Proceedings World Geothermal Congress 2023
Beijing, China, April 17 – 21, 2023

An analysis of the physical characteristics and thermal structure of typical basins in Eastern China

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Keywords: geophysical properties, sedimentary basin, Eastern China, thermal conductivity, heat generation rate

ABSTRACT

China is rich in geothermal resources, which are mainly concentrated in basin areas. Among them, the large sedimentary basins in the east of China have great potential and demand for the development and utilization of geothermal resources. These basins are characterized by a large exploration depth, a long development history, and a high research degree. This paper focuses on the Songliao Basin, North China Basin and Zhangzhou Basin, which are representative of thermal storage characteristics in eastern China. The present study selected deep boreholes above 4000m in three basins, constructed the physical columns (porosity, permeability and thermal properties) deep to the basement of the basin are constructed, and elaborated the water-heat transport patterns in different basins. The main conclusions are as follows: the differences of thermal conductivity and porosity of shallow geotechnical layers are the key factor leading to the redistribution of deep thermal energy in shallow layers of the earth, and the difference of physical properties is an intrinsic influencing factor of hydrothermal transport. The current study proposes the heat model of low permeability homogeneous thermal properties controlled in Songliao basin, high permeability and high thermal conductivity layer controlled in North China basin, and the water and heat by fracture network controlled in Zhangzhou basin. The Curie surface and Moho surface are indicative of the thermal structure of the basin, while the shallow Curie surface represents the strong thermal activity in the present time, which is corresponding to the crustal source heat production, and the shallow Moho surface represents the strong mantle thermal activity in the historical period, corresponding to the mantle source heat production. The study could provide theoretical guidance and data support for the geothermal prospecting in eastern China.

1. PREFACE

Geothermal is an indigenous energy source buried beneath the Earth. During the 4.6 billion years of evolution of the Earth, the heat generated by the continuous decay of radioactive materials in the Earth has been emitted into the atmosphere every moment in the form of geothermal heat flows, though in certain tectonically active areas of the Earth, geothermal energy manifests in the form of volcanoes, hot springs, earthquakes, etc. It has been calculated that the annual heat energy emitted to the surface from the Earth interior is equivalent to the heat generated by burning 50.6 billion metric tons of coal. The geothermal system is a relatively closed whole formed by the interaction of groundwater activities and the geothermal field. The influence of groundwater activity in different tectonic zones on the regional geothermal field and the distribution of heat flow is an important topic in the current research of basic geothermal theory. The convective heat transfer effect of groundwater in the circulation process is a key factor in the formation of geothermal anomalies, and in fact traditional geothermal prospecting is focused on finding geothermal water.

Large sedimentary basins are the main reserves of underground hot water in China, as these areas are suitable for burial, concentrate thermal reservoir stratigraphy, have sufficient water-rock heat exchanges and are suitable for large-scale development. Preliminary estimates show that these sources account for about 70-80% of the total hydrothermal geothermal resources in China, and the large-scale development of basin-type underground thermal reserves has become the main direction of geothermal resource exploration and development in China in recent years. The regional thermal background of the eastern basins of China is significantly higher than that of the central and northwestern basins, and there is a long history of geothermal development[1,2]. Although research has been carried out in basin geothermal for many years and accumulated abundant data, it mainly concentrate the recovery of the thermal history of the basin, the recharge sources of hot water, and the genetic mode of thermal storage. Most scholars proceed from research methods including the geochemical components in geothermal water to determine recharge sources, circulation paths and the storage time of geothermal water, all from the perspective of underground how water circulation and being economical and efficient. However, as the depth of thermal storage exploration increases and more information is obtained from geological exploration, it would be of greater significance to study geothermal heat by combining the hydrothermal cycle in shallow layers and the heat conduction theory of rocks in deep layers.

Groundwater circulation and water-rock heat transfer are the key 3factors of the formation of geothermal anomalies, as the thermal anomalies driven by groundwater circulation are much greater in the shallow surface of the earth than those caused by heat transfer under the difference in rock properties. This paper is based on deep well data from three typical tectonic basins, namely North China basin, Songliao basin and Zhangzhou basin, which have a long history of geothermal development and have been adequately studied to some extent. The present study selects representative ultra-deep scientific drilling that has been completed in recent years. It would provide theoretical support for the exploration and development of the sedimentary basins in Eastern China.

2. TYPICAL EASTERN BASIN THERMAL BACKGROUND

Dr. White was the first to propose the classical model of convective geothermal systems, which suggests that groundwater continuously draws heat from the surrounding rocks during runoff and thus increases in temperature, forming hot springs at the

surface in well-connected tectonic areas and thermal reservoirs in the more permeable subsurface. Dr White discussed the components of a complete geothermal system in terms of "source, passageway, storage and cover"[3].

The North China Basin in Eastern China was the earliest region to carry out the geothermal research. In the 1980s, based on a large number of drilling and temperature measurements, rock sample collection and data analysis, and water sample analysis, Chen Moxiang[4]proposed a geothermal genesis model in which heat conduction was the main factor in North China; based on a large amount of oil exploration holes, Yan Dunshi and Wang Shejiao examined the geothermal resource development potential and distribution pattern in the North China oilfield area[5,6]; Ren Zhanli, He Lijuan and Qiu Nansheng[7-10] systematically investigated the geothermal formation mechanism in the sedimentary basin in eastern China; Pang Zhonghe, Wang Guiling, Ma Feng, Zhang Baojian and others gradually developed and refined a multifaceted polythermal model of ancient subduction mountains based on geothermal development and drilling data in the Xiongan New Area.

There are two perspectives of the formation of the higher thermal background in northern China. One is kraton disruption. The north China crust, which originally boasted kratonic crustal properties, has undergone massive ductile deformation and magmatic-formation activities, and the north China kraton has suffered disruption since the Phanerozoic. This assertion can be supported by the exposure of volcanic veins in several boreholes, such as D16, D19, D17, D21 and so on, which were constructed in Xiongan New Area in recent years[11]. The other is the mantle column theory[12]. It is believed that the lower part of the North China Fault Zone is a mantle uplift, expanding from the center to the periphery in a mushroom shape. At the top of the mantle thermal column, with the light mantle material in the form of basaltic wall or basalt spurting upward, the upper crust warmed and fractured thus forming a series of large compound fracture basins and received the accumulation of loose sediments about 500~30,000 m thick. As a whole, the North China region is regarded as the geothermal resource area formed under the mechanism of geothermal flow, which is mainly of conduction type and low-temperature hot water type. The distribution of geothermal heat flow in the North China Basin is determined by the regional crust-mantle uplift zone, argillic zone and transition zone distribution. The geothermal heat flow values in the basin range from 50 to 80 mW/m^2 , slightly higher than the national continental average.

Shi Shangming, Jiang Guangzheng and Shi Yidao[13-15] conducted a systematic study on the thermal structure of the northeastern basin. They analyzed the sources and composition of subsurface thermal energy in the Songliao Basin in terms of basin steady-state thermometry, thermal property testing, geothermal heat flow, radiogenic heat production and thermal structure, examined the transport mechanism, and discussed the main controlling factors of the geothermal field and the main tectonic-thermal mechanisms that have shaped the presen thermal state of the basin. With sandstone as the dominant thermal storage lithology, the Songliao Basin is a typical Cretaceous terrestrial sedimentary heat basin in China. The average geothermal heat flow in the whole basin is about 68.24 mW/m^2 , higher than the global average of 63 mW/m^2 and the average heat flow value of 61.5 mW/m in China[2] . The average geothermal temperature gradient is about 3.8°C/100m, the highest among sedimentary basins in China, and the value of geothermal temperature gradient in some areas exceeds 5°C/100m. The thermal structure of this area has also been studied by previous authors. Based on the analysis of the thermal structure characteristics of the crust, Han Xiangjun[16] collected 81 geothermal heat flow data in the Northeastern region in a systematic manner and regarded the upper mantle of the region as the intrinsic factors causing the heat flow distribution. The results of the third edition of the geothermal heat flow data compilation[17] showed that in the eastern part of China, the flow extended from the southeast coast to the north in the North China Basin and the Songliao Basin. It constitutes a high heat flow zone in the eastern part of mainland China, where the heat flow value of the Songliao Basin ranges from 44.4 to 90 mW/m^2 , and the average heat flow value is as high as 70.9±14.4 mW/m^2 . The high heat flow of the Songliao Basin and the surrounding area is concordant with the distribution of Cenozoic mantle-derived base-superfundamental volcanism. The deep mantle convection caused by the westward subduction of the Pacific plate is a major factor in the distribution of high heat flow[18,19] .

Plate tectonic theory suggests that the collision, subduction, and subsidence of the Eurasian plate with the Pacific plate and the Philippine plate in the southeastern land margin zone of China directly influence the southern part of China. Located in the Southern China mainland and adjacent to the western Pacific Ocean, the Zhangzhou Basin in Fujian province exhibits the dynamics of crustal growth and continental accretion on the continental margin. Being both a land-ocean transition zone and a zone of intense exchange of crust-mantle material and energy, it is the most remarkable lateral discontinuity region on Earth and is mainly controlled by the NE-oriented deep large fracture zone.

Wang Jiyang, Pang Zhonghe and Sun Zhanxue[20-22] carried out a systematic study on the geothermal genesis pattern of the Zhangzhou Basin along the southeast coast of China. The Zhangzhou Basin is a typical geothermal anomaly in the southeast coast of China, with a tectonic pattern of northeast fracture conducted heat and northwest fracture-conducted water. Most of the hot springs exposed in Zhangzhou area are 40-80°C. It is also the largest area in Fujian Province with abundant geothermal water, with the highest temperature reaching 121.5°C. In some places, the hot springs are exposed in the form of hot springs, and the hot spring development is generally northeast-oriented, which is consistent with the direction of the fractures. Most of the hot springs are exposed at the intersection of north-east and north-west tectonics. Teng Jiwen et al.[23] suggested that there is a deep, large fracture zone between Zhangzhou and Changtai that runs through the crust and reaches the top of the upper mantle, which may constitute a channel for the upward transport of deep material, i.e. a recharge pathway for thermal energy. Pang Zhonghe[21] believed that the Zhangzhou Basin is a medium-to-low temperature convective geothermal system, in which the fracture water in the low-permeability granite body on a high regional thermal background extracts and carries the heat from the rocks to the shallow discharge zone during deep circulation, as groundwater concentrates upward to the surface through the high-permeability zone formed by the intersection of tectonic fracture trunks. It is also believed that the heat storage temperature of the Zhangzhou geothermal field is not higher than 150℃, and the total geothermal resource ratio is not large. Based on a systematic collection of gas isotope analysis, Sun Zhanxue et al[22] concluded that the deep gas in the southeast coastal area has a crustal source component and the crustal source heat production has a large contribution to the heat flow.

