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The Formation Conditions and Enrichment of Karst Geothermal Resources in Bohai Bay Basin

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ABSTRACT

A series of problems such as "there is hot but no water" or "there is water but no hot" were encountered during the process of karst geothermal drilling in the eastern part of China, suggesting that it is not an effective exploration method to look for karst geothermal resources simply in geothermal anomaly areas or the karst reservoir development areas. Both of the geothermal anomalies and karst reservoirs affect the formation of karst geothermal resources and their distribution. In order to accurately obtain karst geothermal resources, it is supposed to find the "geothermal desserts" where there are both heat and water. In this paper, based on the influencing factors of geothermal anomaly and karst reservoir, the karst geothermal formation conditions and enrichment regularity in Bohai bay basin are discussed by comprehensively considering the heat tectonic setting, bedrock buried hill structure, thermal conductivity of rock and groundwater activity, sedimentary and diagenetic factors. The results show that the Meso-cenozoic tectonic activities in Bohai bay basin provides a relatively high thermal background for the region, and the bedrock buried hill structure, thermal conductivity of rock and groundwater activity are the important factors affecting the shallow geothermal anomaly, and the thick carbonate sedimentary and karstification provide favorable conditions for the karst reservoir formation, and the effective matching of the above factors become the key to karst geothermal resources. Overall, surrounding Bohai Bay basin is characterized by low geothermal features due to the downward cold water supply, except for local geothermal anomaly areas due to upward geothermal hot water because of fault blocking; whereas karst geothermal resources tend to enrich in the bedrock uplift or convex area in the inner part of the basin, especially the areas directly covered by the upper Tertiary strata.

1. INTRODUCTION

Studies suggest that karst geothermal resouces are the most important type of geothermal resources except volcanic areas(Goldscheider, et al., 2010), whose importance lies in not only its wide distribution, large reserves, easiness to rejection, but also green utilization with low carbon emission. Karst geothermal resources are typical of low-moderate temperature geothermal resources and can be widely used in space heating, aquaculture, bathing and power generation, and therefore have broad prospects for utilization. They have been widely used in many countries, including many countries of Western Europe, Turkey, North Africa, Algeria, Canada, and the eastern regions of China(SAKİR et al, 1990; Goldscheider, et al., 2010). In China, the famous Xiongxian geothermal field is hosted in the Mesoproterozoic Jixian Wumishan Fm. karst geothermal reservoirs.

The formation of karst geothermal resources generally requires heat and water sources, karst reservoirs, geothermal channels and caps as the basic conditions. As previously mentioned, karst geothermal resources are non-volcanic geothermal resources, and their heat sources are mainly from the deep crust and upper mantle, and the heat flows to the shallow strata primarily by conduction, as well as by convection along certain deep faults, making the stable heat sources of karst geothermal resources in this area. Their waters mainly come from atmospheric precipitation in karst outcrop areas, migrate by paleokarst channels and fault systems, and are heated by surrounding rocks, and then flow upwards to shallow strata and stored in the karst reservoirs or fault zones. Thus, there are two types of karst geothermal resources, one is hosted in deep geothermal reservoirs and the other is hosted in fault-controlled karst reservoirs.

In China, karst geothermal exploration mainly focuses in the eastern region where deep karst reservoirs are developed. Lots of work has been done here and great achievement has been gained. However, a series of problems such as "there is hot but no water" or "there is water but no hot" were encountered during the process of karst geothermal drilling. The “hot” and “water” here mean the temperature and production which meet the indusial requirement. The places where there is “hot” and “water”, namely geothermal desserts, is ideal targets of geothermal exploration.

2. GEOLOGICAL BACKGROUNDS

Bohai Bay Basin is a large Meso-cenozoic rift basin developed in North China platform. The basin is based on Archaean metamorphic rocks, with Meso-Neoproterozoic and early Paleozoic marine carbonates, as well as late Paleozoic paralic sediments on the basement. This area experienced multiphase tectonic activities which reconstructed the previous structural framework and coverings in different degrees. And Yanshan movement determined the nowadays structural framework in this area, which not only made the preformed strata folded and developed series of faults, companied by magmatic activities, at the meantime NorthChina Platform started to disintegrate, making the formation of Taihang, Yanshan and Jiaoliao uplifts and terrestrial deposition of Jurassic and early Cretaceous. In the early Tertiary, a series of fault depressions and uplifts were formed in this area under the tensional stress. And the structural units can be divided into Jizhong depression, Huanghua depressioin, Jiyang depression, Linqing depression, Liaohe depression, Bozhong depression, Cangxian uplifts, Chengning uplifts and so on based on the differences of structural evolution and early Tertiary strata. Secondary

structures such as sags and highs can be subdivided in the depressions and uplifts due to the structural differences, thus the performance of the tectonic framework of multi-Convex and concave and convex and concave with multi sedimentary centers(Fig. 1).

