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Study on Geothermal Flux and Geothermal Genesis of Typical Geothermal Fields in North China

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ABSTRACT

The Rongcheng geothermal field is located in the middle of the Jizhong Depression in North China, it is an ancient and Neoproterozoic sedimentary depression with rich geothermal resources. In this paper, we collected core samples from boreholes in the geothermal field of Rongcheng for rock thermal conductivity and rock heat generation rate testing and analysis, and studied the composition of geothermal flux and stratified heat flow in the area by combining with temperature measurement data. Hydrochemical analysis was performed by typical geothermal fluid samples to establish geothermal fluid circulation pathways in the region. Comprehensive analysis of water-heat sources in geothermal fields and proposal of geothermal resource genesis model in the region. The results show that the thermal conductivity of the rocks in each stratum is the highest in the Jixian system stratum, followed by the Changcheng system stratum, while the thermal conductivity of the Archaean stratum is lower overall. The value of geothermal heat flow is between 35 and 95 mW/m2, which is the area of high value of geothermal heat flow density in Jizhong Depression. Geothermal resources accumulate heat mainly by conduction, with low heat conduction efficiency but wide distribution, and thermal convection from deep bedrock reservoirs as a useful supplement. The results of the study can provide theoretical support for the development and utilization of geothermal resources in the region.

1. INTRODUCTION

Geothermal is an important part of new energy in China. As a carbon free energy, it can play an important role in energy structure adjustment fields such as power generation and heat supply. The development and utilization of geothermal energy can help to achieve "carbon peaking and carbon neutralization". The evaluation of geothermal resources and the analysis of the formation mechanism of geothermal resources can better provide technical and theoretical support for the development and utilization of geothermal resources in this area. The study of geothermal flux and hydrochemistry is conducive to the evaluation of geothermal resources.

Xiong'an New Area is located in Jizhong Depression, which is a sedimentary depression of Paleogene and Neogene. It is rich in geothermal resources. A large number of boreholes preserved after the exploitation of oil and gas resources provide convenience for the study of the current geothermal field in this area. As early as the 1980s, Chen (1988) analyzed the formation mechanism of the regional geothermal field in North China through a large number of logging and terrestrial heat flow data, and explored the formation, properties, development and utilization of regional geothermal water, providing a strong foundation for the geothermal research in the entire North China region. Later generations studied the drilling and exploration technology of geothermal reservoir structure in Xiong'an New Area (Fan et al., 2020; Gao et al., 2021; Ma et al., 2022). In the past few years, there have been many studies on Niutuozhen geothermal field in Xiong'an New Area, analyzed the soil layer and eluviation sedimentation of Niutuozhen geothermal field since the Quaternary, and studied the characteristics of geothermal reservoir and the genetic mechanism of geothermal resources (Ren et al., 1999; Wang et al., 2016; Guo et al., 2017; Yang et al., 2018; Lu, 2018). Rongcheng geothermal field has been studied relatively much in recent years. Wang et al. (2018) studied and developed the second geothermal reservoir space of Rongcheng geothermal field - Gaoyuzhuang Formation through pumping test and core test, and then calculated the dynamic geothermal resources of Rongcheng bulge (Ma et al., 2020; Hu et al., 2020). Zhao et al. (2020), Zhu et al. (2021), Yu et al. (2022) respectively analyzed the hydrochemical isotope of Rongcheng geothermal field and discussed its geothermal water genesis mechanism. Zhang et al. (2022) analyzed the thermal reservoir space characteristics of Rongcheng geothermal field through borehole logging data and hydrochemical results, and obtained the evolution mechanism of hydrogeochemistry. The overall hydrochemical characteristics of Xiong'an New Area and the formation mechanism of geothermal reservoir conditions were systematically studied (Wang et al., 2019; Liu et al., 2020; Guo et al., 2020).

On the basis of previous studies, this paper used the recently measured drilling temperature measurement data in combination with the original logging data collected previously, calculated the earth heat flow value in the study area through the rock thermal conductivity and other information, analyzed the geothermal field distribution and terrestrial heat flow characteristics in the study area, and uses the water chemical isotope data to obtain the geothermal water circulation path, cold water mixing proportion and other information, so as to obtain the genetic mechanism of Rongcheng geothermal field. It enriches the relevant theories of the geothermal system in this area and provides theoretical support for the sustainable and efficient development and utilization of geothermal resources in this area.

2. STUDY AREA

Xiong'an New Area is located in the middle of the North China Plain, 120 km from the center of Beijing in the north, 110 km from Tianjin in the east, 30 km from Baoding in the west, and about 100 km from Cangzhou in the southeast. The planning area involves Xiong County, Rongcheng County, Anxin County 3 counties and some surrounding areas in Hebei Province, covering an area of about 2,000 square kilometers. Rongcheng geothermal field is located in Rongcheng County, in the east of Taihang Mountains, in the middle of Jizhong Plain, on the south bank of the downstream of South Juma River, on the alluvial fan of Daqing River water system, which is the transition zone from Taihang Mountain plain to alluvial plain, and is a gently inclined plain with deep soil layer, open topography and low vegetation cover, and there are many ancient river channels in the territory. To the north of the Rongcheng-Xiongxian line is an alluvial (lake) slightly inclined plain, the upper part of which is recent river alluvium or pre-fan depression accumulation, overlain by alluvial flood deposits; to the south of the Rongcheng-Xiongxian line is an alluvial (lake) low plain, formed by recent river alluvium and lake marsh deposits.

Located in the mid-latitude zone, Rongcheng geothermal field has a temperate continental monsoon climate with four distinct seasons, dry and windy in spring, hot and rainy in summer, cool in autumn, and cold and little snowy in winter. The annual average temperature is 11.9℃, the extreme maximum temperature is 40.9℃, the extreme minimum temperature is -21.5℃, the hottest July average temperature is 26.1℃, and the annual average daily temperature above 0℃ lasts for 273 days. The average annual precipitation is 522.9 mm, the maximum annual extreme precipitation is 1237.2 mm, and the minimum annual extreme precipitation is 207.3 mm.

