



Physical characteristics, thermal structure, geothermal and carbon emission reduction potential of typical basins in Eastern China

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ABSTRACT

The geothermal resources in China are primarily found in its sedimentary basins, particularly in the large basins located in eastern China, which hold significant potential for geothermal energy development. The Songliao, North China, and Zhangzhou basins are of special interest due to their considerable exploration depths, extensive development history, and high levels of research activity. This study focuses on the three basins to analyze their thermal reservoir characteristics in eastern China. Between 2017 and 2023, the research team carried out a comprehensive analysis involving deep boreholes that exceeded 4000 m in depth within these three basins. They meticulously created detailed physical profiles that captured essential characteristics such as porosity, permeability, and thermal properties, reaching down to the basement of each basin. The findings indicated that variations in thermal conductivity within shallow geotechnical layers significantly influence the redistribution of deep thermal energy in the upper layers of the earth. Furthermore, differences in physical properties notably affect heat transport processes. The research proposes distinct heat models tailored for each basin: For the Songliao Basin, a low-permeability model with homogeneous thermal properties is constructed; for the North China Basin, high permeability and thermal conductivity layers are highlighted; and a fracture network controlling water and heat is presented in the Zhangzhou Basin. To elucidate the thermal structure of these basins, the Curie surface and Moho surface were analyzed. The shallow Curie surface indicates ongoing intense thermal activity stemming from crustal heat sources, while a shallow Moho surface signifies historical vigorous mantle thermal activity associated with mantle source heat production. Furthermore, the research evaluates the geothermal resources and the potential for carbon emission reduction in these basins. Total volume of exploitable geothermal fluid is estimated to be $76.9 \times 10^9 \text{ m}^3/\text{a}$, corresponding to an annual renewable geothermal energy $1.47 \times 10^{16} \text{ kJ}$. The implementation of geothermal energy could lead to a reduction in annual CO_2 emissions by nearly $2 \times 10^9 \text{ t}$, which constitutes about 17.4% of China's national carbon emissions in 2022. This estimation provides invaluable theoretical insights and data support for geothermal exploration and sustainable development in eastern China.

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1. Introduction

Geothermal energy, a substantial and indigenous energy resource, is generated by the continuous decay of radioactive materials beneath the Earth's surface. In tectonically active regions such as volcanoes, hot springs, and earthquake-prone

areas, geothermal energy is related prominent. It has been estimated that the annual geothermal heat released to the Earth's surface is equivalent to the energy produced by the combustion of $50.6 \times 10^9 \text{ t}$ of coal.

Geothermal systems operate as relatively closed systems, with groundwater interactions playing a crucial role. The impact of groundwater on geothermal fields and heat flow distribution in various tectonic zones is a primary focus of contemporary geothermal research. Groundwater circulation plays a significant role in the manifestation of geothermal anomalies. Traditionally, geothermal exploration has concentrated on the identification of geothermal water

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sources.

In China, large sedimentary basins serve as the primary reservoirs for geothermal energy due to their advantageous burial conditions, concentrated geothermal reservoir stratigraphy, effective water-rock heat exchanges, and potential for extensive development. The exploration and development of basin-type underground thermal reserves have emerged as central activities in the realm of geothermal resource management in recent years. Notably, the regional thermal background of the eastern basins in China is significantly higher than that of the central and northwestern basins, indicative of a long-standing history of geothermal development (Wang GL and Lin WJ, 2020; Lin WJ et al., 2023). These eastern basins exhibit crustal thinning in environments associated with subduction and back-arc extension related to the Western Pacific Plate. Within the middle and upper crust, geobodies characterized by high conductivity and low velocity are variably developed, thereby creating favorable conditions for the formation and enrichment of geothermal resources (He ZL et al., 2023).

Although research on basin geothermal energy has accumulated extensive data over many years, it has primarily focused on reconstructing the geothermal history of basins, identifying sources of hot water recharge, and understanding the formation modes of geothermal reservoirs. Scholars typically analyze the components of geothermal fluids to determine recharge sources, circulation paths, and the age of geothermal water (Ma F et al., 2022a; Liu CL et al., 2022). This approach has enhanced understanding of underground water circulation but highlights the need for integrating shallow hydrothermal cycle theories with heat conduction theories for deeper rock layers.

Groundwater circulation and water-rock heat transfer are critical determinants in the formation of geothermal anomalies. Shallow geothermal anomalies driven by groundwater circulation are more pronounced than those resulting from heat transfer due to rock property variations. This study uses deep well data from three representative basins—the North China Basin, Songliao Basin, and Zhangzhou Basin (see Fig.1)—to provide insights into recent ultra-deep drilling projects.

The Songliao Basin, a significant terrestrial sedimentary basin from the Middle Cenozoic era, exhibits a dual structure characterized by fault subsidence and subsidence in depressions. There are notable differences in the sedimentary and tectonic characteristics of fault and depression deposits, which are strictly governed by pre-existing basement tectonics. The Cretaceous strata within the basin serve as the primary geothermal reservoirs. The North China Basin, which formed during the Cenozoic era, emerged from the destabilization of an initially stable craton due to the westward subduction of the Pacific Plate. The thinning of the lithosphere led to the development of a geothermal reservoir dominated by buried hill carbonates. The Zhangzhou Basin, a faulted basin located in the uplift area of the land margin, exhibits geological influences from orogenic movements

during the Indosinian, Yanshan, and Himalayan periods, as well as from the collisions between the Eurasian Plate, the Pacific Plate, and the Philippine Plate along the southeastern China land margin. This influence is evident in the heat conduction along northeast-trending faults and water conduction along northwest-trending faults. This research provides theoretical support for the exploration and development of sedimentary basins in Eastern China.

2. Thermal background of the Eastern Basin

Dr. White was the pioneer in proposing the classical model of convective geothermal systems, which posits that groundwater consistently absorbs heat from adjacent geological formations as it flows. This process gradually raises the temperature, leading to the emergence of hot springs on the surface in well-connected tectonic areas and the development of thermal reservoirs in more permeable subsurface formations. His model, which encompasses the components of “source, passageway, storage, and cover” (White DE, 1973), provides a fundamental framework for the comprehension of geothermal systems.

In the 1980s, the North China Basin emerged as a significant area for geothermal research. Mo-xiang Chen (Chen MX, 1988) proposed a geothermal genesis model that highlighted the role of heat conduction, informed by drilling, temperature logging, rock sampling, and data analysis. Dun-shi Yan and She-jiao Wang evaluated the potential for geothermal resource development and the distribution patterns within the North China oilfield area, utilizing data from numerous oil exploration boreholes (Yan DS and Yu YT, 2000; Wang SJ et al., 2020). Zhan-li Ren, Li-juan He, and Nan-sheng Qiu (Qiu NS, 2002; He LJ and Wang JY, 2007; Ren ZL et al., 2014; Qiu NS et al., 2019) conducted systematic investigations into the mechanisms of geothermal formation in the sedimentary basins of eastern China. Additionally, Zhong-he Pang, Gui-ling Wang, and Feng Ma developed and refined a comprehensive polythermal model of ancient subduction mountains, drawing on geothermal development data from the Xiong'an New Area (Pang ZH, 1987; Wang GL et al., 2020; Ma F et al., 2020).

Two perspectives provide insights into the elevated thermal background observed in northern China. The first perspective examines the disruption of the craton, characterized by significant ductile deformation and magmatic activity since the Phanerozoic era. This is supported by evidence from volcanic veins revealed in recent boreholes, including D16, D19, D17, and D21, which were drilled in the Xiong'an New Area (Zhu RX et al., 2012). The second perspective, referred to as the mantle column theory (Niu SY et al., 2017), suggests that mantle uplift in the lower section of the North China Fault Zone results in a mushroom-shaped structure that expands outward from a central point. The basaltic material located at the apex of these mantle thermal columns contributes to the heating and fracturing of the upper crust, leading to the formation of extensive compound fracture basins that can accumulate loose sediments with thicknesses

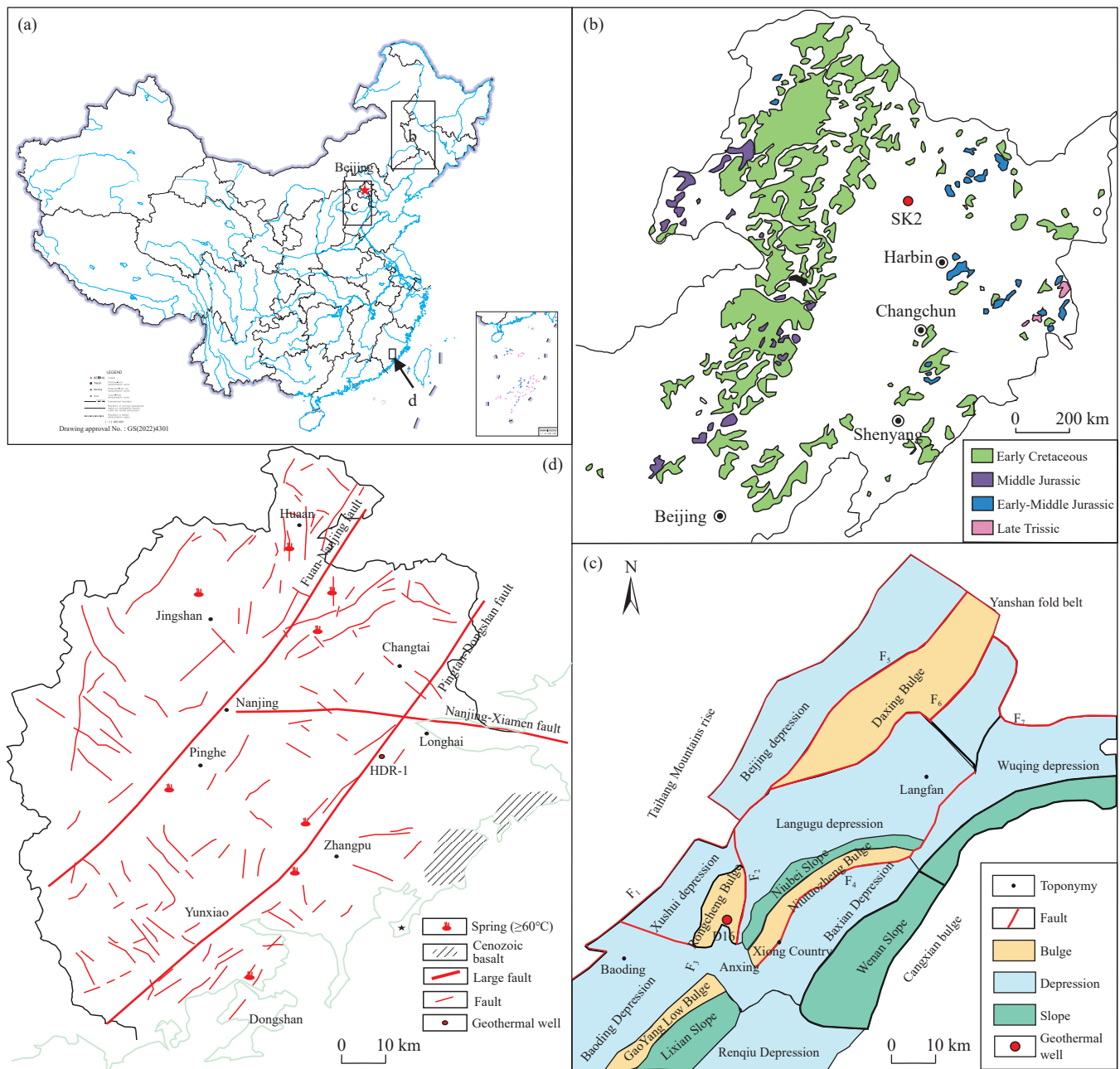


Fig. 1. Typical geothermal basin in eastern China.

ranging from 500 m to 30000 m. Consequently, the North China region is regarded as a geothermal resource area primarily influenced by conduction and low-temperature hot water types. The distribution of geothermal heat flow within the North China Basin is affected by regional crust-mantle uplift zones, argillic zones, and transition zones. The geothermal heat flow values in the basin vary from 50 mW/m² to 80 mW/m², which is slightly above the national continental average of 61.5 mW/m² (Jiang GZ, 2017).

