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Migration characteristics of geothermal fluids in karst geothermal reservoirs in the Beijing-Tianjin-Hebei Plain

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ABSTRACT

The Beijing-Tianjin-Hebei Plain is one of the regions with the largest scale and the fastest growth of medium and deep geothermal heating in China. Based on the test of 82 geothermal fluid samples from 7 geothermal fields in Hebei Province, 2 geothermal fields in Henan and 2 geothermal fields in Shandong Province, and combined with previous studies on the chemical characteristics of karst geothermal water in Beijing and Tianjin, the migration characteristics of geothermal fluids in karst geothermal reservoirs in the Beijing-Tianjin-Hebei Plain were systematically analyzed. Hydrochemical characteristics of karst geothermal water in the research areas show certain differences, the geothermal water in Hebei is more mature than its neighboring provinces. The distribution of total dissolved solids (TDS) and strontium elements in the area is low in the north and south and high in the middle, indicating that the overall flow direction of geothermal fluid is from north-south to the middle. Combined with the groundwater flow field and the change trend of hydrochemical characteristics of geothermal wells along the geological section, a geothermal water migration model is established. The geothermal fluids from Taihang Mountain, Yanshan Mountain and Western Shandong Mountain enter the basin and continue to migrate to the central part of the basin along the water conducting faults. Migration characteristics of the same supply direction are not the same. The geothermal fluids from Taihang Mountain are cut off by Niudong fault in the north and end in the central uplift belt of Jizhong depression, while in the south it enters the east of Jizhong depression relatively quickly along the Hengshui conversion belt. The geothermal fluids from Yanshan Mountain migrate into the basin along the Cangdong fault, but the fault also separates the hydraulic connection between the tectonic units. Considering the effective dynamic conditions, it is recommended to further expand the scale of scientific development and utilization of geothermal energy in the geothermal water catchment areas around Xiong County and southwest Cangzhou City.

1. INTRODUCTION

The world is currently facing the global problem of climate change. Significant changes have taken place in global average temperatures, average precipitation and frequency of extreme weather events as countries use fossil fuels and emit greenhouse gases (Akhmat et al., 2014). According to research by relevant scholars, it is expected that by the end of the 21st century, the temperatures of global urban areas will rise by 1.9~4.4°C (Zhao, L. et al., 2021), leading to a series of serious environmental and social problems. In this context, China' s leaders put forward the carbon emission peak and carbon neutrality goals; in March 2021, the Chinese ***REPORT ON THE WORK OF THE GOVERNMENT*** listed "take solid steps toward the goals of achieving peak carbon dioxide emissions and carbon neutrality" as one of the key tasks. To achieve carbon peaking and carbon neutrality goals, the core work is to control carbon dioxide emissions. Increasing the development and utilization of green energy is one of the most important measures.

As "carbon-free" energy, the development and utilization of geothermal energy have positive significance for realizing "net zero carbon emission". In addition to not producing carbon emissions, geothermal energy also has the characteristics of huge reserves and wide distribution, is not affected by seasonal, climatic, diurnal changes, and more stable than photovoltaic and wind power. Controlled by geological and structural conditions, sedimentary basin-type low-temperature geothermal resources are mainly developed in central and eastern China, which are widely used in geothermal heating, hot spring bathing, tourism & health care, and other industries. Among them, the current mainstream geothermal heating technology does not consume groundwater itself, only extract heat from underground hot water, and replace fossil energy combustion for building heating, which has become an important winter heating mode in Beijing, Tianjin, Hebei and adjacent regions. According to the Chinese National Energy Administration's ***Opinions on Promoting the Development and Utilization of Geothermal Energy***, by 2025, the heating (cooling) area of geothermal energy will increase by 50% compared with that in 2020, and by 2035, the heating (cooling) area of geothermal energy will double that in 2025. The development and utilization of geothermal energy will become an important means of coal reduction and carbon reduction.

In the development process of medium-low temperature geothermal resources, the long-term interaction process between geothermal water and environment can be determined by analyzing the chemical characteristics of geothermal water, revealing its supply source, migration path and renewal ability, which has important reference significance for the scientific deployment of geothermal exploration and development direction. For karst reservoirs geothermal resources in Beijing-Tianjin-Hebei Plain (abbreviated as BTHP), previous researchers paid much attention to regional geothermal background (Zuo, Y.H. et al., 2013; Chang, J. et al., 2016; Wang, Z.T. et al., 2019; Wang, K. et al., 2020; Wang, X.W. et al., 2020), thermal storage characteristics (Ma, L.Q. et al., 2007; Pang, Z.H. et al., 2016; Li, P.W. et al., 2016, 2020; Xiao, J. et al., 2018; Wang, G.L et al., 2020), and hydrochemical characteristics of individual geothermal fields (Wang, X.Y. et al., 2002; Li, J.F. et al., 2008; Gao, B.Z. et al., 2009; Zhang, W.B. et al., 2013; Liu, Y.C. et al., 2015a, b; Jia, Z. et al., 2015; Liu, K. et al., 2017 ; Liu, Z.M. et al., 2017; Lu, C. et al., 2018; Yang, J.L. et al., 2018; Yuan, L.J. et al., 2020; Zhao, J.Y. et al., 2020), while studies on the migration path of basin-level geothermal water were relatively inadequate. Based on the geothermal heating projects carried out by Sinopec in the BTHP, this study uses the geothermal water samples collected during the implementation of the project to carry out the hydrochemical test and analysis. Combined with the relevant reported data of predecessors, this study carries out the analysis of the migration characteristics of underground hot water of karst thermal storage in the BTHP, clarifies the supply direction and migration path of geothermal water, and provides reference for the scientific and sustainable development of geothermal resources from the perspective of geothermal water renewal ability.

2. GEOTHERMAL GEOLOGICAL BACKGROUND

The BTHP is located in the middle of Bohai Bay Basin and can be divided into three depressions (Jizhong depression, Linqing depression and Huanghua depression) and two uplifts (Cangxian uplift and Xingheng uplift, Figure 1). There are abundant geothermal resources in the area, which can be divided into uplift mountain type and sedimentary basin type. The former is mainly distributed along the thermal control faults inside Taihang Mountain uplift and Yanshan uplift, and the latter is mainly distributed in the Bohai Bay Basin. The basement of the BTHP is composed of Archean, Mesoproterozoic, Upper Proterozoic, Paleozoic, and the caprock is composed of Mesozoic and Cenozoic. The bedrock mainly includes Archean metamorphic rocks, Proterozoic, Lower Paleozoic marine carbonate rocks and Upper Paleozoic marine-continental transition to continental carbonate rocks. During the formation and development, the basin experienced Yanshan movement and Himalayan movement. After Yanshan movement, it deposited thick clastic rocks. The sedimentary layers from bottom to top were Mesozoic Jurassic and Cretaceous, Cenozoic Paleogene-Neogene and Quaternary. Among the sedimentary strata, clastic strata of Guantao Formation (Ng), Minghuazhen Formation(Nm), carbonate strata of Ordovician and Wumishan Formation (Jixianian System, Mesoproterozoic) are the principal geothermal reservoirs.

Due to the development of karst fractures, carbonate geothermal reservoirs usually develop vertical seepage and horizontal runoff conditions, its water output and recharge ability are generally better than sandstone clastic geothermal reservoirs (Pang, Z.H. et al., 2020). In Europe such as Paris, France and Bavaria, Germany, it has been decades since the geothermal resources of carbonate geothermal reservoirs were developed for space heating (Ungemach, 2004; Martin, 2020), achieved substantial economic and environmental benefits. At present, the development of geothermal resources in the BTHP is mainly based on the karst geothermal reservoirs of the Ordovician-Cambrian and Wumishan Formation, and a number of space heating projects have been formed, such as China's first heating "smoke-free city" Xiongxian geothermal field or called Niutuozhen geothermal field (Lund and Toth, 2020), Bazhou geothermal field, Xianxian geothermal field in Hebei, the Xiaotangshan geothermal field in Beijing, and the Panzhuang geothermal field in Tianjin, etc. (Zhang, Y.M. et al., 2018; Zhang L.et al., 2019 ; Li, T.X. et al., 2020).