The Rongcheng geothermal field mainly includes most of Rongcheng County and the northern part of Anxin County. The bulge is located in the central part of the Jizhong Terrace Depression, with the Langgu Fault Depression to the north, the Niutuozhen Bulge to the east, the Baoding Fault Depression to the south, and the Xushui Depression to the west, and is distributed in a north-northeast direction, which is consistent with the direction of the main tectonic line fractures in the area (Figure 1). The east side of the Rongcheng Bulge is the Rongcheng Fault and the south side is the Xushui Fault. The Rongcheng Fault is located in the line from Anxin to Baigou Town, and is the boundary between the Niuhuozhen Fault Convexity and the Rongcheng Fault Convexity, with a length of about 30 km, a strike of NNE, a tendency of E, an inclination of about 45°, a vertical break distance of 3000m, and a horizontal break distance of 1000~3000m. The Minghuazhen Formation of the uplifting disk directly overlies the middle and upper metasedimentary strata, and the Neoproterozoic sedimentary thickness of the descending disk reaches 2000~3000m, breaking to the crystalline basement, which is a growth fracture controlling the development of the Neoproterozoic. The Xushui Fault is located along the line from Xushui, Anxin to Zhao Beikou, and is a fracture structure controlling the boundary between the Rongcheng Bulge and the Baoding Fault Depression, with a length of about 35km. The trend is near EW, tendency is S, positive fault, dip angle is about 45°, vertical break distance is 1200~3200m, horizontal break distance is 1000~2500m. This fracture disconnects the crystalline base and is a long-term active deep major fracture.

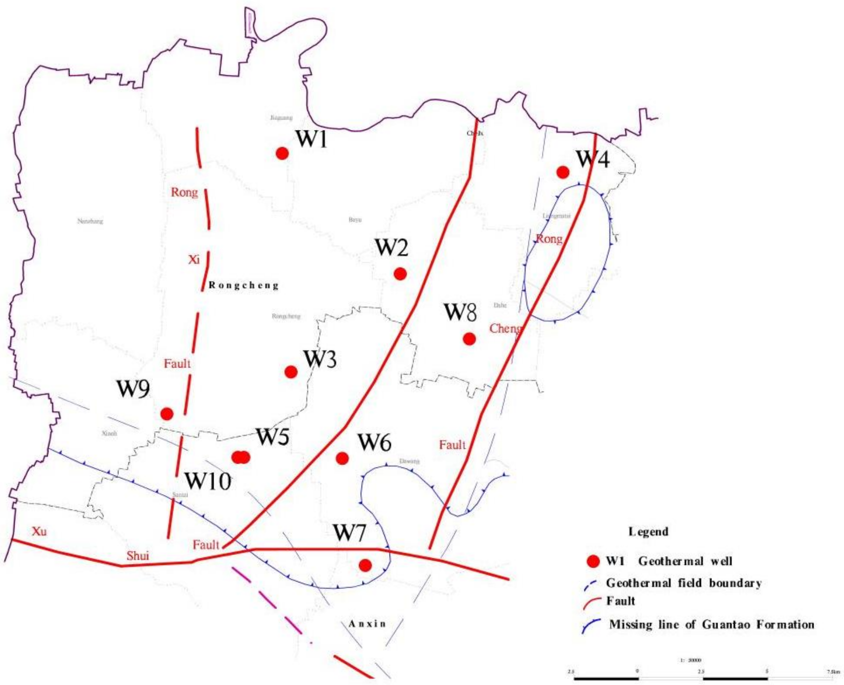


Figure 1: Geological map and sampling points of Rongcheng geothermal field

3. MATERIALS AND METHODS

In this study, geothermal water samples as well as Jixian system rock samples were obtained for testing. The results of the water samples were mainly taken from 9 groups (RC01-RC09) of underground geothermal water of the Wumishan Formation in the geothermal field of Rongcheng, totaling 9 groups. The rock samples were mainly taken from 11 geothermal wells in the Rongcheng geothermal field, and a total of 49 rock samples were obtained at different depths and layers. 29 thermal conductivity and specific heat capacity tests were conducted respectively, and 20 were used for heat generation rate tests.

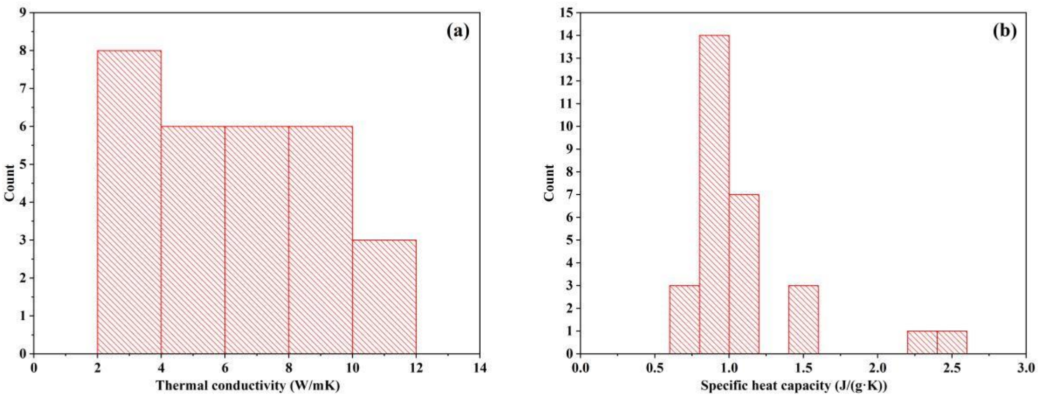
The water samples were collected in 2.5L plastic bottles and sealed, and the full analysis of water quality, trace elements and hydrogen and oxygen isotope tests were completed at the Key Laboratory of Groundwater Science and Engineering, Ministry of Land and Resources. ^{14}C isotopes were done by Beta Analytic Laboratories. Sr and S isotopes were completed by the Central South Geological Science and Technology Innovation Center, Wuhan Geological Survey Center, China Geological Survey. The water samples were collected and filtered through a 0.45 μm microporous membrane and then stored in a Teflon bottle washed twice with the water sample to be collected. According to the drinking natural mineral water testing method "GB 8538-2016" and groundwater quality testing method "DZ/T0064-93" for testing, the testing instrument is plasma emission spectroscopy (model ICAP6300), the anion and cation balance error is less than 3%, the test environment 23 ℃, 48% relative humidity. Hydrogen and oxygen isotopes were detected using a water isotope analyzer (model Picarro 2140-i) with a testing accuracy of up to 0.1‰.

The rocks were all collected in situ after being cored by geothermal wells. The rock thermal conductivity, specific heat and heat generation rate tests were done by the State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences. Thermal Conductivity Scanning (TCS) is used for thermal conductivity testing, with a measurement accuracy of ±3% and a range of 0.2-25W·$(m·K)^{-1}$. The specific heat test was performed using a Hot Disk system with a temperature range of 10 K-1000 K. The heat generation rate test was performed using an inductively coupled plasma mass spectrometer (model ICAP-RQ).

