the South China refers to the area south of the Qinling Mountains and east of the Qinghai-Tibet Plateau, and consist of the Yangtze Block in the northwest and the Cathaysian Block in the southeast, which was assembled along the Jiangshao fault zone during 0.8-1.0 billion years (Li et al., 2012). The lower Yangtze area refers to the lower reaches of the Yangtze River, with the Yellow Sea to the east and northeast, the North China Craton to the west and northwest separated by the Tanlu fault zone, and the Cathaysian Block to the south and southeast, bounded by the Jiangshao fault zone (Fig. 1), and covers an area of about 225,000 km2 (Pan et al., 2011).

Since the Late Paleozoic, the tectonic evolution and sedimentary environment in the Lower Yangtze region have been changed repeatedly. It was firstly in a marginal sea environment during the early Paleozoic, while in the Late Paleozoic it turned into the epicontinental sea environment. During the Mesozoic, it entered the terrestrial environment and intermediate-acid magmatism prevailed in this area. Accordingly the early Paleozoic marine facies, Late Paleozoic marine-terrestrial interaction facies and Mesozoic terrestrial strata were deposited (Pan et al., 2011; Liang et al., 2004; Huang et al., 2013). In the Cenozoic, affected by the interaction between the Eurasian plate and the Pacific plate, a rifting basin dominated by terrestrial deposits was formed in the northern Jiangsu of the Lower Yangtze region (Li et al., 2010; Wang et al., 1995).

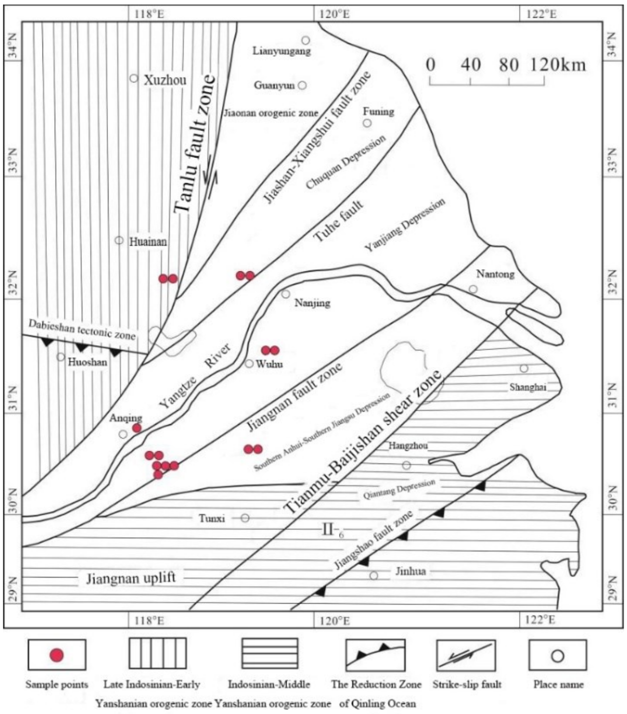


Figure 1: Sketch showing the tectonic subdivision of the Lower Yangtze area and sampling location for thermal properties measurement

3. METHODS AND DATA

The related geothermal data used in this paper come from two aspects: one is the borehole temperature data and published geothermal parameters, such as thermal properties and heat flow; the other is the measurement of thermal properties of rocks sampled from some outcrops to obtain the representative rock thermal properties data in this area. The new sampling points are shown in Figure 1. The data of temperature gradient, heat flow and thermal properties in this study mainly come from Wang et al. (1986, 1995, 2013) and Yuan et al. (2006) and some unpublished data in this area over the years, the total number of data is more than 190 (Fig. 2). The recent measured thermal properties data of sedimentary rocks from this area was included (Fig. 3) (Li et al., 2015). Using the inverse distance interpolation in ArcGIS, the distribution maps of geothermal gradient, heat flow and deep temperature in the lower Yangtze area are compiled to reveal their spatial patterns.