3. PHYSICAL CHARACTERISTICS OF THE EASTERN BASIN

3.1 Thermal conductivity column construction

The thermal conductivity column construction in the Songliao Basin was represented by the Songke 2 well, and thermal conductivity samples were tested from 2865 to 6995m with an interval of about 10m, covering strata including the Cretaceous Nengjiang Formation, Denlouku Formation, Yingcheng Formation, Shahezi Formation, Jurassic Huoshiling Formation and basemen. The lithologies of the samples included sandstone, conglomerate, mud shale, tuff, volcanic agglomerate and shallow metamorphic sedimentary rocks. The 435 groups of rock thermal conductivity data were collected to obtain the average thermal conductivity of different strata and lithologies based on the comparison and analysis. From the average thermal conductivity of the different stratigraphic groups (Figure 1), the basement had the highest thermal conductivity with an average value of 3.1 W/（m·K）, followed by the Yingcheng Formation, the Huashi Ling Formation and the Shahezi Formation, with the Shahezi Formation at 2.84 W/（m·K）.

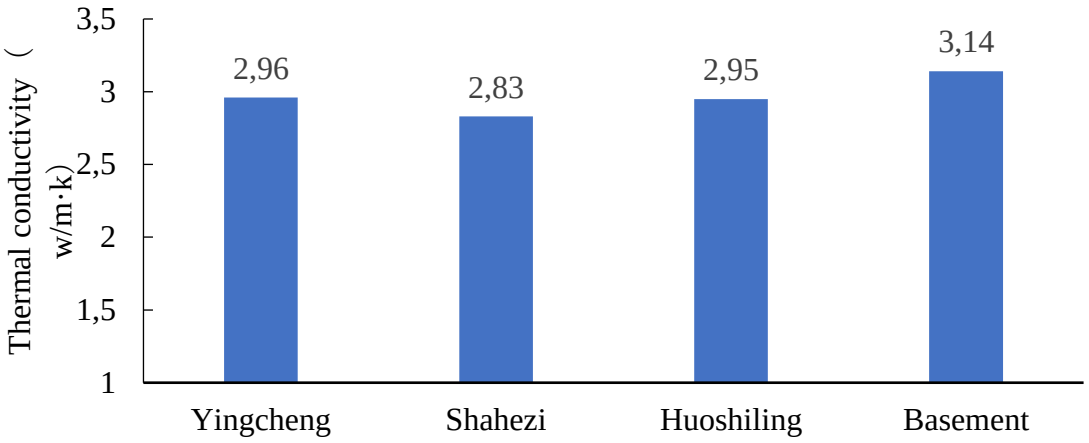


Figure 1: Distribution of the average thermal conductivity corresponding to the different layer groups

The lithology was classified according to the encounter stratigraphy of the drilling. The conglomerates, sandstones and mudstones were classified in the order of grain size. The analysis of the data shows (Figure 2) that conglomerate registers the highest average thermal conductivity of 2.93 W/（m·K）, while sandstone and mudstone both have an average thermal conductivity of 2.85 W/（m·K）. This suggests a close relationship between the rock composition and its thermal conductivity, which is essentially determined by its constituent minerals. The thermal conductivity of rocks decreases with the increasing mud content.

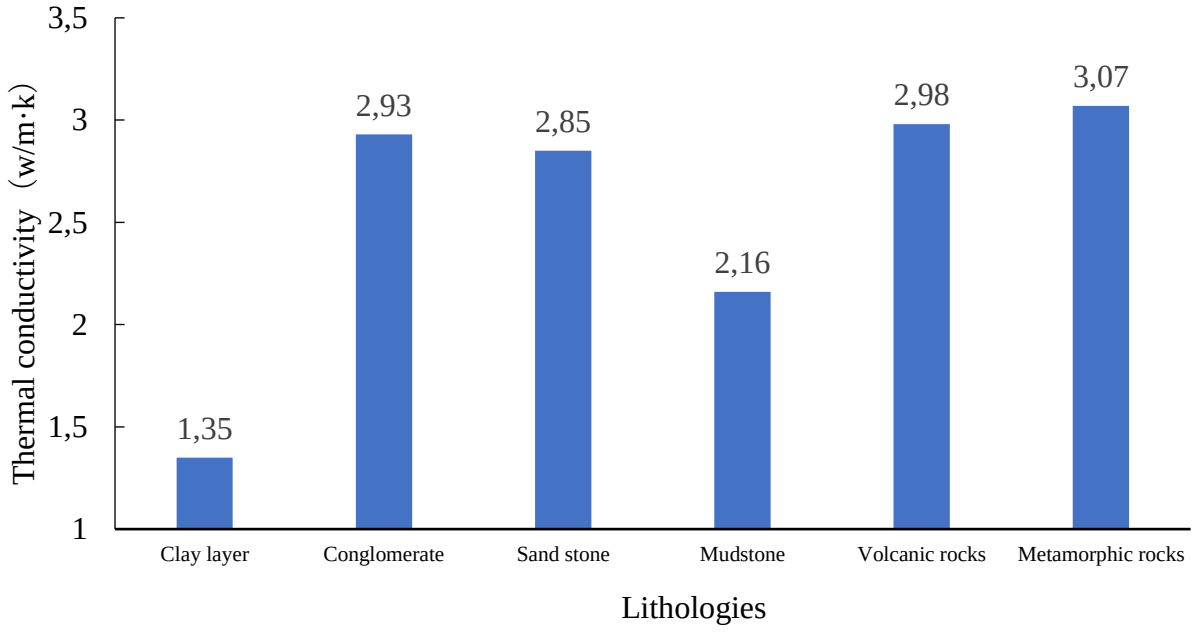


Figure 2: Distribution of average thermal conductivity corresponding to different lithologies

Overall, the measured thermal conductivity ranges from 1.99 to 3.42 W/（m·K），with an average thermal conductivity of 2.74 W/（m·K）. The thermal conductivity varies less from shallow to deep, but with an increasing depth, the thermal conductivity data tends to be more divergent. The entire vertical variation of thermal conductivity can be divided into three sections. From the bottom of the Yingcheng Formation to about 5000m in the middle of the Shahezi Formation, the stratigraphy is dominated by sandstone and Lmudstone and the thermal conductivity remains relatively stable, with an average value of 2.66 W/（m·K）. From the bottom of the Shahezi Formation to the bottom of the Huashi Ling Formation, the lithology is mudstone sandstone interspersed with andesite and rhyolite, et al., and the difference in thermal conductivity becomes larger, with an average value of 2.78W/（m·K）. In the basal tuffs and coarse andesites, the average thermal conductivity reaches 3.15 W/（m·K） (Figures 4-5). It should be noted that the thermal conductivity data presented here are all test results of the samples in an indoor environment. In real conditions, the factors influencing the thermal conductivity by temperature and pressure gradually increase with the increasing depth, and by the maximum depth of 7000 m, the difference between the in situ thermal conductivity and the actual indoor measurements could reach 30%.

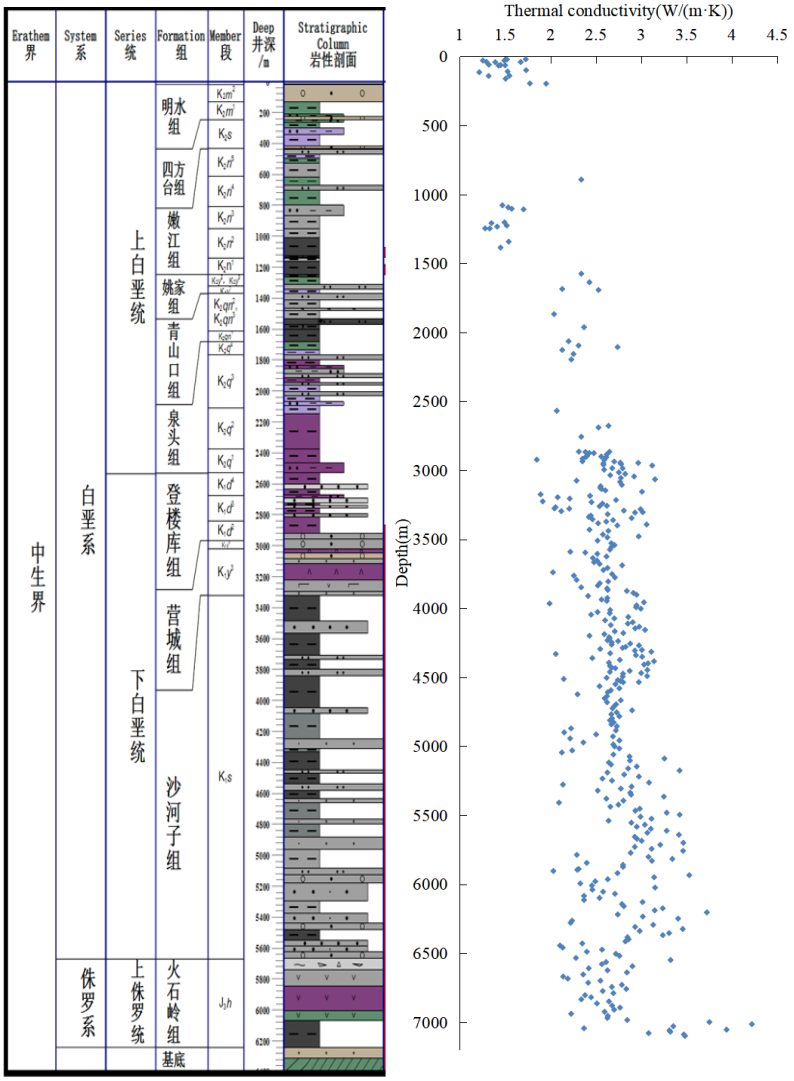


Figure 3: Stratigraphic structure and vertical distribution of thermal conductivity in Songke 2 well

Thirty-two core samples from typical geothermal boreholes in the tectonic bulge area of the North China Basin were selected for the indoor testing of thermal conductivity and radiogenic heat generation rates. Sampling depths reached 4000m and samples included 10 sandstone samples, 18 carbonate samples and 4 sets of metamorphic samples.