4. RESULTS AND DISCUSSION

4.1 Thermal property characteristics and their distribution

Rock thermal conductivity is a physical quantity characterizing the heat transfer properties of rocks, its physical meaning is the heat passed per unit area along the direction of heat transfer, when the temperature difference per unit length is 1°C per unit time, the unit is W·$(m·K)^{-1}$ (Lang et al., 2016). Rock thermal conductivity, as an important parameter for studying the thermal structure of the Earth's crust and upper mantle as well as the deep thermal state of the Earth, is usually inversely proportional to the geothermal gradient and directly proportional to the heat value (Qiu et al., 2002)。 There are many factors that affect the thermal conductivity of rocks, including the characteristics of the rock itself (rock composition, particle size and structure of the granular material, porosity, water saturation, permeability, etc.), temperature, pressure, etc. (Yang et al., 1993; Song et al., 2011). In this study, thermal property tests were conducted on in-situ rock samples from 10 geothermal scientific drilling wells at different strata and depths in the Rongcheng geothermal field to obtain thermal conductivity, specific heat capacity and radioactivity results of the rocks and calculate the heat generation rate. As shown in Figure 2, the thermal conductivity and specific heat capacity of the 29 groups of rock samples tested in this study mainly involve the Jixian system, Changcheng system, and Archaean stratum, with depths ranging from 873m to 3792m. The thermal conductivity values of the Jixian system strata in the Rongcheng geothermal field range from 2.78 to 11.98 W·$(m·K)^{-1}$, with an average value of 7.33 W·$(m·K)^{-1}$; the measured thermal conductivity value of the Changcheng system strata is 3.72 W·$(m·K)^{-1}$; and the thermal conductivity values of the Archaean strata range from 2.09 to 4.87 W·$(m·K)^{-1}$, with an average value of 3.55 W·$(m·K)^{-1}$. From the thermal conductivity test results, it can be found that the thermal conductivity of the rocks of the Jixian system strata is significantly higher, and the thermal conductivity values of the rocks of the Changcheng system and the Archaean strata are mainly distributed below 5 W·$(m·K)^{-1}$. It is noteworthy that the results of the thermal conductivity tests of rocks from the Jixian Formation have a wide range of variation, probably due to the influence of the mud content in the dolomite received, resulting in the variation of the mineral thermal conductivity test results (Wang et al., 2019). Mudstones have lower thermal conductivity values compared to dolomites, and muddy dolomites as well as dolomitic mudstones have lower measured thermal conductivity values. The specific heat test was conducted on 29 rock samples collected from the Rongcheng geothermal field, and the test results are shown in Tab 1. From the specific heat test of 29 rock samples, the specific heat capacity of Jixian system rocks ranged from 0.72 to 2.48 J·$(g·K)^{-1}$, with an average value of 1.14 J·$(g·K)^{-1}$; the specific heat value of Changcheng system stratigraphic rocks was 0.9 J·$(g·K)^{-1}$; the specific heat of Archaean stratigraphic rocks ranged from 0.83 to 1.49 J·$(g·K)^{-1}$, with an average value of 0.98 J·$(g·K)^{-1}$. It can be seen that the specific heat of rocks in the Jixian system formation of the Rongcheng geothermal field is slightly higher than that of the Changcheng system formation and the Archaean formation.



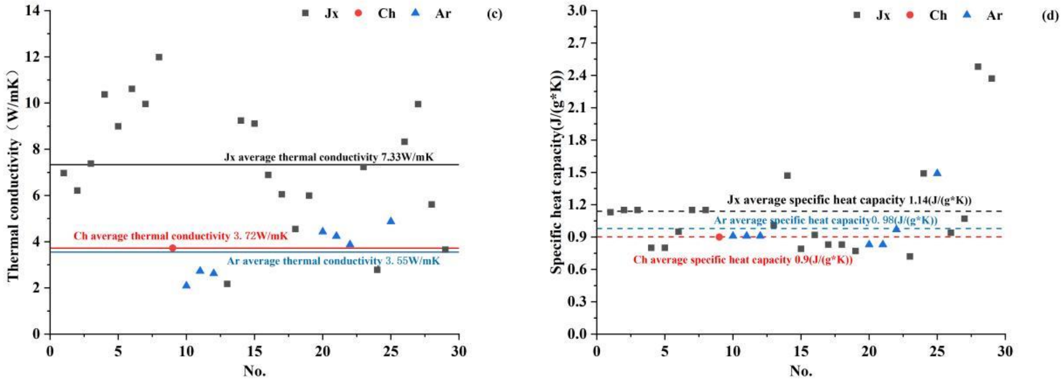


Figure 2: Histograms of the distribution of thermal conductivity (a) and specific heat (b) of rocks in the Rongcheng geothermal field. Distribution of thermal conductivity (c) and specific heat (d) of different strata

The radioactive heat generation rate (A) of a rock is the energy produced by the radioactive decay of the radioactive elements contained in a unit volume of rock in a unit time. Depending on the unit of heat generation rate, the formula proposed by Rybach (1976) based on the modified natural radioactive nuclear parameters was used：

$$A = 0.01 \cdot \rho \cdot (9.52C_U + 2.56C_{Th} + 3.48C_K) \qquad (1)$$

where A is the radiogenic heat generation rate of the rock, in $\mu W/m^3$; ρ is the rock density in g/cm^3, C_U、C_{Th} are the U and Th contents of the rocks, respectively, in μg/g, C_K is the K content of the rock in %. According to the above formula, the radioactive heat generation rate of the samples was calculated by combining the test data.

The results show that the maximum value of radioactive heat generation rate of Jixian system rocks in Rongcheng geothermal field of Xiong'an New Area is 1.45 $\mu W/m^3$ and the mean value is 0.42 $\mu W/m^3$; the radioactive heat generation rate of Changcheng system rocks is 2.18 $\mu W/m^3$; the maximum value of radioactive heat generation rate of Archaean rocks is 1.82 $\mu W/m^3$ and the mean value is 1.39 $\mu W/m^3$. From the calculation results of the above measured data, we can find that the radiogenic heat generation rate of the rocks of the Jixian system strata is low.