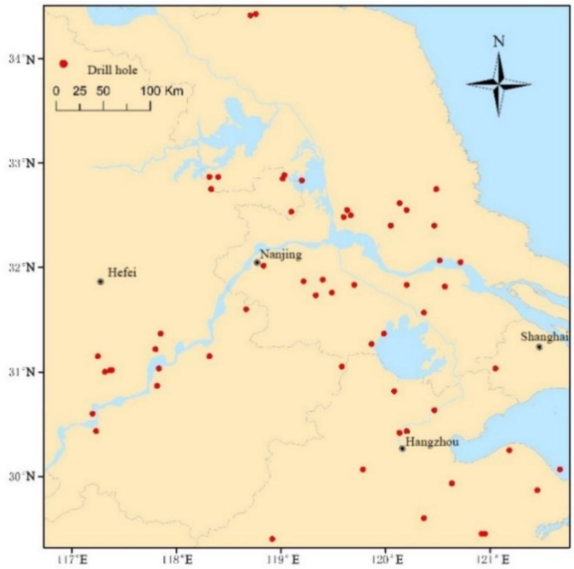


Figure 2: Borehole distribution of the Lower Yangtze area, east China

The measured thermal properties of the Paleozoic mudstones and shales are shown in Figure 3. Most of thermal conductivities range from 1.50 to 3.00W/(m.K) with an average of 2.17 (±0.68W/(m.K). Most of the heat generation productions varied from 2.00 to 2.50 μW/m^3, with an average of 2.04±0.86 μW/m^3. Therefore, compared with other sedimentary rocks, mudstone as a whole has the characteristics of low thermal conductivity and high heat generation.

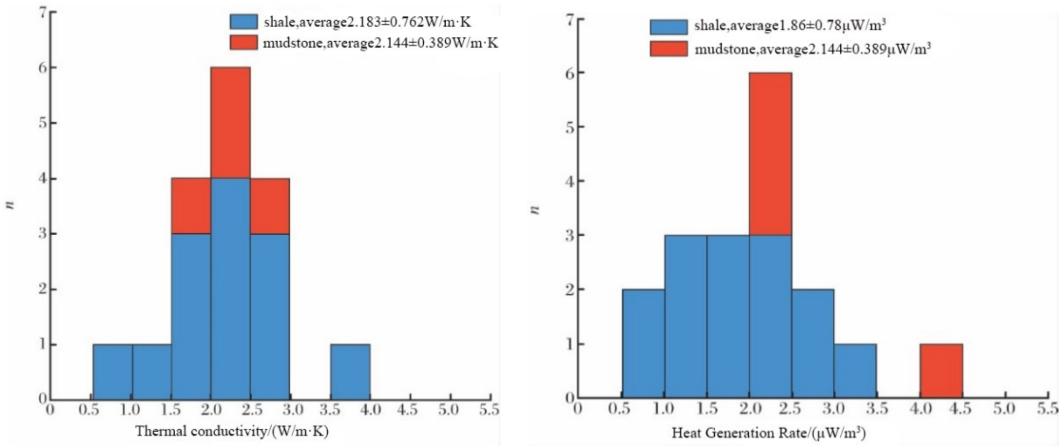


Figure 3: Histogram of thermal properties of Paleozoic shales in the Lower Yangtze area

Heat flow (Q, mW/m^2) is an important parameter to characterize the thermal state of the earth's interior. Q is equal to rock thermal conductivity (Kr) multiplied by geothermal gradient (dT/dZ). Geothermal gradient (dT/dZ) refers to the growth rate of formation temperature with depth, in units of ℃/km. For boreholes with abundant temperature measurement data, the geothermal gradient can be obtained by linear fitting of the least square method. Generally speaking, the temperature in the middle-shallow stratum (< 2000m) can be obtained directly from temperature measurement, while the temperature in the deep stratum (especially deeper than 5000m) is not easily measured. It can be estimated by combining the heat transfer equation and the related thermal properties.