The thermal conductivity of the North China Basin presents a “sandwich” distribution, meaning “small at the both sides and large in the middle” (Fig. 4). The thermal conductivity of the overlying Neoproterozoic and Paleoproterozoic sandstones ranges from 1.27 to 2.57 W/（m·K），with an average value of 2.12 W/（m·K）. The thermal conductivity of the carbonate reservoir in the middle part is significantly higher, 5.51 W/（m·K）on average, higher than most of the sedimentary rocks. Under the conditions of high porosity

and high water-richness, hydrothermal convection is strong and heat forms secondary heat, gathering with water transport which is therefore an intrinsic factor for the formation of high-quality thermal reservoirs in the tectonic bulge area of the North China Basin. In the bottom terrigenous gneiss, with an average thermal conductivity of 3.03W/（m·K）, the regional thermal conductivity is stable and consistent. The dense lithology forms a steady-state thermal conduction mechanism. Taking boreholes D17 and D01 in Xiongan New Area as an example, after uncovering the target thermal reservoir into the Tertiary, the gneiss thermal conductivity is 3.16 W/（m·K） and 3.51 W/（m·K） respectively, and the ground temperature gradient under steady-state logging conditions is 17.4-21.5°C/km, with an average value of 19.3°C/km which shows no obvious warming anomalies. This also provides supporting evidence that no high-quality thermal reserves exist in the deep Terrigenous basement of the North China Basin that could be developed on a large scale under current economic conditions. Based on the steady-state thermometry and thermal conductivity of the metamorphic basement section with underdeveloped fractures in the Terrigenous, a geothermal heat flow value of 64.5 mW/m was calculated for the first time in the North China Basin. The vertical variation characteristics of the thermal conductivity column show that the heat flow value is a steady-state beneath the thermal reservoir dominated by heat conduction which reflects the steady-state heat flow background in the form of heat conduction to the shallow surface in the North China Basin. The geothermal heat flow values calculated from the heat conduction-dominated Swalterian gneiss section are closer to reality than those from the more convective Cenozoic cover and Middle and Upper Palaeogene karst reservoirs[24,25].

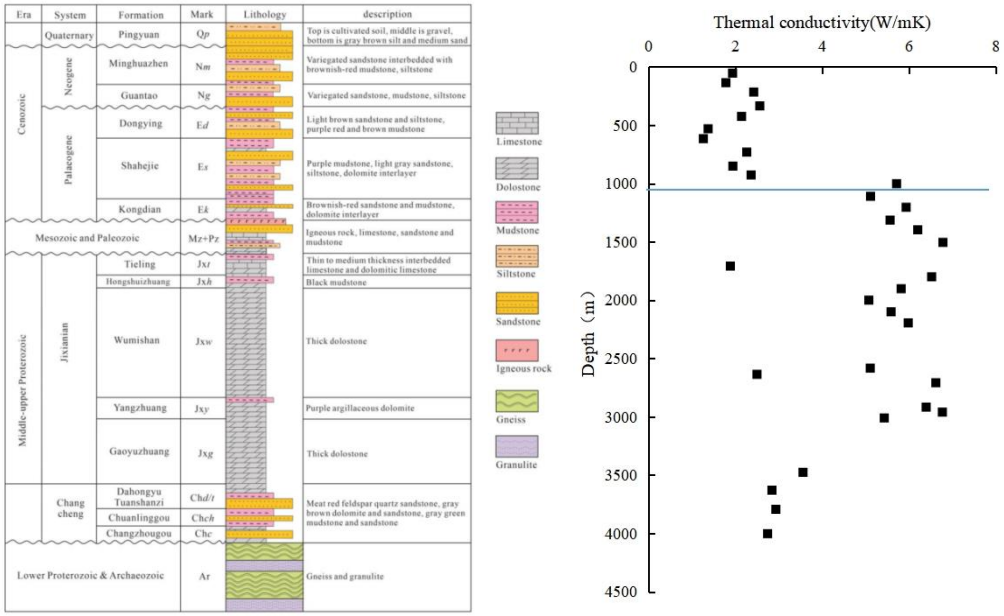


Figure 4: Vertical distribution of thermal conductivity in the North China Basin

The thermal conductivity of the Zhangzhou Basin shows a gradual increase from top to bottom (Figure 5), with an average thermal conductivity of 3.14 W/（m·K）, higher than the other two basins. Due to the homogeneous lithology, heat is relatively evenly distributed throughout the rock layer, and the large thermal conductivity does not produce a zone of heat accumulation similar to that in the North China Basin. Therefore, in Mesozoic granite basins like the Zhangzhou Basin, the controlling factor is still fracturing tectonics, despite the high heat flow values. The longer the fluid is circulated in the rock, the more adequate the heat exchange and the higher the fluid temperature.

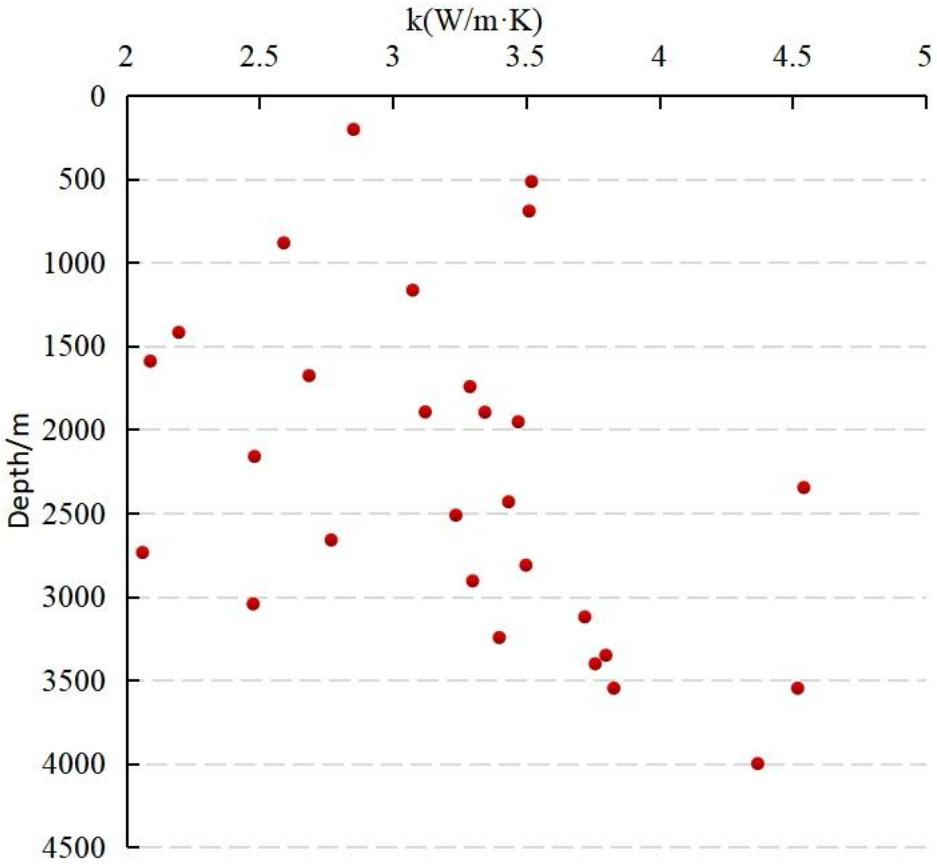


Figure 5: Thermal conductivity of Zhangzhou HDR 1 well

3.2 Heat generation rate column construction

Songliao Basin: From the analysis of the stratigraphic data of the Songke 2 well drilled from top to bottom (Figure 6), the highest content of Th elements is found, followed by K and U elements. In general, the content of U and Th elements decreases with the increasing depth, while the content of K elements is relatively stable. The Yaojia Formation has the highest Th content of 10.8 (μg/g) followed by the Nengjiang Formation, Dengluku Formation, Shahezi Formation, Base rock, Huoshiling Formation and Yingcheng Formation. The Yingcheng Formation having the lowest Th content. The highest U content is 3.71 (μg/g) in the Nengjiang Group, followed by the Denglouku Group, Yingcheng Formation, Yaojia Formation, Shahezi Formation, Kidi and Huoshi Ling Formation, with the lowest U content in the Huoshi Ling Formation; the highest K content is 3.19% in the Yingcheng Formation, followed by the Denglouku Formation, Shahezi Formation, Yaojia Formation, Huoshi Ling Formation, Baserock and Nengjiang Formation, with the lowest K content in the Nengjiang Formation.