The thermal contribution diagrams of U and Th relative to K are often used to analyze the specific contributions of the three radioactive elements to the radioactive heat generation rate A. The thermal contributions of the Jixian, Changcheng, and Archaean formations in the Rongcheng geothermal field are shown in Figure 3. In general, the U contribution tends to be the largest, but when the Th and U contents are the same, the fact that U has two decay systems and a faster decay rate results in a U contribution to the heat generation rate that is about four times higher than that of Th. However, the contributions of U and Th to the heat generation rate tend to show a closer approximation, probably mainly due to the average Th/U of about 3.7 in the rocks. Moreover, most of the rock samples show a low contribution of K to the radiogenic heating rate, and only the Changcheng system and the Archaean formation in well W3 show a contribution of K to the radiogenic heating rate of about 50%, presumably due to the high content of potassium-containing minerals in the samples taken.

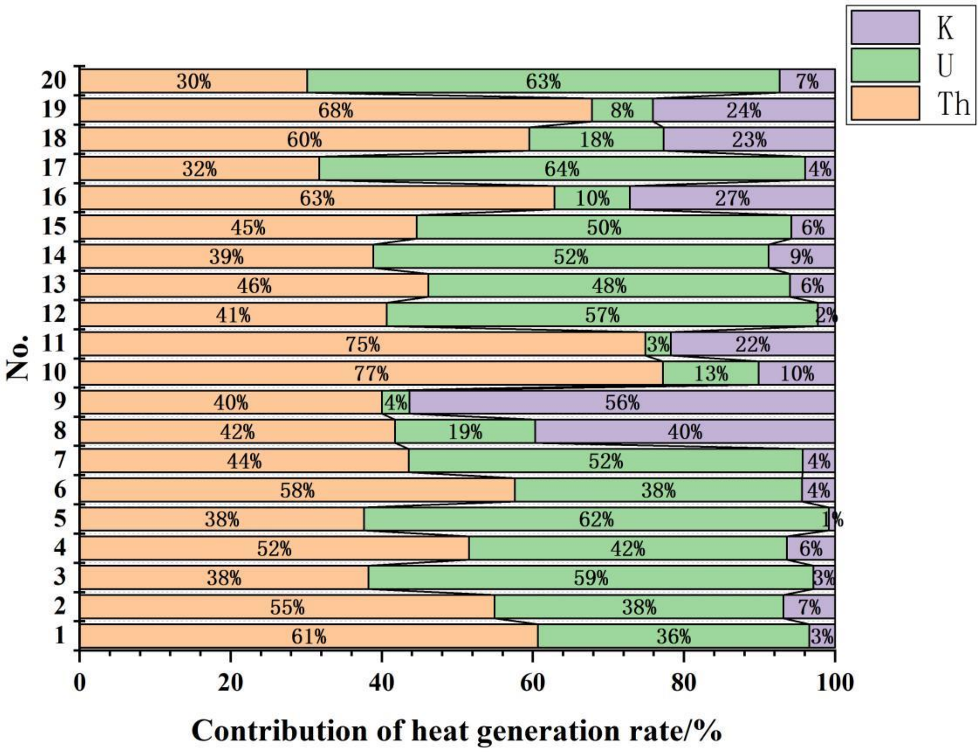


Figure 3: U、Th、K Thermal Contribution Chart

4.2 Geothermal field distribution and its characteristics

In order to deeply study the thermal state of the strata at different depths in the Rongcheng geothermal field, the ground temperature measured data of W7 and W9 geothermal wells in the Rongcheng geothermal field were selected for analysis and discussion in this study. Based on the measured geothermal temperature data of geothermal wells, the temperature and geothermal gradient profiles are drawn. As shown in Figure 4, W7 geothermal well is 4000 m deep and penetrates the upper cover of the Rongcheng geothermal field, exposing the Jixian system carbonate thermal reservoir, and the highest ground temperature from 0 to 4000 m can reach 84.1°C. Above 2920 m is the cover stratum, and the average geothermal gradient is 14.07 ℃/km, and the geothermal temperature increases significantly with depth, 2920 m enters the Jixian system carbonate geothermal reservoir stratum, and after entering the carbonate stratum, the geothermal temperature increases to the highest temperature of 84.1 ℃ and then falls back, and then the geothermal temperature basically remains stable, and the average geothermal gradient of the Jixian system carbonate stratum is low, only 5 ℃/km. The average ground temperature gradient of the Jixian carbonate formation is low, only 5 ℃/km, and the ground temperature gradient at some depths is frequently negative. It can be seen that since the cap layer entered the geothermal reservoir, the ground temperature showed a small increase and then gradually leveled off, and the ground temperature gradient decreased from 14.07 ℃/km to 5 ℃/km. Geothermal well W9 is 3000 m deep, which also penetrates the upper cover of the Rongcheng geothermal field and exposes the Jixian system carbonate geothermal reservoir, and the highest ground temperature from 0 to 3000 m can reach 70.6 ℃. Above 2440 m is the cover stratum, the average ground temperature gradient is 16.8 ℃/km, and the ground temperature gradually increases with depth. 2440 m enters the Jixian system carbonate geothermal reservoir stratum, and unlike W7, the ground temperature still gradually increases after entering the carbonate thermal storage stratum, but the ground temperature gradient decreases compared to the cover stratum, and the average ground temperature gradient is 10.5 ℃/km.

By comparing the geothermal temperature curves of W7 and W9 geothermal wells and the geothermal gradient curves, it can be found that the geothermal gradient of the Jixian system carbonate geothermal reservoir formation is significantly lower than the geothermal gradient of the overburden, which is presumed to be due to the convection of geothermal fluids in the reservoir during the circulation and upward transport, which affects the geothermal gradient. At the same time, the influence of the in-homogeneous distribution of the aquifer in the vertical direction, the non-homogeneous fractures existing in the reservoir rock and the fracture of the tectonic location where it is located leads to fluctuations in the geothermal curve with increasing depth. The vertical variation of temperature is controlled by stratigraphic lithology, basement relief and deep tectonics. The stratigraphic and geothermal gradients of different lithologies in the Rongcheng geothermal field are different, but the overall pattern shows that the geothermal gradients of the middle and Cenozoic strata are significantly larger than those of the Paleozoic strata. Therefore, as the depth increases, the stratum changes from new to old, the gradient of ground temperature becomes smaller and the vertical increase of ground temperature tends to slow down from fast.