Systematic studies have been conducted on the thermal structure of the northeastern basin (Shi SM et al., 1998; Jiang GZ, 2017; Shi YZ, 2019). These studies analyzed subsurface thermal energy sources and compositions using basin steady-state thermometry, thermal property testing, geothermal heat flow measurements, radiogenic heat production assessments,

and thermal structure analysis. The research focused on the transport mechanisms and primary controlling factors of the geothermal field, as well as the principal tectonic-thermal mechanisms that influence the current thermal state of the basin. The Songliao Basin, which is characterized by sandstone lithology, represents a typical Cretaceous terrestrial sedimentary heat basin in China. The average geothermal heat flow within the basin is approximately 68.24 mW/m², surpassing the global average of 63 mW/m² and China's average of 61.5 mW/m² (Davies JH, 2013). The average geothermal temperature gradient is approximately 3.8°C per 100 m, the highest recorded among sedimentary basins in China, with certain areas exhibiting gradients exceeding 5°C per 100 m. Prior research, including that conducted by Han XJ and Jin Xu (2002), systematically compiled 81 geothermal

heat flow data points in the northeastern region, identifying the upper mantle as a significant factor influencing the distribution of heat flow. Data compilation from the third and fourth editions (Hu SB et al., 2001; Jiang GZ et al., 2016) revealed a high heat flow zone extending from the southeast coast to the north within the North China Basin and the Songliao Basin, which is a notable characteristic of the eastern part of mainland China. In the Songliao Basin, heat flow values range from 44.4 mW/m² to 90 mW/m², with an average of 70.9±14.4 mW/m². This elevated heat flow is correlated with the distribution of Cenozoic mantle-derived basalts and supergene volcanism, which are influenced by deep mantle convection resulting from the westward subduction of the Pacific Plate (Jiang GM et al., 2012; Fan QC et al., 2007; Yang WF et al., 2024; Dai DL et al., 2024; Li C et al., 2024).

According to the theory of plate tectonics, the interactions involving the collision, subduction, and subsidence of the Eurasian Plate with the Pacific Plate and the Philippine Plate at the southeastern land margin of China exert a considerable influence on the southern region of the country. Many scholars conducted a systematic study on the geothermal genesis pattern of the along the southeast coast of China (Wang JY, 1993; Pang ZH, 1987; Sun ZX et al., 2014). Zhangzhou Basin, located in Fujian Province, serves as a representative case for understanding crustal growth and the dynamics of continental accretion. Characterized by geothermal anomalies, the Zhangzhou Basin is significantly influenced by a deep, northeast-oriented fracture zone. The region's hot springs, with temperatures ranging from 40°C to 80°C, are indicative of the tectonic processes at play. A considerable number of these springs are found at the convergence of northeast and northwest tectonic zones. Jiwen Teng (Teng JW et al., 2017) posited the existence of a substantial deep fracture zone between Zhangzhou and Changtai, which extends from the crust into the upper mantle. This fracture zone is believed to facilitate the upward movement of deep-seated materials, acting as a pathway for the recharge of thermal energy. Zhong-he Pang (Pang ZH, 1987) proposed that the Zhangzhou Basin is characterized by a medium-to-low temperature convective geothermal system. In this system, fracture water within low-permeability granite formations, situated in a region of elevated thermal background, extracts and transports heat to shallower discharge zones during deep circulation processes. Groundwater is directed upward to the surface through high-permeability zones created by intersecting tectonic fractures. Furthermore, Zhan-xue Sun (Sun ZX et al., 2014), through systematic gas isotope analysis, concluded that the deep gases in the southeastern coastal region possess a crustal source component, with the heat production from this crustal source playing a significant role in influencing regional heat flow.

3. Physical characteristics of the Eastern Basin

3.1. Construction of thermal conductivity column

In the Songliao Basin, a comprehensive thermal

conductivity profile was established utilizing data obtained from the Songke 2 well. Samples were systematically collected from depths ranging from 2865 m to 6995 m, with intervals of approximately 10 m. These samples represented a variety of geological formations, including the Cretaceous Nengjiang Formation, Denlouku Formation, Yingcheng Formation, Shahezi Formation, as well as the Jurassic Huoshiling Formation and underlying basement rocks. The lithological diversity included sandstone, conglomerate, mud shale, tuff, volcanic agglomerate, and shallow metamorphic sedimentary rocks. A total of 435 sets of rock thermal conductivity data were analyzed to ascertain the average thermal conductivity across various strata and lithologies. The findings indicated that basement rocks exhibited the highest average thermal conductivity at 3.14 W/(m·K), followed by the Yingcheng Formation, Huoshiling Formation, and Shahezi Formation, with the latter averaging 2.83 W/(m·K).

The lithological classification was conducted based on the stratigraphic observations made during drilling, which involved the categorization of conglomerates, sandstones, and mudstones according to their respective grain sizes. The analysis presented in Fig. 2 revealed that conglomerates exhibited the highest average thermal conductivity, measured at 2.93 W/(m·K), with sandstones and mudstones closely following, both averaging 2.85 W/(m·K). This finding indicates a significant relationship between rock composition and thermal conductivity, predominantly influenced by lithological characteristics. Mudstones and clay layers demonstrated lower thermal conductivities, ranging from 2.85 W/(m·K) to 3.07 W/(m·K), with values remaining consistent within this specified range. Collectively, the relatively uniform thermal conductivity observed throughout the Northeast Basin suggests the presence of a stable mechanism facilitating heat transfer from deeper geological strata to the near-surface environment.

In the Songliao Basin, the measured thermal conductivity exhibit a range from 1.99 W/(m·K) to 3.42 W/(m·K), with a mean value of 2.74 W/(m·K). While thermal conductivity remains relatively consistent from shallow to deeper strata, the variability of the data tends to increase with depth. The vertical thermal conductivity profile can be categorized into three distinct sections: The first section extends from the base of the Yingcheng Formation to approximately 5000 m in the middle of the Shahezi Formation, where the stratigraphy, predominantly composed of sandstone and mudstone, demonstrates stable thermal conductivity with an average of 2.66 W/(m·K). The second section, spanning from the base of the Shahezi Formation to the base of the Huoshiling Formation, encompasses a lithology that includes mudstone, sandstone interspersed with andesite, rhyolite, and other materials, and reveals an increase in variability in thermal conductivity, averaging 2.78 W/(m·K). Lastly, in the basal tuffs and coarse andesites, the average thermal conductivity rises to 3.15 W/(m·K) (Fig. 3). It is crucial to note that these measurements are derived from laboratory tests; *in situ* conditions, characterized by elevated temperature and

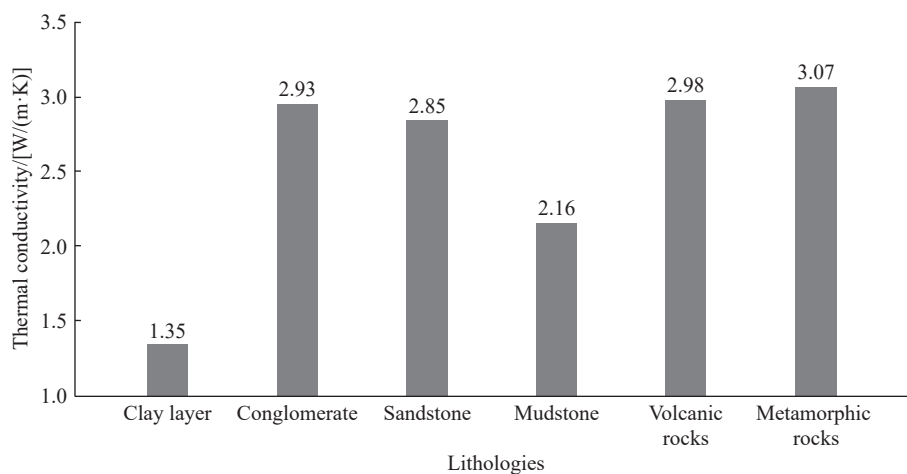


Fig. 2. Distribution of average thermal conductivity corresponding to different lithologies.

pressure at greater depths, may lead to discrepancies of up to 30% between the actual in situ thermal conductivity and the laboratory measurements.

In the North China Basin, a study was conducted that involved the selection of 32 core samples from geothermal boreholes located in the tectonic bulge region for laboratory testing. These samples, which were collected from depths up to 4000 m, comprised 10 sandstone samples, 18 carbonate samples, and 4 metamorphic samples. The focus of the testing was to measure thermal conductivity and radiogenic heat generation rates in these representative geological formations.

In the North China Basin, thermal conductivity exhibits a distribution pattern, characterized by lower values at both extremes and elevated values in the central region (see Fig. 4). The Neoproterozoic and Paleoproterozoic sandstones, located at the uppermost layer, demonstrate thermal conductivities ranging from 1.27 W/(m·K) to 2.57 W/(m·K), with an average of 2.12 W/(m·K). Conversely, the carbonate reservoirs located in the central portion of the basin reveal significantly higher thermal conductivity, averaging 5.51 W/(m·K). This increase is attributed to the high porosity and water content, which promote vigorous hydrothermal convection and secondary heat generation. Such conditions are essential for the formation of high-quality thermal reservoirs within the tectonic bulge area of the North China Basin. At the base, within the terrigenous gneiss, the average thermal conductivity remains consistent at 3.03 W/(m·K), a phenomenon attributed to the dense lithology that supports a stable thermal conduction mechanism. For instance, boreholes D17 and D01 in the Xiong'an New Area, which target thermal reservoirs in the Tertiary layer, exhibit thermal conductivities of 3.16 W/(m·K) and 3.51 W/(m·K), respectively. Under steady-state conditions, the ground temperature gradient ranges from 17.4°C/km to 21.5°C/km, with an average of 19.3°C/km, indicating the absence of significant thermal anomalies. Consequently, this suggests that the large-scale development of high-quality thermal reserves in the deep terrigenous basement of the North China Basin is currently not economically feasible. A heat flow value of 64.5 mW/m² was calculated for the fractured metamorphic basement in the

terrigenous region for the first time, underscoring a steady-state heat flow predominantly governed by conduction beneath the thermal reservoir. This reflects the background of steady-state heat flow through conduction to the shallow surface in the North China Basin. The geothermal heat flow values derived from the heat conduction-dominated Swalterian gneiss section are considered more realistic in comparison to those obtained from the more convective Cenozoic cover and Middle and Upper Paleogene karst reservoirs (Duo J, 2003; Sun AQ, 2010).

In the Zhangzhou Basin, thermal conductivity exhibits a gradual increase from the upper layers to the deeper strata (Fig. 5), with an average value of 3.14 W/(m·K), which is higher compared to those in the other two basins. The homogenous lithological characteristics of the Zhangzhou Basin contribute to relatively uniform thermal conductivity values, which facilitate an even distribution of heat throughout the rock layers. In contrast to the North China Basin, the elevated thermal conductivity observed in the Zhangzhou Basin does not result in the development of a heat accumulation zone. Instead, heat is uniformly conducted within the rock matrix and experiences considerable convection between the rock and fluid at the surfaces of fissures. The consistently high and stable thermal conductivity from the surface to deeper underground layers promotes effective heat dissipation at the surface, thereby aiding in the preservation of high-temperature fluids at shallower depths within the region.