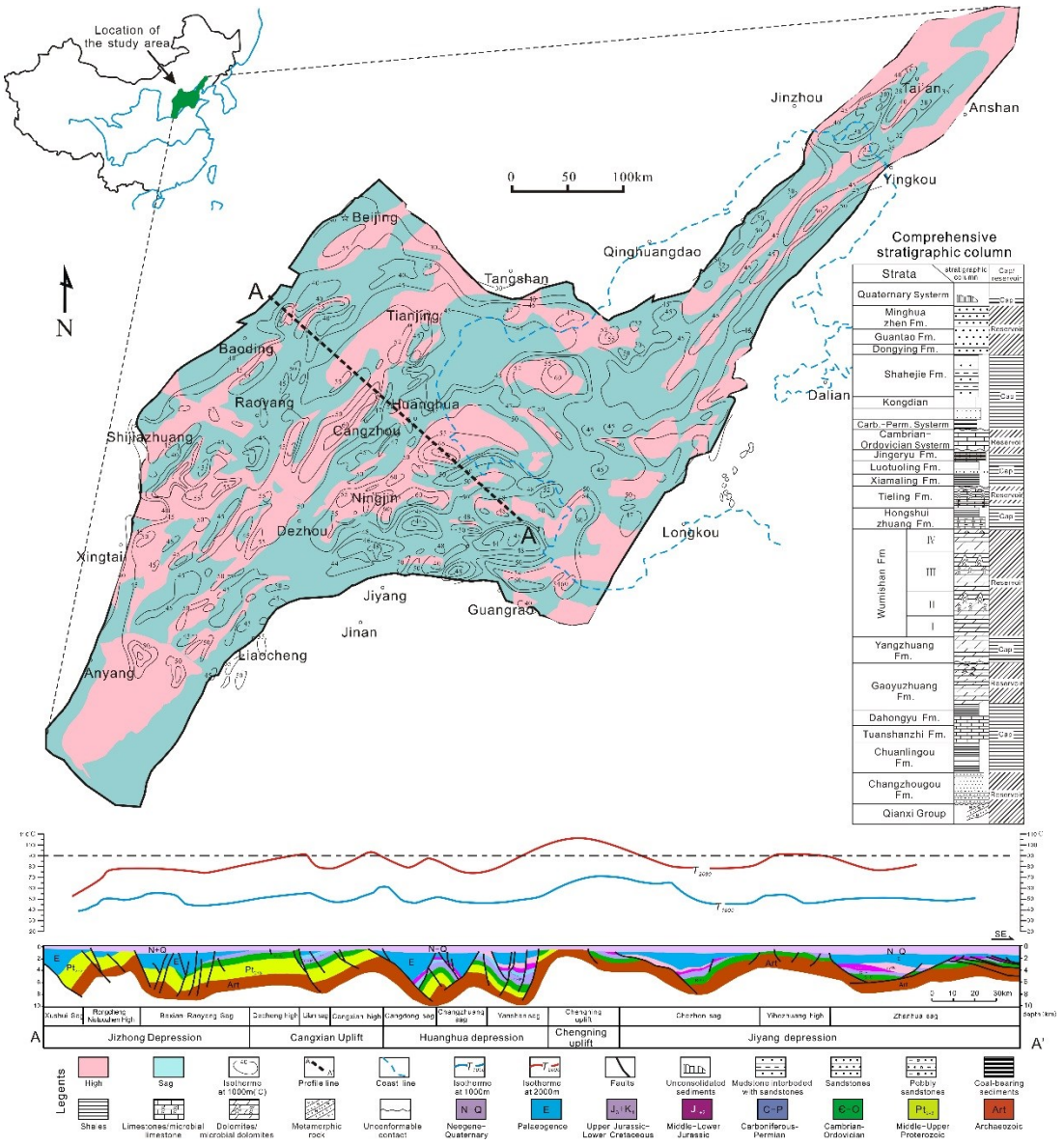


Figure1 The structural geological map of Bohai Bay basin

3. THE FORMATION CONDITIONS OF KARST GEOTHERMAL RESOURCES

3.1 Heat sources

The nowadays temperature field in one area has its occurrence, the process of development and evolution, which is the product of the regional geological development. Bohai Bay basin is no exception, and the nowadays temperature field in this area is inseparable with the tectonic evolution since Mesozoic.

Through analysis of the regional tectonic and thermal evolution of North China, the Mesozoic and early Cenozoic are considered to be the important turning point of the regional geothermal evolution. During the period of 80Ma or 90Ma to 25Ma before (Cretaceous to Early Tertiary), Kula plate in the north of pacific ocean and the western part of Pacific Plate successively plunged into the eastern marginal island arcs of Asia, transferring the tectonic stress from NW trending compress to NW trending extension (Uyeda, et al., 1974; Hilde, 1977; Huai et al., 1982) (Figure2). A series of large, continental rift extensional graben formed in the east part of China on the base of the preformed uplift-depression tectonic framework. And crustal thinning occurred where graben developed due to isostatic adjustment, making the upper mantle arch and forming the mantle uplift belt. With crustal thinning and rifting, the mantle-derived materials upwelled, and the deep heat carrier (magma, hydrothermal) erupted along fault zones to the surface or shallow crust, which widely developed in the North China Plain and the early Tertiary basalt and andesite which are widely distributed in North China Plain are the products. From geothermal prospective, magmatism occurred during this period constitutes the most important tectonic event in

the area during the geological history since the Mesozoic. The North China Basin thermal conditions at that time was somewhat similar to the western United States mountains province heat flows, and the heat flow can be inferred up to about 2HFU. Therefore, the mantle heat flow values were also undoubtedly quite high (Wang et al., 1988).