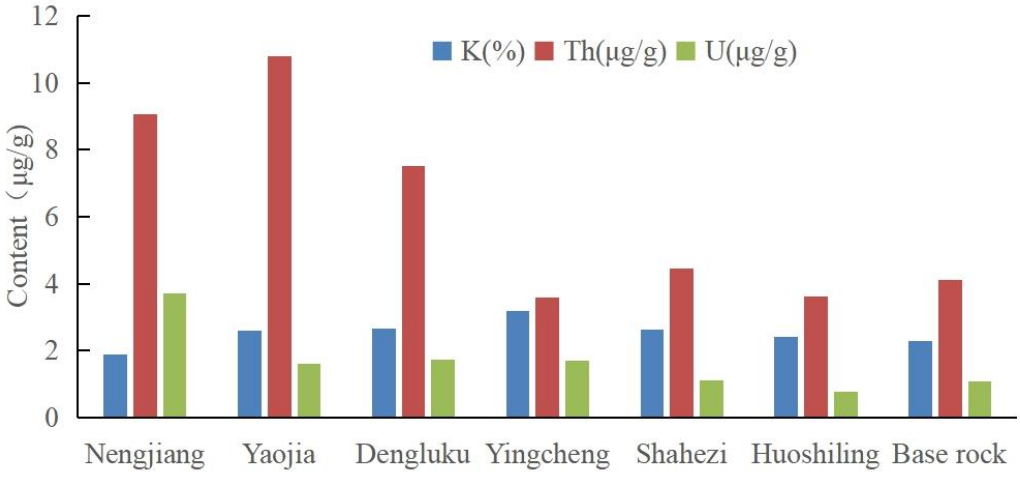


Figure 6: Average radioactive element content of different layer groups in the Songke 2 well

The radiogenic heat generation rates for the Songke 2 ranges from 0.228 to 1.65μW/m^3 with a mean value of 0.772μW/m^3. It is clear from the rock heat generation rate results (Figure 7) that the lithology varies. The mudstone corresponds to the largest heat generation rate with a mean value of 0.825μW/m^3, followed by volcanic, sandstone, conglomerate, and metamorphic rocks. The main reason is that the content of U and Th varies considerably between lithologies, and it is clear from the graphs of radioactive element content corresponding to different lithologies that mudstones contain more Th and K than sand conglomerates, volcanic rocks, and metamorphic rocks.

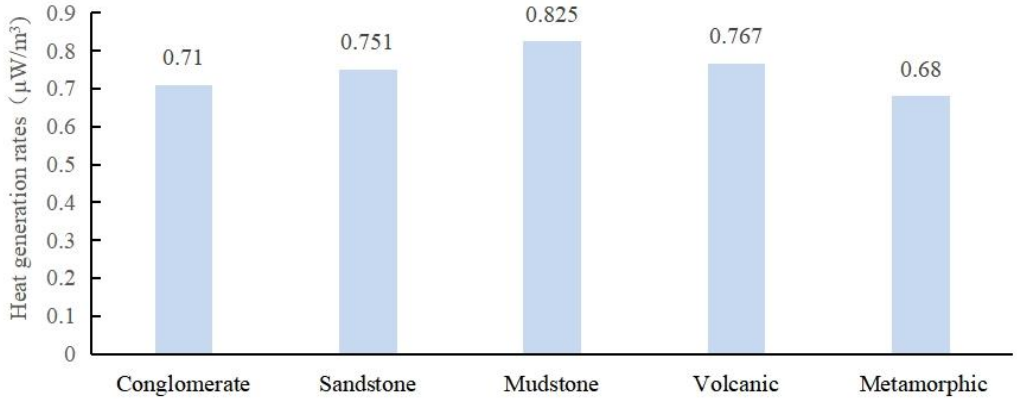


Figure 7: Heat generation rates corresponding to different lithologies

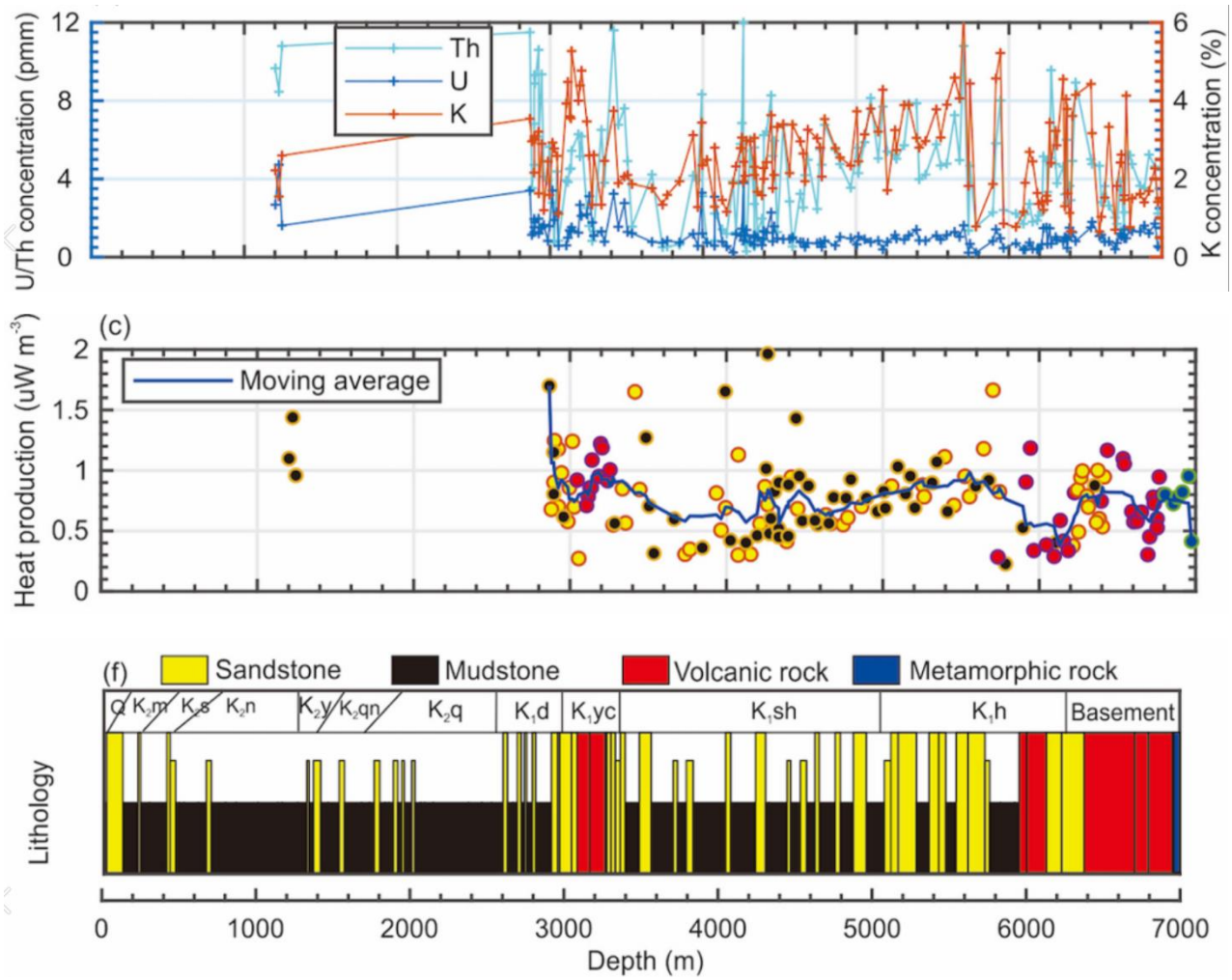


Figure 8: Heat generation rate with Depth (Jiang Guangzheng et al.)

(a) U-Th-K concentrations (b) heat production rates (c) Songke-2 stratigraphic column. Stratigraphic markers: Huoshi Ling Formation (K_1 h), Shahezi Formation (K_1 s), Yingcheng Formation (K_1 y), Denglouku Formation (K_1 d), K_2 q for the Quantuo Formation, K_2

qn for the Qingshankou Formation, K_2 y for the Yaojia Formation, K_2 n for the Nengjiang Formation, K_2 s for the Sifangtai Formation, K_2 m for the Mingshui Formation, and Q for the Quaternary.

In summary, in terms of the content of radioactive elements uranium, thorium and potassium, the Yaojia Formation has the highest Th content, followed by the Nengjiang Formation and the Denlouku Formation, with the lowest basal Th content; the content of K and U elements decreases from top to bottom. From the content of radioactive elements in different lithologies, it is known that the Th content is the highest in conglomerates, sandstones and mudstones which is two to three times higher than the U content. The heat generation rate depends on the lithology but is caused by the difference in the content of uranium, thorium and potassium in the rocks, with the largest heat generation rate in the mudstone area, because the mudstone contains more Th and K than the sand and conglomerate.

North China Basin: Overall, the heat generation is small. Being large at both side and small in the middle, the "sandwich" distribution pattern of this area is contrary to the thermal conductivity pattern (Figure 9). The average heat generation rate for the entire 4000m is 0.56μW/m^3, the lowest among the three basins discussed in this paper, also lower than most geothermal regions in China. Among them, the overburden is Neoproterozoic and Paleoproterozoic sandstone and mudstone, with heat generation rates ranging from 0.37 to 1.81μW/m^3 , 1.06μW/m^3 on average; the heat generation rate of the carbonate reservoir decreases significantly into the Mesoproterozoic, with an average value of only 0.29μW/m^3 . Due to the development of intrusive veins in the Mesoproterozoic period, the heat generation rate exceeds 1μW/m in some places, . The result shows that with an average thickness of 2000m, the heat generation rate of the Middle Yuan Dynasty strata contributes only 2.5% to the crustal heat flow. The heat generation rate of the metamorphic basement of the Taiyuan Dynasty ranges from 0.44 to 0.83 μW/m^3 , with an average value of 0.59 μW/m^3 , which is slightly higher than that of the Proterozoic strata. Because the metamorphic rocks are several kilometres thick, they become the main crustal heat generation layer in North China. This also indicates that the "hot mantle-cold crust" structure in North China is directly related to the low heat generation rate of the ancient strata within the crust.