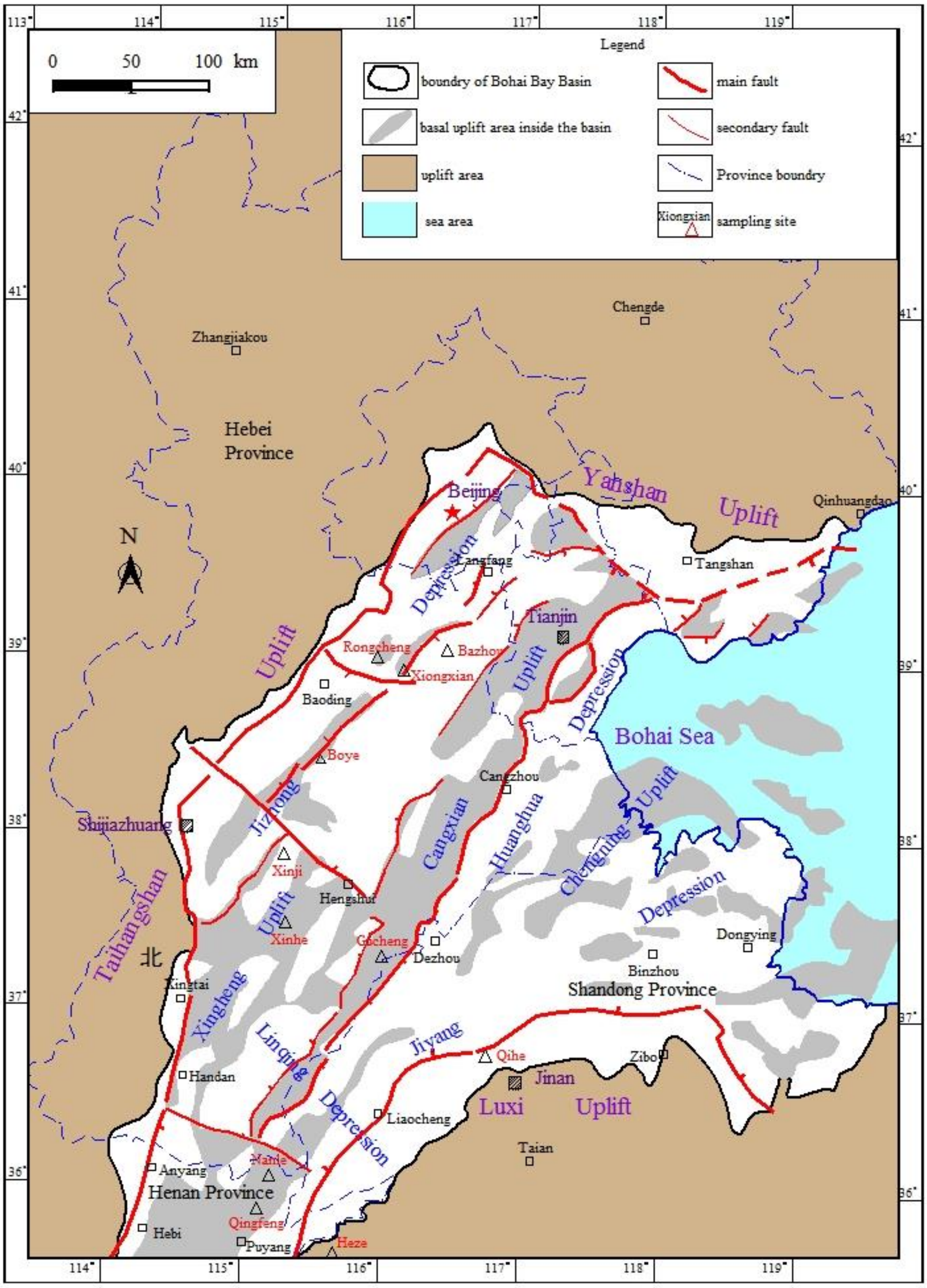

Figure 1: Schematic diagram of tectonic regionalization in the BTHP and adjacent areas

Terrestrial heat flow in the BTHP is regularly distributed, the heat flow value is low in the mountains on the north and west sides, and high in the plain area inside the Bohai Bay Basin. In the Yanshan uplift in the north and Taihangshan uplift in the west, the geothermal temperature is obviously lower than that inside the basin due to the interference of natural cold water. In addition to the relatively high terrestrial heat flow value in a few small basins such as Yanqing-Huailai basin, the terrestrial heat flow value is generally not more than 55 mW/m^2. In the west of Fangshan in Beijing, Xinglong County-Weichang County in Hebei Province and southwest of Chicheng County, there are also three low terrestrial heat flow areas (less than 40 mW/m^2) (Fig. 2). In the Bohai Bay Basin, controlled by the secondary structural units and faults distributed in the NE direction, the geothermal field is distributed in alternating high and low phases. In return, the terrestrial heat flow value increases gradually from west to east, from north and south sides to the middle, and the average value is close to 62 mW/m^2 (Wang, G. L. et al., 2017). Among them, the south of Caofeidian in Hebei, the south of Xiongxian, and the junction of Huanghua City in Hebei and Binhai New Area in Tianjin are the high value distribution areas of regional terrestrial heat flow, and the highest terrestrial heat flow value can reach more than 100 mW/m^2.

In the BTHP, the plane distribution of geothermal gradient of Cenozoic clastic rock cover above the karst geothermal reservoirs has obvious zoning and segmentation characteristics. The highest geothermal gradient is in the central uplift belt of Jizhong depression and Cangxian uplift (3.5~4.5°C/100m), and in the Xiongxian county and Jinghai area in Tianjin the geothermal gradient is up to

7.5°C/100m. On the contrary, the lowest geothermal gradient distributed in the west sag of Jizhong depression, which is basically less than 2.5°C /100m. The eastern sag belt of Jizhong depression is characterized by segmentation. In the north section (north of Renqiu), the geothermal gradient is less than 3°C/100m, and in the middle south section (south of Renqiu), the geothermal gradient is 3~3.2°C/100m. In the local buried hill areas such as Renqiu, Suning, Dawangzhuang and Wuji, the geothermal gradient is as high as 3.5~5.0°C/100m.