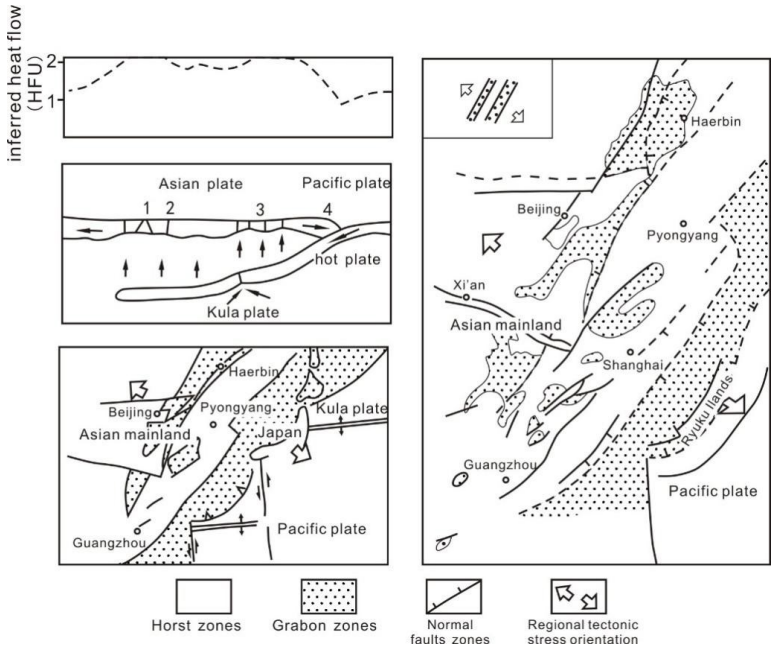


Figure2 the End-Mesozoic and Early Cenozoic（K_2-E）deformation of North China and regional tectonic stress orientation (after Huai, et al.,1982）

1.Graben of NorthChina; 2.Tancheng-Lujiang fault zones; 3.Japan sea；4.Japan island arc

Since the Late Tertiary, the overall trend of Bohai Bay Basin thermal conditions started to gradually decline from the early peak condition. The magmatic activities greatly diminished, also did the heat caused by rising magma. However, the recession has not been too long and the late Tertiary and Quaternary unconsolidated sediments play a certain degree of "insulation" effect, North China basin retains high residual surface and mantle heat flows, which is not only different from the deep thermal conditions of the old stable blocks, but also from that of the Cenozoic continental rift zones with intense tectonic activities (Wang et al., 1988).

3.2 Water sources

According to the comparative analysis of the Hydrogen and Oxygen isotopic composition of the surface and underground thermal waters in North China plain, the surface, Quaternary and part of the Upper Tertiary waters fell on the Craig precipitation line, while the other Tertiary waters and karst thermal waters deviated but not far from the meteoric water line(Figure 3), indicating that the underground thermal waters are mainly from atmospheric precipitation and experienced strong water-rock interaction during the process of migration.

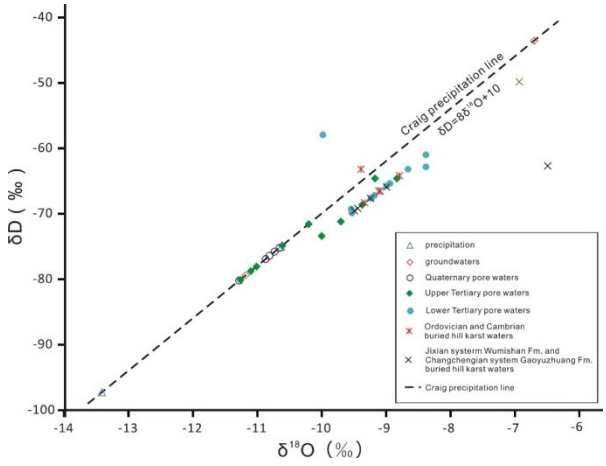


Figure3 The plots of Hydrogen and Oxygen isotopic composition of the thermal waters in Plain of NorthChina

Salinity is the sum of the chemical composition of the groundwater. Changes in salinity are closely related with the reservoir temperature, the nature of surrounding rocks, water-rock contacting time, the relationship between water recharge and discharge, the runoff distance, as well as the opening and closing of the reservoirs. Therefore, the distribution of salinity can be used to infer the relationship between recharge and discharge of the groundwater, and the runoff direction, and also indirectly to infer certain physical properties of the geothermal reservoirs (Yan et al., 2000).

