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The Particularity and Direct Utilization Prospect of Deep Geothermal Resources in Eastern China

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ABSTRACT

Eastern China, east of the Hu Huanyong line that connects Heihe and Tengchong cities, accounts for 36 percent of China's total land area, but 96 percent of the population. The area is generally dominated by plain, hilly, karst and Danxia landform, with large population density and developed economy, and an extremely strong demand for energy. The eastern region is rich in deep geothermal resources, and the rational development and utilization is of great significance to ensuring the security of energy supply and achieving the goal of carbon peak and carbon neutralization. In eastern China, there are three geological units adjacent to each other tectonically, for instance, the eastern section of the E-W-direction Central Asia Orogenic Belt, the North China plate and the South China plate from north to south successively, which are superposition regions of the three global tectonic regimes, i.e. Paleo-Asia, circum-Pacific and Tethys. Since the late Mesozoic, influenced by back-arc extension of the circum-Pacific regime, the second depression belt developed subsequently and were composed of a series of Meso-Cenozoic basins, including Songliao, Bohai Bay, southern the North China, northern Jiangsu, Jianghan, Sanshui, Beibuwan and so on. The complicated tectonic movements of multiple stages and various geodynamic mechanisms formed the structure of "overpass" mode for the earth’s crust and mantle in eastern China, while the shallow surface showed the patchwork distribution pattern of orogen and basin, uplift and depression in graceful disorder. The study shows that the deep geothermal resources in eastern China are huge, mainly distributed in the Meso-Cenozoic sedimentary basin area, but the resource abundance is relatively low, mainly with intermediate temperature geothermal resources, and lack of high temperature geothermal resources. In terms of the development and utilization of geothermal resources, it is generally not suitable for geothermal power generation, but should be utilized directly. For instance, the northeast and North China are suitable for large-scale geothermal house-heating, the Yangtze River watershed is suitable for geothermal house-heating in winter and house-cooling in summer, and south China is suitable for geothermal house-cooling all the year round. At the same time, geothermal can also be used for high-profit-attached agriculture and tourism according to local conditions.

1. INTRODUCTION

The area east of the Huanyong Line connecting Heihe and Tengchong accounts for 36 percent of China's total land area and 96 percent of its population, respectively. From north to south, this region covers Northeast China, North China, Jianghuai, Southwest and South China, etc., with large population density and developed economy, and extremely strong demand for energy (Figure 1).

With the development of economy, the demand for energy is more intense and the demand for environment is also higher. As a result, the development of middle and shallow geothermal resources has been unable to meet the current demand, and it has become the only way to advance to the deep earth. This is mainly reflected in the gradual strengthening of research on the characteristics of deep crustal geothermal and the dynamics mechanism of crust and mantle in recent years (Shi, 1990; Xu, et al., 1995; He, et al., 2001; An, et al., 2007; Wang, et al., 2012; Qiu, et al., 2015).

The Northeast geothermal anomaly, North China geothermal anomaly and South China geothermal anomaly are distributed from north to south in eastern China (Zhang, et al., 2022) (Figure 1). The Northeast geothermal anomaly area is mainly related to the magmatic activity of the modern subduction plate in the Western Pacific, the North China geothermal anomaly area is mainly related to the destruction of the Mesozoic North China Craton and the Cenozoic magmatic activity, and the South China geothermal anomaly area is mainly related to the back-arc extension of the Pacific plate and the expansion of the South China Sea. These three geothermal anomaly areas are rich in medium and deep geothermal resources. It is of great scientific significance to study the characteristics of deep high temperature geothermal system and the distribution law of resources for rational development and efficient utilization of geothermal resources.

Figure 1 Topographic map of China

The NE-direction bold broken line shows Huhuanyong Line of China. The NW-direction thin broken lines of AB, CD and EF show synthetic seismic profiles locations.

2. GEOLOGICAL AND GEOTHERMAL CONDITIONS

The eastern part of China is tectonically divided into three geological units from north to south, namely the eastern segment of the Central Asian orogenic belt, the North China Plate and the South China Plate. It is a superposition area of three global tectonic domains, namely the PaleoAsia, the coastal Pacific and the Tethys. Since the late Mesozoic, under the influence of the back-arc extension of the Pacific tectonic domain, the second subsidence zone, which is composed of a series of meso-Cenozoic basins, has developed in the northeast direction, including the Songliao Basin, Bohai Bay, South North China, North Jiangsu Basin, Jianghan Basin, Sanshui Basin and Beibu Gulf Basin. The combination of multiple epochal and geodynamic mechanisms has formed a "flyover" pattern of crust-mantle structure in eastern China, and the shallow surface is characterized by a pattern of scattered distribution of basin-mountain, uplift and depression.