There are two ways to estimate deep geotemperature: one is to estimate by known average geothermal gradient as $T=T_0+G.Z$. Among them, T is the specific temperature, T0 is the geotemperature at known depth, G is the geothermal gradient, and Z is the depth difference between the target depth and the known depth (Zhou et al., 1997). Another one is to use the analytical solution of 1D heat conduction equation (Chapman, 1986), which requires accurate stratified data and rock thermal properties (heat generation and thermal conductivity). Combining these two methods, the boreholes with complete thermal properties and stratigraphic data are estimated by 1D heat conduction equation, and most wells are estimated by average geothermal gradient, and verified by measured temperature.

T_0 here is taken as the temperature of constant temperature strata in the Lower Yangtze region. Constant temperature strata is generally about 10m underground, and the temperature is equivalent to the local annual average air temperature. The annual average temperature distribution in China from 1971 to 2000 shows that the annual average temperature in the Lower Yangtze region is between 10 and 20 ℃ (Liu et al., 2007). In this study, the constant temperature strata T_0 in Yangtze area is 10 m underground and the temperature is 15 ℃.

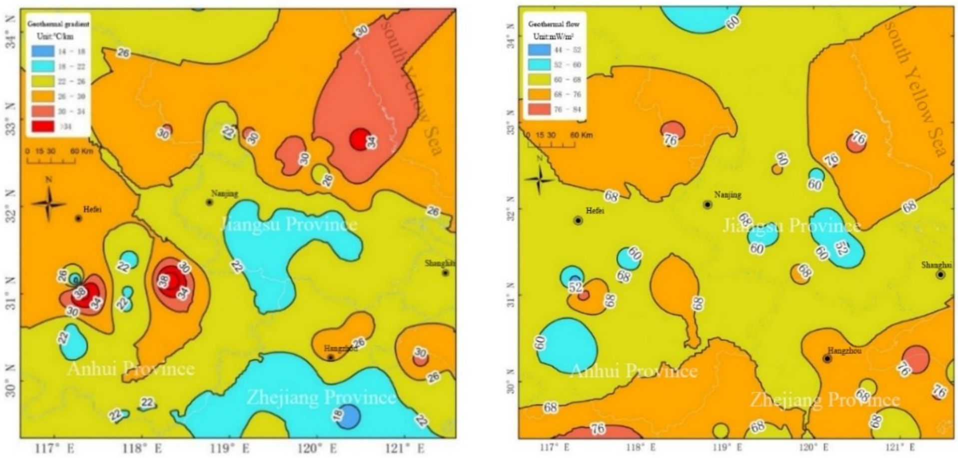
Based on the above methods, combined with thermophysical and heat flow data, we estimated the present-day temperature at the depth of 1000m to 5000m in the lower Yangtze region, and also calculated the depth of stratum corresponding to the isotherms of 60 and 120 ℃, respectively.

4. RESULTS

4.1 Distribution pattern of geothermal gradient

The present-day geothermal gradient in the Lower Yangtze region is 16-41 ℃/km (Fig. 4a). Among them, Shaoxing area of Zhejiang Province has the lowest geothermal gradient, about 16-18 ℃/km, and Lujiang area near the Tanlu fault zone has the highest geothermal gradient (41 ℃/km). Overall, the geothermal gradients in most areas of the lower Yangtze are between 18 and 25 ℃/km. However, the geothermal gradient in the North Jiangsu Basin is relatively high, and reaches 28-35 ℃/km, averaging 30 ℃/km; the geothermal gradient in the periphery of the basin is about 24 ℃/km, and the isoline of geothermal gradient is basically consistent with the boundary of the basin. This indicates that the difference in geothermal gradient within the basin is closely related to its geological structure. The North Jiangsu Basin and the Tanlu Fault Zone are both formed by Cenozoic crustal thinning. The lithosphere here is also thinned and the magmatism is intense. Therefore, the geothermal gradient is higher than that of the surrounding areas (Wang et al., 1986; Yuan et al., 2006; Wang et al., 2013).