According to Figure4, the salinity of the underground bedrock waters gradually increases from 0.4g / L to 10 ~ 30g / L, even more than 50 g / L, which is related to the structural environments, reflecting the variation rules of groundwater recharge-alternating cycle-residence-discharge (Zhou, 1987).

Hydrodynamic conditions are relatively active in the uplifts and highs, indicating a strong groundwater activity, and the groundwater is mainly supplied by lateral recharge with the runoff directions corresponding to the distribution of the uplift and high structure, and secondarily recharged by the deep groundwater through vertical movement along fault zones and inclined strata. Thus, the waters entered the uplift and high areas with better runoff conditions form stronger groundwater runoff, while the groundwater flows slowly in the depressions and sags with bad runoff conditions. On the plane, the sparse direction of the bedrock groundwater salinity contours is the main direction of deep groundwater runoff (Figure4).

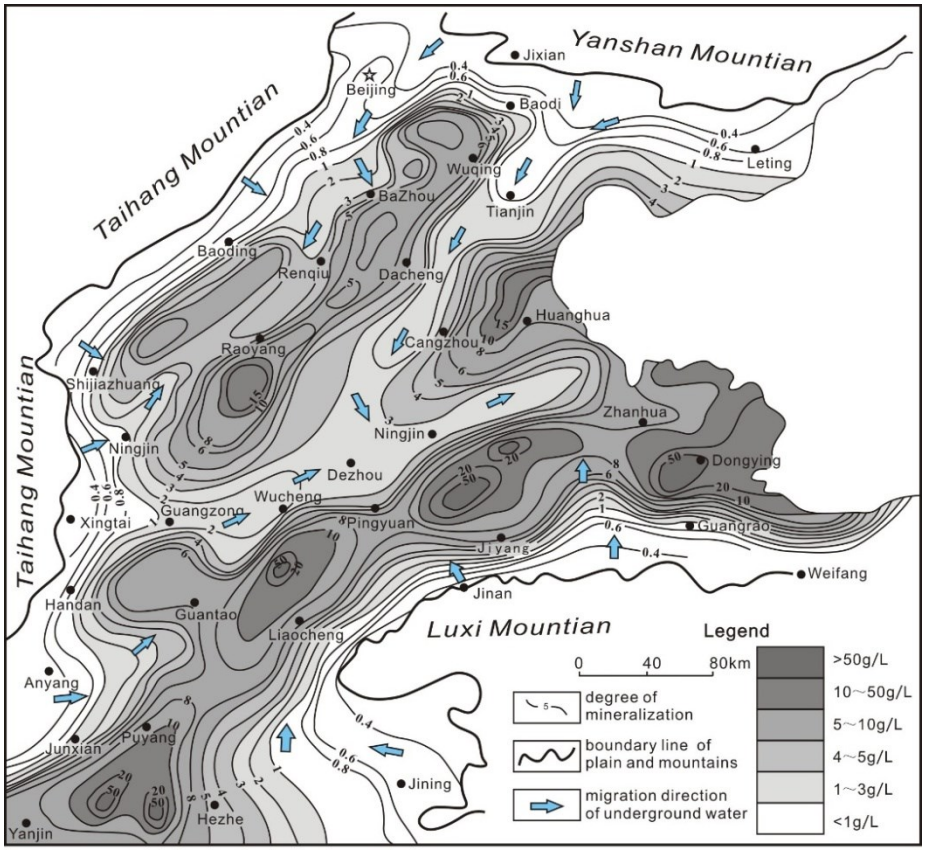


Figure4 The salinity contours of the ground waters in the Pre-Cenozoic strata in North China Plain (modified after Zhou, et al.,1987a)

3.3 Karst geothermal reservoirs

From Neoproterozoic to Mesozoic, Bohai Bay basin and adjacent areas experienced superposition of the different nature of the prototype basin, depositing a series of strata including Meso-neoproterozoic Changchengian, Jixian, Qingbaikou, Palaeozoic Cambrian, Ordovician, Carboniferous, Permian and so on, with the characteristics of huge thickness, diverse sedimentary formations, stronger reformation and extremely complex geological structure. Among them, Changchengian Gaoyuzhuang Fm., Jixian Wumishan Fm. and Cambrian - Ordovician are the three main strata dominated by carbonates and also the main strata in which karst geothermal reservoirs are developed. As for the sedimentary scope, the Meso-neoproterozoic strata in this area are mainly confined in Yanliao Trough with huge deposition thickness of more than 5000m, while the Cambrian – Ordovician strata are widely distributed in carbonate platform which formed in the continental marginal tectonic setting under the large-scale marine invasion, almost covering the entire North China platform (Figure5).

As previously mentioned, this area experienced multiphase tectonic activities since Lvliang movement, making carbonate strata repeatedly exposed and undergoing long-time weathering and erosion, and thus forming multiple sets of karst and fractured geothermal reservoirs. The karst and fractured geothermal reservoirs are characterized by multiple output layers, diverse rock types, complex

causes, diverse reservoir spaces and strong heterogeneity. Isotope geochemistry analysis showed that Indosinian and Yanshanian are the main fracturing and karstification stage.