3.2. Construction of the heat generation rate column.

In the Songliao Basin, the authors conducted an analysis of the stratigraphic data obtained from the Songke 2 well to investigate the distribution of radioactive elements (Fig. 6). The findings indicate that thorium (Th) is the most prevalent radioactive element, followed by potassium (K) and uranium (U). Generally, the concentrations of uranium and thorium exhibit a decreasing trend with increasing depth, whereas the potassium content remains relatively constant. The Yaojia Formation exhibits the highest concentration of Th at 10.8

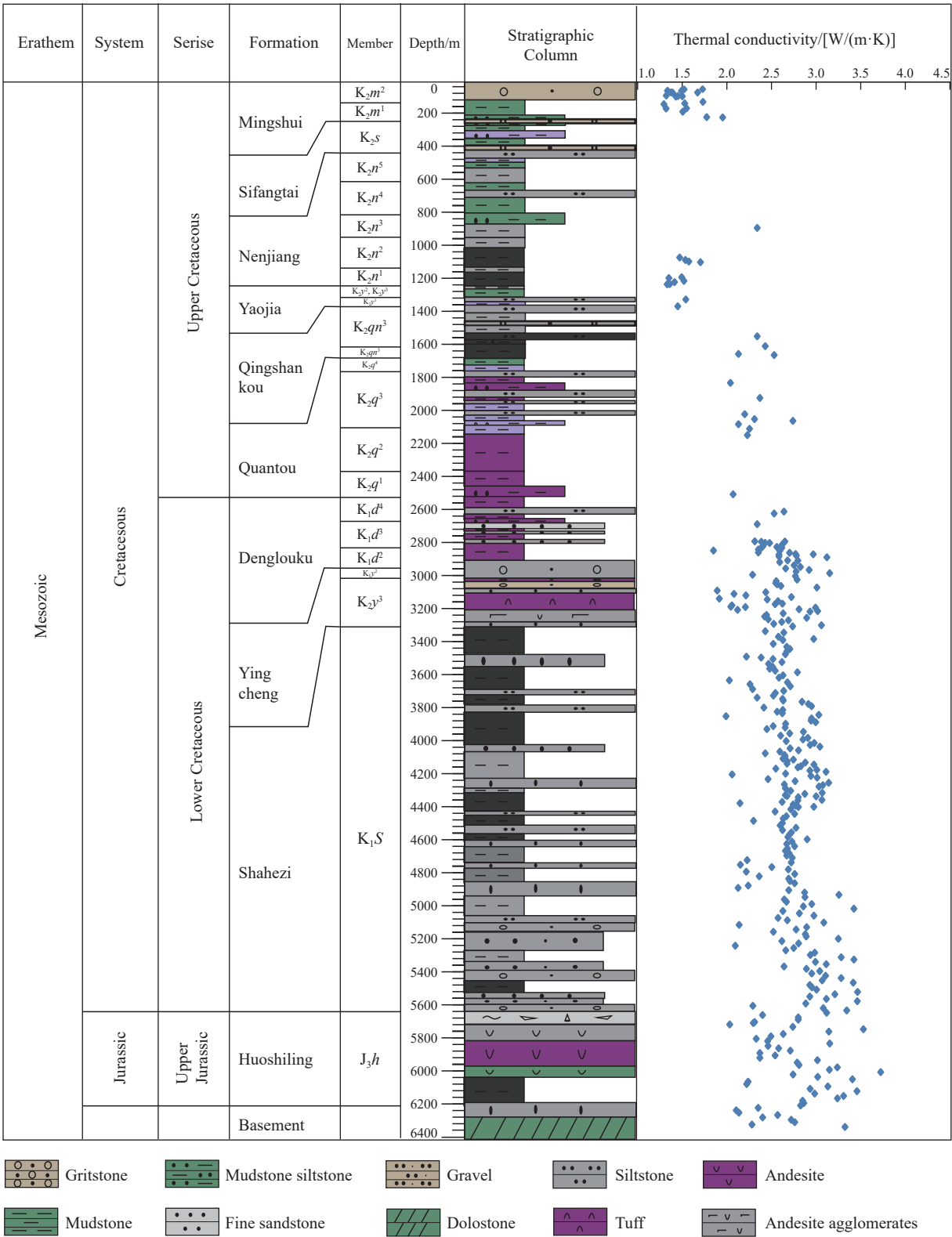


Fig. 3. Stratigraphic structure and vertical distribution of thermal conductivity in Songke 2 well.

μg/g, followed by the Nengjiang, Denglouku, Shahezi, Basal rock, Huoshiling, and Yingcheng formations, with the Yingcheng Formation displaying the lowest Th concentration. The Nengjiang Group contains the highest concentration of U at 3.71 μg/g, followed by the Denglouku Group, Yingcheng Formation, Yaojia Formation, Shahezi Formation, Kidi, and Huoshiling Formation, where U concentrations are at their

lowest. Potassium content reaches its maximum at 3.19% in the Yingcheng Formation and subsequently declines in the following formations: Denglouku, Shahezi, Yaojia, Huoshiling, Basal rock, and Nengjiang, with the Nengjiang Formation exhibiting the lowest potassium concentration. The radiogenic heat generation rates of the Songke 2 well range from 0.228 μW/m³ to 1.65 μW/m³, with a mean value

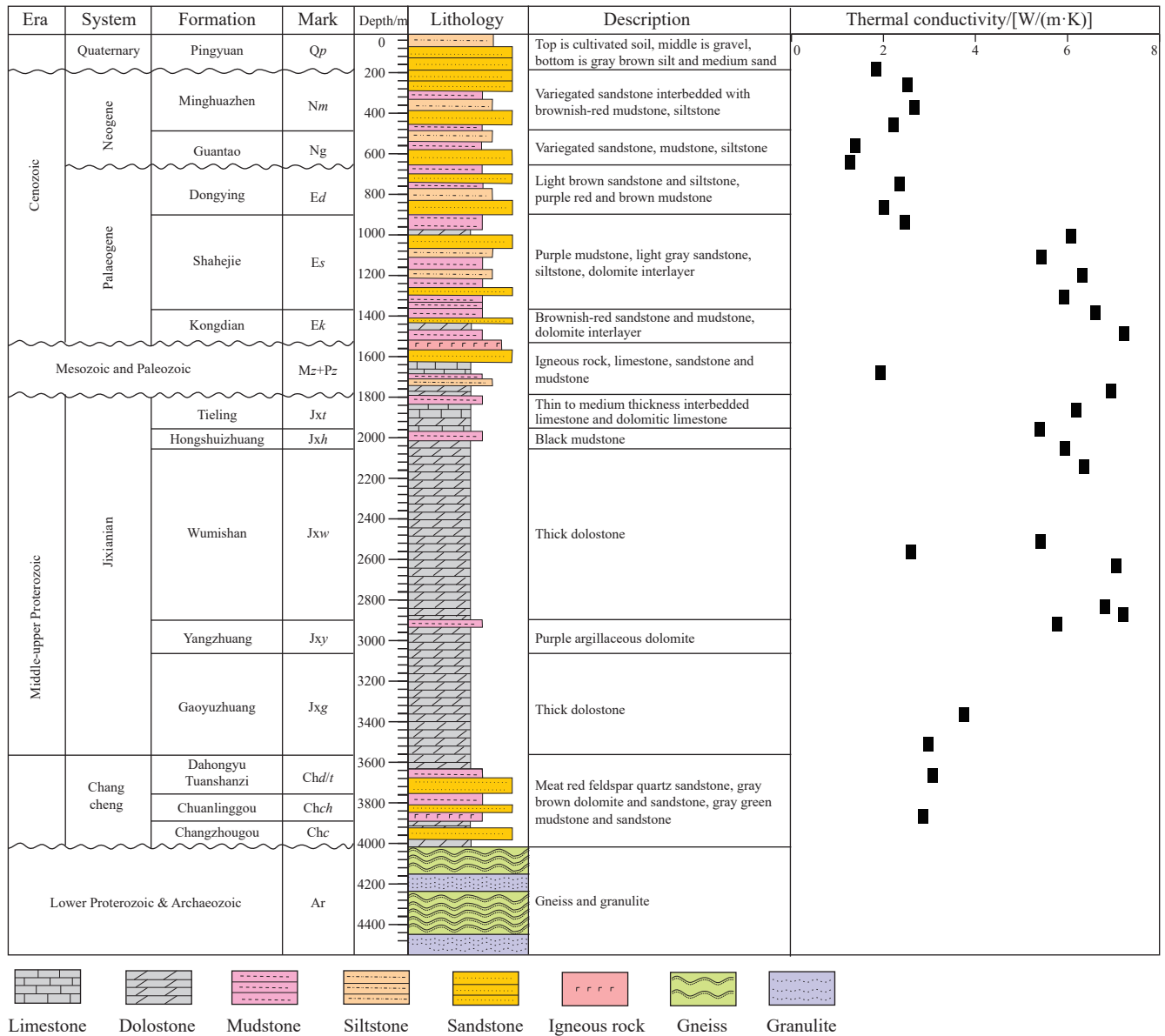


Fig. 4. Vertical distribution of thermal conductivity in the North China Basin.

of $0.772 \mu\text{W}/\text{m}^3$. These rates exhibit variability according to lithology (Fig. 7). Among the lithologies analyzed, mudstones exhibit the highest average heat generation rate of $0.825 \mu\text{W}/\text{m}^3$, followed by volcanic rocks, sandstones, conglomerates, and metamorphic rocks. This variability is primarily attributed to the differing concentrations of uranium and thorium present in the various lithologies (Fig. 8). Notably, mudstones possess elevated concentrations of thorium and potassium when compared to sandstones, conglomerates, volcanic rocks, and metamorphic rocks. In summary, the Songliao Basin is characterized by relatively low levels of radiogenic heat production, indicating that crustal heat does not serve as the predominant source of thermal energy in this region.

In conclusion, the examination of uranium (U), thorium (Th), and potassium (K) concentrations within the Songliao Basin indicates that the Yaojia Formation possesses the highest levels of Th, succeeded by the Nengjiang and

Denglouku formations, while the basal formations exhibit the lowest Th concentrations. Furthermore, the contents of uranium and potassium tend to diminish with increasing depth. Among the lithologies analyzed, conglomerates, sandstones, and mudstones demonstrate the highest Th concentrations, which are two to three times greater than those of uranium. The rates of heat generation are influenced by lithological variations, primarily attributable to the differing concentrations of U, Th, and K. Notably, mudstones are characterized by the highest heat generation rates, which can be ascribed to their elevated concentrations of Th and K in comparison to sandstones and conglomerates.

In the North China Basin, the rates of heat generation are significantly low, exhibiting a “sandwich” distribution pattern characterized by elevated values at both ends and a diminished value in the central region (Fig. 9). The average heat generation rate over 4000 m is $0.56 \mu\text{W}/\text{m}^3$, which is the lowest among the three basins analyzed and falls below the

average for most geothermal regions in China. The overburden is composed of Neoproterozoic and Paleoproterozoic sandstones and mudstones, with heat generation rates ranging from 0.37 $\mu\text{W}/\text{m}^3$ to 1.81 $\mu\text{W}/\text{m}^3$, yielding an average of 1.06 $\mu\text{W}/\text{m}^3$. Conversely, the heat generation rate within the Mesoproterozoic carbonate reservoir experiences a substantial decline, averaging 0.29 $\mu\text{W}/\text{m}^3$, although certain intrusive veins may exceed 1 $\mu\text{W}/\text{m}^3$. These observations indicate that the heat generation

rate of the Mesoproterozoic Erathem strata accounts for merely 2.5% of the total crustal heat flow. The metamorphic basement of the Mesoproterozoic Erathem presents heat generation rates between 0.44 $\mu\text{W}/\text{m}^3$ and 0.83 $\mu\text{W}/\text{m}^3$, with an average of 0.59 $\mu\text{W}/\text{m}^3$. These metamorphic rocks, which extend several kilometers in thickness, are the principal contributors to crustal heat generation in North China. This phenomenon reflects a "hot mantle-cold crust" structure, which is associated with the low heat generation rates of the ancient strata within the crust.