2.1 Lithosphere structure

2.1.1 Northeast lithosphere terrain

The lithosphere blocks in Northeast China include Songliao Plain and Greater Khingan Mountains in the east of Northeast China, and are connected to the North China lithosphere block in the south by the North China Platform Taibei fault zone. In the west and north, they may include eastern Mongolia and the vast areas south of the Khingan Mountains outside Russia, and connect to the Sikhote Mountains in the east.

The variation of lithospheric thickness in this area shows that it is thicker in the west and thinner in the east. The Greater Khingan Mountains in the west is a gradient zone of lithospheric thickness, and the thickness of the lithosphere is 90 ~ 130km and 130 ~ 150km in the north of the Greater Khingan Mountains. The lithosphere of Songliao Plain is relatively thin, 70 ~ 90km, reflecting the tensile tectonic setting. The eastern Jihei orogenic belt is thinner, measuring 63 ~ 70km. The average crustal thickness is 30 ~ 40km, showing that the orogenic belt on the east and west sides is thick, and the Songliao Basin in the middle is thin. The western Greater Khingan range is generally 35 ~ 40km, and the northern Greater Khingan range is 40 ~ 44km. The central Songliao Plain is generally 30 ~ 34km; Eastern orogenic belt 34 ~ 37km. The lithospheric mantle thickness is about 40km (Figure 2), and the shear wave velocity is 4.20-4.40km /s. Therefore, the lithosphere structure of this area is characterized by thin crust and thin mantle and light crust and light mantle. The crust is divided into upper layer and lower layer by the seismic interface of 15 ~ 21km. There are high conductivity layers in the upper crust at a depth of 10km and in the lower crust at a depth of 30-40km.

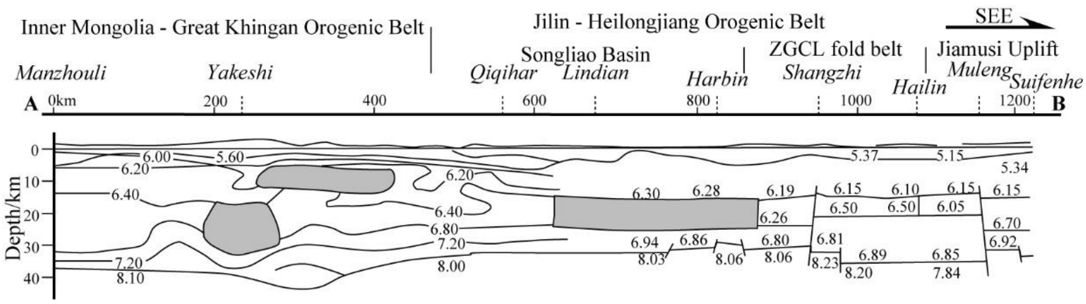

Figure 2 Synthetic seismic profile from Manzhouli to Suifenhe

Location of the profile was showed in Figure 1.

P-wave velocity: km/s.

Shadows were interpreted as low velocity zones (LVZ) (modified after Li et al., 2013)

2.1.2 North China lithosphere terrain

The North China lithosphere block is bounded by the North China Platform Taipei margin fault zone and adjacent to the northeast lithosphere block. In the south, Shangdan fault zone, Mozitan fault zone and Zhoushan fault zone are bounded by the lithosphere block of South China, and the west boundary is a north-south tectonic belt. To the east includes the Yellow Sea. Tectonically, it mainly belongs to the North China platform. Bounded by Yinshan-Yanshan in the north, Helan Mountain in the west and Qinling-Dabie Mountain in the south, North China constitutes a unified lithosphere block in an east-west direction. The thickness of the lithosphere gradually thinned from west to east, 125 ~ 155km from Ordos in the west; 90 ~ 120km in Shanxi Plateau; North China Plain 70 ~ 90km; The

Bohai Sea is only 65 to 70 kilometers long. The crustal thickness shown by seismic sounding is also thicker in the west and thinner in the east. The Ordos Plateau in the west is 40 ~ 45km. 38 ~ 40km in central Shanxi Plateau; The North China Plain in the east is 32 ~ 38km; At its thinnest point, the Bohai Sea is only 20km. The average thickness of the crust is 30-35km (Figure 3). The lithospheric mantle thickness is 50 ~ 70km in most areas and 80 ~ 100km in the west. The shear wave velocity is only 4.30 ~ 4.50km/s. These data indicate that the lithospheric mantle in the eastern part of North China is not hard and has the lithospheric structure of thin crust and thin mantle and light crust and light mantle.