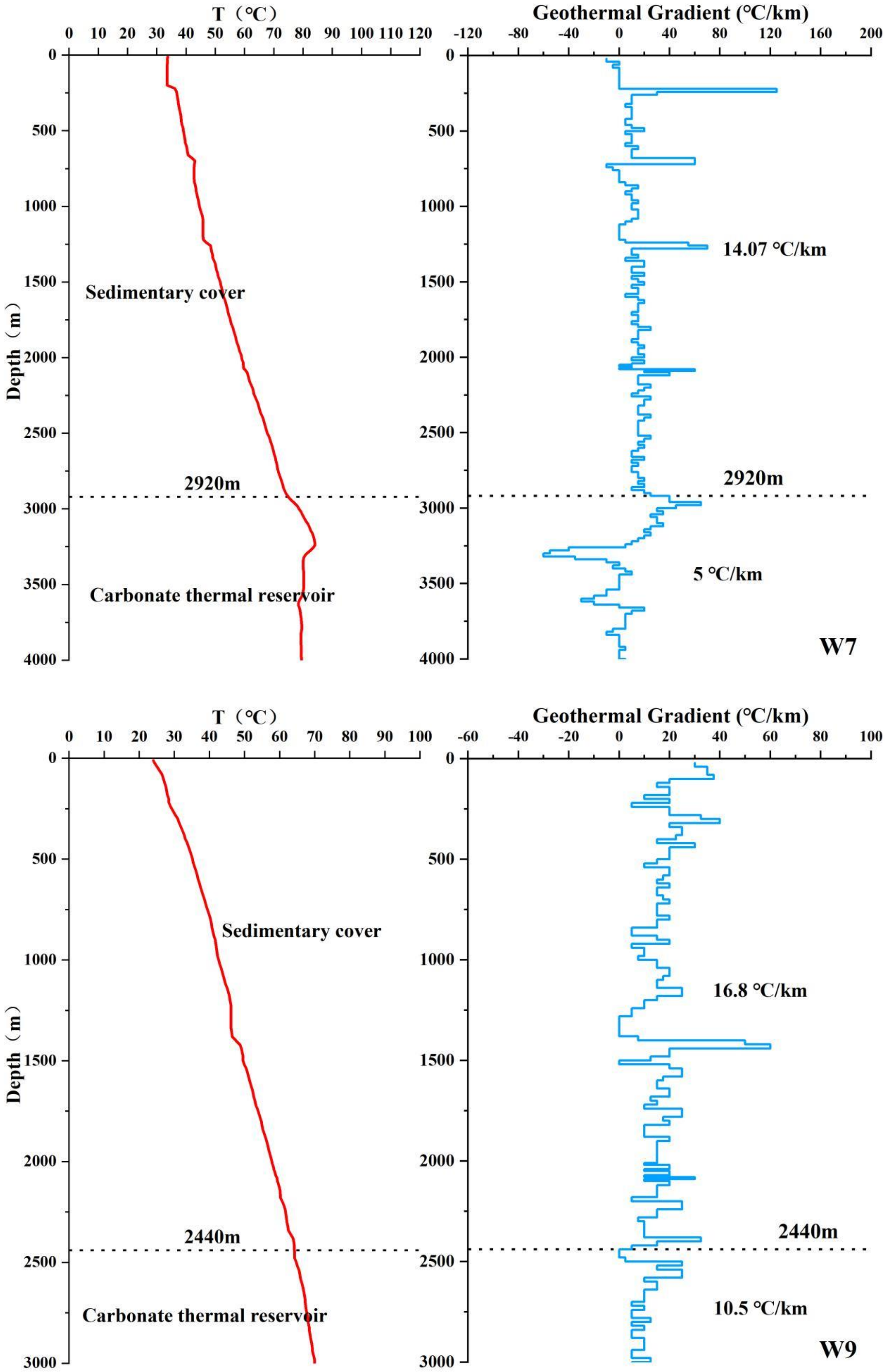


Figure 4: Geothermal temperature and geothermal gradient map of W7 and W9 geothermal wells in Rongcheng geothermal field

4.3 Spatial distribution characteristics of the earth's heat flow

According to the logging and data collection results (Zhang et al., 2022), the geothermal gradient of the cover layer of the Rongcheng geothermal field is between 14.07-74.75 ℃/km with a thermal conductivity of 1.709 W/(m·K), and the geothermal gradient of the carbonate formation is between 4.06-15.13 ℃/km with a rock thermal conductivity between 4.34-9.14 W/(m·K). The heat flow value is equal to the product of the ground temperature gradient and the thermal conductivity of the rock, and according to Fourier's law, the heat flow value can be calculated by the following equation (Wang et al., 2019)：

$$Q = -k\frac{dT}{dZ} \tag{2}$$

where Q is the geothermal heat flow (mW/m^2); K is the rock thermal conductivity W/(m·K); and dT/dZ is the geothermal gradient (°C/1km). The negative sign represents that the direction of geothermal heat flow conduction is opposite to the direction of geothermal gradient.

The geothermal heat flow values of the cover layer in wells W1, W5, and W6 in the study area were calculated to be 127.75 mW/m^2, 68.34 mW/m^2, and 40.49 mW/m^{2,} and the geothermal heat flow values of the bedrock were 36.78 mW/m^2, 51.77 mW/m^2, and 65.66 mW/m^2, and it is found that the geothermal heat flow values of the cover layer in well W1 are much higher than those of the deep carbonate rock. The geothermal heat flow values of the W1 well are not used, because the W1 well is more severely affected by groundwater runoff, resulting in a small geothermal temperature gradient, which leads to lower geothermal heat flow values.

By calculating the weighted average of geothermal heat flow value through the reservoir thickness, it is found that the geothermal heat flow value in the study area is basically between 35-95 mW/m^2, and the average value of heat flow is 64.66 mW/m^2, which is a high density value area in the North China Plain. Geothermal heat flow values ranged from 57.24-95.97 mW/m^2 at the top of the RongCheng bulge and 36.15-42.9 mW/m^2 in the depression between the bulges (Table 1). Spatially, the geothermal heat flow values are relatively high in the raised areas with thin cover and relatively low in the depressions. The sedimentary rocks in the raised area directly overlie the carbonate rocks of the Middle and Upper Paleozoic, which, together with the carbonate rocks of the Paleozoic, have undergone a long period of leaching and weathering, forming a porous and highly permeable hot water reservoir, which is conducive to the conduction of heat flow. When the heat flow from the lower part is conducted upward, it will preferentially converge in the raised area with high thermal conductivity, resulting in high heat flow along the raised core and relatively low heat flow values along the slope on both sides (Zhao, 2020).