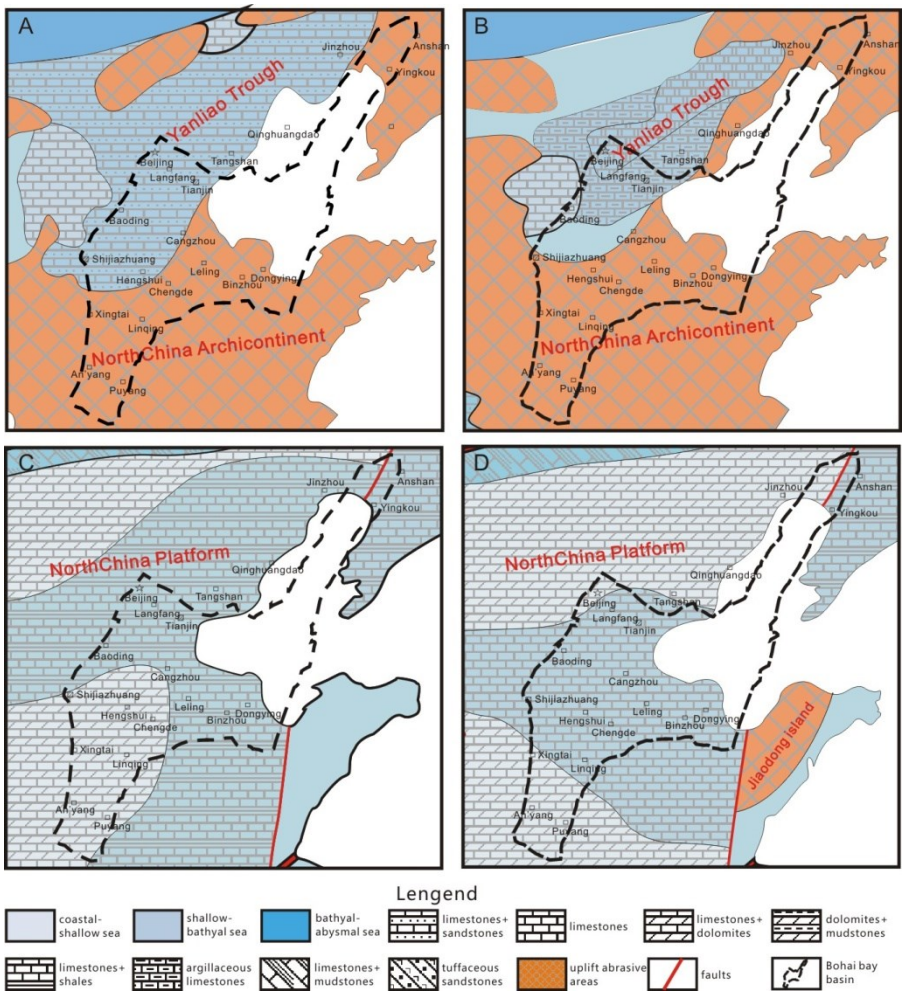


Figure5 Lithofacies paleographic map of Bohai Bay Basin and the surrounding areas
A. Gaoyuzhuang period; B.Jixian period; C.Cambrian period; D.Ordovician period

3.4 Geothermal channels

In the formation of Bohai Bay Basin, multiple sets of faults were formed in the basement of the basin and its periphery, with the main trending of NE and NNE, as well as NW, near NS, near WE and so on. Most of these faults formed in the Cenozoic, mainly characterized by tensional properties, and some of which possess strike-slip properties. And these faults constitute the important geothermal channels of the karst geothermal resources in this area, affecting the formation and enrichment of karst geothermal resources.

3.5 Caps

Caps play a significant role for the formation of sedimentary geothermal resources. And in Bohai Bay Basin, the Cenezoic huge sedimentary strata play a good thermal insulation role for the karst geothermal resources in this area (Wang et al., 1988). Cenozoic strata can be divided into three strata including Lower Tertiary, Upper Tertiary and Quaternary, wherein the Lower Tertiary strata are mainly distributed in the deep depression with lacustrine mudstones interbedded with sandstones, the Upper Tertiary is mainly fluvial mudstones and sandstones which were deposited on the base of the Lower Tertiary filling and leveling up, and are almost distributed throughout the region. The depth of the Lower Tertiary generally ranges from 500m to 2500m, which is the direct cap of the buried hill karst geothermal systems in Bohai Bay Basin.