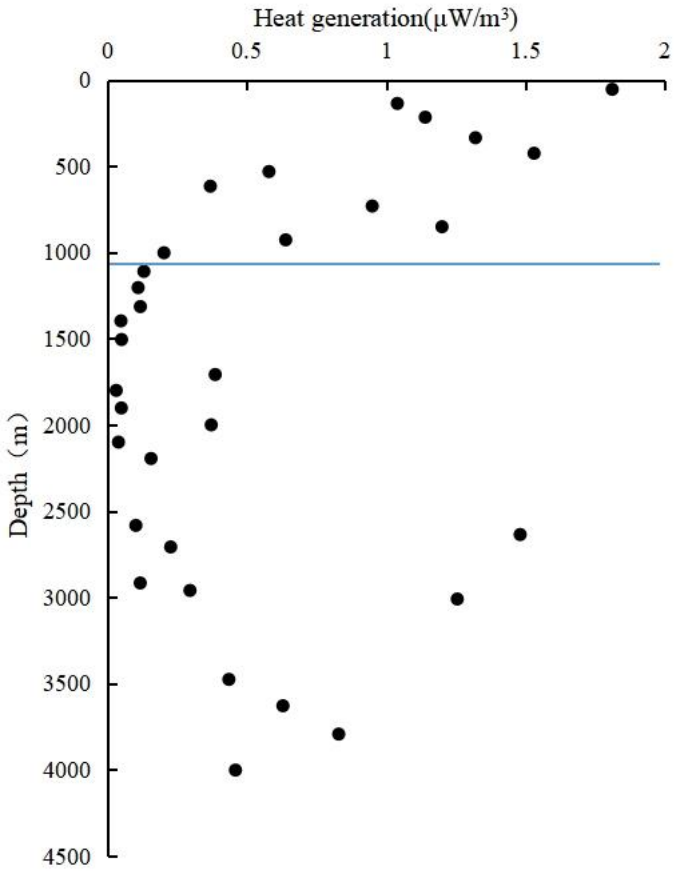


Figure 9: Combined heat generation rate of boreholes in the North China Basin (D16+D17)

Zhangzhou Basin: Based on the date of HDR 1 well, we established the thermal property column, Figures 10 and 11 show that as the lithologies of the whole hole are all dominated by granite without obvious lithological differences, there is no obvious regularity in the vertical distribution of the three radioactive elements U, Th and K. From the radiogenic heat production of the whole borehole, it is still the highest content of Th element with an average value of 18.7 μg/g, significantly higher than that of the Songliao and North China basins, while the average value of U element content is 3.14 μg/g, slightly higher than that of the above two basins. In comparison with previous data, the radiogenic heat generation rate obtained from this borehole is lower, which is related to the representativeness of the sampling and the predominance of deep core samples in this case.

Similarly, the Zhangzhou Basin shows a high Th/U ratio with a mean value of 3.87 which is higher than the global mean value of 2.5. Given the linear relationship between Th/U ratio and D-value proposed by Jaupart et al.[26]which represented the thickness of the

radio-concentrated layer in various heat flow regions around the world and the inference of a D-value of 10 km in eastern Fujian Province concluded by Wan Tianfeng et al.[27,28], the Th/U result of this sampling is slightly lower than the previous result of 3.98. The current results are slightly lower than the previous knowledge of 3.98 Th/U, but generally fall within the D-value range put forward by Wan Tianfeng, which proves that the knowledge obtained from this deep drilling is consistent with that of the previous studies. The low Th/U ratio indicates that the thickness of the radio-concentrated layer in the Zhangzhou Basin should be slightly greater than 10 km.

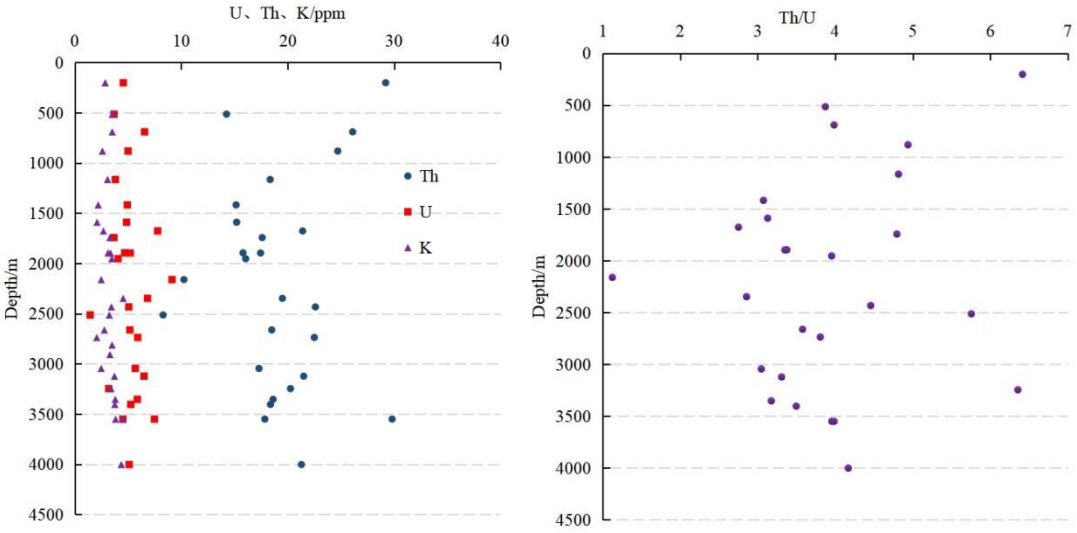


Figure 10: Radioactive element abundance map and U and Th ratios for the Zhangzhou HDR 1 well

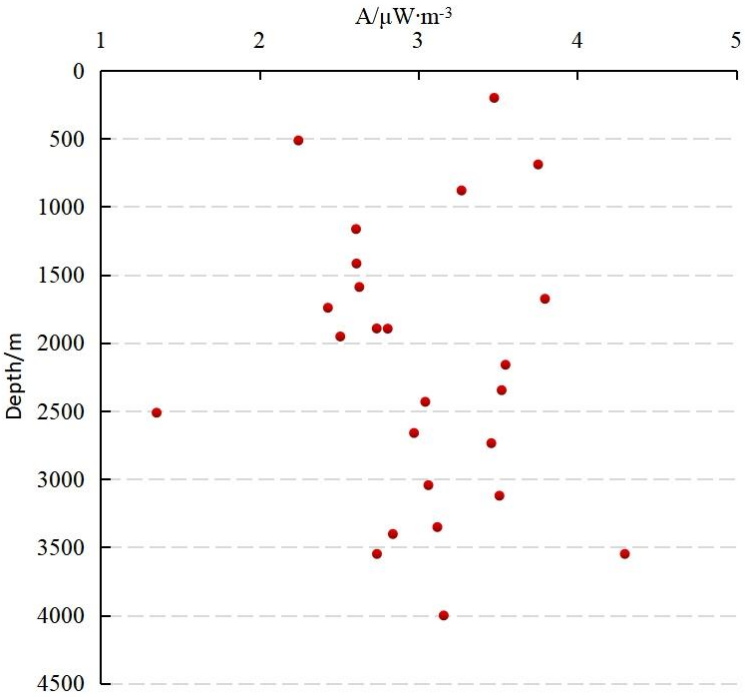


Figure 11: Radiogenic heat generation rate of Zhangzhou HDR 1 well

4. BASIN THERMAL STRUCTURE

4.1 Thermal structure of the Songliao Basin

The Songliao Basin shows a shallow depth of burial in the center of the basin and a high level in the periphery, a pattern which is the opposite of that shown by the Moho surface. This indicates that the center of the basin is dominated by heat production from deep mantle sources, while the periphery of the basin has a significantly higher proportion of heat production from crustal sources. The heat demonstrates a tendency to spread from the center of the basin to the periphery from deep to shallow in the Songliao Basin. The average Moho surface in the Songliao Basin (Figure 13) is 32km deep and dominated by mantle-sourced heat production, while the relatively shallow Moho surface in the center of the basin provides a steady heat flow in the region. The average radiogenic heat generation rate is less than 1 $\mu W/m^3$, which is a “cold crust hot mantle” type thermal structure. In the periphery of the basin, large areas of Yanshan-age granite are developed, and the surface uranium content has been reported to be as high as 7.0 $\mu g/g$[29] which increases the proportion of heat production from crustal sources. The Manzhouli-Suifenhe section shows that the curved surface increases to more than 30 km around Mudanjiang, close to the Moho surface depth. This nonconformity between the curved surface and the Moho surface region is mainly due to the Mesozoic upwelling of mantle material, followed by a period of geothermal activities which form regional extensional subsidence.

Compared with other basins in China, the spatial structure of thermal reservoirs in the Songliao Basin shows more obvious characteristics of layer control. The effective thermal reservoir thickness in the Songliao Basin is significantly smaller than that in the sedimentary basins of North China and Guanzhong[30]. The thin layer structure with strong sandstone mudstone interstratification forms a distinct layer-controlled hydrothermal system in the basin. This phenomenon could be attributed to two aspects. On the one hand, the whole basin is dominated by river and lake deposits, and the frequent alternation of river and lake deposits creates a depositional environment with weak groundwater activities in the later stages. On the other hand, the Songliao basin is dominated by Mesozoic sedimentary strata with a thick overburden, and under long-term high-pressure stress conditions, the consolidation and compression of the strata increase. As the porosity decreases the seepage, the connectivity becomes poor, which affects the formation of regional thermal reservoirs. Therefore, it is difficult to find high-quality large-scale thermal reservoirs in the Songliao Basin, and even if there are laminated sandstone thermal reservoirs with high permeability, they do not form significant thermal anomalies in terms of temperature[31, 32].