In the Zhangzhou Basin, a thermal property profile was established utilizing data from the HDR 1 well. The analysis (Figs. 10, 11) reveals that the borehole predominantly contains granite with minimal lithological variation, resulting in a consistent vertical distribution of uranium (U), thorium (Th), and potassium (K). The data on radiogenic heat production demonstrate that thorium has the highest average concentration at 18.7 $\mu\text{g}/\text{g}$, which is significantly greater than the levels observed in the Songliao and North China basins. The average concentration of uranium is recorded at 3.14 $\mu\text{g}/\text{g}$, which is also marginally higher than that found in the aforementioned basins. However, despite these elevated concentrations, the radiogenic heat generation rate in this borehole is comparatively lower. This inconsistency is attributed to the representativeness of the sampling methodology and the predominance of deep core samples (Fig. 10).

The Zhangzhou Basin is characterized by a notably elevated Th/U ratio, with a mean value of 3.87, exceeding the

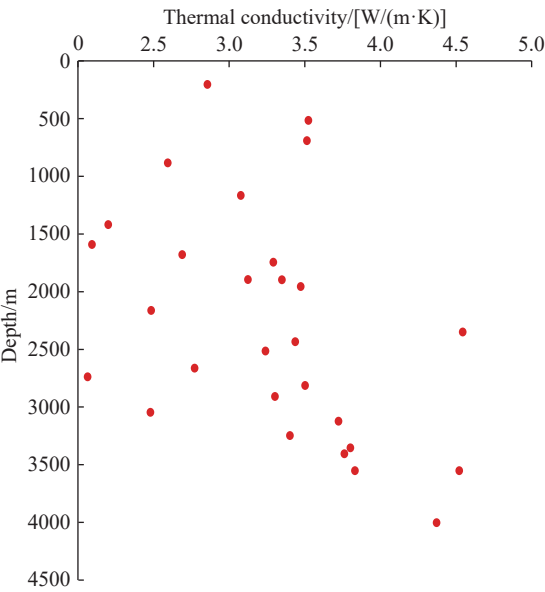


Fig. 5. Thermal conductivity of Zhangzhou HDR1 well.

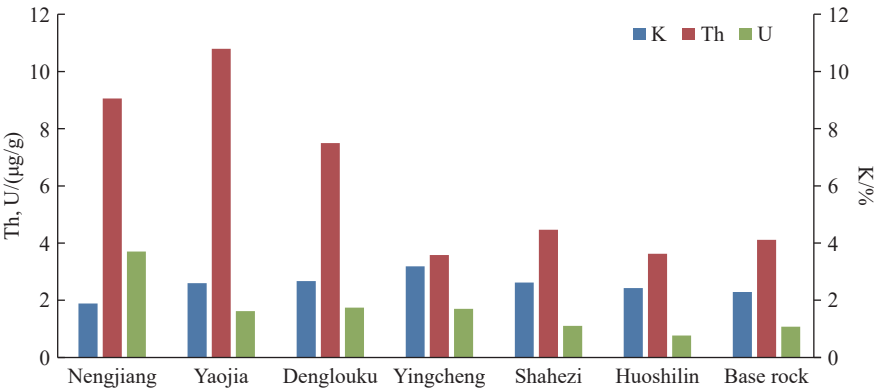


Fig. 6. Average radioactive element content of different layer groups in the Songke-2 well.

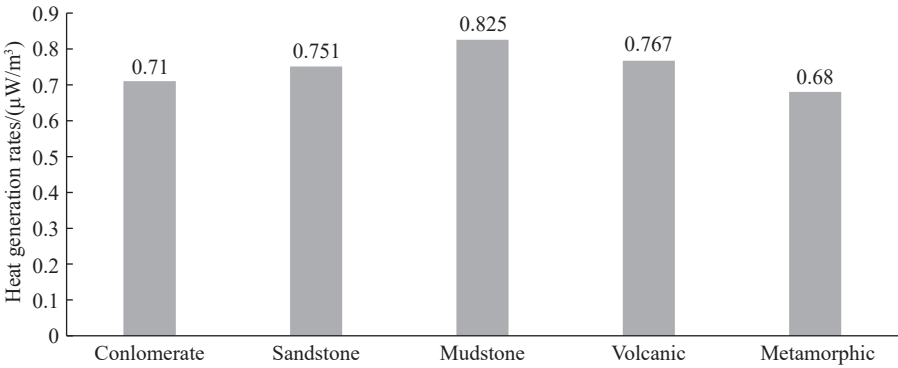


Fig. 7. Heat generation rates associated with various lithological types.

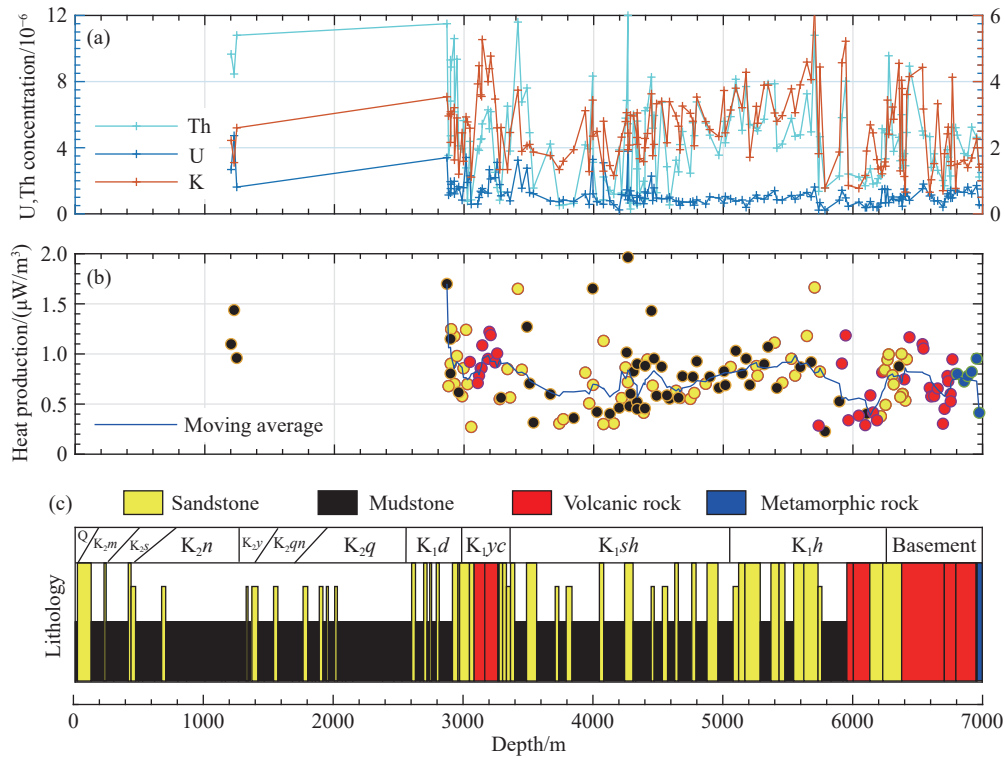


Fig. 8. Heat generation rate with Depth (after Jiang GZ et al., 2016). a–U–Th–K concentrations; b–heat production rates; c–Songke-2 stratigraphic column. K_{1h} –Huoshiling Formation; K_{1s} –Shahezi Formation; K_{1y} –Yingcheng Formation; K_{1d} –Denglouku Formation; K_{2q} –Quantuo Formation; K_{2qn} –Qingshankou Formation; K_{2y} –Yaojia Formation; K_{2n} –Nengjiang Formation; K_{2s} –Sifangtai Formation; K_{2m} –Mingshui Formation; Q–Quaternary.

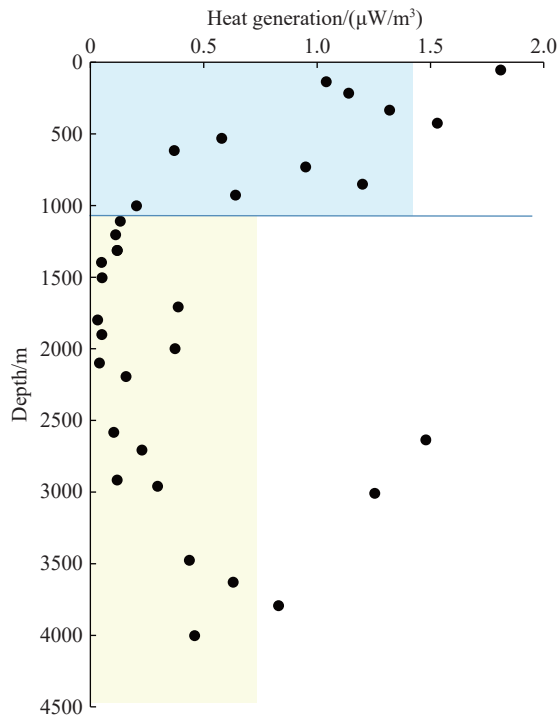


Fig. 9. Combined heat generation rate of boreholes in the North China Basin (D16+D17).

global average of 2.5. This elevated ratio aligns with the linear correlation between Th/U and D-value, as proposed by Jaupart C et al.(1981), which represents the thickness of the radio-concentrated layer across various global heat flow

regions. Additionally, Tian-feng Wan’s analysis (Wan TF et al., 1988, 2012) posits a D-value of approximately 10 km for eastern Fujian Province, thereby corroborating these observations. Although the current Th/U ratio is marginally lower than the previously reported estimate of 3.98 (Fig. 11), it remains generally consistent with Tian-feng Wan’s proposed range. This suggests that the thickness of the radio-concentrated layer in the Zhangzhou Basin is in agreement with prior research, indicating a value slightly exceeding 10 km.

3.3. Construction of porosity and permeability column

The analysis of logging data from the Songke 2 well indicates a distinct trend in the relationship between porosity and permeability with respect to depth. The average porosity is recorded at 35%, while the average permeability is measured at 4 mD. It is important to note that these parameters demonstrate considerable variability at depths less than 1800 m. However, between the depths of 1800 m and 2700 m, there is a pronounced decline in both porosity and permeability, which subsequently stabilizes below 2700 m. This observed fluctuation corresponds with the positioning of the primary thermal reservoir within the basin (Fig. 12).

Similarly, data obtained from borehole D17 in the Rongcheng Bulge of the North China Basin present comprehensive profiles of porosity and permeability across various geological formations. The Quaternary loose layer (Q) exhibits an average porosity of 35.95% and a permeability of 10 mD. In contrast, the Neogene sandstone (N) demonstrates

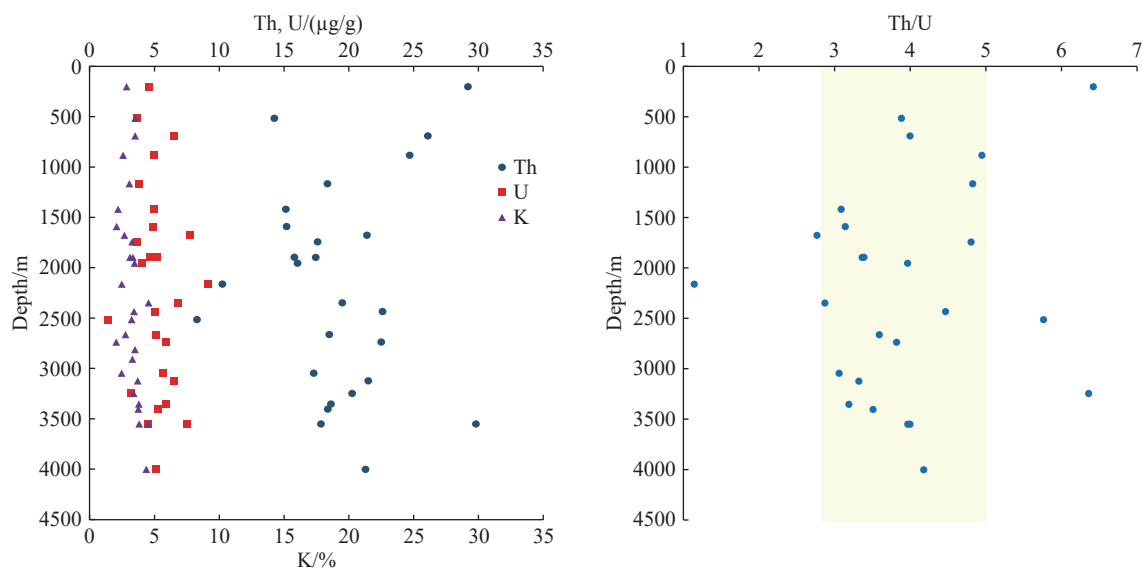


Fig. 10. Radioactive element abundance map and U and Th ratios of the Zhangzhou HDR1 well.