According to the statistic analysis of the dry samples' thermal conductivity of Bohai Bay Basin, Cenozoic thermal conductivity is quite low, generally less than 2W/m • K, whereas the Meso-neoproterozoic - Lower Paleozoic thermal conductivity is relatively high, typically greater than 2.5 W/m • K. From this prospective, Cenozoic strata play a good thermal insulation role in the formation of the buried hill karst geothermal resources

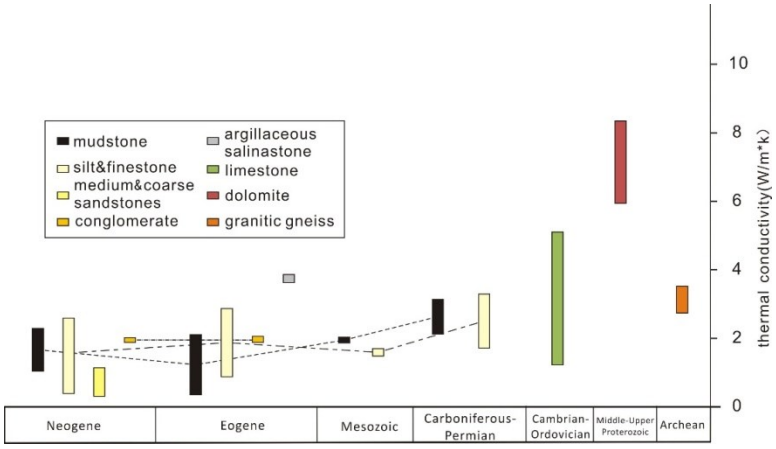
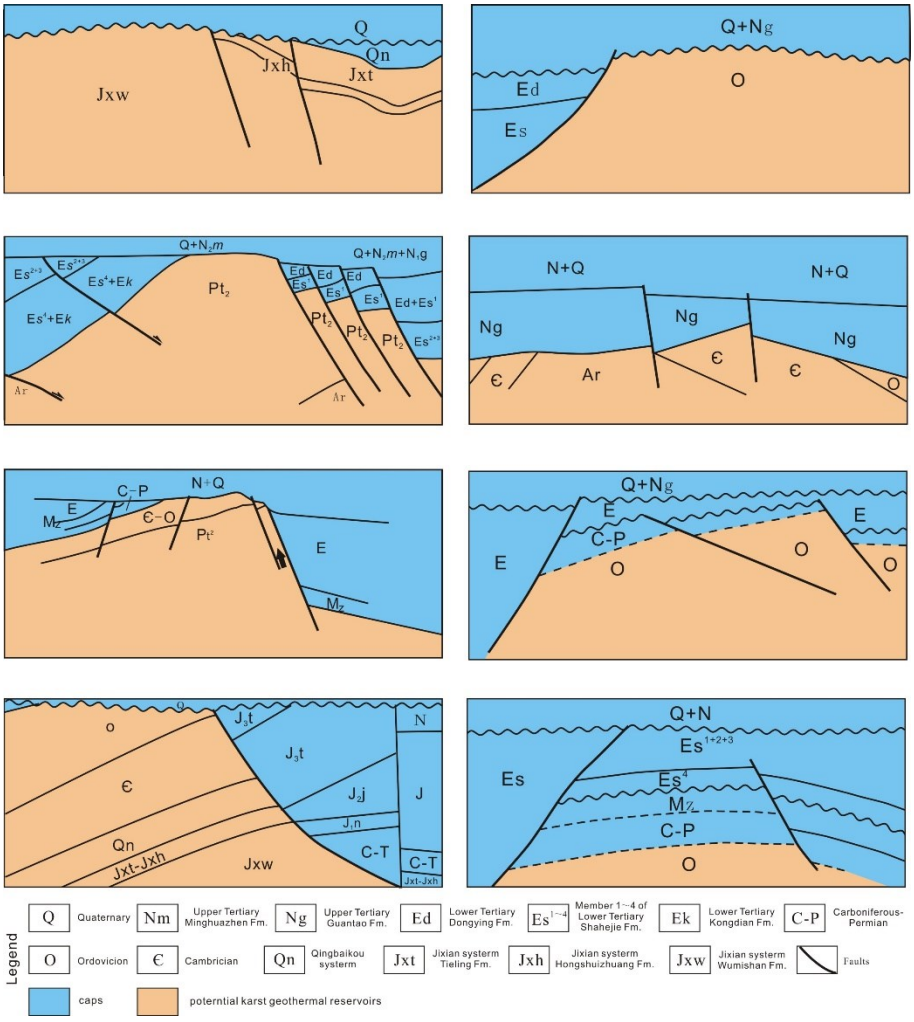


Figure6 The variation ranges of thermal conductivity of the dry samples from different strata

3.6 Reservoir-Cap assemblage

In Bohai Bay Basin, there are several distinct kinds of reservoir-cap assemblages, which are determined by the types and the strata texture of buried hills. At least eight types of buried hills are summarized as figure7. The reservoirs can be developed in the Meso-neoproterozoic or Lower Paleozoic strata, or combination of the both, while the caps is mainly Cenozoic strata, as well as Mesozoic and Carboniferous-Permian strata. Whatever reservoirs and caps, the thermal conductivity of the caps is much less than that of the reservoirs. Thus, such kinds of reservoir-cap assemblages are favorable for the formation of karst geothermal resources.