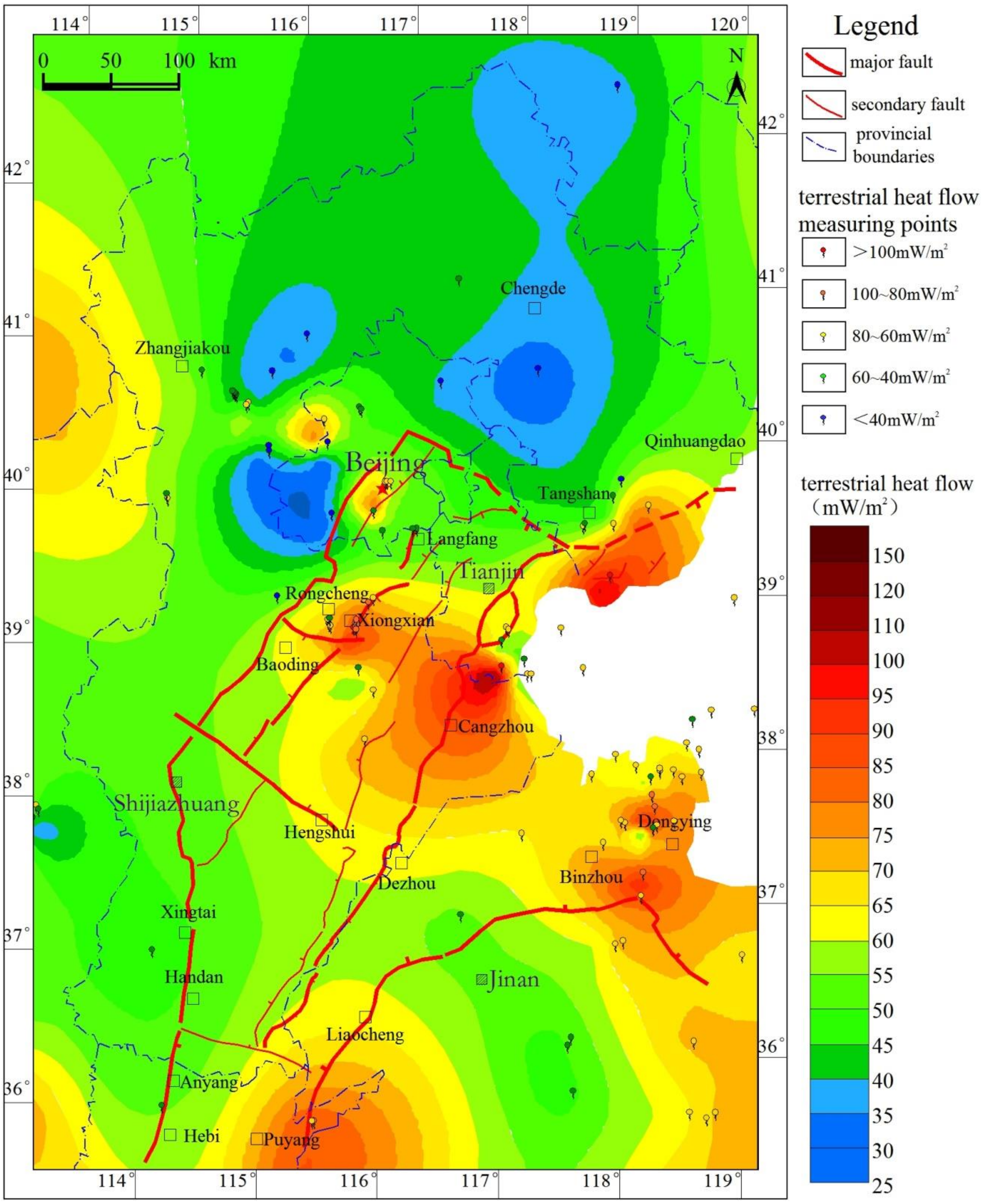

Figure 2: Contour map of terrestrial heat flow in the in the Beijing-Tianjin-Hebei plain（abbreviated as BTHP） and adjacent areas (after Jiang, G. Z. et al., 2016)

Two sets of karst geothermal reservoirs of Jixian system and Ordovician are mainly developed in Bohai Bay basin. Due to the exposure of multi-stage tectonic uplift, there are great differences in the formation loss of different tectonic units, and there are various residual formations near the weathering crust. The zoning and segmented structures of Bohai Bay Basin determine that the buried depth characteristics of geothermal reservoirs in the study area are also zonal distribution (Figure3). The high-quality geothermal reservoirs of Wumishan Formation in Jixian System are mainly distributed in the central uplift of Jizhong depression, and high quality Ordovician geothermal reservoirs are mainly distributed in Cangxian uplift. The thickness of the Ordovician thermal reservoirs in the BTHP is mainly between 90~110 m, in Langfang-Bazhou, Huanghua, Hengshui-Nangong it can reach 120-150 m, in Beijing it is generally less than 90m, and in the central and western Jizhong depression and eastern Cangxian uplift it is missing. The roof of Ordovician karst geothermal reservoirs is deeply controlled by NE-trending structure, and the main buried depth is 1000 ~ 2500 m. In the deep fault depressions of the Cenozoic basin, such as Langfang, the eastern side of Bazhou, Raoyang, Nangong, Huanghua-Binhai New Area, the Ordovician geothermal reservoirs are relatively deep, and the roof depth can reach 3000~5000 m. The main thickness of Wumishan Formation geothermal reservoirs of in BTHP is 300 ~ 500 m, in the middle of Jizhong depression and the east of Cangxian uplift - Huanghua depression it is more than 500 m, and in the middle-south segment in the west of Jizhong depression-Cangxian Uplift it is less than 300 m. The main buried depth of geothermal reservoirs are 2000 ~ 3000 m, which is less than 1500 m in Rongcheng, Xiongxian and Cangxian uplifts of central Jizhong depression, and more than 4000 m in Bazhou depression and Raoyang depression of central Jizhong depression.

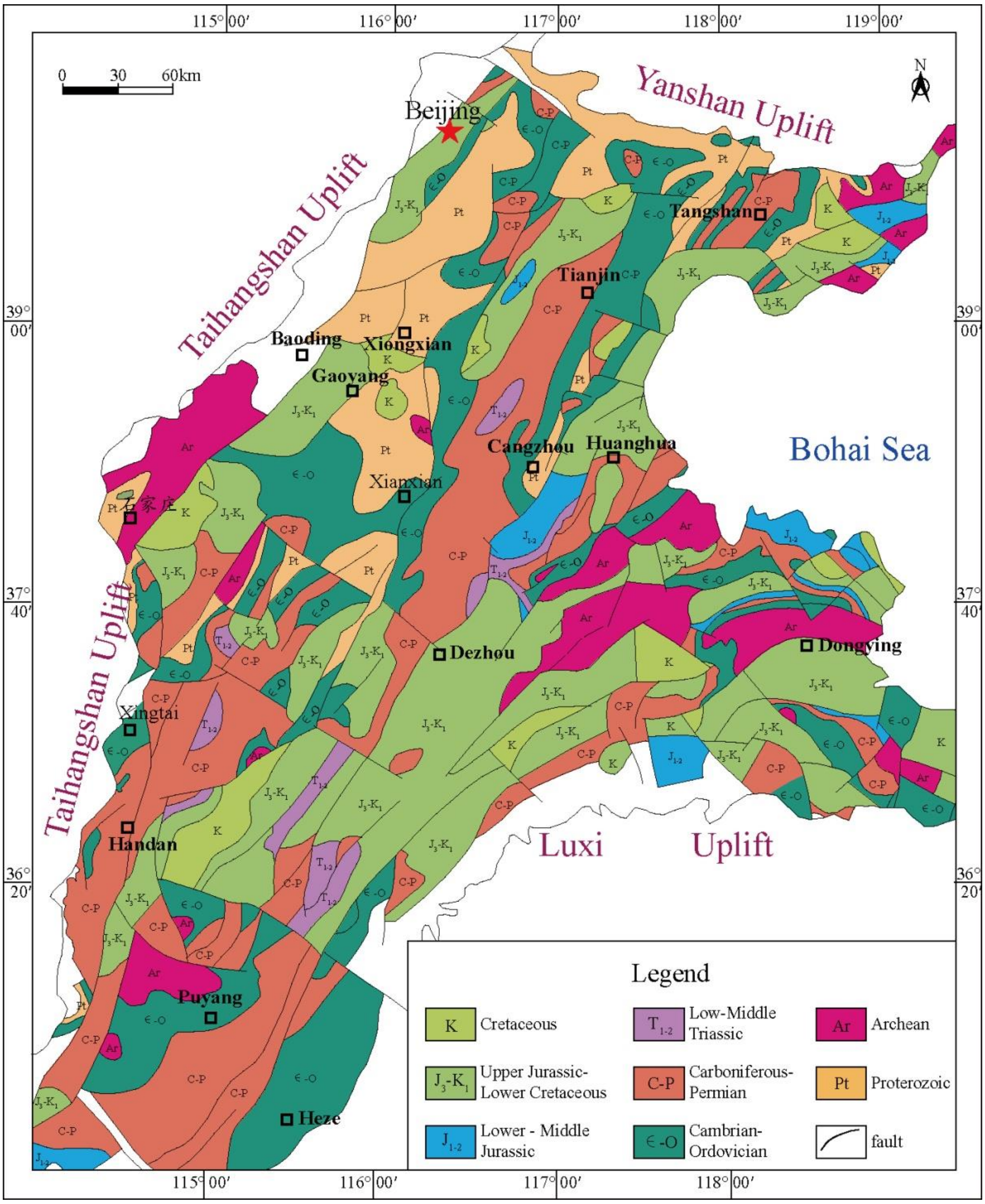

Figure 3: Geological map of pre-Cenozoic bedrock in the BTHP and adjacent areas (after Zhang Y. et al., 2020)