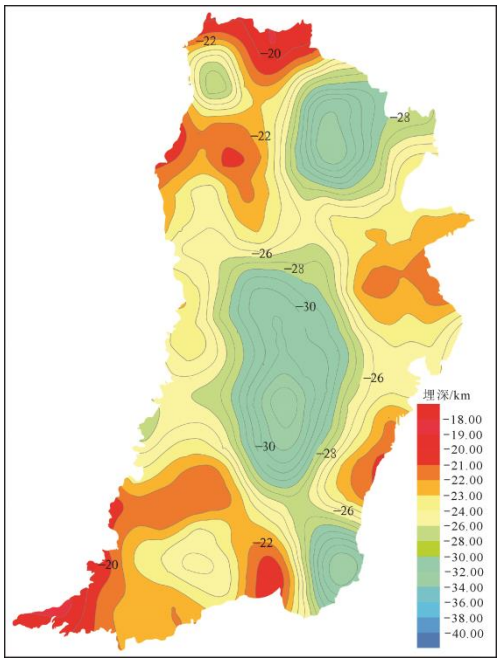


Figure 12: Depth of burial in the Songliao Basin

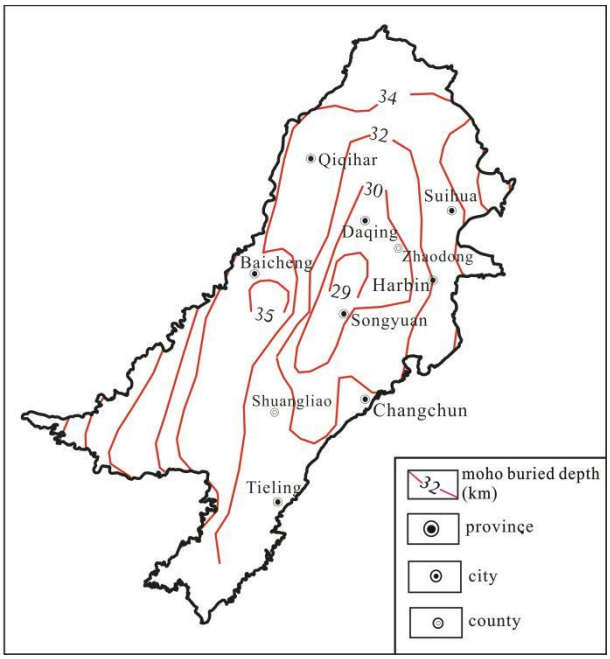


Figure 13: Depth of Moho surface in the Songliao Basin

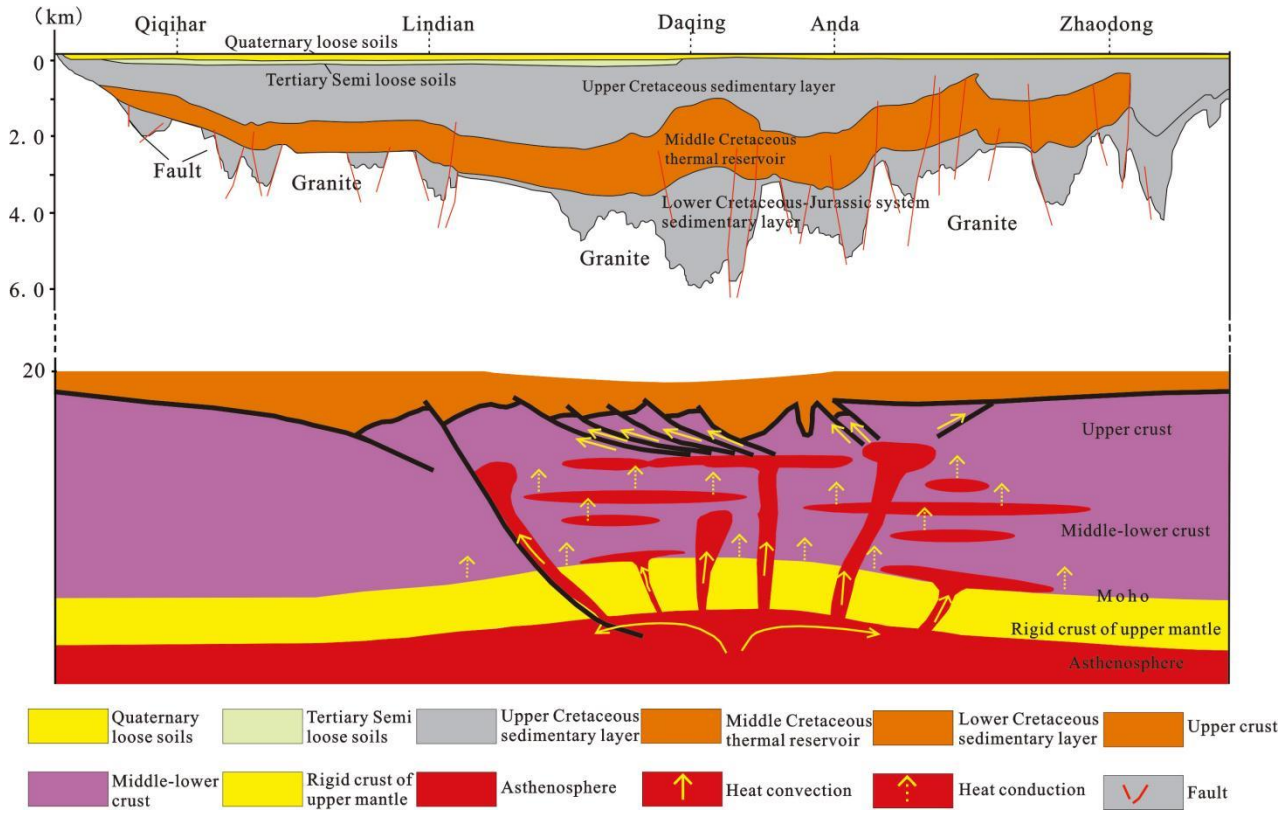
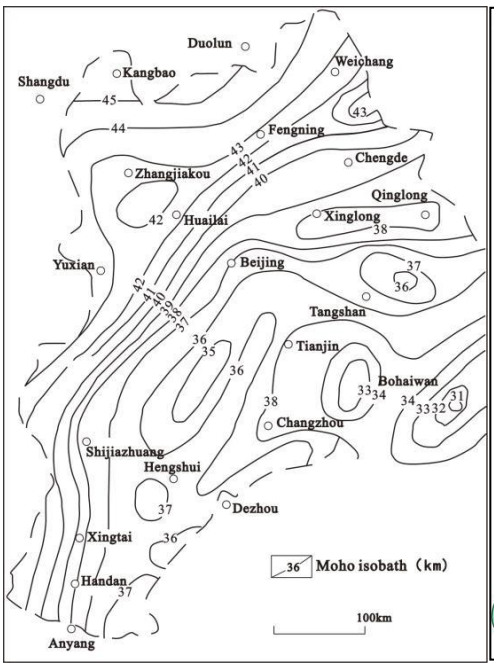


Figure 14: Heat control model in the Songliao Basin(Ma et.al)

4.2 Thermal structure of the North China Basin

The Moho surface in the North China Basin (Figure 15) records a depth of 28-37km, while the depth of the Curie surface (Figure 16) is 20-25km. In general, both surfaces show a relatively uplifted area, and the undulation of the Curie surface is concordant with the pattern of metamorphic basement uplift and depression. Across the whole North China Basin, the Moho surface and Curie feature "deep in the east and shallow in the west". There also exist obvious differences between the thermal states in the east and west, with the crustal and mantle sources producing heat better in the east than in the west. At the same time, the interior of the dwelling shows a pattern of shallow north and deep south. By comparison, the dwelling south of the Shijiazhuang-Hengshui line lies about 1.6km below the Moho surface, indicating that the top of the upper mantle in this region is also magnetic. This situation is associated with low radiogenic heat production in the overburden and relatively inactive tectonic activity at depth, which is a "cold crust-cold mantle" type of thermal structure with low overall geothermal heat flow values. In contrast, the Moho surface in north of Shijiazhuang-Hengshui inside the curved surface becomes shallower at the same time, the heat from the mantle source increases and the proportion of heat production from the shell source decreases, showing a "cold crust-hot mantle" type of thermal structure[33-36].



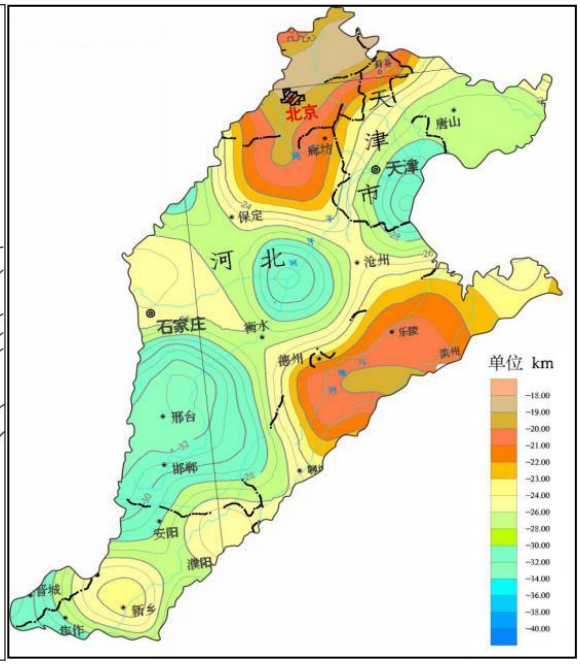


Figure 15: Burial depth contours of the Moho surface in the North China Basin Figure 16: Burial depth contours of the Dwelling in the North China Basin

The measured results of steady temperature of the basement section in the North China Basin show that the average heat flow value is 64.5mW/m^2 , and the average heat generation rate of the entire stratum within 4000m is 0.56μW/m^3 , lower than most regions in China, and is characterized by the "cold crust and hot mantle" type of thermal structure. The shallow thermal conductivity shows a "sandwich" structure featuring "small at both ends and large in the middle" and a strong water-rock interaction of the carbonate thermal reservoir, creating favorable conditions for geothermal development in the region. The steady-state temperature measurement shows a thermal homogenization of the reservoir section with a geothermal gradient close to zero. This geothermal condition is caused by thermal conductivity. The geothermal condition is formed by the layered distribution of thermal conductivity differences that allow heat refraction and aggregation, resulting in a high thermal conductivity and high permeability layer conduction convection heat control pattern in the North China Basin.