In addition, the lithology of the thermometric strata in the North Jiangsu Basin is mostly Paleogene mud and sandstone, whose loose structure leads to low thermal conductivity, so the geothermal gradient is relatively high. In other areas, the lithology of thermometric strata is generally Mesozoic volcanic rocks, carbonate rocks and sandstones. The thermal conductivity of these rocks is large, so the geothermal gradient is relatively low (Wang et al., 2013). As shown in the figure 4a, the geothermal gradient in the northern part of the lower Yangtze region is large as a whole, while that in the southern part is generally low. The regional geothermal gradient shows the predominant pattern of NNE direction, basically consistent with the strike of the Tanlu fault zone, and also reflects the control of the Cenozoic deep and large fault structures on the present-day geothermal field.



(a) Geothermal gradient **(b) heat flow**

Figure 4: Present-day geothermal field of the Lower Yangtze area

4.2 Distribution pattern of heat flow

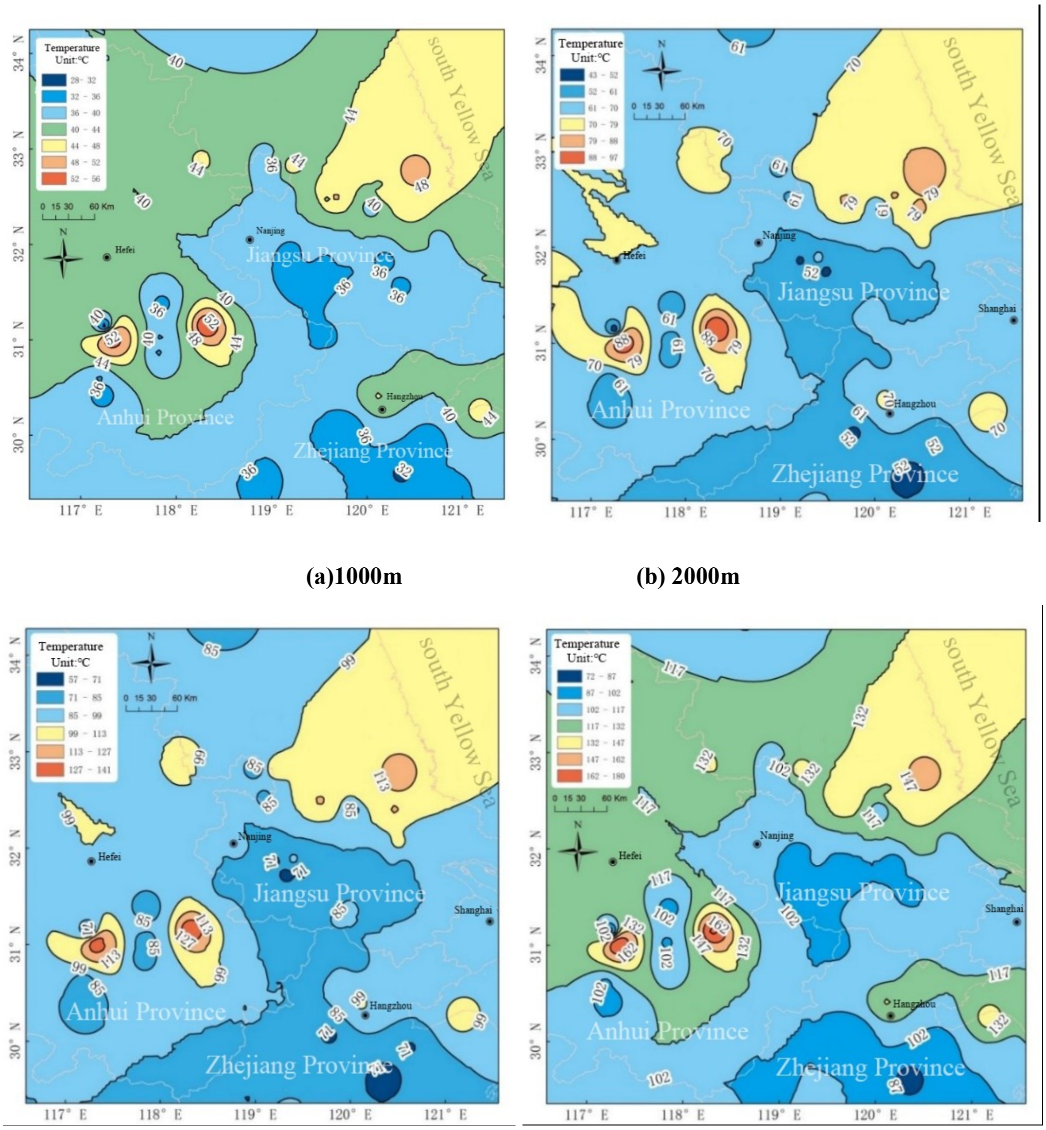
The whole heat flow in the lower Yangtze region ranges from 48 to 80 mW/m^2, and most of which are above 60 mW/m^2 (Fig. 4b). Among them, Ma'anshan (48mW/m^2) in Anhui Province and southern Jiangsu Province (50-55mW/m^2) are low heat flow areas, while the North Jiangsu Basin (54-83 mW/m^2, with an average of 68 mW/m^2) and the Tanlu fault zone are high value areas. The heat flow in the Ningbo Basin in southeastern Zhejiang is 73 mW/m2, which is also relatively high. Similar to the regional geothermal gradient distribution, the heat flow distribution in the lower Yangtze region also reflects the NNE-trending pattern. In addition, the heat flow in most areas of the lower Yangtze area is about 60 mW/m^2, which is representative of the background heat flow value, and is close to the global average. As mentioned above, local high heat flow areas in the lower Yangtze region, such as the Tanlu fault zone, North Jiangsu basin and southeastern Zhejiang orogenic belt. Generally speaking, the lower Yangtze region presents a medium-high geothermal state. Among them, the geothermal gradient