3. CHEMICAL CHARACTERISTICS OF GEOTHERMAL WATER

Groundwater belongs to the underground runoff stage in the natural water cycle. Its formation, movement and evolution are closely related to atmospheric precipitation and surface water. The hydrochemical composition of geothermal water is gradually formed in the long underground runoff process, and the hydrochemical characteristics of geothermal water are also quite different since the different storage medium, hydrodynamic conditions and temperature (Lu Q. Y., 2017). The chemical components can be used as the basis for studying the migration characteristics and help to analyze the formation of geothermal water (Yu X. H., et al., 2011).

In order to analyze the genesis of geothermal water in karst geothermal reservoirs in BTHP, geothermal water samples from 82 karst geothermal reservoirs wells (58 in Jixian system and 24 in lower Paleozoic) were collected in 11 areas of Xiongxian County, Rongcheng, Bazhou, Boye, Gucheng, Xinhe and Xinji in Hebei Province, Qingfeng and Nanle in Henan Province, Heze and Qihe in Shandong Province from 2017 to 2019. The anion and cation indexes were determined by the Key Laboratory of Geothermal Resources Development and Utilization of SINOPEC. The HCO_3^- test instrument is Switzerland Metrohm automatic potentiometric titrator 905, the titration accuracy is 0.1 μL, and the detection limit is 1.65 mg/L; the detection instrument is Dionex-500 ion chromatography, the accuracy is 3%, and the detection limit is 0.05 mg/L.

The geothermal water samples in Hebei region come from 68 carbonate geothermal wells. Among them, 58 geothermal wells of Jixian system karst geothermal reservoirs are from Jizhong depression, including 43 wells in Xiongxian, 12 wells in Rongcheng, 2 wells in Bazhou and 1 well in Boye (Figure4); 10 geothermal wells of Lower Paleozoic karst geothermal reservoirs are from Jizhong depression, Xingheng uplift and Cangxian uplift, including from 2 wells in Xinji, 3 wells in Xinhe and 5 wells in Gucheng. Gucheng and Xinhe are far away from Taihang Mountain in the West and Yanshan Mountain in the north, and the average TDS value of samples from these areas are relatively high, which are up to 7404~10960mg/L. However, in Xinji area close to Hengshui conversion zone, it is speculated that due to the rapid light water supply of Taihang Mountain in the west, the average TDS value of geothermal water in lower Paleozoic karst geothermal reservoirs are quite low, which is about 2564mg/L.

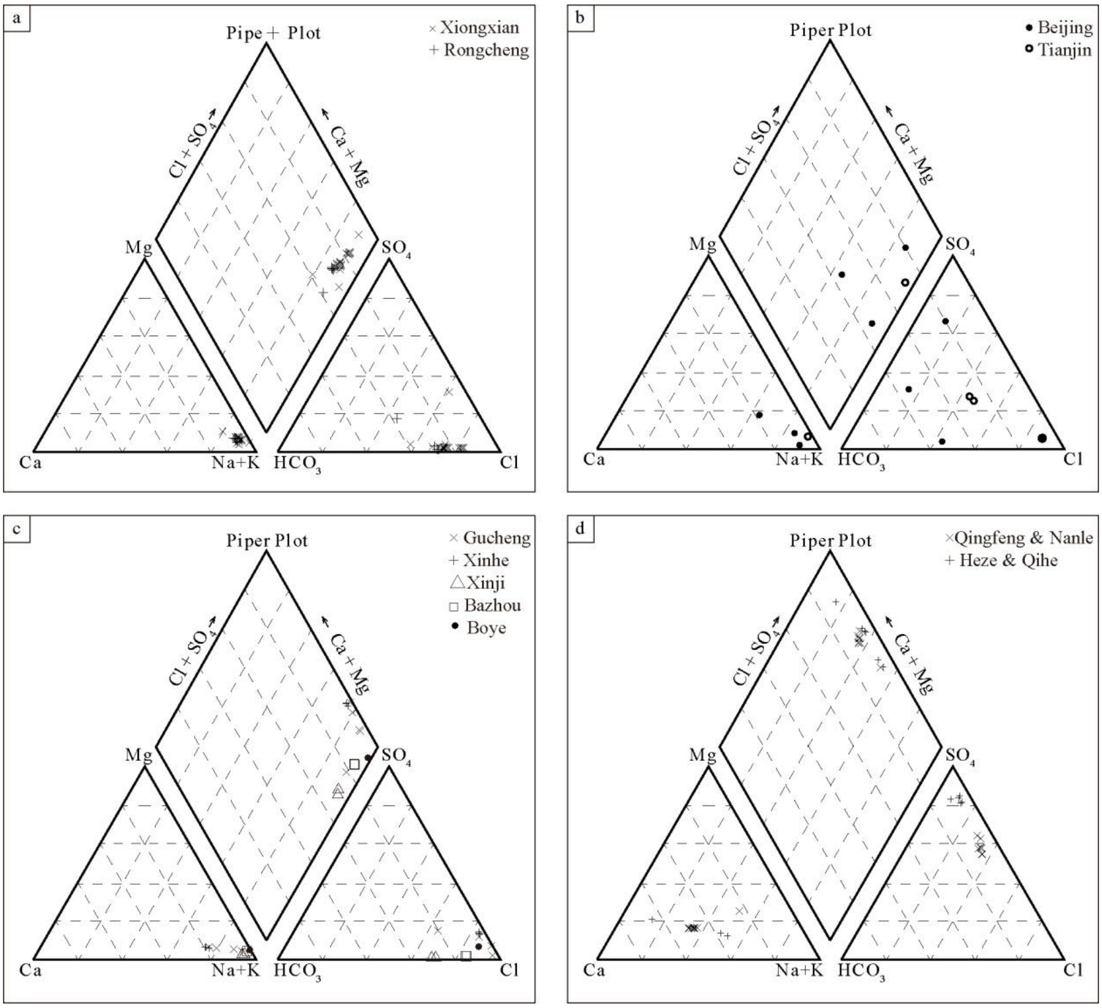

Figure 4: Piper diagram of geothermal fluids from carbonate geothermal reservoirs wells（a from Xiongan New Area，b from Beijing and Tianjin, c from Hebei and d from Henan

Jixian system is the most exploited karst geothermal reservoirs in the 10 geothermal fields inBeijing, and the geothermal water in this reservoirs usually shows relatively complex chemical characteristics (Figure4) (Zhang W. B., et al., 2013; Liu Y. C. et al., 2015a, b; Liu Z. M. et al, 2017 ; Yuan L. J. et al., 2020). The hydrochemical types of most geothermal fields are mainly HCO_3-Na·Ca, HCO_3-Na and HCO_3·SO_4-Na, which belong to the subtype of HCO_3-Na. Among these fields, Yanqing, Northwest Beijing and other 5 fields have similar low total dissolved solid (TDS) geothermal water, and the average TDS in these fields are 484~694mg/L. Compared to them, the average TDS value of the geothermal water in Tianzhu geothermal field is 1605mg/L, which is higher. The reservoirs in Houshayu geothermal field are Lower Paleozoic, that is different from other geothermal fields. The hydrochemical type of Houshayu geothermal field is SO_4-Na, and the average TDS is 1303 mg/L. The hydrochemical type of Fengheying geothermal field located above Daxing uplift is Cl-Na type, and the TDS value reaches 6700 mg/L, which is much higher than other geothermal fields in Beijing.