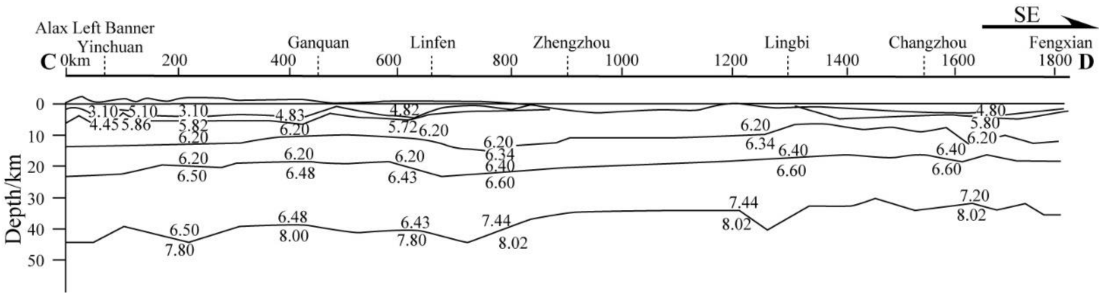

Figure 3 Synthetic seismic profile from Alax Left Banner to Fengxiain of Shanghai

Location of the profile was showed in Fig.1.

P-wave velocity: km/s. (modified after Li et al., 2013)

The seismic and magnetotelluric data show that there is a low-speed high-conductivity layer about 20km below the ground, with a thickness of 10km. There is a crust-mantle transition layer at the bottom of the crust, with a thickness of 2 ~ 8km. There are high conductivity layers in the upper mantle with resistivity values of about 10Ωm and buried depths of 72 ~ 103km, which may be the bottom boundary of the lithosphere mantle.

Terrestrial heat flow value (> 65mW/m^2) and geothermal gradient (3℃ / 100m) are both high in the middle and northern parts of the North China Plain, and gradually decrease outward, indicating the heterogeneity of the thermal structure of the lithosphere in this area. According to the discontinuity of lithosphere shown by geological and geophysical characteristics in North China, craton type, orogenic belt type and rift type lithosphere in North China can be distinguished.

2.1.2.1 Erdos cratonized lithosphere

The North China Platform has the same history as the major cratons in the world and was formed in the Paleoarchaean-Paleoproterozoic (Cheng, 1994; Deng, et al., 1999). The geological history of North China shows that the North China platform was a stable platform before the Jurassic period, and after the Jurassic period, the platform was strongly reformed, that is, the platform "activation" : the magmatic activity was limited to the edge of the platform before the Yanshanian (Figure 4), while the Yanshanian magmatic activity was deep inside the platform and distributed throughout the central and eastern parts of the North China Platform (Figure 5). The basalt eruption associated with the Cenozoic rifting occurred mainly in the eastern part of the North China Plain. After the formation of the Ordos block in the western part of North China from the ancient Archaean to the Paleoproterozoic, there has been no magmatic activity until now, indicating that there has been no injection of convective mantle material into the continental crust and mantle lithosphere, and there is no active fault in the block at present, maintaining the characteristics of stability.

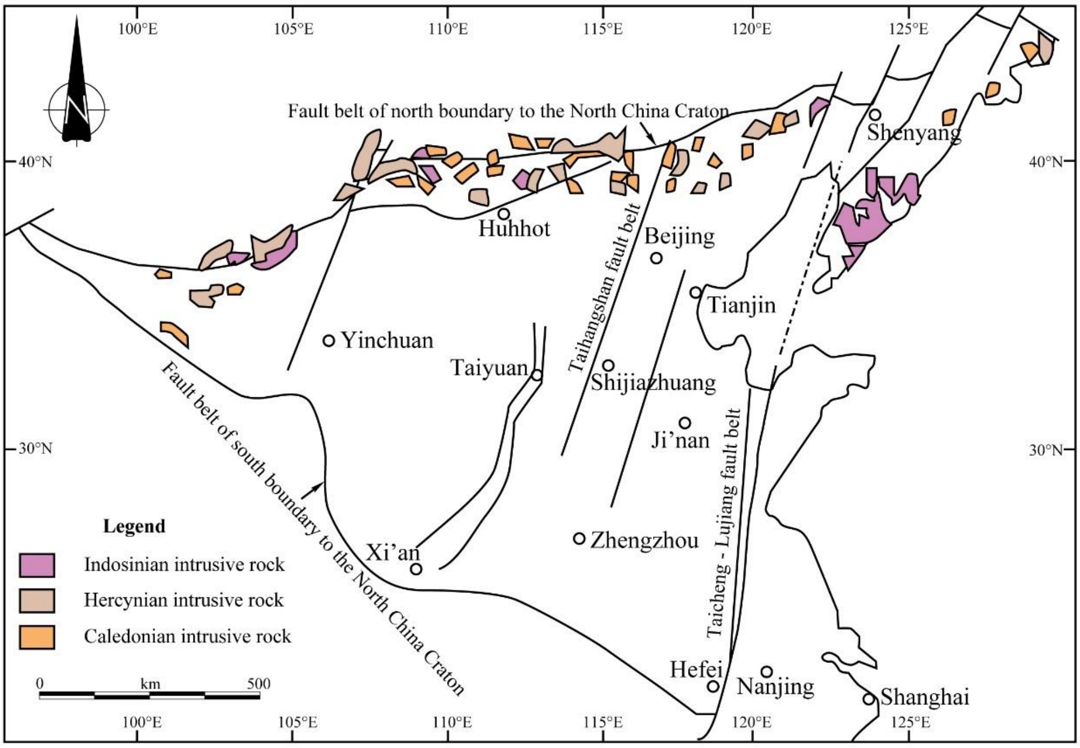

Figure 4 Schematic diagram of granite distribution from Caledonian to Indosinian period(modified after Cheng, 1994)