Table 1: Geothermal heat flow values in the study area

Well	Earth Heat Flow(mW/m^2)	Location
W2	80.49	Bump Top
W3	64.60	Bump Top
W4	42.90	Depression
W5	57.24	Bump
W6	48.79	Fault Eastern
W7	36.15	Depression
W8	95.53	Fault
W9	95.97	Bump

Xiong'an New Area is a medium and low temperature hot water geothermal resource area mainly formed by the geothermal flow mechanism, and the geothermal flow spreading is controlled by the regional crust-mantle uplift zone, depression zone and transition zone spreading. Due to the lithospheric thinning and shallow Moho surface caused by the disruption of the North China Craton, large-scale ductile deformation and magmatism occurred in the North China crust, and the massive overlying volcanic bodies in the lower Cenozoic of North China prove the assertion. The geothermal heat flow in the study area is influenced by the geological structure characteristics, stratigraphic lithology and hydrogeological conditions. The geothermal temperature is basically consistent with the undulation of the underlying basement structures, with positive structures having high geothermal temperature and large geothermal gradient, while negative structures have low geothermal temperature and small geothermal gradient. The higher geothermal heat flow value of 48.79-95.53 mW/m^2 at the Rongdong Fracture is due to the higher thermal conductivity of the fracture, faster heat conduction in the fracture channel, and more rapid heat arrival at the shallow part, forming a bump in the geothermal contour (Yue et al., 2019).

4.4 Geothermal fluid sources and circulation characteristics

4.4.1 Groundwater recharge sources

Based on the hydrogen and oxygen isotope characteristics of groundwater, it can determines the origin of groundwater, the conditions of groundwater recharge and the extent to which atmospheric precipitation is linked to surface water and groundwater, and understand the circulation pathways of groundwater. The groundwater δD value depends mainly on the recharge temperature and recharge elevation, except for the mixing effect which is less affected, while the δ^{18}O value depends mainly on the exchange degree of water-rock reaction and the ratio of water and rock (Ni et al., 2016).

According to the data (Wang et al., 2013), the linear hydrogen-oxygen isotope correlation of atmospheric precipitation in the area where the Rongcheng geothermal field is located is $\delta D=8\delta^{18}O+9$. The graph of atmospheric precipitation and hydrogen-oxygen isotope relationship in the study area (Figure 5) shows that the underground geothermal water in the study area basically falls near the atmospheric precipitation line, indicating that atmospheric precipitation is the main source of underground hot water recharge in the study area. However, the hydrogen and oxygen isotope values are partially shifted to the right compared to the atmospheric precipitation line, and an "oxygen drift" has occurred. This relatively low isotope value indicates that the deep geothermal water recharge source is not direct recharge from local atmospheric precipitation, but may be lateral recharge from a distant location after a long period of subsurface runoff (Zhang et al., 2010). It indicates that the deep geothermal reservoir of Xiong'an New Area is in a more closed state, and there is basically no hydraulic connection between aquifers. Due to the relatively long runoff, the deep geothermal reservoir is a carbonate rock geothermal reservoir with strong water-rock reaction and strong oxygen isotope exchange ability, so oxygen drift will occur.

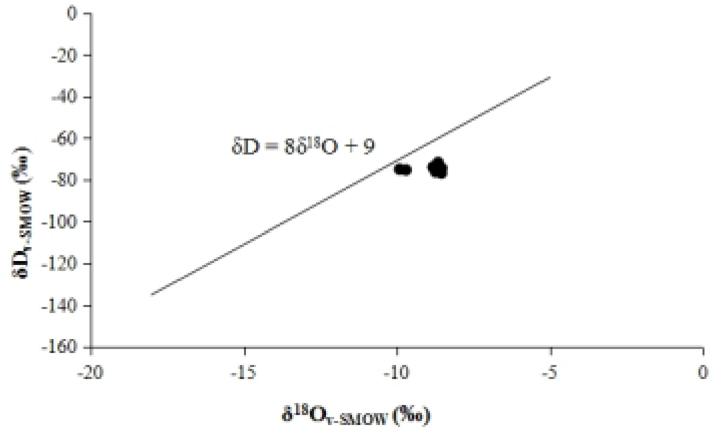


Figure 5: Groundwater δD-δ^{18}O relationship in the study area

4.4.2 Groundwater recharge elevation

The δD and δ^{18}O of atmospheric precipitation are linearly related to the temperature, and the elevation effect means that the higher the altitude, the lower the temperature, and the values of δD and δ^{18}O decrease at the same time (Sun et al., 1992). The groundwater recharge elevation is inferred from the hydrogen and oxygen isotopes, and the groundwater recharge elevation formula is known from the information：

$$H = \frac{\delta_G - \delta_P}{k} + h \tag{3}$$

where δ_G is the value of δ^{18}O in the sample, δ_P is the value of δ^{18}O in the atmospheric precipitation, k is the elevation gradient of δ^{18}O in the atmospheric precipitation, and h is the elevation of the sampling point (m). According to the information given by Liu et al. (2009), the value of δ^{18}O in atmospheric precipitation in North China is -6.72, and the elevation gradient of δ^{18}O in atmospheric precipitation is -0.276‰/100m. The calculated recharge elevation of the study area is 705.03-802.86m, which coincides with the elevation of Baoding Mountain. Based on the topographic features and the recharge elevation, it is inferred that the source of underground hot water recharge in the study area is mountain front water mixed with atmospheric precipitation.

4.4.3 Cold water mixing ratio

Since the hot water beneath the Rongcheng geothermal field is located between partially balanced and immature water with cold water mixing (Zhu et al., 2021), the effect of cold water mixing can be eliminated by using the silica-enthalpy model to analyze the proportion of hot water before cold water mixing.

$$\begin{cases} S_c x + S_h(1-x) = S_s \\ SiO_{2c} x + SiO_{2h}(1-x) = SiO_{2s} \end{cases} \tag{4}$$

Where S_c is the enthalpy of cold water near the surface (J/g), S_h is the initial enthalpy of hot water (J/g), S_s is the final enthalpy of spring water (J/g), SiO_{2c} is the SiO_2 (mg/l) content of cold water near the surface, SiO_{2h} is the initial SiO_2 content of hot water (mg/l), SiO_{2s} is the final SiO_2 content of spring water (mg/l), and x is the mixing ratio of cold water underground.