The geothermal fields also developed the Lower Paleozoic and Jixian system karst geothermal reservoirs (Wang X. Y. et al., 2002; Li J. F. et al., 2008). Former researches reported the data of geothermal waters from 55 wells of karst geothermal reservoirs (Figure4) (Gao B.Z. et al., 2009; Liu Y. C. et al., 2015a, b; Jia Z. et al., 2015; Yang J. L. et al., 2018). Among them, 36 geothermal water samples from geothermal wells exploiting Jixian geothermal reservoirs are Cl-Na type (Gao B.Z. et al., 2009; Jia Z. et al., 2015; Yang J. L. et al., 2018), that are consistent with the fields in Hebei and Fengheying geothermal field in southeast of Beijing. The average TDS of the 36 geothermal water samples, which is lower than that of samples from Hebei and Beijing Fengheying, indicating good water supply conditions. The hydrochemical type of geothermal water samples from 19 geothermal wells exploiting Ordovician Cambrian reservoirs are SO_4·Cl-Na type (Gao B.Z. et al., 2009; Jia Z. et al., 2015; Yang J. L. et al., 2018), which is similar to Beijing Houshayu geothermal field that exploiting same reservoirs, but the average TDS of the 19 samples is 2517mg / L, which is higher than that of Houshayu. It is speculated that the higher average TDS is related to its longer distance from the surface water supply source in Yanshan area.

Geothermal water samples from wells exploiting Lower Paleozoic reservoirs around the BTHP are comparative compared and analyzed. Analysis of 6 samples in Heze and Qihe, Shandong, and 8 samples in Qingfeng and Nanle, Henan shows higher SO_4^{2-} and Ca^{2+} proportion, displaying the carbonate reservoirs geothermal water in Hebei is more mature than that in Shandong and Henan (Figure 4).

Comparing the hydrochemical characteristics of geothermal water samples from carbonate geothermal reservoirs in BTHP and its surrounding areas, it shows that the water samples from various provinces show certain differences (Figure 5). The short distance between Beijing and the surface water supply area of Taihang Mountain in the West and Yanshan Mountain in the north, resulted in the fact that the geothermal water from Beijing has the lowest TDS value and comparatively higher proportion of Ca^{2+} and HCO_3^- ions. The geothermal water samples in Hebei Province and Tianjin are similar in TDS and the proportion of main anion and cation, except that the proportion of SO_4^{2-} ion in Tianjin is higher. Shandong and Henan geothermal water samples also have a high proportion of SO_4^{2-}, indicating that the carbonate geothermal water in Hebei is more mature than that in Beijing, Tianjin, Shandong and Henan. In addition, the higher proportion of Ca^{2+} in geothermal water samples from Henan and Shandong may also be related to the mineral composition of their lower Paleozoic carbonate reservoirs, which are different from the two sets of carbonate reservoirs in Hebei and Tianjin. The metamorphic coefficient (γNa/γCl) of the geothermal water is another important indicator. The metamorphic coefficients of samples from Hebei and Henan are close to the value of seawater (0.85), indicating that the water body is relatively closed. The γNa/γCl values of samples from Tianjin were higher than those in Hebei and Henan, but the average value was less than 2, which were much lower than that from Beijing and Shandong (Figure 5). Based on above phenomena, it is speculated that the order of geothermal water renewability from strong to weak is Beijing, Shandong, Tianjin, Henan and Hebei.

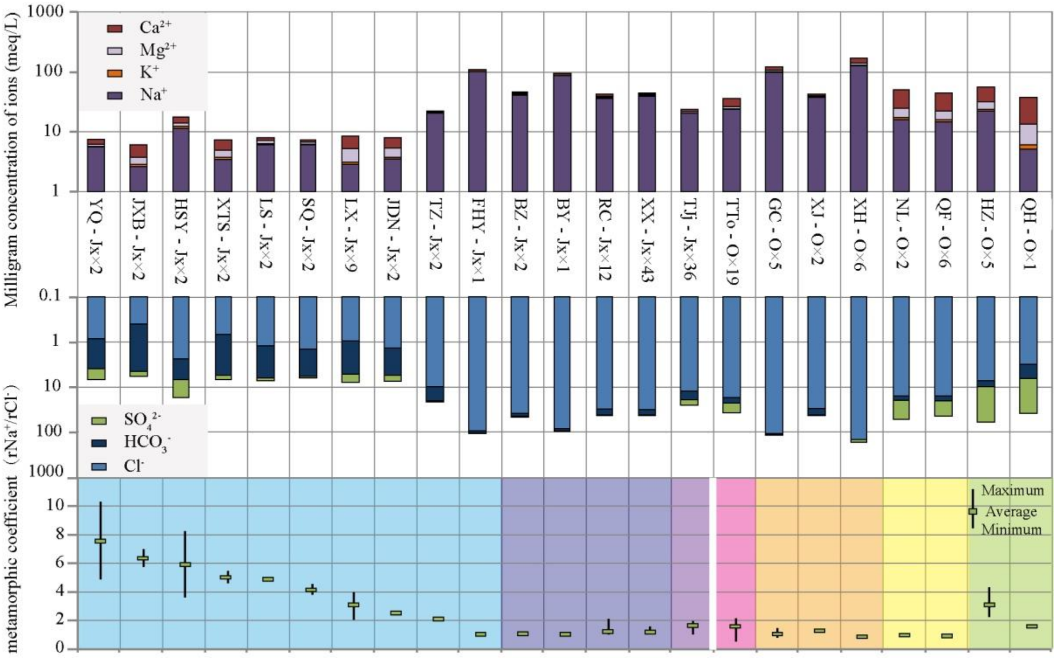

Figure 5: Statistical diagrams of ionconcentration (mg/L) and metamorphic coefficient of geothermal fluids from carbonate reservoirs in the BTHP and adjacent areas. (data from 82 carbonate geothermal wells tested in this study, combined with 81 samples in Beijing and Tianjin from Gao, B. Z. et al., 2009; Liu, Y. C. et al., 2015a, b; Jia, Z. et al., 2015; Yang, J. L. et al., 2018). Abbreviation of geothermal field name: 1YQ- Yanqing, 2JXB- Jingxibei(NW Beijing), 3HSY- Houshayu, 4XTS- Xiaotangshan, 5LS- Lisui, 6SQ- Shuangqiao, 7LX- Liangxiang, 8JDN- Jingdongnan(SE Beijing), 9TZ- Tianzhu, 10FHY- Fengheying, 11BZ-Bazhou, 12BY- Boye, 13RC- Rongcheng, 14XX- Xiongxian, 15TJj- Tianjin(Jixianian System reservoirs), 16TJo- Tianjin(Lower Paleozoic reservoirs), 17GC- Gucheng, 18XJ- Xinji, 19XH- Xinhe, 20NL- Nanle, 21QF- Qingfeng, 22HZ- Heze, 23QH- Qihe.