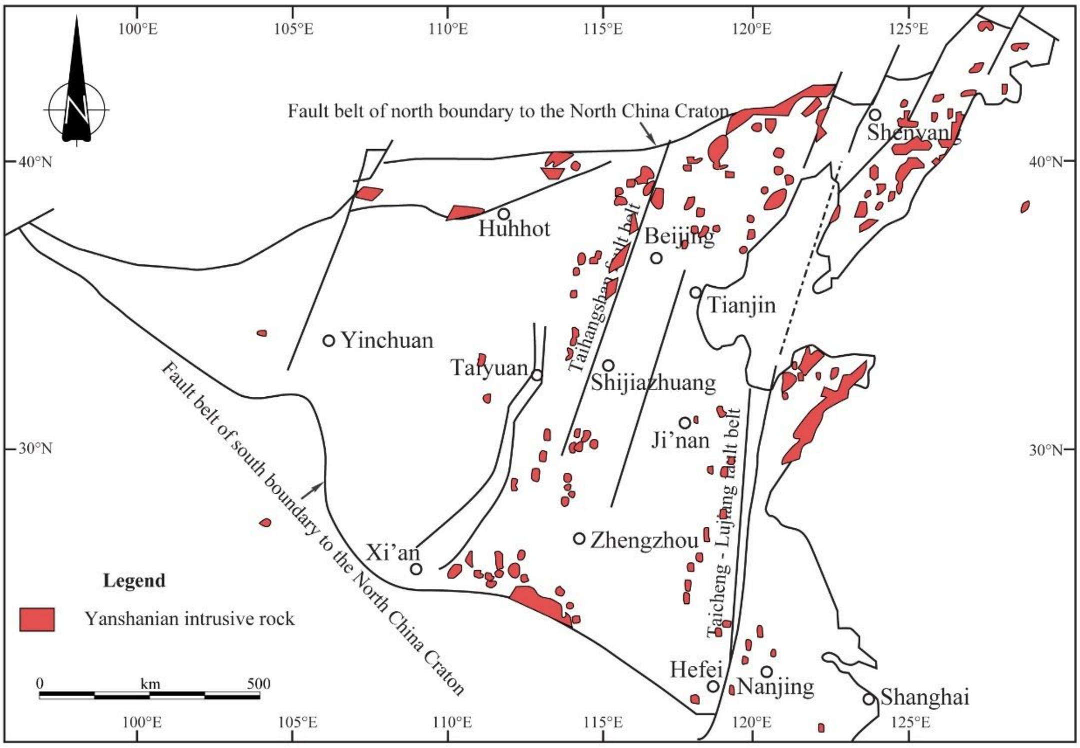

Figure 5 Schematic diagram of granite distribution for yanshanian period(modified after Cheng, 1994)

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2.1.2.2 Yanshan-Taihangshan orogenic lithosphere

The Yanshanian intrusive rocks were distributed throughout the eastern part of the North China Platform (Figure 5), indicating that the reconstruction of the North China platform accompanied by the Yanshanian orogeny was mainly in the central and eastern part of the platform. The geophysical survey shows that the crustal velocity structure in Yanshan and Taihang Mountains is similar with density inversion. There are two low velocity bodies in the lower crust (16 ~ 20km) and the crust mantle transition zone (32 ~ 40km), respectively. It has a high average surface heat flow value (60mW/m^2)(Wang, et al., 1988), and these features are significantly different from the Ordos block to the west. In terms of rock composition, the upper crust is mainly composed of Mesozoic granites and granodiorite granites; the middle crust is composed of granitic low-velocity granites and amphibolite gneiss; the lower crust is composed of acid granulites, granodiorite low-velocity granites, pyroxene rocks and basalts; and the upper mantle lithosphere is mainly composed of diopidolite and diopidolite.

2.1.2.3 North China Plaine rift valley lithosphere

In the Himalayan period, the North China Plain was the environment for the development of continental extensional structures, which belonged to the typical continental rift volcanism and was characterized by the mantle-derived basaltic magma eruption in the Paleogene and Neogene Quaternary cycles (Figure 6). By comparing the distribution of Yanshanian intrusions (Figure 5), it is not difficult to understand that Himalayan rifting in the North China Plain was carried out on the basis of Yanshani-Taihang orogenic lithosphere, and the Yanshani-Taihang orogenic lithosphere can be an important reference for understanding the North China Plain rift lithosphere. The Cenozoic basalt eruption in Hanuoba may be related to the local geological conditions of the North China platform margin, and the lithosphere type can still be classified as rift lithosphere.