Fiture7 The common types of buried hills and the reservoir-cap assemblages in Bohai bay basin

4. THE ENRICHMENT OF THE KARST GEOTHERMAL RESOUCES

According to the previous analysis, Bohai Bay Basin has adequate water and stable heat sources, widely developed karst geothermal reservoirs, and favorable geothermal channels and caps, indicating Bohai Bay Basin has excellent conditions for the formation of karst geothermal resources in this area. However, not everywhere has large-scale and economic karst geothermal resources. Karst geothermal-rich regions must be both the geothermal anomaly areas but also the large-scale karst reservoirs development zones, reaching the coupling of karst "hot" and "reservoir", namely "geothermal desserts". Studies have shown that the surrounding piedmont and internal part of Bohai Bay Basin (basin margin) show significant differences in karst geothermal enrichment. The karst geothermal resources in the piedmont of the basin are mainly controlled by groundwater movement and faults, and generally enriched in structural position where is favorable for the geothermal fluid upwelling; whereas the karst geothermal resources in the inner part of the basin are mainly controlled by the uplifts or highs (a general term of “buried hill”) in the depression, and especially enriched in the buried hills where are in favor of deep geothermal fluid excretion. And the enrichment of the karst geothermal resources depends on the temperature field and the karst fractured geothermal reservoirs.

4.1 The piedmonts of the basin

The piedmonts of Bohai Bay Basin are characterized by strong groundwater activities and thin caps with the thinnest of less than 200m which has a bad thermal insulation effect for the karst geothermal resources. And the karst geothermal resources are mainly affected by the activities of groundwater and active faults. Due to the interference of cold water recharge, the geothermal gradients and temperature fields are significantly reduced in the periphery of the basin. The geothermal gradients of the piedmonts along Yanshan, Taihang Mountains, Luxi mountain and Liaodong are commonly less than 2.5℃/100m, and the temperature at 1000m is generally less than 40℃ and the temperature at 2000m is generally less than 60℃. Therefore, the geothermal resources at the depth of less than 2000m are dominated by warm or moderate thermal waters. Local areas with geothermal gradients of more than 2.5 ℃/100m are closely associated with the faults, and the karst geothermal resources tend to be enriched in the fault zones where there are deep thermal water upwelling.

The formation of Xiaotangshan geothermal field, one of the two most important geothermal fields in Beijing, is such a case. It is famous for hot springs and has been exploited for more than 700 years. The karst geothermal resources are mainly stored in limestones and dolomites. Wumishan (Jxw), Tieling (Jxt) and Cambrian system (Є) are the main geothermal reservoirs and the three karst geothermal reservoirs are relatively independent, but have certain hydraulic connections with each other (Wang, 2007). Up to 2008, there have been more than 90 geothermal wells drilled in this fields, and the drilling deepness has exceeded the maximum depth of 3500m. The range of geothermal investigation has expanded to more than 40km^2. The exploited waters from the geothermal field ranges from 38 to 70℃ in temperature, a typical low-temperature mediate-scale geothermal fields. By analyzing the relationship between the temperature at 1000m and the faults in this area, the geothermal anomalies are mainly controlled by intensive tectonic fault zones. The long axis of the temperature field is especially consistent with Daliushu-Hulu River fault (F3), and the nearer is the wells to the fault, the higher is the water temperature and production of the wells. Therefore, the F3 is the major hydraulic and heat conduction structure, and also the enrichment zone of the karst geothermal resources in this field. As can be seen from the geothermal geological section, the shape of the isotherm at 1000m is not consistent with the bedrock. The temperature at northeastern part of the section is significantly decreased by the cold water recharge, while the temperature at and near F3 is much higher with the highest temperature of 59℃. Thus, Xiaotangshan geothermal field is a typical conduction-convection type geothermal field, which is more affected by faults and groundwater movement than the morphology of the bedrock,

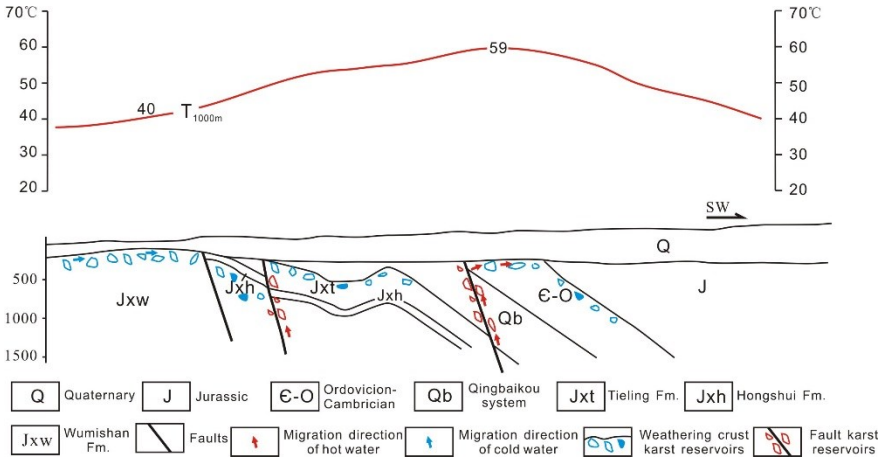


Figure8 The geological profile of Xiaotangshan geothermal field

4.2 The inner of the basin

Compared with the piedmonts, the inner part of the basin is characterized by relatively weak water movement and moderate thickness (800 ~ 2500m) of caps, especially in the buried hills which are the advantageous structures for the formation of karst geothermal