4. CHARACTERISTICS OF GEOTHERMAL WATER MIGRATION

The study area is located in the Bohai Bay Basin, which is surrounded by mountains on both sides of the north and west. The deep karst can be divided into three types: bedding deep subsurface flow, vertical deep subsurface flow and thermal fluid karst. The karst geothermal fluid requires existing or newly formed seepage channels (Zhang B.M. et al., 2009), and seepage channels have no obvious direction. Therefore, the karst geothermal water in the formation mainly has two movement directions: bedding and vertical. Due to the regional development of a series of faults through the upper and lower strata, the vertical hydraulic connection between different aquifers is generally close, and the difference between the layers of geothermal water chemical characteristics is relatively small. On the plane, due to the different water conductivity properties and capabilities of faults and other structures, the hydrogeochemical zoning characteristics are obvious (Zhang B.J., 2015).

According to the rule of groundwater runoff and water-rock interaction, groundwater generally develops from low TDS to high TDS along the direction of groundwater flow. the overall flow direction of groundwater is from north-south to middle. Due to the stable chemical properties of strontium, its contents in different rocks have significant difference. The change of strontium concentration in groundwater can reflect different environmental characteristics and is not affected by mass fractionation (Wang Z. Y. et al., 2003).

Therefore, strontium can be used as a tracer element for groundwater migration analysis. In general, the longer the karst geothermal water runoff time and the longer the path, the more sufficient the contact with the surrounding rock, and the corresponding increase in the strontium concentration (Pu J. B. et al., 2017). In other words, the strontium concentration in groundwater is different due to different runoff conditions and water-rock reaction time (Zhang Q. L. et al., 2011). The distribution of strontium in theBTHP is similar to that of TDS, and it also has the characteristics of low in the north-south and high in the middle (Figure 6), which supports the understanding of the overall flow of groundwater from north - south to middle.

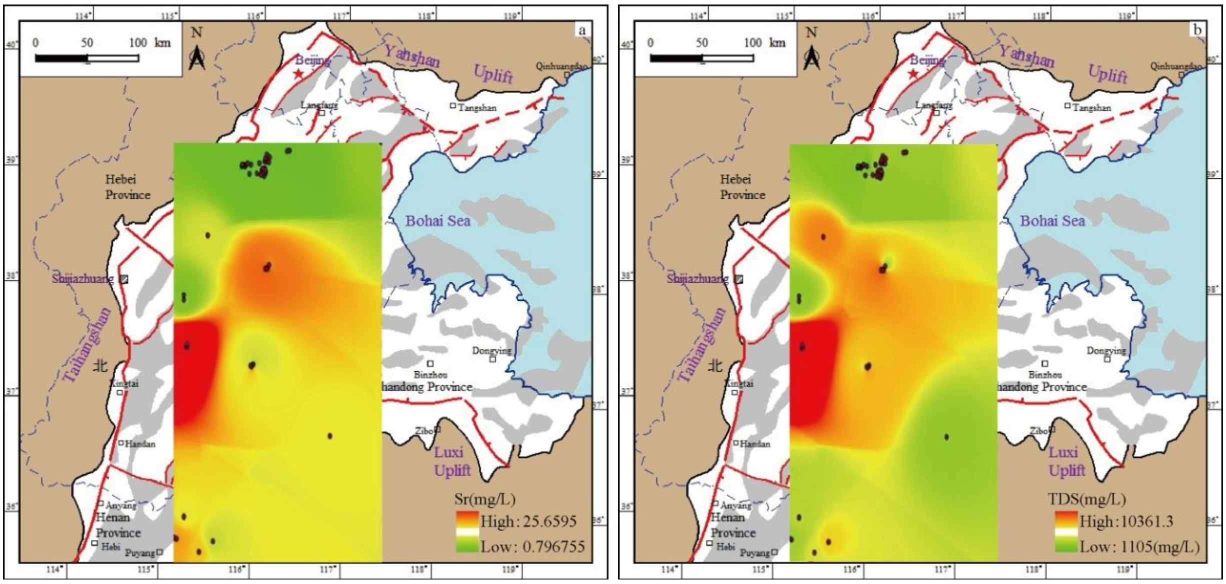

Figure 6: TDS (a) and strontium (b) distribution maps of geothermal fluid samples from carbonate geothermal reservoirs in the BTHP and adjacent areas

In order to determine the characteristics of regional groundwater flow field, the static water level of 163 carbonate geothermal wells in BTHP and its surrounding areas was calculated and corrected into elevation data. Combined with regional structures (such as water conductivity and water resistance of main regional faults), the groundwater flow field diagram of karst reservoirs in BTHP area and adjacent areas was drawn (Figure 7). The overall results show that the karst geothermal water in the plain area of Bohai Bay Basin mainly comes from the three directions, Taihang Mountain, Yanshan Mountain and southwest Shandong uplift. The southwest side of Cangzhou is the catchment area of recharge on both sides of the north and south (the convex part of -60 m contour line in the Figure7), and the recharge influence range of the north and south also forms a dividing line. The-60m contour line is obviously convex in the Cangdong fault, which shows that the Cangdong fault has good water conductivity. The recharge from the northern Yanshan movement along the fault is faster than that away from the fault. The Niutuozhen uplift in the Jizhong depression and the boundary fault （Niudong fault）in Baxian sag show obvious water blocking characteristics, and the Niutuozhen uplift in the west is mainly supplied from Yanshan and Taihang Mountains. The southeast of the study area is far away from Taihang Mountain and Yanshan Mountain, but the buried depth of the static water level is lower than that of the catchment area. It is speculated that the water was remote supplied from the mountains in west Shandong.