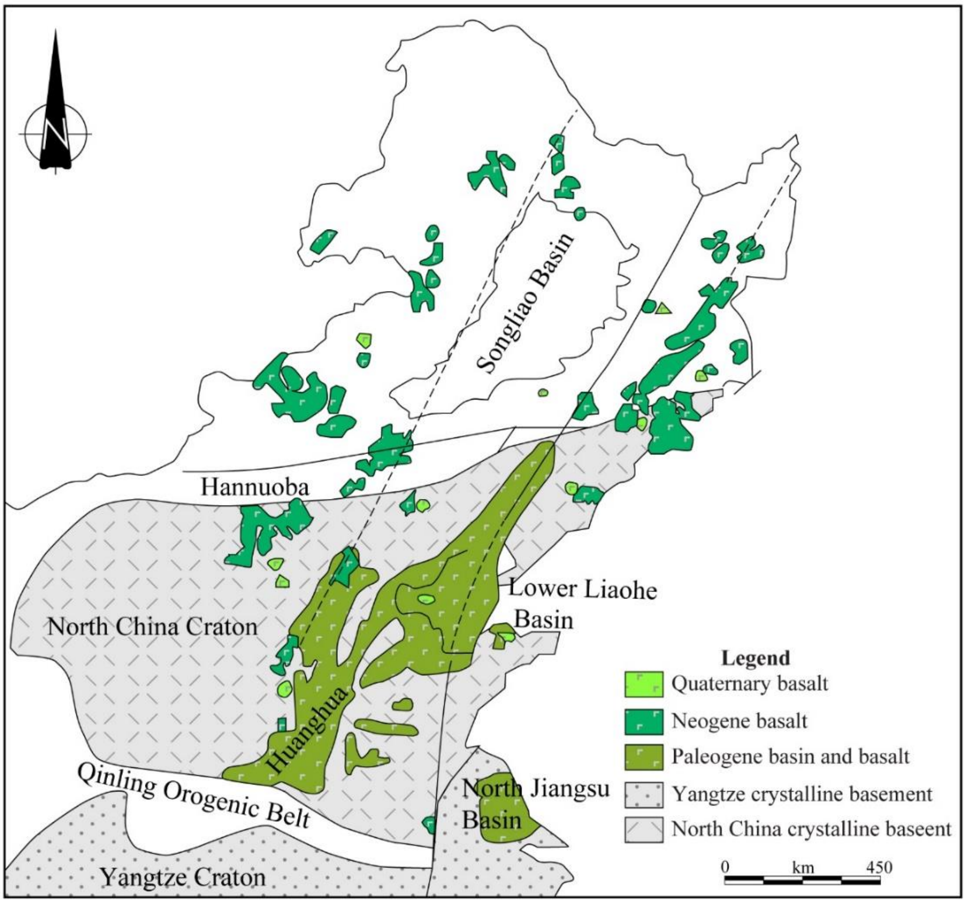

Figure 6 Schematic diagram of Cenozoic basalt distribution in the North China plain and adjacent region (modified after Cheng, 1994)

The overall continental crust thickness of the North China Plain is relatively thin (30 ~ 34km), indicating the characteristics of the new crustal structure of longitudinal thinning, transverse extension and low velocity formed by fracture extension (Jia, et al., 2001). In the depression area of the rifted basin, the extensive water content, the development of micro-cracks and micro-pores, and the high ground temperature can greatly affect the seismic wave velocity, while in the uplift area, the Vp wave velocity structure can generally represent the velocity structure after removing these influences, such as the west Luxi area. The lithosphere thickness derived from Cenozoic basalt is about 70 ~ 80km(Deng, et al., 1996), which is different from the craton type and orogenic belt type lithosphere with huge thickness. In the late Mesozoic and early Paleogene rifting stages, the paleo-heat flow value reached 80mW/m^2, while the current observed value is about 63mW/m^2(Wang, et al., 1988), and the lithospheric thermal state gradually decreased with the development of continental rifting. In terms of rock composition, the upper crust is mainly composed of schist, granite and granitic gneiss, the middle crust is granodiorite, the lower crust is acidic granulite and basalt, and the upper mantle lithosphere is mainly composed of diperidotite and a small amount of diperidotite.

A large amount of Cenozoic basaltic magma eruption is a sign of convective mantle material injection during this period. The lack of Himalayan intrusions in the North China Plain indicates that there was no melting of continental crust rocks. Therefore, the North China rift type continental crust structure is a direct addition of the new continental crust (basalt) to the Yanshan-Taihang orogenic continental crust. As reflected in the mean wave velocity, compared with the Yanshan-Taihang orogenic belt (mean continental crust Vp= 6.2-6.3km/s), the average Vs of the west Luxi uplift (mean continental crust Vp=6.3km/s) is increased, that is, the mean continental crust composition is equivalent to granodiorite. Therefore, if the Yanshan-Taihang orogenic belt is taken as the reference of the Yanshanian Period, The average composition of the west Luxi uplift was granitic from Yanshanian to granodiorite from Himalayan, that is, the continental crust was "mafic", which was the result of convective mantle injection into the continent during continental rifting.