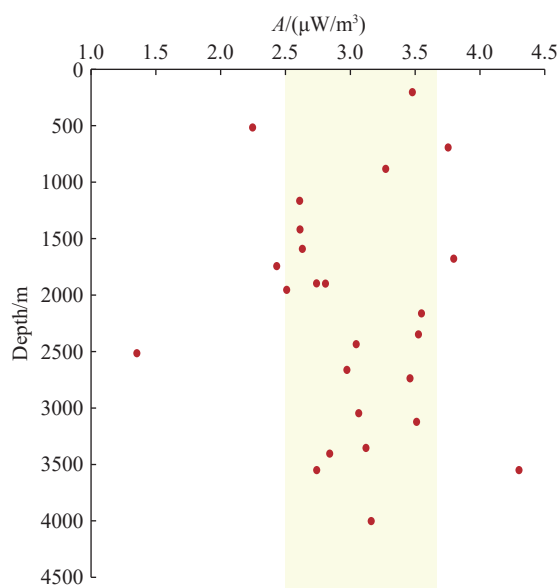


Fig. 11. Radiogenic heat generation rate of Zhangzhou HDR 1 well.

lower average values, with porosity at 28.7% and permeability at 0.8 mD. The Paleocene sandstone mudstone (E) further diminishes these metrics, yielding an average porosity of 21.8% and permeability of 0.5 mD. The Metazoan Jixianian System carbonate rock (Jx) records the lowest average porosity at 15.2% and permeability at 0.3 mD, while the Archean boundary metamorphic rocks (Ar) show extremely low values, with an average porosity of 3.5% and permeability of 0.05 mD (Fig. 13).

The shallow section of borehole D17, dominated by sandstone and mudstone, features a well-developed thermal reservoir with increasing permeability. This suggests a primarily steady-state conduction of water-rock heat exchange. Conversely, the lower stratigraphic layers, which are predominantly composed of gneiss, demonstrate significantly low porosity and permeability, suggesting that heat transfer in this region is largely governed by steady-state

conduction with limited hydrothermal activity.

In the Zhangzhou Basin, data obtained from the HDR1 well reveal a consistent decline in porosity with increasing depth, suggesting that hydrothermal activities exert a more pronounced influence at depths shallower than 2500 m. Below this depth, the influence of hydrothermal activities diminishes. A similar pattern is observed in permeability, which generally ranges from 1 mD to 10 mD at depths less than 2500 m, but decreases to below 0.1 mD at greater depths (Fig. 14).

4. Thermal structure of typical basin

4.1. Thermal structure of the Songliao Basin

The Songliao Basin exhibits a unique thermal structure, characterized by a shallower burial depth at its center and a deeper burial at the periphery (Fig. 15). This pattern indicates that the heat in the central region is predominantly derived from the deep mantle, whereas the peripheral areas are more reliant on crustal heat sources. As a result, thermal heat disperses from the center towards the outer regions, transitioning from deeper to shallower strata. The average depth of the Moho surface within the Songliao Basin is approximately 32 km, where mantle-sourced heat is most significant. Conversely, the shallower Moho located at the basin's center facilitates a consistent heat flow. The average radiogenic heat generation rate is recorded at less than $1 \mu\text{W}/\text{m}^3$, indicative of a “cold crust-hot mantle” thermal regime. In the peripheral regions, the presence of extensive Yanshan-age granite, which exhibits surface uranium (U) concentrations of up to $7.0 \mu\text{g}/\text{g}$ (Hu XZ et al., 2006), enhances crustal heat production. The Manzhouli-Suifenhe section reveals that the curved surface extends over 30 km around Mudanjiang, closely corresponding to the Moho depth. This variation between the curved surface and the Moho is primarily attributed to Mesozoic upwelling and subsequent geothermal activities, which have resulted in

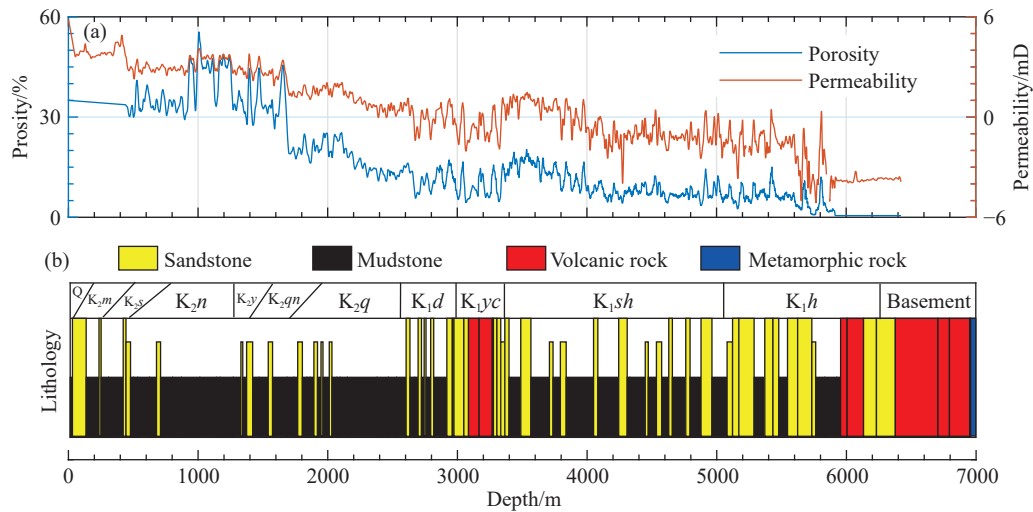


Fig. 12. Porosity and Permeability varies with depth of SK2 in Songliao Basin.

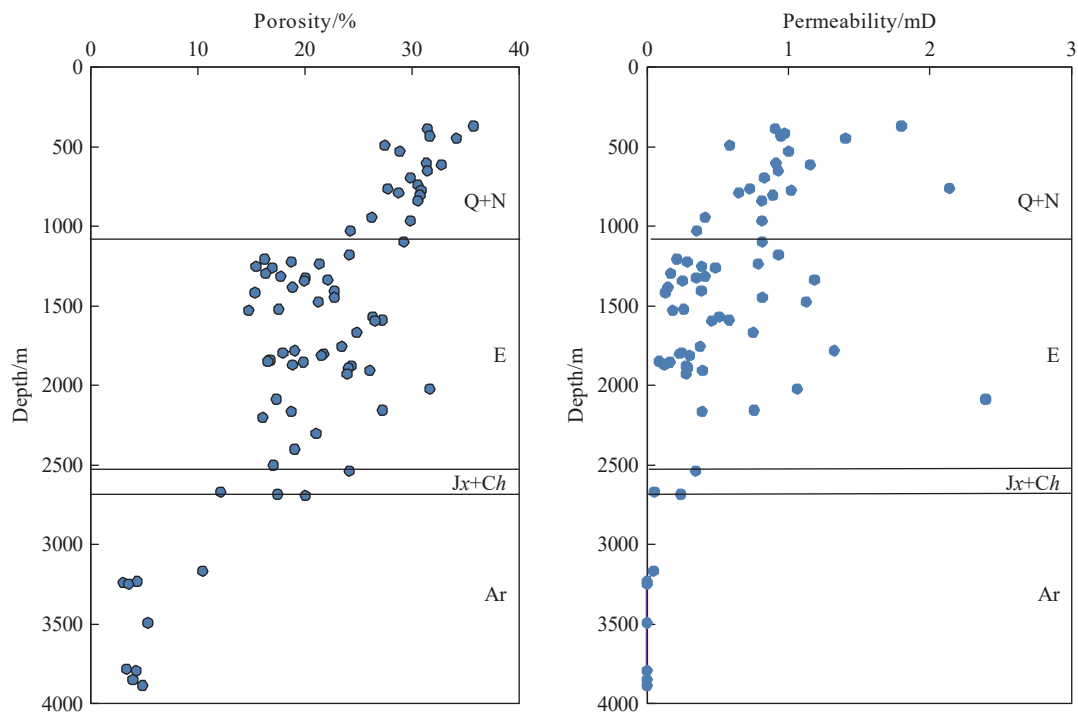


Fig. 13. Porosity and permeability varies with depth of boreholes in the North China Basin (D16+D17).

regional extensional subsidence.

The Songliao Basin exhibits a unique layer-controlled thermal reservoir structure that distinguishes it from other basins in China. The effective thickness of thermal reservoirs in this basin is significantly less than that observed in the sedimentary basins of North China and Guanzhong (Sun HL, 2015; Fig. 16). The basin's thin-layered architecture, characterized by extensive interstratification of sandstone and mudstone, results in a hydrothermal system that is predominantly influenced by its layering. This phenomenon can be attributed to two primary factors: The basin's dominant river and lake deposits, which contribute to limited groundwater movement in later geological stages, and the considerable overburden of Mesozoic sedimentary layers. The prolonged exposure to high-pressure conditions has led to

increased consolidation and compression of these strata, thereby diminishing porosity and hindering fluid seepage. As a result, the identification of large-scale, high-quality thermal reservoirs within the Songliao Basin proves to be a complex challenge. Even laminated sandstone thermal reservoirs with high permeability often exhibit a lack of significant thermal anomalies in temperature (Wang Y et al., 2001; Yang H, 2015).

4.2. Thermal structure of the North China Basin

The North China Basin presents a varied thermal structure. The Moho surface (Fig. 17) ranges from 28 km to 37 km in depth, while the Curie surface (Fig. 17) lies between 20 km and 25 km deep. Both surfaces display uplifted areas,

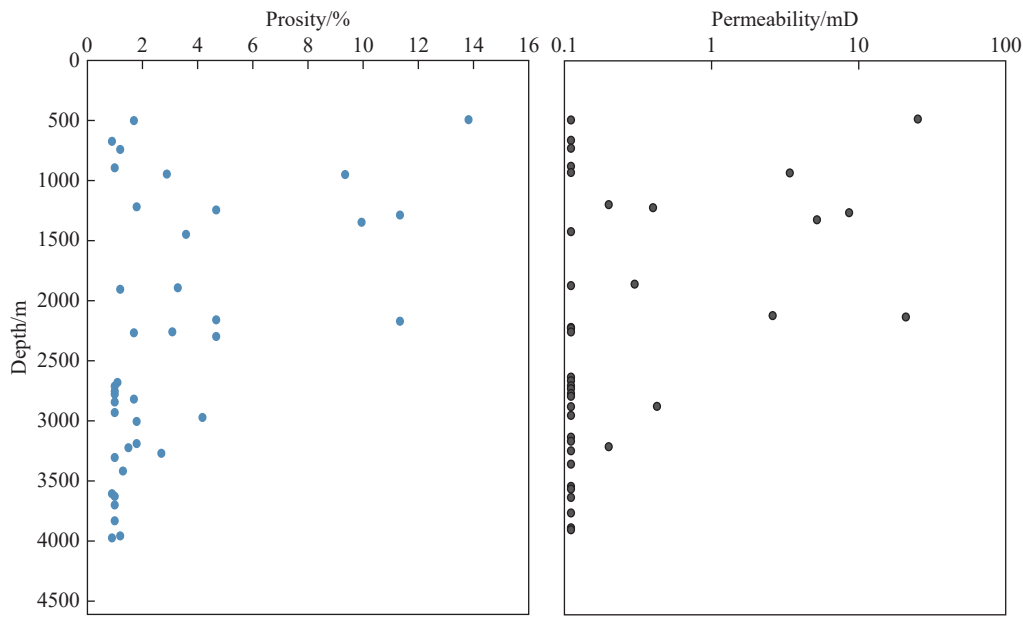


Fig. 14. Porosity and permeability varies with depth of HDR1 in Zhangzhou Basin.