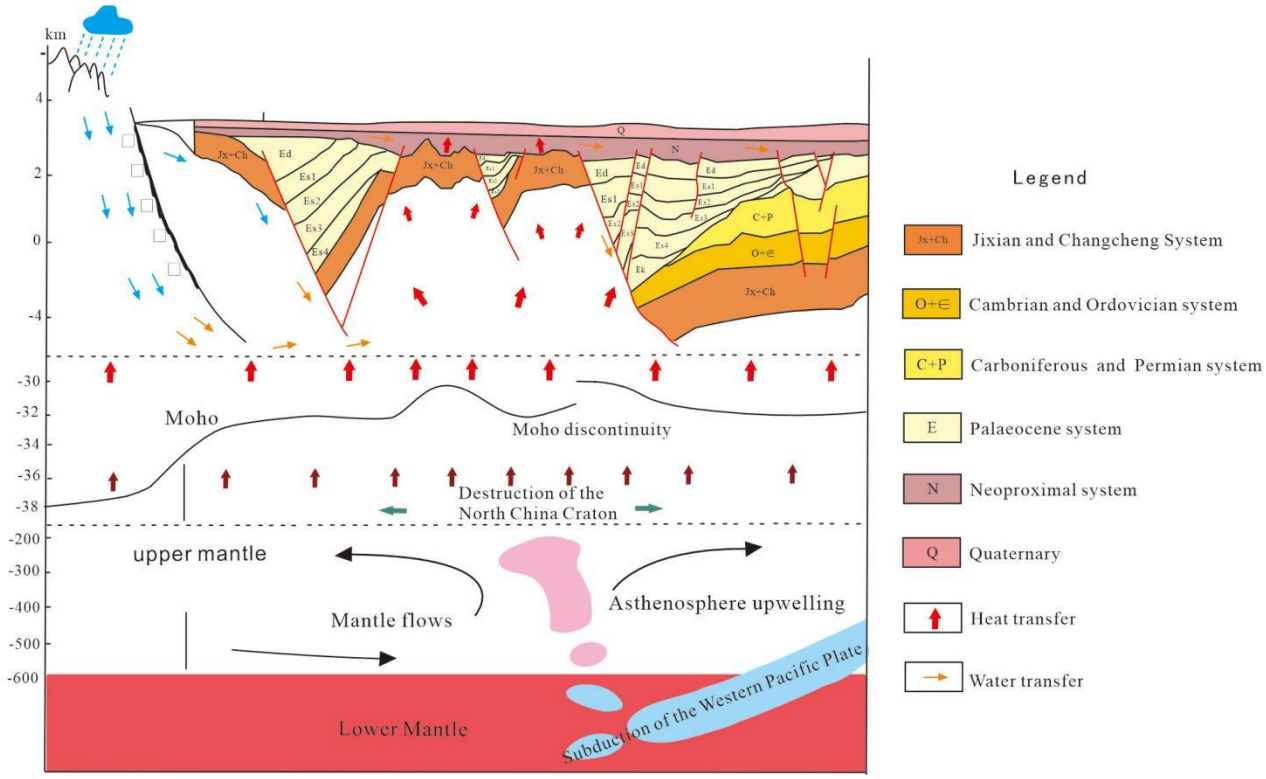
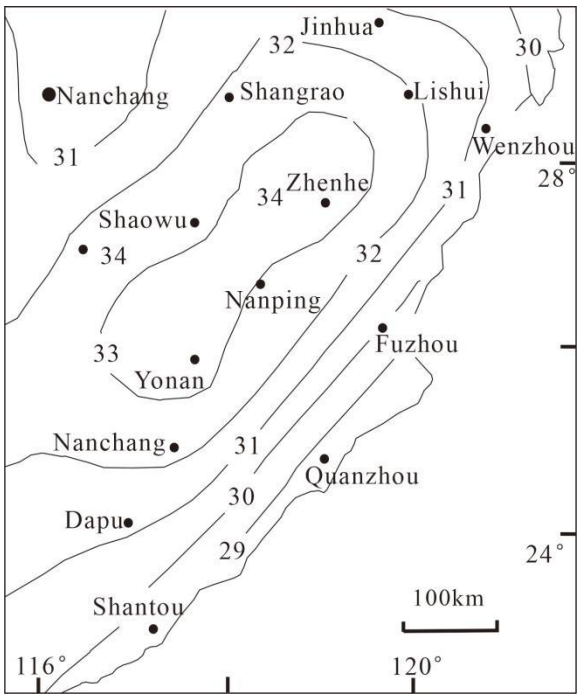


Figure 17: Patterns of heat gathering in the ancient subduction mountains of northern China

4.3 Thermal structure of the Zhangzhou Basin

The Moho surface of the Southeast coast where the Zhangzhou Basin is located at a depth of 29~31km (Figure 18), and the depth of Curie is 22~26km (Figure 19). In general, both the Curie and Moho surfaces are relatively shallow, but the Curie is shallower than the Moho surface. Both the mantle source heat production and the crust source heat production have a greater contribution to the heat flow, but the mantle source heat flow is still higher than 50%, showing a "cold crust and hot mantle" type of thermal structure. From the regional point of view, the inside of the dwelling is highly undulating, showing a trend of increasing the burial depth of the dwelling from coastal to inland. The burial depth of the Moho surface also shows the shallow characteristics in the Eastern coastal area and deep inland area. This indicates that the Zhangzhou Basin would continue to experience strong deep tectonic activities in the future geological period, and which remains a favorable target area for future geothermal exploration and development in terms of thermal structure type.

Steady-state temperature measurements in the Zhangzhou Basin HDR 1 well show a regional background heat flow value of 79.5 mW/m^2 , which is a "cold crust-hot mantle" type of thermal structure in a high heat flow context. This cold crust is significantly hotter than the western basin and accounts for a high proportion of crustal heat when compared to the North China Basin and the Songliao Basin. The fact that the basin is shallower than the Moho surface indicates that it is still in a relatively active thermal tectonic environment. The HDR 1 well reveals a mean radiogenic heat rate of 3.02 μW/m at $4000m^3$ and a mean thermal conductivity of 3.14 W/（m·K） with a scattered distribution. The whole-hole geothermal gradient is stable and tends to increase from top to bottom, from an average geothermal gradient of 1.82°C/100m at shallow depths of 2000m to an average geothermal gradient of 2.69°C/100m at 3000-4000m. The basin is influenced by a single lithology and the relatively homogeneous thermal physical structure which does not lead to a regionally homogeneous geothermal field. The spatially inhomogeneous character of the porosity permeability properties plays a role in the heat-controlling and water-controlling tectonics and hydrothermal activity became the key causal factors of the geothermal anomaly, finally forming the water-controlling and heat-controlling pattern of the Zhangzhou Basin rift network[37].



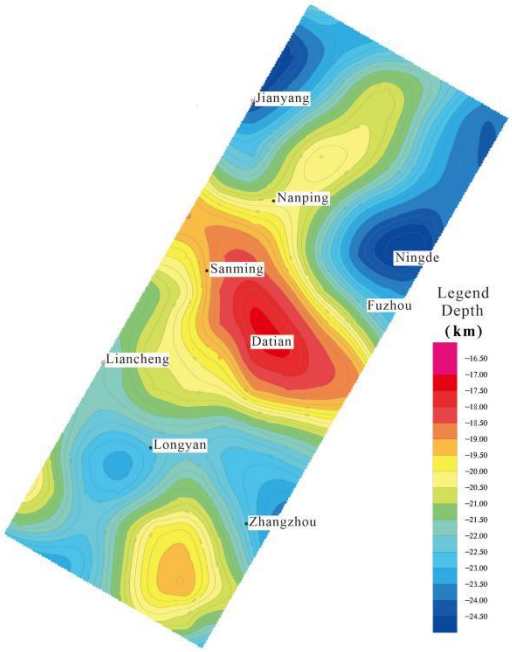


Figure 18: Depth of burial map of the Moho surface along the southeast coast[38] Figure 19: Depth of dwelling map along the southeast coast

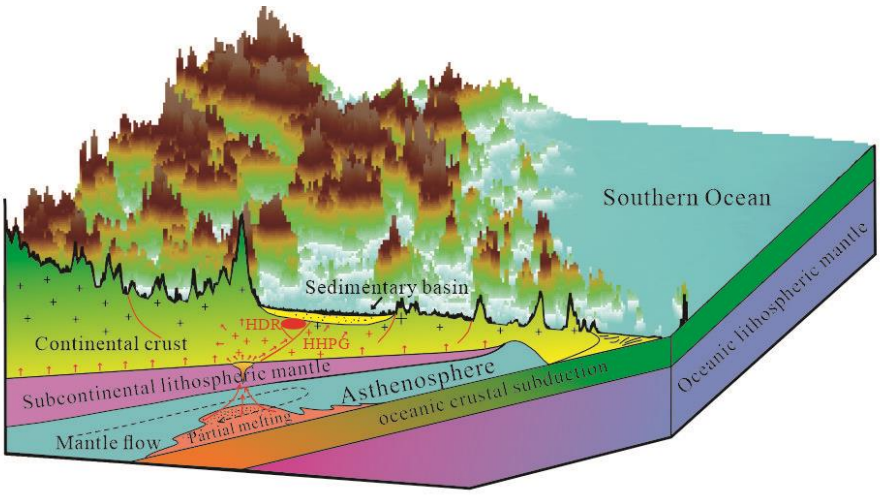


Fig. 20: Map of the genesis of the hydrothermal system of the Southeast Coastal Thermal Control Structure[39]

5. CONCLUSION

This paper starts from the study of physical characteristics and heat aggregation under different physical conditions in typical basins in China as well as the seepage heat transfer in fissures. By analyzing the temperature measurement data and physical vertical variation patterns of typical deep boreholes in the Songliao Basin, North China Basin and Zhangzhou Basin, combined with the analysis of heat transfer and heat aggregation of underground hot water, the current study establishes a representative physical column in the three basins and proposes the heat control pattern of the shallow surface layer under the influence of geothermal water circulation in the three basins. The thermal structure of the basins are also analyzed by combining the spatial variation characteristics of the Curie and Moho surfaces. The main results and insights are as follows.

(1) By constructing the physical columns of three typical basins in eastern China, the spatial distribution pattern characteristics of thermal conductivity and radiogenic heat generation in the basins are analyzed, concluding that the Northeast Basin and the Zhangzhou Basin have relatively homogeneous thermal conductivity characteristics in the vertical direction, indicating that heat has steady-state conduction characteristics in the rock bodies of the two basins. The North China Basin shows a sandwich structure with a large middle and small sides, and the carbonate strata with high thermal conductivity in terms of heat generation rate. Both the Northeast Basin and the North China Basin exhibit a small radiogenic heat generation value, while the Zhangzhou Basin thermal storage granite has a relatively high heat generation rate, indicating that the crustal source heat generation in the Zhangzhou Basin is significantly higher than that in the Northeast and North China Basins.