2.1.3 South China lithosphere terrain

The South China lithosphere block is separated from the North China lithosphere block by the Shangdan fault-Mozitan fault-Zhoushan fault zone, and adjacent to the South China Sea lithosphere block by the Qiongbei and Taiwan Strait fault zone in the south. It reaches the Sichuan-Yunnan North-South tectonic belt in the west, and includes the East China Sea in the east.

Tectonically, this lithospheric block spans three tectonic units, namely the Yangtze Platform, the South Qinling orogenic belt and the South China orogenic system. In the western part of the region, namely Sichuan Basin, Guizhou, Hunan, Hubei and other places, the crust is relatively stable, and the tectonic and seismic activities are weak. In the eastern part, especially Taiwan and its adjacent areas, the tectonic and seismic activities are strong, mainly shallow earthquakes.

The lithospheric thickness in this area varies greatly and the bottom surface of the lithosphere fluctuates greatly. In general, with Chengdu-Xuanchang-Wuhan east-west axis, the lithosphere is thick in the west and middle, and gradually thinning in the north, east and south. The triangle zone to the southwest of Daba Mountain, to the northwest of Dalou Mountain, and to the east of Longmen Mountain has the thickest lithosphere, reaching 175 ~ 185km, 160 ~ 200km in central Hunan and northern Jiangxi, 90 ~ 160km in north, east and south, 70 ~ 80km in coastal areas, and only 65 ~ 70km in the East China Sea shelf.

The appearance of 200km thick lithosphere in Hunan-Jiangxi area is a major feature of the lithosphere in this area. The crust in this area has a three-layer structure, which is generally thicker in the west and thinner in the east, with an average thickness of 32 ~ 35km and up to 38 ~ 46km in the west. The East China Sea shelf and Ryukyu Island arc are about 28km, the Okinawa Trough is about 14 ~ 21km, and the Ryukyu Trench and its east is only about 5.5km (Figure 7).

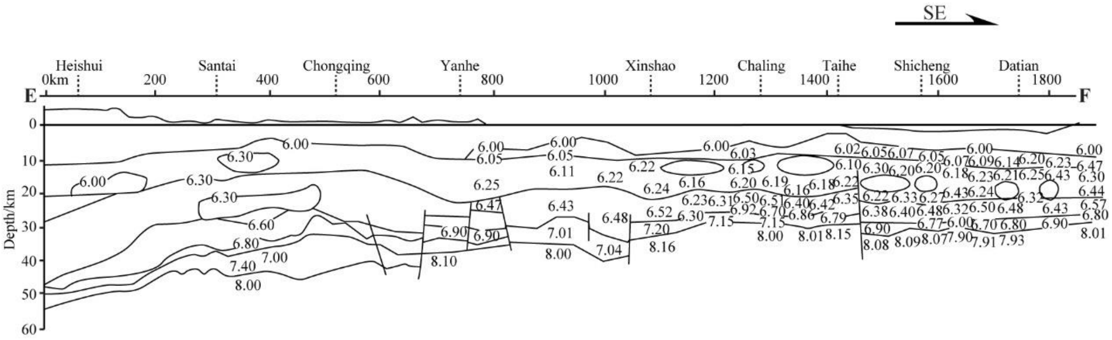

Figure 7 Synthetic seismic profile from Heishui of Sichuan Province to Datian of Fujian Province

Location of the profile was showed in Figure 1.

P-wave velocity: km/s. (modified after Li et al., 2013)

In conclusion, the northeast lithosphere and North China lithosphere are similar in structure and structure, with thin crust and thin mantle and light crust and light mantle, while the South China lithosphere has thin crust and thick mantle and light crust and heavy mantle, which reflects from another aspect that mantle-derived heat may occupy a larger proportion in the heat source composition of South China lithosphere.

2.2 Geothermal gradient field characteristics

Terrestrial heat flow value is the direct display of geothermal in the surface, through the study of heat flow value can roughly understand the crustal thermal state. The statistics of terrestrial heat flux data show that continental heat flux values tend to decrease with the increase of the age of the last tectonic thermal event experienced by the body (Chapman and Pollack,1975; Pollack, et al.,1993). The tectonic thermal event age of a tectonic unit is defined as the age of the tectonic activation event or tectonic magmatic activity event experienced by the unit. Table 1 lists the ages of the major tectono-thermal events experienced by each tectonic unit in mainland China. For the basin, the age of the major tectonic event refers to the age of the formation of the basin, while for the orogenic belt and other tectonic units, it refers to the age of the latest orogeny. The time range of the age is based on the value of Ren(1999). The latest magmatism refers to the epoch when the basin experienced major magmatism again after the major orogeny or the formation of the basin. The time range of its age is based on the data of Liu (1992). If a tectonic unit has not been subjected to magmatic activity following a major tectonic event it has experienced, it is the most recent tectono-thermal event it has experienced.