According to the silicon-enthalpy model equation to make enthalpy and SiO_2 content as a function of temperature, respectively (Figure 6), the intersection of which is the proportion of cold water mixed in. As can be seen from the figure, the proportion of cold water mixing in the study area is between 40% and 63%, and the temperature of deep thermal storage is between 90°C and 140°C. There is also uncertainty in the calculation of the geothermal reservoir temperature using the silicon-enthalpy model because the geothermal reservoir temperature obtained by this method depends on the SiO_2 content of the hot spring water, which may be too high due to the loss of steam from the expansion of the underground hot water before mixing with the cold water (Tong et al., 1981). However, because the silicon-enthalpy model is more comprehensive and the SiO_2 content is more accurate, it can be used as a relatively reliable standard for calculation.

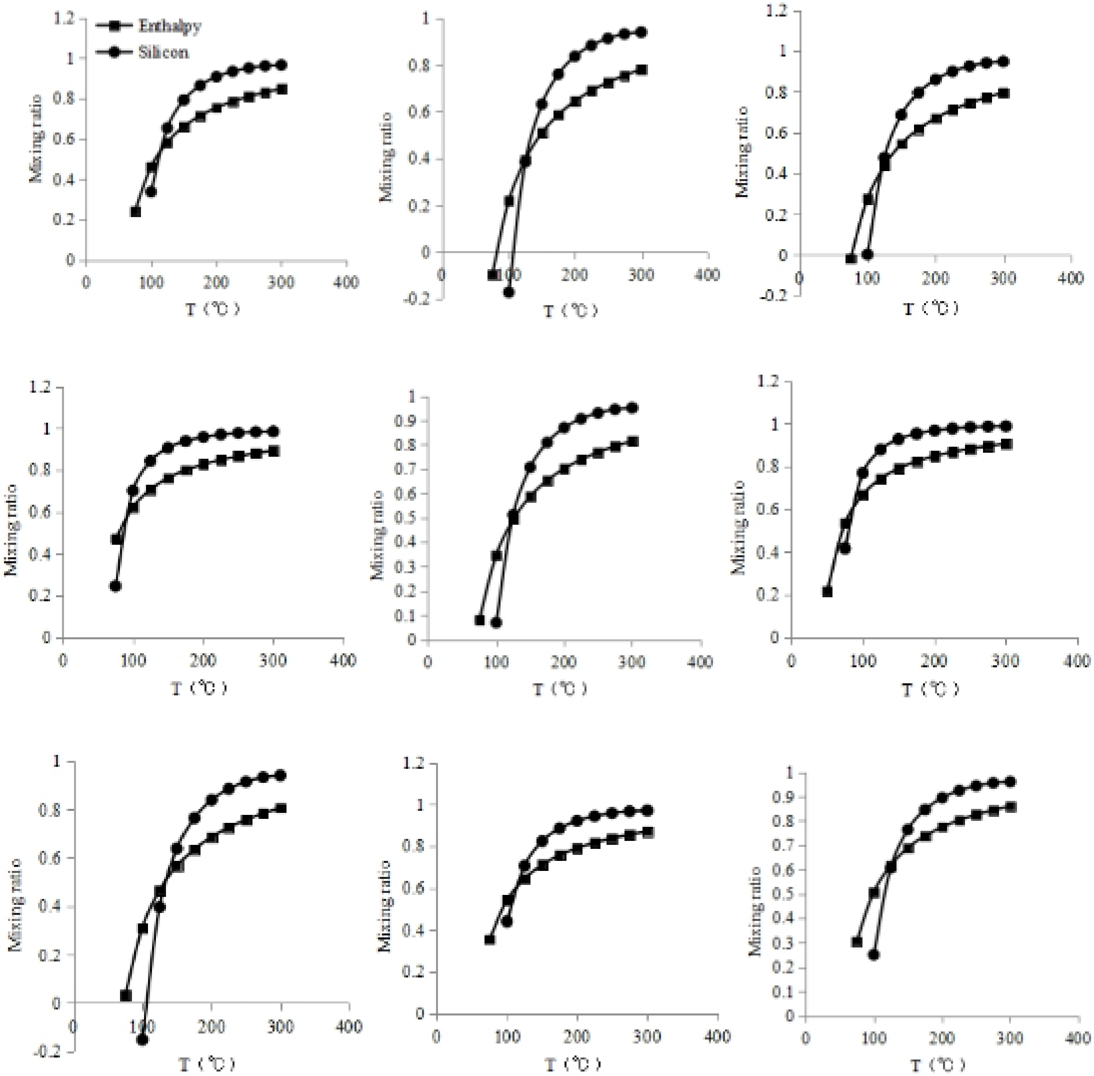


Figure 6: Silicon-enthalpy model of study area

4.4.4 Thermal cycle depth

The Xiong'an New Area is located in the North China Plain, which is a sedimentary basin type geothermal resource, and the geothermal reservoir depth of underground hot water is calculated by the following formula：

$$H=\frac{t_1-t_2}{I}+h \tag{5}$$

Where H is the geothermal reservoir depth (m), t_1 is the thermal storage temperature (℃), t_2 is the local average annual temperature (℃), I is the ground temperature gradient (℃/100m), and h is the thickness of the thermostatic zone (m).

According to the data, the depth of the annual constant temperature zone in Xiong'an New Area is 5~45m, the average is 26m, the annual average temperature is 11.9℃, the ground temperature gradient is generally 3.0~8.0℃/100m, here take 3.5℃/100m(Chen, 1988 ; Lu et al., 2018). The calculated thermal circulation depth of the study area is 2257.43-3686m (Table 2), the geothermal reservoir temperature is between 100℃-140℃, the geothermal fluid receives the influence of cold water mixing in the ascending process, mixing 40%-60% of shallow cold water, combined with the borehole data shows that the geothermal reservoir temperature is between 42-81℃ at one or two kilometers.

Table 2: Depth of thermal cycle in the study area

Sample ID	Geothermal reservoir temperature(℃)	Thermal cycle depth(m)
RC01	110.00	2828.86
RC02	128.00	3343.14
RC03	123.00	3200.29
RC04	90.00	2257.43
RC05	120.00	3114.57

RC06	95.00	2400.29
RC07	140.00	3686.00
RC08	126.00	3286.00
RC09	120.00	3114.57

4.5 Composition of Geothermal Fluxes and Causal Model of Rongcheng Geothermal Field

Combining the above studies, the parameters related to the heat flux of the Rongcheng geothermal field are shown in Table 3. Among them, the thermal conductivity of the thermal layer in the Rongcheng geothermal field shows that the carbonate geothermal reservoir is higher than that of the basal Archaean formation, and the thermal conductivity of the Jixian system formation in the carbonate thermal reservoir even shows twice the thermal conductivity of the basal Archaean formation. The specific heat and thermal conductivity patterns are basically the same, and again the carbonate geothermal reservoir is higher than the basal Archaean formation, but the difference between the specific heat of the carbonate geothermal reservoir and that of the basal Archaean formation is not significant. The radiogenic heat generation is the opposite of the thermal conductivity and specific heat pattern, which shows that the basal Archaean strata are higher than the carbonate strata, among which the Changcheng System strata show higher radiogenic heat generation but are not representative due to the small number of sample samples. The geothermal temperature gradient between the cover layer and carbonate reservoir in the Rongcheng geothermal field shows a large difference. The geothermal temperature gradient of the cover layer is higher, and the average value reaches 4-5 times of the geothermal temperature gradient of the carbonate reservoir, but the difference between the geothermal heat flow value of the cover layer and the carbonate reservoir is not large when combined with the geothermal physical characteristics of the formation rocks.