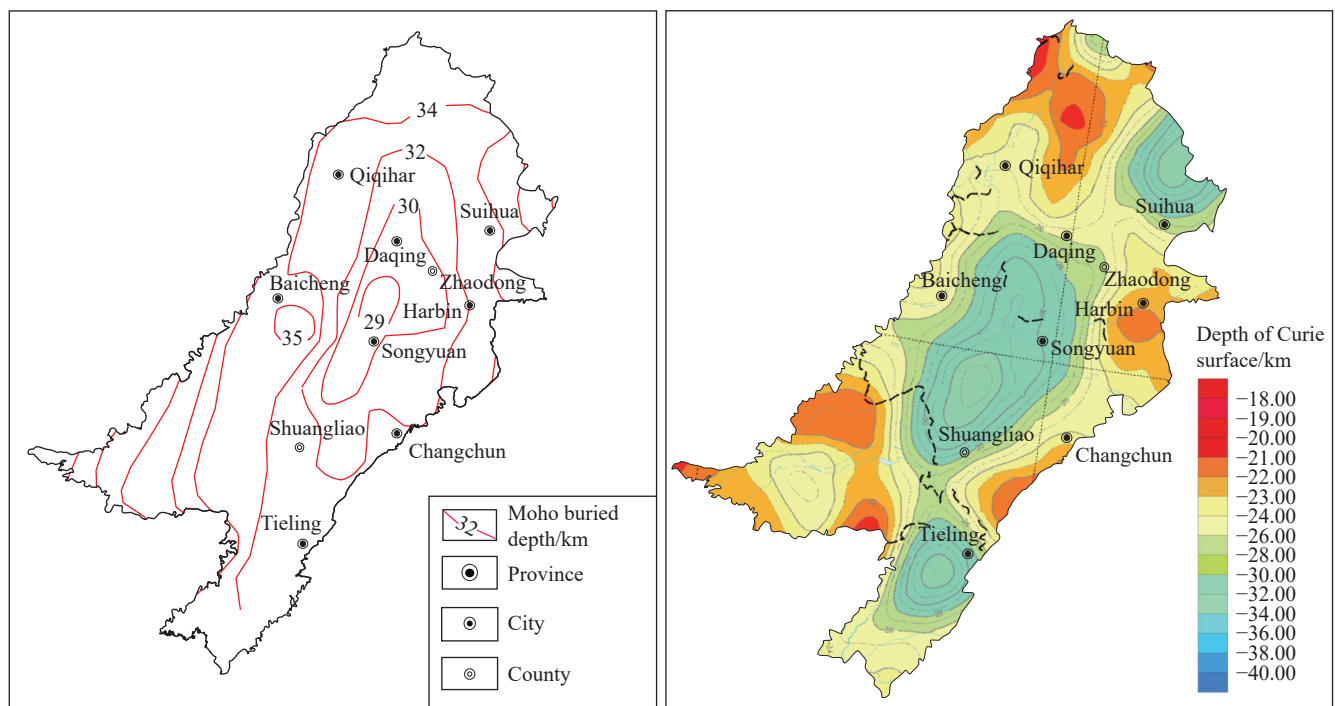


Fig. 15. Depth of Curie surface and Moho surface in the Songliao Basin.

with the Curie surface undulations mirroring the metamorphic basement's uplift and depression patterns. A notable “deep in the east and shallow in the west” trend is evident in the Moho and Curie surfaces throughout the basin, leading to significant thermal state disparities between the eastern and western sections. The eastern region is associated with higher heat production from both crustal and mantle sources, in contrast to the western region, which exhibits lower heat production levels. Furthermore, the basin displays a thermal gradient characterized by a shallow northern area and a deeper southern area. Specifically, south of the Shijiazhuang-Hengshui line, the Moho surface is approximately 1.6 km

deeper, suggesting a magnetic upper mantle with low radiogenic heat production and relatively subdued tectonic activity. This results in a “cold crust-cold mantle” thermal structure characterized by low geothermal heat flow. In contrast, north of this line, the Moho surface is shallower, exhibiting increased mantle heat and reduced crustal heat production, indicative of a “cold crust-hot mantle” thermal structure (He DF et al., 2018; Ma F et al., 2020, 2022b; Wu AM et al., 2018).

In the basement region of the North China Basin, steady-state temperature assessments indicate an average heat flow of 64.5 mW/m² and an average heat generation rate of 0.56

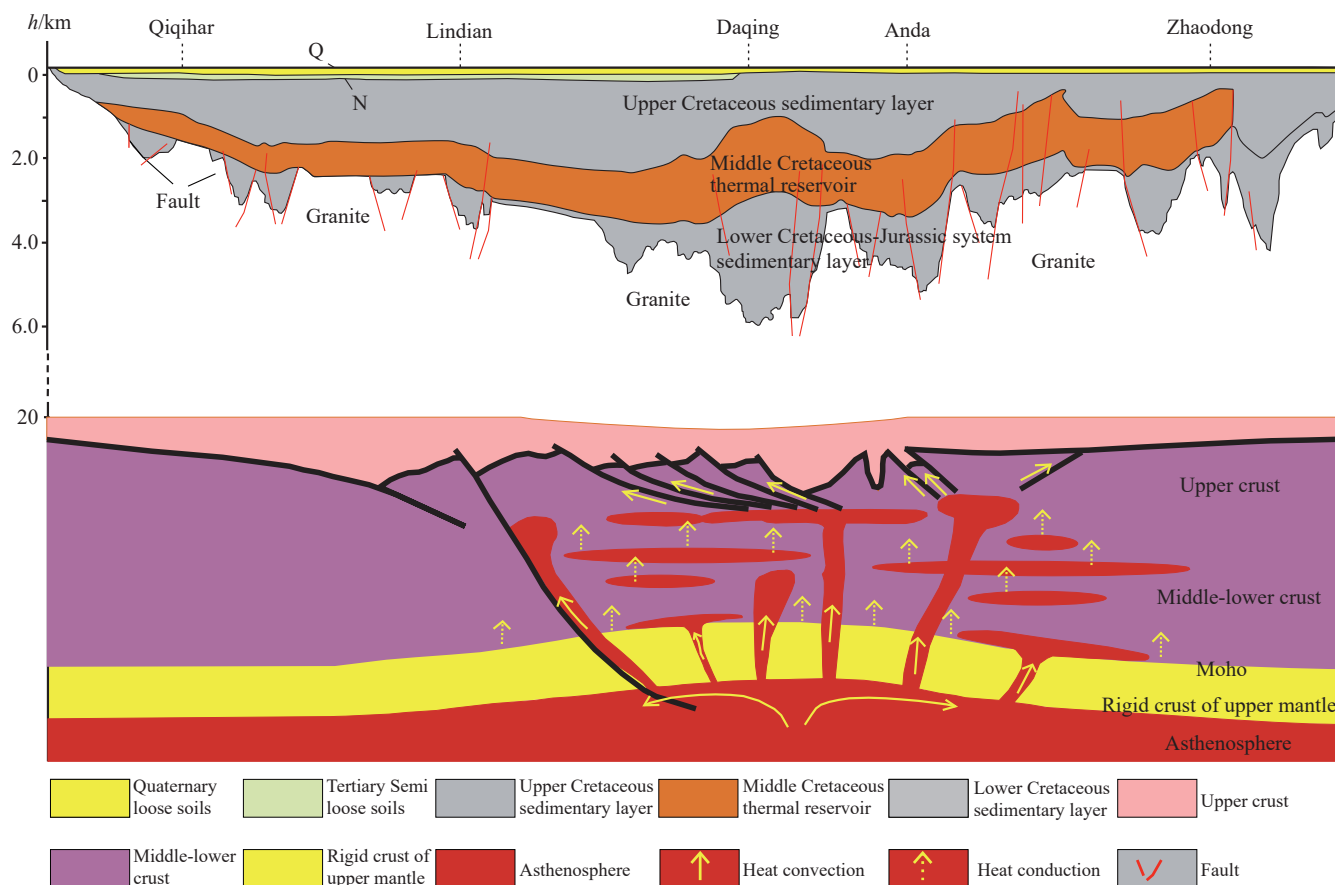


Fig. 16. Heat control model in the Songliao Basin.

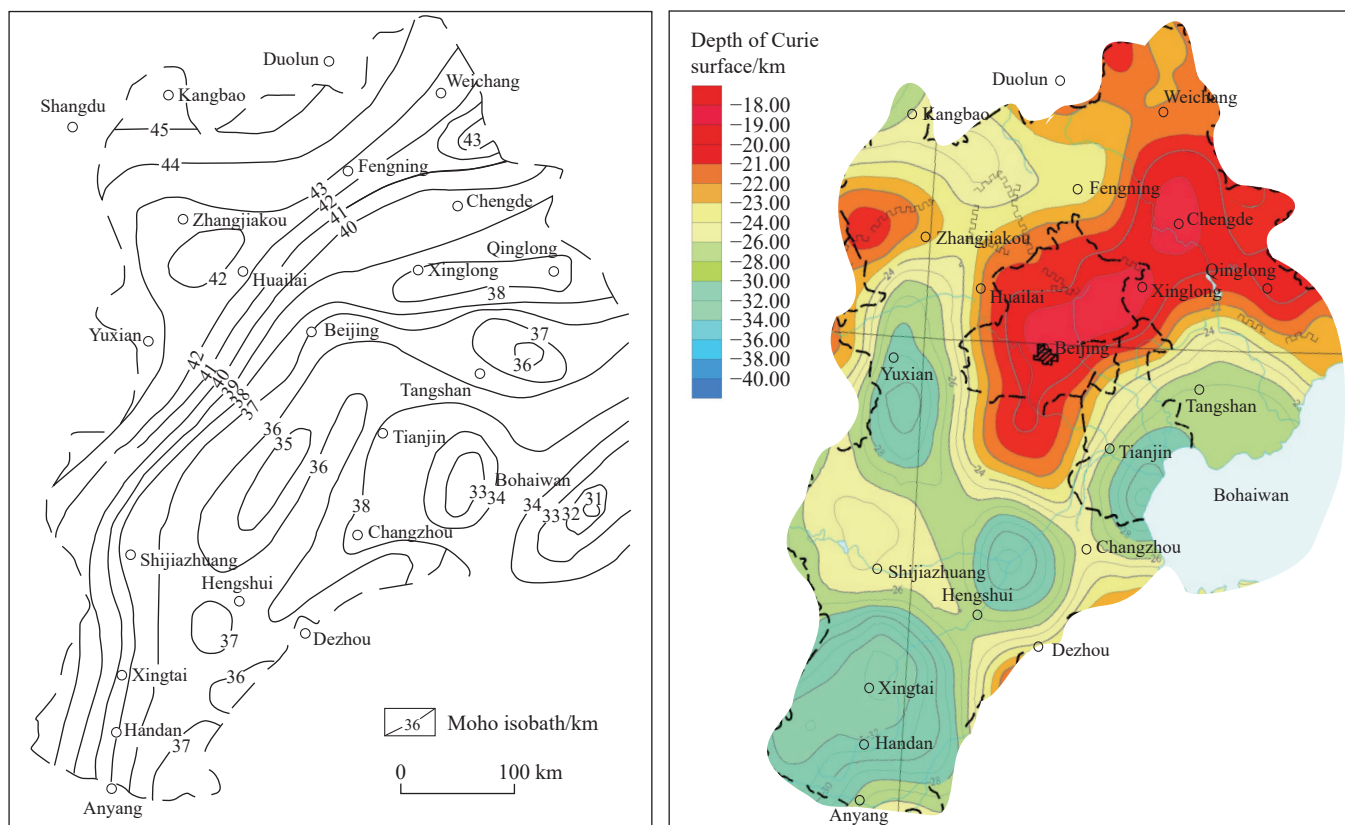


Fig. 17. Depth of the Moho surface and Curie surface in the North China Basin.