It can be seen from Table 1 and Figure 8 that the heat flow value of each tectonic unit has a discrete correlation with the age of basement formation, and a good correlation with the age of the latest magmatic activity or major orogeny. In other words, the heat flow value of mainland China is inversely correlated with the age of the latest tectonic thermal event experienced by each geological unit. The longer the age of the latest tectonic thermal event experienced, the lower the heat flow value, and vice versa.

It can also be seen from Table 1 that: The Tarim, Junggar and Qaidam basins (less than 55mW/m^2) experienced the latest tectono-thermal events in the Hercynian period 260 ~ 350Ma ago, the Hunan-Guizhou area experienced the latest tectono-thermal events in the Yanshanian period 130 ~ 180Ma ago, and the heat flow values were less than

50mW/m². This indicates that the continental lithosphere cooled to a temperature equivalent to that of the stable craton or platform area 130 ~ 350Ma after the end of the tectonothermal event. The heat flow values of the Songliao Basin in North China and Northeast China are higher than 65 mW/m², and the Songliao Basin is as high as 70 mW/m². The latest magmatic activity ages of the two are the Himalayan period of 30 ~ 65Ma. The earth heat flow values of the Lower Yangtze region in South China and the South China orogenic belt are 65 mW/m² and 72 mW/m², respectively. Although the most recent tectonic activity in the area was mainly concentrated in the Yanshanian period between 80 and 160Ma, the magmatic activity continued to the present, which laid the foundation for the formation of the high heat flow value. Therefore, the distribution pattern of present high heat flow (> 65 mW/m²) in mainland China is controlled by tectono-thermal events since Cenozoic, but has little relationship with tectono-thermal events in Mesozoic and its predecessors.