is generally in the range of 18-25 ℃/km, the heat flow is in the range of 48-80 mW/m^2, and the mean value is 60 mW/m^2. The relatively high value area of temperature gradient in the region is located in the North Jiangsu Basin, while the relatively high value area of heat flow is located in the Tanlu fault zone, the North Jiangsu Basin and the southeastern Zhejiang orogenic belt, which is related to the tectonic movement during the Cenozoic period (Wang et al., 1986; Yuan et al., 2006; Wang et al., 2013).

4.3 Estimation of deep formation temperature

The following figures demonstrate the temperatures at the depth of 1000-4000 m in the Lower Yangtze area with inverse distance interpolation (Fig. 5). Among them, the temperature range of the formation is between 30 and 54 ℃ at 1000 meters depth, 50~95 ℃

at 2000 meters, 65 to 130 ℃ at 3000 meters, 80 to 170 ℃ at 4000 meters. With the increase of depth, formation temperature increases correspondingly, which reflects the influence of depth on temperature field.

Interestingly, the spatial distribution of deep temperature also shows a similar trend with the geothermal gradient and heat flow. Relatively high temperature areas mainly occur in the Tanlu fault zone, North Jiangsu Basin and southeastern Zhejiang orogenic belt. As shown in Fig. 5a, the temperature in southern Jiangsu, southern Anhui and Western Zhejiang is lower than 36 ℃ at 1000m depth, while that in Tanlu fault zone and Northern Jiangsu basin is above 44 ℃, even as high as 52 ℃, with a temperature difference of 8-16 ℃ at the same depth. The lateral difference in deep temperature reflects the control of the difference of geothermal gradient. In addition, the high temperature area shows a NE direction, which also describes the control of Cenozoic tectonics on the geothermal field. Similarly, at a depth of 3000 m, the temperature in southern Jiangsu and Western Zhejiang is lower than 85 ℃, while the high temperature anomalies are above 100 ℃, even as high as 130 ℃. Low temperature anomalies such as southern Jiangsu and Western Zhejiang are between 100 and 126 ℃, and in high temperature anomalies are above 160 ℃, even up to 210 ℃.