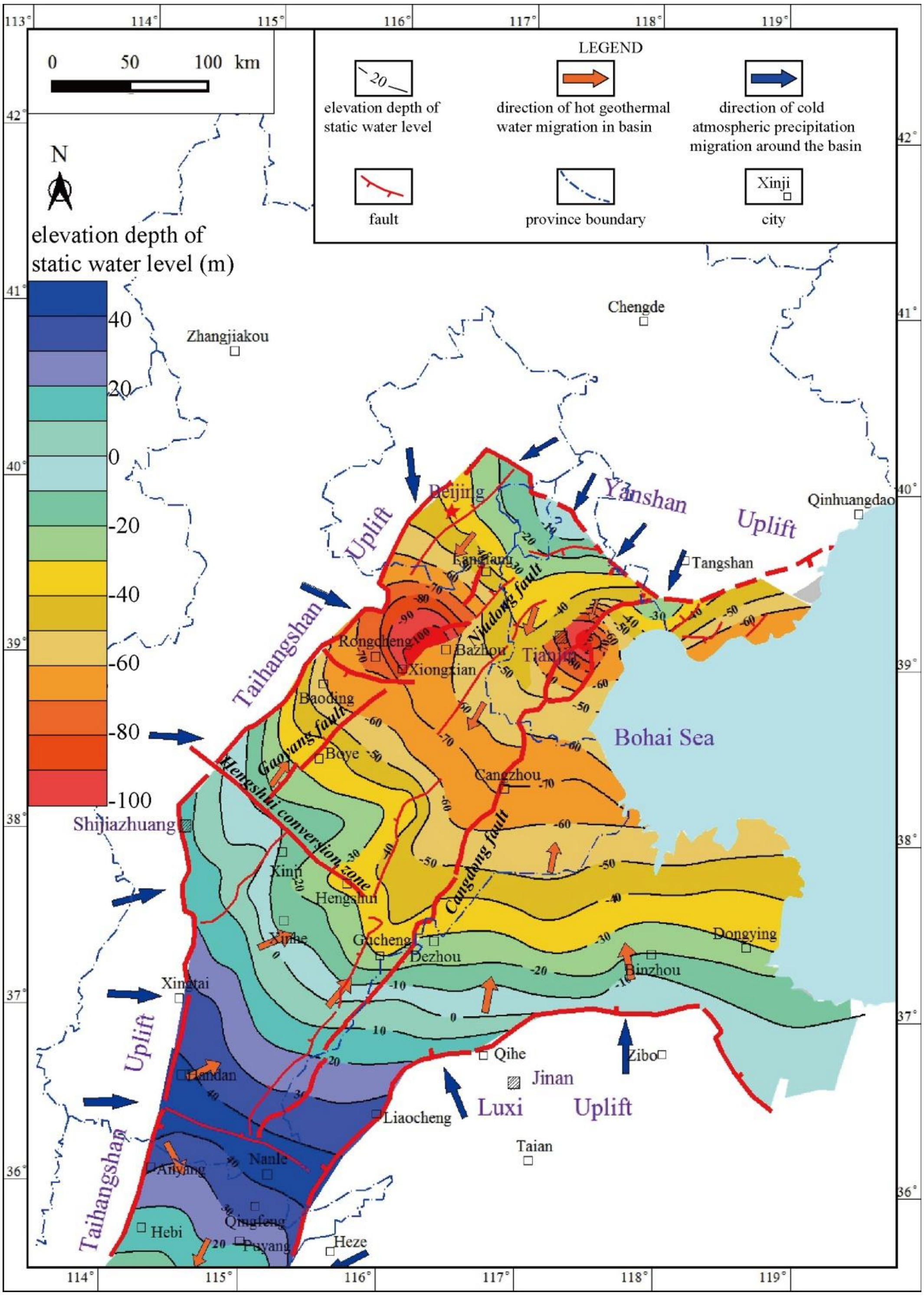

Figure 7: Geothermal flow field of carbonate geothermal reservoirs in the BTHP and adjacent areas

In order to analyze the vertically migration characteristics of underground geothermal water of carbonate geothermal reservoirs in BTHP, four geological sections across the Bohai Bay Basin are drawn (Figure 8). Section A-A' is along NW-SE trend and passes through Taihangshan uplift, Shijiazhuang sag, Wuji-Gaocheng uplift, Jinxian sag, Ningjin uplift, Shulu sag, Xinhe uplift, Qianmotou Fault depression, Guangzong uplift, Nangong sag, Minghuazhen uplift, Dayingzhen sag, Wucheng uplift and Dezhou sag. Hydrogeochemical information of geothermal wells along the profile shows that the hydrochemical type of Ordovician karst geothermal water changes from Cl·HCO3-Na to Cl-Na from Shijiazhuang sag to Xinhe uplift, and tends to mature without a good runoff channel between them. It is speculated that the recharge comes from the geothermal flow along the Hengshui conversion zone and the groundwater of adjacent aquifers. In the east part of section A-A', the Ordovician karst geothermal reservoirs in Cangxian uplift on the east side are relatively independent and have no connection with the west side. Section B-B' is along NW-SE trend and passes through Baoding sag, Gaoyang Low uplift, Lixian Slope and Raoyang sag in Jizhong depression, Dacheng uplift, Litan sag and Huanghua depression in Cangxian uplift, Litan sag and Huanghua depression, Cangdong sag and Changzhuang sag in Huanghua depression. The hydrogeochemical information of geothermal wells along the profile shows that the hydrochemical type of geothermal water in the Jixian system Wumishan Formation has not changed from the Gaoyang low uplift in the Jizhong depression to the Cangxian uplift. The TDS is similar, and the geothermal water tends to be parallel. Section C-C' is along NW-SE trend passes through Langgu sag, Niutuozhen uplift, Baxian sag, and Wenan Slope in Jizhong depression, and Dacheng uplift in Cangxian uplift. Hydrogeochemical information of geothermal wells along the profile shows that Niudong fault is a water-blocking fault for Wumishan Formation reservoirs, and there is no obvious evolutionary relationship and hydraulic connection between geothermal water on both sides of the fault. The geothermal well in Nanmengarea in Bazhou is located in the Niudong fault, its geothermal water of the Wumishan Formation is homologous to that of the Niutuozhen uplift. Section D-D' is along NW-SE trend and passes through the Rongcheng uplift, Niutuozhen uplift and Anxin transition zone in Jizhong depression. The hydrogeochemical information of geothermal wells along the profile shows that the hydrochemical types of geothermal water from Rongcheng uplift to Niutuozhen uplift remain unchanged, and the increased TDS values along the section show that the groundwater flow direction has a trend from west to east.

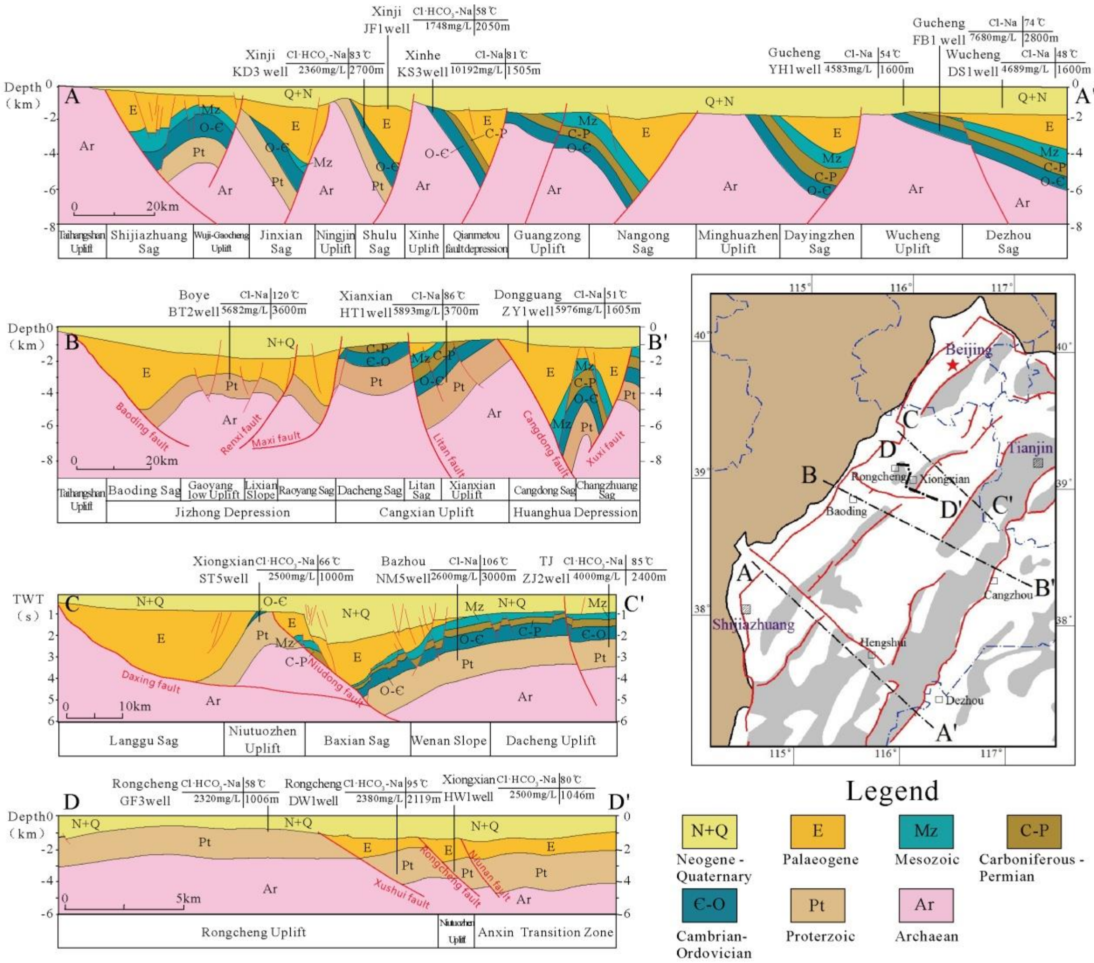

Figure 8: Geological sections and their locations of BTHP, indicating geothermal well hydrochemical information along the profiles (after Xu, J. et al., 2015; Shan, S. Q. et al., 2016; He, D. F. et al., 2017, 2018; Dai, M. G. et al., 2019)