$\mu\text{W}/\text{m}^3$ at a depth of 4000 m. This heat generation rate is comparatively lower than that observed in most areas of China, suggesting a thermal structure characterized by a “cold crust and hot mantle.” The thermal conductivity profile displays a “sandwich” configuration, characterized by lower thermal conductivity values at both extremes and elevated values in the central region. Significant water-rock interactions within the carbonate thermal reservoir facilitate geothermal development. The steady-state temperature measurements imply a near-zero geothermal gradient, which can be attributed to the specific thermal conductivity properties. The stratified distribution of thermal conductivity enables heat refraction and accumulation, resulting in a layer with high thermal conductivity and permeability that affects convective heat patterns in the North China Basin (Fig. 18). Additionally, the enhancement of heat accumulation through conduction and convection within the thixotropic system further delineates the basin’s inherent thermal storage

characteristics.

4.3. Thermal structure of the Zhangzhou Basin

In the Zhangzhou Basin, the Moho surface is located at a depth of 29 km to 31 km beneath the Southeast coast (Fig. 19), while the Curie depth ranges from 22 km to 26 km (Fig. 20). Both surfaces are relatively shallow, with the Curie surface being closer to the surface than the Moho. This configuration reflects a significant contribution of heat from both mantle and crustal sources, with mantle-derived heat accounting for over 50%. This results in a “cold crust-hot mantle” thermal structure.

The interior of the basin shows considerable undulations, with burial depths increasing from the coastal areas to the inland regions. The Moho surface is shallower along the eastern coast and deepens inland, indicating that the Zhangzhou Basin is likely to continue experiencing

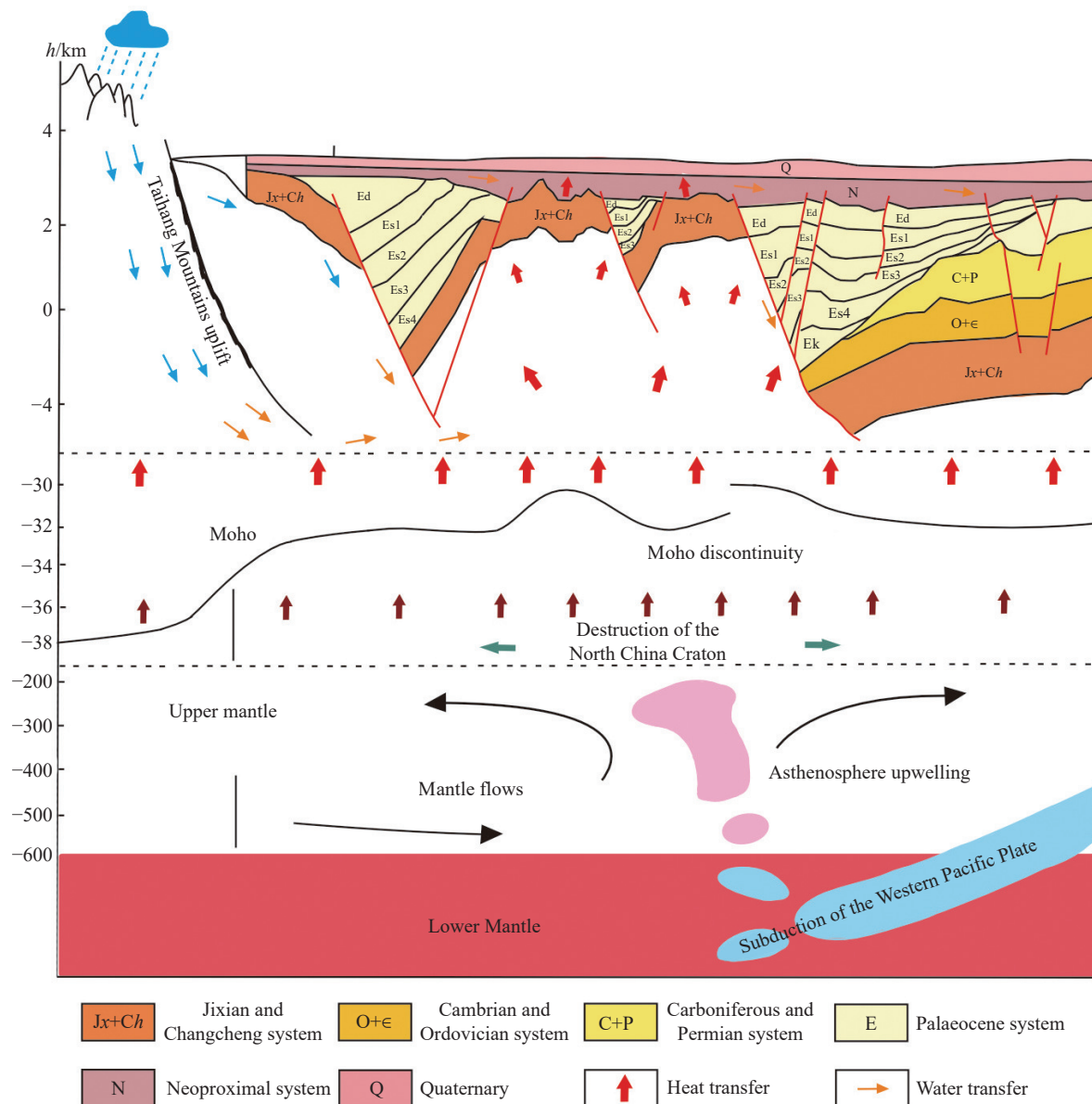


Fig. 18. Patterns of heat gathering in the ancient subduction mountains of northern China.

substantial deep tectonic activity. This thermal structure suggests that the basin has promising potential for future geothermal exploration and development.

Steady-state temperature measurements from the HDR 1 well reveal a regional heat flow value of 79.5 mW/m^2 , indicating a “cold crust-hot mantle” thermal structure in a high heat flow context. Despite the crust is relatively cold, the region exhibits significant crustal heat compared to the North China and Songliao Basins, suggesting a more active thermal tectonic environment. At a depth of 4000 m, the HDR 1 well records a mean radiogenic heat generation rate of $3.02 \mu\text{W/m}^3$

and a mean thermal conductivity of $3.14 \text{ W/(m}\cdot\text{K)}$, though the thermal conductivity shows some variability.

The geothermal gradient exhibits an increase from an average of 1.82°C per 100 m at shallow depths (approximately 2000 m) to 2.69°C per 100 m at greater depths (ranging from 3000 m to 4000 m). This gradient is primarily influenced by the dominant lithological characteristics and a relatively uniform thermal-physical structure. Nevertheless, the spatial variability in porosity and permeability has a significant impact on the distribution of heat and water. Furthermore, hydrothermal activity is instrumental in the

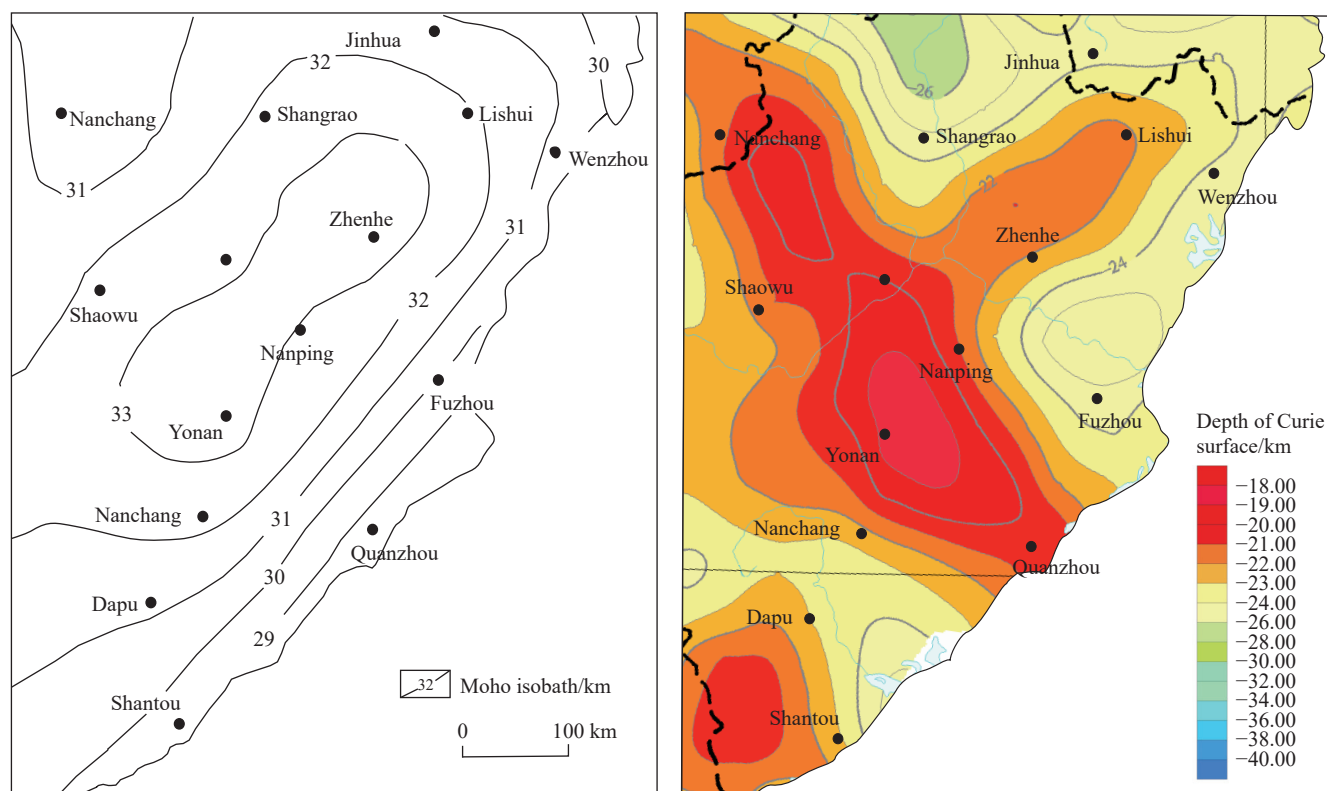


Fig. 19. Depth of the Moho surface (after Xiong SB and Jin DM, 1991) and Curie surface along the southeast coast.