(2) This paper explores the characteristics of the thermal structure of three typical sedimentary basins in eastern China, constructs a physical column of the basin deep to the basement, and illustrates the intrinsic control factors of heat transfer from deep to shallow. The process of groundwater circulation and percolation is also a process of water-rock heat exchange. Differences in thermal conductivity and porosity of shallow geotechnical layers are key factors leading to redistribution of deep heat energy in shallow layers, and the differences in physical properties are intrinsic influences on water-heat transport. The heat control model is low permeability homogeneous thermal properties in the Songliao Basin, as high permeability high thermal conductivity layers in the North China Basin and fracture networks controlled in the Zhangzhou Basin. The shallow Curie and Moho faces are indicative of the thermal structure of the basin, with the shallow Curie representing strong present-day thermal activity, corresponding to crustal heat production, and the shallow Moho face representing strong mantle-derived thermal activity in historical times, corresponding to mantle-derived heat production.

(3) It is recommended that future exploration of geothermal resources in the basin should be carried out on the basis of figuring out the thermal structure of the basin and the mechanism of geothermal genesis. Further work should focus on the exploration of regional high-permeability thermal reserves in the North China Basin and the Northeast China Basin, and the exploration of high-quality rift-controlled thermal geothermal fields in the Zhangzhou Basin. The development of medium- and low-temperature heating in the north and geothermal hot springs for therapeutic heat production in the south should be promoted comprehensively.

REFERENCES

[1] WANG Guiling, Lin Wenjing. 2020. Main hydro- geothermal systems and their genetic models in China[J].Acta Geologica Sinica,94(7):1923-1937.

[2] Wang G L, Wang W L, Zhang W, et al. 2020. The status quo and prospect of geothermal resources exploration and development in Beijing-Tianjin-Hebei region in China[J]. in China[J]. China Geology, 3(1):173-181.

[3] White, D. E.. Thermal waters of volcanic origin. Geol. Soc. Am. Bull, 1957, 68: 1637-1659.

[4] Chen Moxiang. 1988. Geothermal in North China [M]. Beijing: Science Press .

[5] Yan Dunshi, Yu Yingtai .2000.Evaluation and utilization of geothermal resources in the oil region of Beijing, Tianjin and Hebei [M]: China University of Geosciences Press .

[6] Wang Shejiao, Li Feng, Yan Jiahong, et al. Evaluation methods and applications of geothermal resources in oil fields[J]. Acta petrole sinica, 2020, 41(5):12.

[7] Ren Zhanli, Tian Tao, Li Progress, et al. Review on Methods of Thermal Evolution History in Sedimentary Basins and Thermal Evolution History Reconstruction of Superimposed Basins[J]. Journal of Earth Science and Environment, 2014, 36(3): 1-21.

[8] He LJ, Wang JY. Tectono-thermal modeling of sedimentary basins:review and outlook[J]. Progress in geophysics, 2007, 22(4):1215-1219.

[9] Qiu Nansheng, Hu Shengbiao, He Lijuan. Geothermics of sedimentary basins [M]. China University of Petroleum Press, 2019.

[10] Qiu Nansheng. Analysis of the thermal evolution and hydrocarbon formation history of sedimentary basins in western China[J]. Petroleum Exploration and Development, 2002, 29(1): 6-8.

[11] Zhu Rixiang, Xu Yigang, Zhu Guang, et al. Disruption of the North China Craton[J]. Sci China: Earth Science, 2012, 42(8): 1135-1159.

[12] Niu Shuyin, Sun Aijun, Zhang Jianzhen, et al. Tectonic regime transformation and basin-mountain coupling genesis in eastern North China[C]. Geological Society of China; Geological Survey of China; Qingdao Geological Society. Geological Society of China; Geological Survey of China; Qingdao Geological Society, 2013.

[13] Jiang Guangzheng. Geodetic heat flow measurements and lithospheric thermal structure in Northeast China[D]. Beijing: University of Chinese Academy of Sciences, 2017.

[14] Shi Yizhuo. Thermal structure of the lithosphere and geothermal resources in the northern Songliao Basin[D]. Beijing: University of Chinese Academy of Sciences, 2019.

[15] Shi Shangming, Sun Xiaojie, Yu Qinghua. Characteristics of the geothermal field in the Lindian area of the Songliao Basin[J]. Journal of Daqing Petroleum Institute, 1998(4): 79-81.

Han Xiangjun, Jin Xu. Geothermal resources and thermal structure in northeast China[J]. Geology and prospecting, 2002, 38(1): 74-76.

[16] Hu Shengbiao, He Lijuan, Wang Jiyang. Compilation of heat flow data in the china continental area (3rd edition)[J]. Chinese Journal of Geophysics, 2001, 44(5):611-626.

[17] Jiang G. M., Zhang VIP, Xu Z. Subducting Characteristic of the Pacific Slab Beneath Northeast China[J]. GEOSCIENCE, 2012, 26(6): 1125-1135.

[18] Fan Qicheng, Sui Jianjian, Wang Tuanhua, et al. History of volcanic activity, magmatic evolution and eruption mechanism in Changbai Volcanic Province[J]. Geological Journal of China Universities, 2007, 13(2): 175-190 .

[19] Wang JiYang. Convective Geothermal Systems in Medium and Low Temperatures [M]. Beijing: Science Press, 1993.

[20] Pang Zhonghe. Geothermal systems in the Zhangzhou Basin: A study of the geothermal system-genesis model, thermal energy potential and hot water distribution pattern[D]. Beijing: Institute of Geology and Geophysics, Chinese Academy of Sciences, 1987.

[21] Sun Zhanxue, Gao Bo, Zhang Zhanshui. Isotopic and geochemical evidence for the origin of geothermal gases in Gannan[J]. Geoscience, 2014, 49(3): 791-798.

[22] Teng Jiwen, Si Xiang, Zhuang Qingxiang, et al. Analysis of the anomalous structure of the Fujian land margin crust and mantle and deep thermal storage potential[J]. Science, Technology and Engineering, 2017, 17(17): 6-38.

[23] Dou ji. Basic characteristics of a typical high-temperature geothermal system-Yangpai thermal field [J]. China Engineering Science , 2003, 5(1): 42-47.

[24] Sun Aiqun, Niu Shuyin, Wang Qiang, et al. Exploring the mechanism of subthermal column type earthquakes in the North China mantle[J]. North China Earthquake Science, 2010, 28(2): 6-12.

[25] Jaupart C, Sclater J G, Simmons G. Heat flow studies: Constraints on the distribution of uranium, thorium and potassium in the continental crust[J]. Earth & Planetary Science Letters, 1981, 52(2):328-344.

[26] Wan Tianfeng, Chu Mingji, Chen Mingyou. Thermal state of the lithosphere in Fujian Province and prospective evaluation of geothermal resources[J]. Journal of Geology, 1988(2): 85-96.

[27] Wan Tianfeng, Zhao Qingle. The genesis of tectonics-magmatism in eastern China[J]. Science of China: Earth Sciences, 2012, 42(2): 155-163.

[28] Hu Xuzhi, Xu Mingjie, Xie Xiaoan, et al. Aeromagnetic characteristics of northeastern China and analysis of the dwellings[J]. Journal of Geophysics, 2006, 49(6): 1674-1681.

[29] Sun Hongli. Geothermal resources in the Guanzhong Basin: Characteristics and genesis model[D]. Beijing: China University of Geosciences (Beijing), 2015.

[30] Yang Hai. Study on the characteristics of land area habitation in China[D]. Chengdu: Chengdu University of Technology, 2015.

[31] Wang Yang, Deng Jinfu, Wang Jiyang, et al. Characteristics of heat flow distribution and thermal-tectonic zoning in mainland China[J]. Journal of the University of Chinese Academy of Sciences, 2001, 18(1): 51-58.

[32] He Dengfa, Cui Yongqian, Shan Shuaiqiang, et al. Characteristics of geologic framework of buried-hill in Jizhong depression, Bohai Bay Basin[J]. Geoscience, 2018, 53(1): 1-24.

[33] Ma Feng, Wang Guiling, Zhu Xi, et al. Experimental study of the enhanced stimulation of a deep carbonate thermal reservoir in the Xiong'an New Area. Chinese Journal of Engineering, October 2022, Vol. 44, No. 10: 1789-1798.

[34] MA Feng, WANG Guiling, ZHANG Wei, et al. Spatial structure and resource potential of thermal storage in the Rongcheng geothermal field of Xiong'an New Area[J]. Journal of Geology,2020,94(7),1981-1990.

[35] WU Aimin, MA Feng, WANG Guiling, et al. Exploration of deep karst thermal storage and parameters of high-yield geothermal wells in Xiongan New Area[J]. Journal of Geosciences,2018,39(05):14-23.

[36] WANG Guiling,LIN Wenjing.2020.Main hydro-geothermal systems and their genetic models in China[J].Acta Geologica Sinica,94(7):1923-1937.

[37] Xiong Shaobai, Jin Dongmin, Sun Kezhong, et al. Deep crustal tectonic features of the Zhangzhou geothermal field and its adjacent areas in Fujian[J]. Journal of Geophysics, 1991(1): 55-63.

[38] Wenjing Lin, Guiling Wang, Hannan Gan, Andong Wang, Gaofan Yue, Xiting Long. 2022. Heat Generation and Accumulation for Hot Dry Rock Resources in the Igneous Rock Distribution Areas of Southeastern China. Lithosphere, 2021 (Special 5): 2039112.doi：10.2113/2022/2039112.

[39] Wenjing Lin, Guiling Wang, Haonan Gan, Shengsheng Zhang, Zhen Zhao, Gaofan Yue, Xiting Long, 2022. Heat source model for Enhanced Geothermal Systems (EGS) under different geological conditions in China, Gondwana Research, in press.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

FUNDING

This study was funded by National Key R&D Program of China ((no. 2019YFB1504101) and National Natural Science Foundation of China(NO: 41602271) and China Geological Survey (NO: DD20160207,DD20189112).