resources. The distribution of the geothermal gradients and temperature fields presents a certain regularity, showing NE and near EW trending distribution in general. As for the reason, the distribution is mainly controlled by concave-convex structural framework(Chen et al.,1982; Chen et al., 1985; Zhou et al., 1987b; Chen et al., 1999; Yan, et al., 2000). And the higher-temperature areas are consistent with the buried hills with the high geothermal gradients of more than 3.5℃/100m and up to 9.0℃/100m, whereas the lower-temperature areas are accordant with the depression with the geothermal gradients of less than 3.0℃/100m. The temperature at 1000m and 2000m in the buried hills ranges from 50 to 65℃ and 75 to 100℃ respectively, generally 15～20℃ higher than the piedmonts at the same depth. Petroleum and geothermal exploration shows that the topmost of the buried hills are also favorable structural positions for the development of karst and fractured reservoirs. Therefore, the buried hills in the inner part of the basin are favorable for accumulation of geothermal resources, and the local upwellings of geothermal fluids along the fault strengthen the enrichment of the karst geothermal resources.

Xiongxian geothermal field is such a typical example. The field is located in the central high belt of Jizhong Depression, which is mainly composed by Niutuozhen and Rongcheng highs with a NE trending. Temperature field study shows that the geothermal gradient of Xiongxian geothermal field ranges from 3.5℃/100m to12.6℃/100m, which are the highest geothermal gradients in the north part of North China plain. And the distribution of the geothermal gradient basically coincides with the shape of the basement. As previously mentioned, Xiongxian geothermal field is a non-volcanic geothermal field, and its heat mainly comes from the deep crustal radioactive decay and upper mantle residual heat. And the heat is transferred to the surface mainly in the conduction style, and relocated and then accumulated in buried hills in the shallow strata. Therefore, the temperature field is mainly controlled by the structure of the buried hills, although the surrounding faults, especially Niudong Fault also plays an important role for the karst geothermal resources.

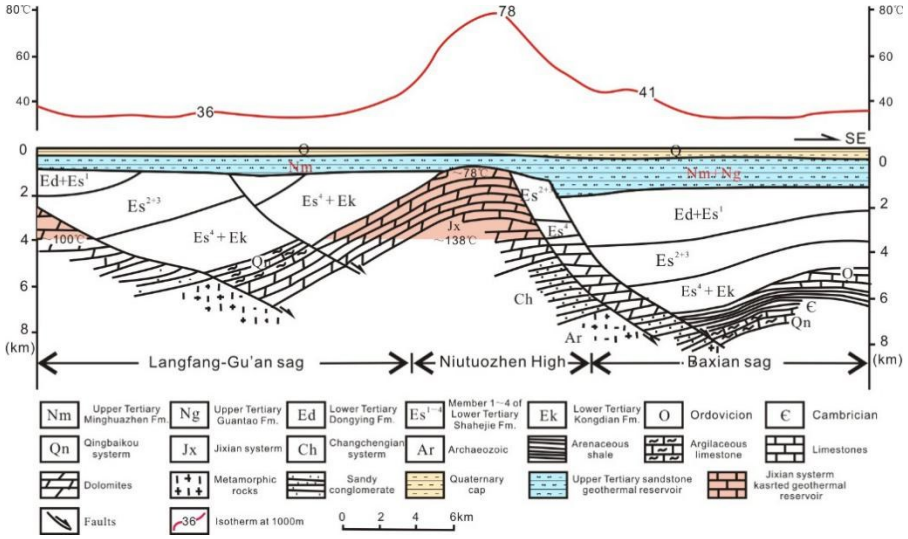


Figure9 the geological profile of Xiongxian geothermal field

4 CONCLUSIONS

Bohai Bay Basin has excellent conditions for the formation of karst geothermal resources. The adequate water and stable heat sources, widely developed karst geothermal reservoirs, favorable geothermal channels and caps, as well as the advantageous reservoir-cap assemblages guarantee the formation of large-scale and high-quality karst geothermal resources.

The surrounding piedmont and internal part of Bohai Bay Basinshow significant differences in karst geothermal enrichment. The karst geothermal resources in the piedmont of the basin are mainly controlled by groundwater movement and faults, and generally enriched in structural position where is favorable for the geothermal fluid upwelling; whereas the karst geothermal resources in the inner part of the basin are mainly controlled by the buried hills in the depression, and especially enriched in the buried hills where are in favor of deep geothermal fluid excretion.

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