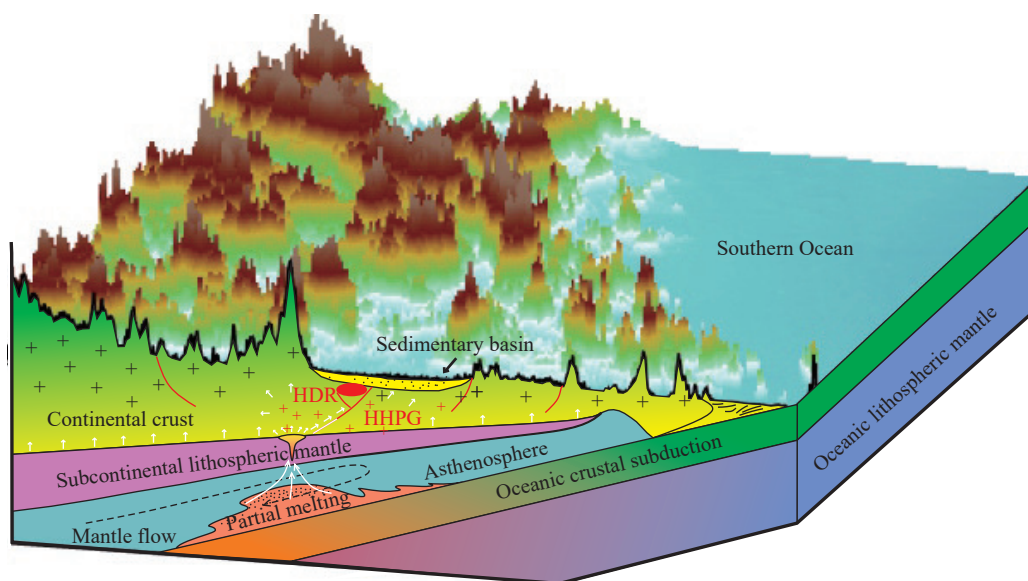


Fig. 20. Genesis of the hydrothermal system of the southeast coastal thermal control structure (after Lin WJ et al., 2022).

formation of geothermal anomalies, which in turn influences the rift network of the Zhangzhou Basin through specific patterns of water and heat regulation.

5. Assessment of geothermal resources potential and carbon Emission Reduction

5.1. Assessment of geothermal resources

The assessment of geothermal resources employs a variety of methodologies, including the geothermal reservoir method, analytical modeling, numerical simulation, statistical correlation, and analogical approaches.

The geothermal reservoir method primarily evaluates static reserves; however, it frequently neglects the effects of elastic water release. Although some scholars recognize the significance of elastic yield, a thorough understanding of its correlation with recoverable extraction volumes remains insufficiently developed.

The analytical modeling method formulates groundwater flow models grounded in the principles of groundwater dynamics. These models estimate the recoverable water volume within a reservoir through analytical solutions, which are then used to calculate the thermal energy contained therein. To optimize the utilization of geothermal energy, it is essential to comprehend the reservoir’s structural characteristics, hydrodynamic parameters, well water inflow, and the management of geothermal wells. Furthermore, extensive data from pumping tests are necessary to validate the assumptions of the models and to ensure precise evaluations.

The numerical modeling method is noted for its high accuracy, integrating water and energy balance models. This methodology necessitates a comprehensive understanding of the reservoir’s architecture, physical characteristics, water levels, pressure, and extraction dynamics. Modifying these parameters can be intricate, which complicates real-time assessments. Conversely, the statistical correlation method formulates relationships among water levels, extraction volumes, and other dynamic variables through statistical techniques, thereby enhancing the evaluation of recoverable resource quantities.

In the North China Basin and the Songliao Basin, the thermal storage method is used to estimate geothermal resources. The North China Basin features five primary geothermal reservoirs: The Neogene Minghuazhen Formation, Neogene Guantao Formation, Paleogene Dongying Formation, Middle Paleozoic Cambrian-Ordovician reservoir,

and the Middle-Upper Proterozoic reservoir. The first three reservoirs are classified as porous layered geothermal reservoirs, whereas the latter two are identified as karst layered geothermal reservoirs situated within bedrock. The heat source for these reservoirs primarily comes from the upper mantle and deep granitic layers containing radioactive elements.

The intricate tectonic framework of the North China Basin, characterized by alternating depressions and uplifts, facilitates the movement of thermal fluids along fault systems. Geothermal resources are assessed individually for each reservoir located within a depth of 4000 m. Through statistical analysis, the total geothermal fluid storage capacity has been estimated to be $14.5 \times 10^{12} \text{ m}^3$, while the heat content of the geothermal fluid is calculated to be $7.23 \times 10^{18} \text{ kJ}$. The available geothermal resource is quantified at $1.46 \times 10^{18} \text{ kJ}$, with an estimated annual exploitable geothermal fluid volume of $3.99 \times 10^9 \text{ m}^3$, which translates to a renewable geothermal energy output of $596 \times 10^{12} \text{ kJ}$ per year. Under conditions of reinjection, the exploitable geothermal fluid volume is projected to increase to $68.4 \times 10^9 \text{ m}^3$ annually, yielding a renewable geothermal energy potential of $12.4 \times 10^{15} \text{ kJ}$ per year (Table 1).

In the Songliao Basin, geothermal reservoirs are primarily located in the sandstones of the Cretaceous Yaojia Formation, Qingshankou Formation, and Quantou Formation. These geological formations establish a geothermal system that is stratigraphically controlled, characterized by a reduction in reservoir thickness from the periphery of the basin towards its center. The thermal uplift that occurred during the Middle and Late Jurassic periods resulted in the uplift of the Moho surface, which subsequently formed a fault-depression structure in the overlying strata. The total estimated thermal fluid storage capacity within the Songliao Basin is approximately $1.92 \times 10^{12} \text{ m}^3$, with the geothermal fluid’s heat content calculated at $1.24 \times 10^{18} \text{ kJ}$. The available geothermal resource is quantified at $1.24 \times 10^{15} \text{ kJ}$, while the annual exploitable geothermal fluid volume is estimated to be $2.17 \times 10^8 \text{ m}^3$, yielding a renewable geothermal energy output of $48.6 \times 10^{12} \text{ kJ}$ per annum. Taking into account the conditions for reinjection, the exploitable geothermal fluid volume is projected to be $8.45 \times 10^9 \text{ m}^3$ annually, resulting in a renewable geothermal energy potential of $2.26 \times 10^{15} \text{ kJ}$ per year.

The Zhangzhou Basin is characterized by an open geothermal field that is influenced by fault zones, with the assessment of geothermal resources conducted through the hot

Table 1. Assessment of geothermal resources and the mitigation of carbon emissions in representative basins located in the Eastern China.

Basins	Area/km ²	Geothermal fluid storage/(10 ⁹ m ³)	Available geothermal resources/(10 ¹⁵ kJ)	Volume of renewable geothermal fluid/(10 ⁶ m ³ /a)	Renewable geothermal energy/(10 ¹² kJ/a)	Annual CO ₂ emission reduction/(10 ³ t)
North China	196000	13369.64	1468.2	68400	12400	1682965
Songliao	260000	1917.83	1235.1	8450	2260	306733
Zhangzhou	941	0.969	6.56	7.53	0.473	64

spring heat release method. Data obtained from Zhangzhou City's application to be recognized as a hot spring city indicates the presence of seven hot springs and forty geothermal wells within the area. The total capacity for geothermal fluid storage in the Zhangzhou Basin is estimated at $9.69 \times 10^8 \text{ m}^3$, while the available geothermal resources are quantified at $6.56 \times 10^{15} \text{ kJ}$. Furthermore, the annual volume of exploitable geothermal fluid is calculated to be $2.06 \times 10^4 \text{ m}^3$, which corresponds to a renewable geothermal energy output of $4.73 \times 10^9 \text{ kJ}$ per annum. These statistics provide a detailed assessment of the geothermal potential in the Zhangzhou Basin, emphasizing both the overall geothermal fluid storage capacity and the projected annual figures for exploitable geothermal fluid and energy.

5.2. Carbon emission reduction prediction

The estimation of carbon emission reductions attributable to geothermal resources is primarily conducted through two methodologies:

5.2.1. National Standard GB/T 11615-2010

This method calculates annual CO_2 emissions reductions by estimating the net heat supplied by geothermal resources and converting this heat into equivalent annual standard coal savings.

5.2.2. CCER Methodology CM-022-V01

This method determines CO_2 emissions reduction by substituting heat generated from fossil fuels with geothermal energy. It calculates the difference between baseline emissions and project emissions, considering any leakage emissions.

Utilizing the initial methodology, this study quantifies the reductions in carbon emissions across three distinct basins. The aggregate annual reduction in CO_2 emissions attributable to geothermal fluid in these basins is estimated to be approximately $2 \times 10^9 \text{ t}$, comprising $1.68 \times 10^6 \text{ t}$ in the North China Basin, $3.1 \times 10^8 \text{ t}$ in the Songliao Basin, and 64000 t in the Zhangzhou Basin (Table 1). These findings emphasize the considerable potential of geothermal resources within China's eastern basins, thereby affirming their significance as a dependable source of clean energy. The advancement of geothermal resources in these regions is essential for the attainment of national dual-carbon objectives and for ensuring energy security in a clean energy context.

6. Conclusions

This paper analyzes the physical characteristics and heat accumulation patterns of typical basins in China, with particular focus on the Songliao Basin, North China Basin, and Zhangzhou Basin. By examining temperature data and vertical lithological variations from deep boreholes, the study establishes representative physical profiles for these regions. Furthermore, it integrates spatial variations of the Curie isotherm and Moho discontinuity to evaluate heat distribution

mechanisms in shallow layers influenced by geothermal fluid circulation. The principal findings are summarized as follows:

(i) The physical profiles developed for the three basins reveal significant spatial heterogeneity in thermal conductivity and radiogenic heat generation patterns. The Songliao and Zhangzhou Basins exhibit vertically uniform thermal conductivity profiles, suggesting steady-state heat conduction conditions. In contrast, the North China Basin displays a distinct “sandwich” structure characterized by high thermal conductivity in central carbonate rock layers and reduced conductivity in marginal lithologies. Radiogenic heat generation assessments indicate low values for both the Songliao and North China Basins, while the granitic crust of the Zhangzhou Basin demonstrates markedly elevated crustal radiogenic heat production rates.

(ii) The study emphasizes thermal structure characteristics by constructing profiles that extend down to the basement. It identifies key factors influencing heat transfer from deeper to shallower geological layers. The variations in thermal conductivity and porosity of the shallow layers play a critical role in the redistribution of heat energy originating from deeper strata. The Songliao Basin is characterized by low permeability and uniform thermal properties, whereas the North China Basin exhibits high permeability and layers with elevated thermal conductivity. In contrast, the Zhangzhou Basin is distinguished by the presence of fracture networks. Additionally, shallow Curie surfaces are indicative of current thermal activity and crustal heat generation, while shallow Moho surfaces provide insights into historical thermal activity derived from the mantle.

(iii) This study systematically evaluates geothermal resources and the potential for carbon emission reductions. Notably, The North China Basin shows the greatest potential for both resource utilization and carbon reduction. The total volume of exploitable geothermal fluid across the basins is estimated to be $76.9 \times 10^9 \text{ m}^3/\text{a}$, corresponding to an annual renewable geothermal energy output of $1.47 \times 10^{16} \text{ kJ}$. The implementation of geothermal energy could lead to a reduction in annual CO_2 emissions by nearly $2 \times 10^9 \text{ t}$, which represents approximately 17.4% of China's carbon emissions in 2022. The development of geothermal resources in these eastern basins is poised to make a substantial contribution toward achieving the national dual-carbon objectives and enhancing the security of clean energy.

(iv) Based on a comprehensive analysis of the thermal structure and geothermal mechanisms of each basin, the paper proposes future exploration strategies. It recommends focusing on high-permeability geothermal reservoirs in the North China Basin and Northeast China Basin, exploring high-quality rift-controlled geothermal fields in the Zhangzhou Basin, and promoting medium and low-temperature heating systems in northern regions. Additionally, prioritizing the development of hot springs for therapeutic purposes in southern regions should be part of a comprehensive geothermal utilization strategy.

CRedit authorship contribution statement

Feng Ma and Gui-ling Wang conceived of the presented idea. Wei Zhang completed the revision of the paper. Xi Zhu, Hao-nan Gan, and Guang-zhen Jiang carried out the field work. Chen Luo carried out graphic editing. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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