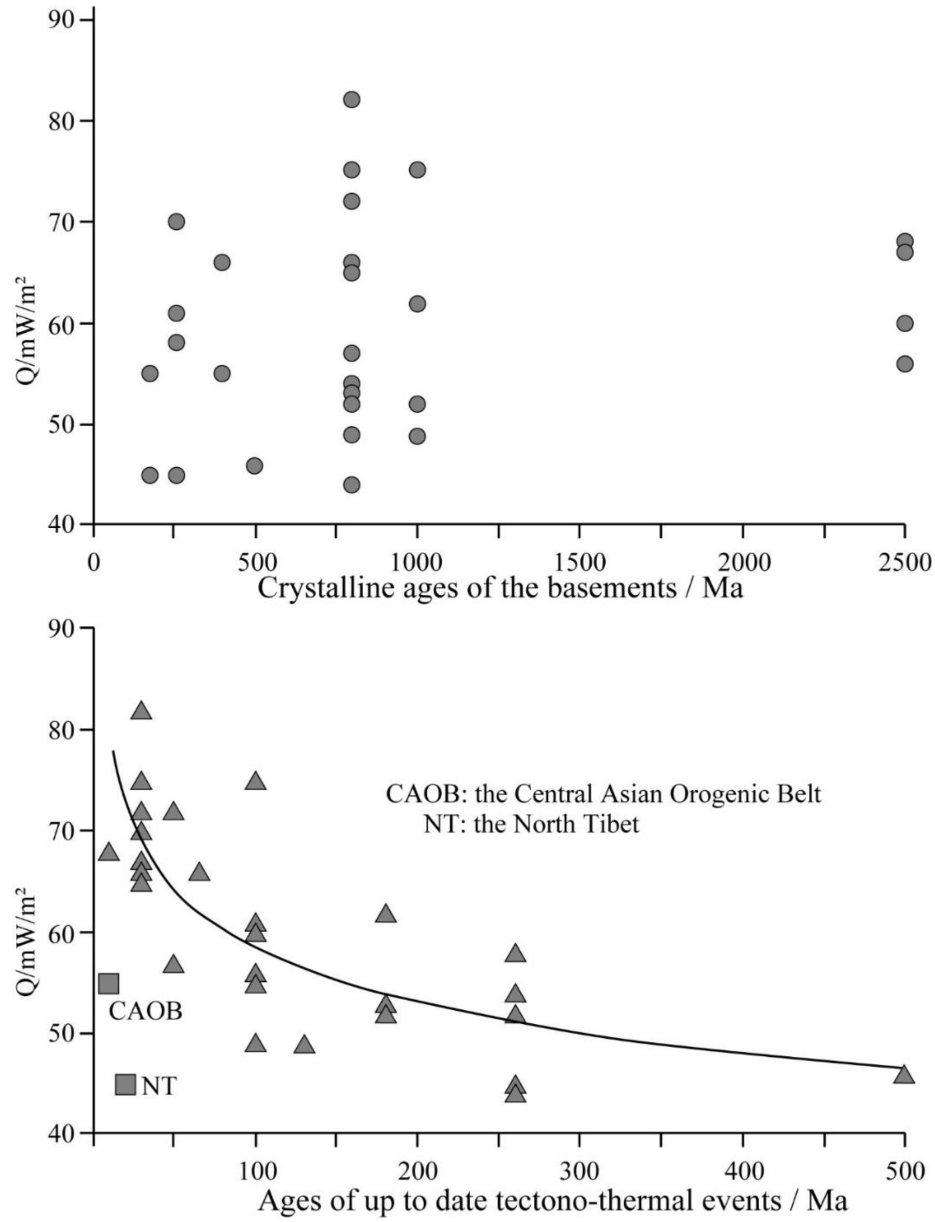

Figure 8 Relationships between average heat flow values with ages of tectono-thermal events for tectonic units in mainland China (modified after Li, et al., 2013)

Table 1 Average values of terrestrial heat flow and their relationships with tectonic and magmatism ages of eastern mainland of China (Li, et al., 2013)

Tectonic units types	Tectonic units names	Values of terrestrial heat flow （mW/m^2）	Latest magmatism ages（Ma）	Major tectonic events ages （Ma）	Crystalline ages of basement （Ma）
Northeast geothermal abnormal zone	Hailar	61	-	100～160	260～800
	Songliao Basin	70	30～65	80～160	260～800
	Great Khingan and Inner Mongolia	55	0～25	100～400	＞400
North China geothermal abnormal zone	Erdos Basin	60	100～140	180～230	2500
	Fen-Wei Graben	68	-	10～65	2500
	North China Craton	67	30～65	30～65	2500
	QinLing Orogenic belt	62	-	180～230	＞1000
	Dabie Orogenic belt	52	-	180～230	＞1000
	SuLu Orogenic belt	75	-	100～160	＞1000
	Southern North China Craton	49	-	100～160	＞1000
	Nanyng Basin	55	-	100～160	180～230
	North Jiangsu Basin	72	30～65	100～160	800～1700
South China geothermal abnormal zone	Jianghan Basin and adjacent zone	57	50～60	100～160	800～1700
	Hunan and Guizhou zone	49	-	130～180	800～1700
	Lower Yangtze zone	65	30～65	80～160	800～1700
	South China Orogenic belt	72	0～50	80～130	800～1700
	Zhangzhou basin	47	5～100	80～130	800～1700
	Shanshui Bain	72	34～56	80～130	800～1700
	Maoming Basin	62	0～5	80～130	800～1700
	Beibuwan Basin	71	0～5	80～130	800～1700

The geothermal geological conditions are different in Northeast, North and South China geothermal anomaly areas(Chen, et al., 1996; He et al., 2001; An et al., 2007; Wang, et al., 2012, 2014; Jiang, et al., 2016, 2019).

4. PROSPECTS OF DIRECT UTILIZATION OF DEEP GEOTHERMAL

The high temperature geothermal resources suitable for power generation in China are mainly distributed in Xizang, Yunnan and Taiwan. The eastern land area is mainly dominated by medium-low temperature geothermal resources, which are mainly distributed in Songliao, North China, Northern Jiangsu, Sanshui, Beibu Gulf and other sedimentary basins, with a wide distribution area and large reserves. Most of these geothermal resource distribution areas are located in the economically developed areas of China, and the geothermal resources in these areas are actively exploited, which has a broad market application prospect.

In terms of exploitation and utilization of geothermal resources, geothermal power generation is not suitable on the whole, and direct utilization should be the main.

Northeast and North China are suitable for geothermal heating on a scale. The Yangtze River Basin is suitable for geothermal heating in winter and geothermal cooling in summer. South China is suitable for geothermal cooling.

5. CONCLUSIONS

(1) The NE-trending second subsidence zone, which consists of a series of meso-Cenozoic basins, is developed in eastern China, including Songliao Basin, Bohai Bay Basin, South North China Basin, North Jiangsu Basin, Jianghan Basin, Sanshui Basin, Beibu Gulf Basin, etc. The combination of multiple epochal and geodynamic mechanisms has formed a "flyover" pattern of crust-mantle structure in eastern China, and the shallow surface is characterized by a pattern of scattered distribution of basin-mountain, uplift and depression.

(2) Since Cenozoic, the differences in deep geological structure and deep thermal regime of different blocks in eastern China have formed the enrichment and distribution characteristics of geothermal resources with their own characteristics. The deep geothermal resources are mainly distributed in the Mesozoic and Cenozoic sedimentary basins, but the abundance of resources is relatively low, mainly in the medium temperature geothermal resources, lack of high temperature geothermal resources.

(3) In terms of development and utilization, geothermal power generation is generally not recommended, and direct utilization is recommended. Geothermal heating is proposed for Northeast and North China, and geothermal heating in winter and cooling in summer are proposed for the Yangtze River Basin, and geothermal cooling is proposed for southern China. At the same time, geothermal energy can also be used for agriculture and tourism according to local conditions.

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