(a)1000m **(b) 2000m**

(c) 3000m **(d) 4000m**

Figure 5: estimated temperatures-at-depths in the Lower Yangtze area

5. DISCUSSION

Geothermal resources can be divided into four categories according to their distribution and occurrence status (Wang et al., 2015): 1. Shallow geothermal resources, generally not more than 200 m in depth, it can be used for heating or refrigerate with ground source heat pump technology; 2. Hydrothermal geothermal resources, generally at a depth of 3 km or shallow, with groundwater as the carrier, heat can be extracted by hot water or water vapor mixture; 3. Dry-hot rock geothermal resources, generally at depths below 3 km, it basically contains heat in non-aquiferous strata or rocks, which must be exploited by means of artificial geothermal storage and artificial fluid circulation; 4. Magma type, that is, heat stored in unconsolidated magma, which is impossible to exploit under the current economic and technological conditions. Generally, geothermal resources below 5 km depth can only be regarded as prospective resources.

According to the present-day geothermal regime of the Lower Yangtze region, we can identify the high temperature anomalies in the region, such as the Tanlu fault zone and the North Jiangsu Basin. Relatively high temperature can be obtained at shallow depth, favorable for geothermal energy exploration and development. For the shallow depth of 3 km in the Lower Yangtze region, the potential of geothermal resources in the southern Jiangsu Province and southern Anhui Province with lower geothermal gradient is worse than that in northern Jiangsu area with higher geothermal gradient. In the depth of 2100-3000m in the North Jiangsu Basin, the temperature can reach 90-150 ℃, so the medium-temperature geothermal resources can be used for industrial utilization, drying and power generation. While in the depth of 1400-2100m in the northern Jiangsu Province, the temperature can reach 60-90 ℃. This low-temperature geothermal resource can be used as heating and other technological processes.

6. CONCLUSION

The lower Yangtze area has a medium-high geothermal regime. The present-day geothermal gradients are mostly 18-25 ℃/km, and the heat flow is 48-80 mW/m^2, averaging 60 mW/m^2. The North Jiangsu Basin, Tanlu fault zone and southeastern Zhejiang orogenic belt are high heat flow areas, while southern Anhui Province and southern Jiangsu Province are the low heat flow areas. The geothermal field is generally characterized by high in the north and low in the south, and shows a predominant NNE distribution, which is closely related to the Cenozoic tectonics.

In the lower Yangtze area, the temperature at 1000 meters depth is 30-54 ℃, 50-95 ℃ at 2000 meters, 65-130 ℃ at 3000 meters, 80-170 ℃ at 4000 meters. Among them, the deep geotemperature in northern Jiangsu is higher than that in southern Jiangsu and southern Anhui Province, and the general trend is consistent with the geothermal gradient distribution. Since the temperature presented here are estimated from conduction method, it should keep in mind that such temperatures in the geothermal reservoir could be reduced because of the heat convection process commonly dominant in the geothermal reservoirs.

The Lower Yangtze area has abundant geothermal resources potential, mainly in the North Jiangsu Basin and the Tanlu fault zone. The temperature in the depth of 2100-3000m in North Jiangsu Basin can reach 90-150 ℃. Geothermal resources can be used for industrial utilization and power generation. The temperature at 1400-2100m in the North Jiangsu Basin is 60-90 ℃. Geothermal resources can be used as heating and technological processes.

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