Based on the distribution characteristics of TDS and strontium elements, geothermal flow field and geological section characteristics of karst geothermal water in BTHP, a regional karst geothermal water migration model is established (Figure 9). Groundwater from Taihang Mountain on the west side, Yanshan Mountain on the north side and mountains in west Shandong on the southeast side of the basin enters and migrates into the basin along a series of water diversion faults. The recharge from Taihang Mountain on the west side is blocked by NNE trend Niudong fault in the north, and stops at the Niutuozhen uplift. The low TDS value in Xinji area on the south side shows that Hengshui conversion zone may be a fast water diversion channel for water supply in Taihang Mountain. The recharge from Yanshan mountain area on the northern side migrates to the south along Cangdong fault, but the differences in hydrochemical characteristics of karst geothermal water in Jizhong depression, Cangxian uplift and Huanghua depression show that there is no obvious hydraulic connection between carbonate aquifers. Therefore, Cangdong fault and other faults only constitute the migration channel of water supply to the basin, and from the east-west direction, the hydraulic connection between each tectonic unit is separated. Taking into account the better groundwater dynamic conditions in the geothermal water catchment area, the large amount of geothermal water supply and the fast supply speed, it is recommended to carry out further geothermal resources exploration and scientific development planning in the southwest of Cangzhou and around Xiongxian, so as to expand the scale of scientific development and utilization of geothermal energy.

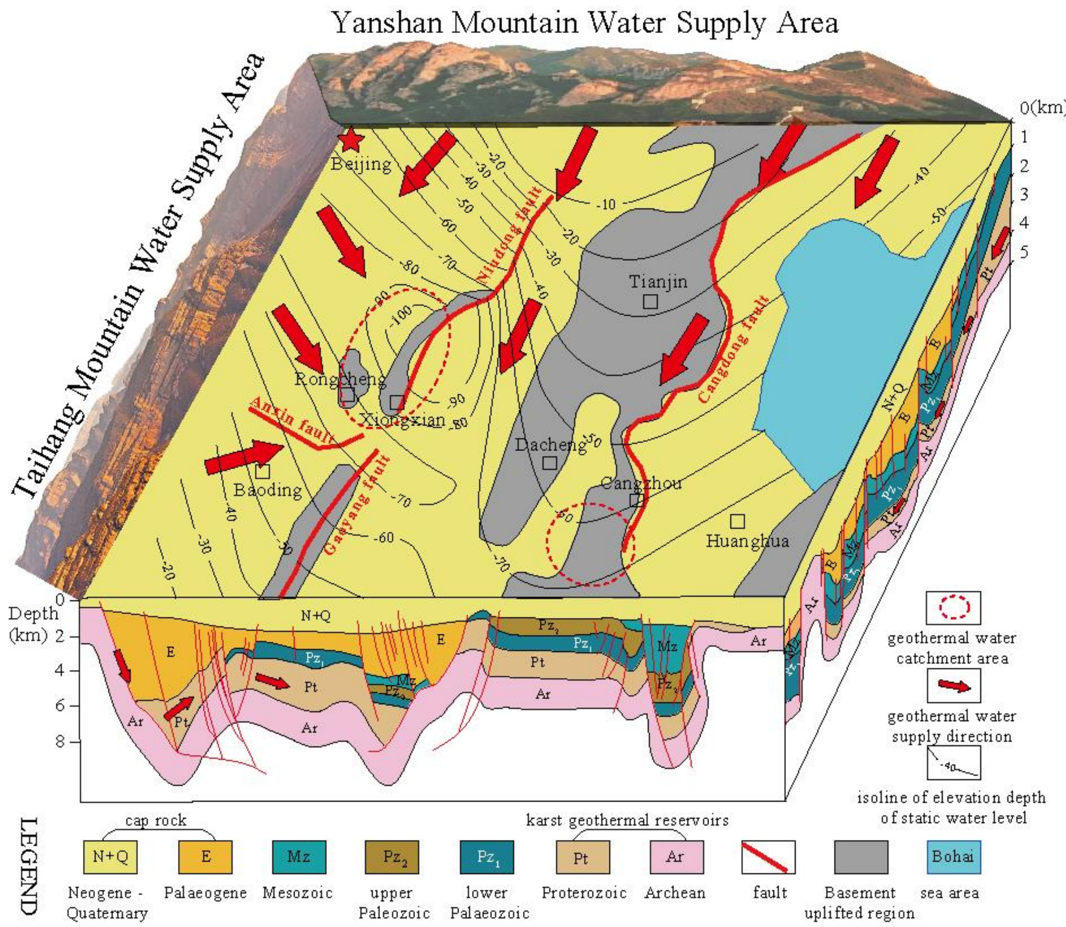

Figure 9: Migration model of geothermal fluids from carbonate geothermal reservoirs in the BTHP

5. CONCLUSIONS

Located in the Bohai Bay Basin, the BTHP mainly develops Ordovician-Cambrian and Jixian Wumishan Formation carbonate karst geothermal reservoirs. The former is mainly distributed in the Cangxian uplift. The thickness of the heat reservoirs are mainly between 90 and 110 m, and the buried depth is 1000-2500 m (in the fault depression it can be 3000-5000 m). The latter is mainly distributed in the central uplift belt of Jizhong depression, the main thickness is 300 ~ 500 m, the buried depth is 2000 ~ 3000 m, (less than 1500 m in the uplift area, more than 4000 m in the depression area).

The water chemical characteristics of geothermal samples in karst geothermal reservoirs in BTHP and its surrounding areas show certain differences. Due to the proximity of Taihang Mountain in the west and Yanshan surface water supply area in the north, the TDS value of geothermal water in Beijing is the lowest, and the proportion of Ca^{2+} and HCO_3^- ions is relatively high. The TDS and the ratio of main anions and cations of geothermal water samples in Hebei and Tianjin are close, but the SO42- ion ratio in Tianjin is higher. Samples from Shandong and Henan also have a high proportion of SO_4^{2-}, indicating that the carbonate geothermal water in Hebei is more mature than Beijing, Tianjin, Shandong and Henan. The distribution of TDS and strontium in the study area is low in the north & south, and high in the middle, indicating that the overall flow direction of geothermal water is from north & south to the middle. The characteristics of groundwater flow field show that the karst geothermal water in the plain area of Bohai Bay Basin is mainly recharged from Taihang Mountain, Yanshan Mountain and southwest uplift of Shandong Province. The southwest area of Cangzhou is the catchment area of recharge on both sides of the north and south, and the influence range of recharge on the north and south also forms a boundary. The Niutuozhen uplift area is the catchment area of recharge from Taihang Mountain on the west side.

Based on the distribution characteristics of TDS and strontium elements of karst geothermal water in the BTHP, as well as the geothermal flow field and geological section characteristics, a three-dimensional geothermal geological model for regional geothermal water migration is established. Groundwater from Taihang Mountain, Yanshan Mountain and mountains in west Shandong enters and migrates into the basin along a series of water diversion faults. The supply from the Taihang Mountain on the west side is blocked by the NNE trend Niudong fault in the north, and stops at the Niutuozhen uplift. The low TDS value in the Xinji area on the south side shows that the Hengshui conversion zone may be a rapid water diversion channel for water supply in the Taihang Mountain on the west side. Groundwater recharge from Yanshan Mountain mainly migrates in the basin along Cangdong Fault, but the fault also block the hydraulic connection between each tectonic unit.

The groundwater dynamic conditions in the geothermal water catchment area are relatively good since the large geothermal water supply and fast supply speed. It is suggested that further geothermal resource exploration and scientific development planning should be carried out in the geothermal water catchment areas such as southwest Cangzhou and surrounding Xiongxian, so as to expand the scale of scientific development and utilization of geothermal energy.

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