Table 3: Heat flux parameters of Rongcheng geothermal field

Average	Stratigraphy			
	Cover layer	Thistle system	Changcheng system	Archean
Thermal conductivity W/(m·K)	/	7.33	3.72	3.55
Specific heat J/(g·K)	/	1.14	0.9	0.98
Radiogenic heat μW/m^3	/	0.42	2.18	1.39
Geothermal gradient ℃/km	44.41	9.6		/
Earth Heat Flow mW/m^2	54.42	51.4		/

In summary, the geothermal fluid in the Jixian system geothermal reservoir of the Rongcheng geothermal field mainly comes from atmospheric precipitation, which infiltrates from the Taihang Mountains in the northwestern part of the Rongcheng geothermal field, carries out deep transport and enters the geothermal reservoir fluid circulation system. In this process, the fluid is transported along the deep fracture or tectonic favorable position and enters the deep geothermal reservoir through lateral recharge. After receiving heat from the mantle, the fluid is transported upward along the deep large fractures distributed in the Rongcheng geothermal field, and at the same time receives exothermic heat generation from carbonate rocks as well as convective heat transfer, and the temperature gradually increases. Moreover, the Rongxi Fracture, the Xushui Fracture and the Rongcheng Fracture, which are distributed in the Rongcheng Geothermal Field, have a great influence on the transport and formation of geothermal fluids. These three fractures provide good upward channels for geothermal fluids in the Rongcheng Geothermal Field, so that the geothermal fluids can transport along the fractures in the vertical direction to the near-surface position, and after mixing with the shallow water bodies, the geothermal fluids in the current reservoir are formed, and finally the geothermal anomaly area,, the current Rongcheng Geothermal Field, is formed.

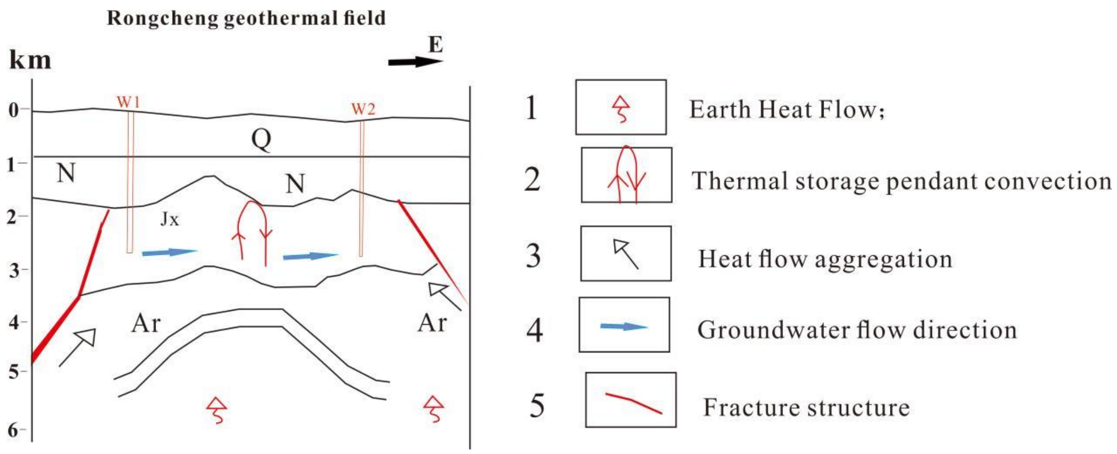


Figure 7: Geothermal field genesis model of Rongcheng

5. CONCLUSIONS

The analysis of rock thermal properties shows that the average value of thermal conductivity of the Jixian system stratum in the Rongcheng geothermal field is 7.33 W·(m·K)$^{-1}$; the measured thermal conductivity of the Changcheng system stratum is 3.72

W·(m·K)$^{-1}$; and the average value of thermal conductivity of the Archaean stratum is 3.55 W·(m·K)$^{-1}$. From the thermal conductivity test results, it can be found that the thermal conductivity of the rocks of the Jixian system strata is obviously higher, and the thermal conductivity values of the rocks of the Changcheng system and the Archaean strata are mainly distributed below 5 W·(m·K)$^{-1}$, showing a pattern of gradual decrease with increasing depth. Based on the measured temperature data of geothermal boreholes, the geothermal gradient of the cover layer of Rongcheng geothermal field is between 14.07-74.75℃/km, and the geothermal gradient of carbonate formation is between 4.06-15.13℃/km. Combined with the thermal conductivity test results, it is estimated that the geothermal field geothermal heat flow value of Rongcheng is basically between 35-95 mW/m^2, and the average value of heat flow is 64.66 mW/m^2, which belongs to the high density value area in the North China Plain. The geothermal heat flow values are between 57.24-80.49 mW/m^2 at the top of the RongCheng Bulge and 36.15-42.9 mW/m^2 in the depression between the bulges, reflecting the good geothermal geological background of the RongCheng Geothermal Field。

The geothermal fluid in the carbonate geothermal reservoir of the Rongcheng geothermal field mainly comes from atmospheric precipitation, which is infiltrated from the Taihang Mountains at an elevation of 705.03-802.86m and transported through the deep part of the thermal cycle at a depth of 2257.43-3686m and enters the fluid circulation system of the geothermal reservoir. The fluid is transported along the deep fracture or tectonic favorable position, and after receiving heat from the mantle, it is transported upward along the deep large fracture, and at the same time receives exogenous heat production from carbonate rocks and convective heat transfer, and after mixing with 40%-60% of shallow cold water, it forms the geothermal fluid in the current reservoir, and finally forms the geothermal anomaly area, which is the current Rongcheng geothermal field.

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