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Karst Geothermal System in Taiyuan Basin of North China

Wang Xinwei, Wang Tinghao, Zhang Xuan, Mao Xiang, Luo Lu, Liu Huiying, Lu Zhao, Wang Di

Sinopec Star Petroleum Corporation Limited, Beijing 100083, China

wangxinwei.xxsy@sinopec.com, wangtinghao.xxsy@sinopec.com

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ABSTRACT

The Taiyuan Basin of North China, as a typical intermountain fault basin, is located in the middle part of the Fen-Wei graben system-an extensional faulting belt of the Chinese mainland. With an area of about 1 000 km^2, it is one of the urban areas where the distribution of the exploitable karst geothermal reserves matches the demand of heating market in Taiyuan City. By the end of 2018, 54 geothermal drilling wells have been completed. Most of the wells have a water temperature of 61~74℃, a single well water volume of 79~150 m^3/ h. And the geothermal heating area has reached 3.5 million square meters. Therefore, the study on the genetic model of karst geothermal system and the distribution of karst thermal reservoir is of great significance for the overall development of geothermal resources in Taiyuan Basin. In this paper, based on the previous research results and the latest geothermal well data, the formation, distribution and hydrothermal characteristics of the karst geothermal system in Taiyuan Basin are analyzed, and its geothermal resources are evaluated by 8 effective stuctural units. The results show as flow: (1) The strata of karst thermal reservoir in Taiyuan Basin are mainly the Ordovician system of Lower Paleozoic, which is widely distributed in North China Plate. And the evolution of the karst geothermal system has gone through five stages, i.e. the epigenic karstification at the end of the early Paleozoic, the direct caprock deposition in the late Paleozoic, the initial formation of the karst geothermal system during Mesozoic, the transformation during Himalayan and the final setting during the Quaternary. (2)The heat source of the geothermal system comes from the high terrestrial heat flow (> 1.7HFU) of the Cenozoic asymmetric fault basin, and the heat transfer mode can be divided into two different types: the strong convolution type (at the edge of the basin) and the heat conduction type (inside the basin). (3)The residual thickness of Ordovician is 600~750 m, and as an geothermal reservoir, the cumulative thickness of effective reservoir section is 160~180 m. The main water-bearing section of 3~ 4 layers can be identified, where "overflowing" is easy to occur during migration. (4)Controlled by the structure and geomorphology of the intermountain fault basin, the recharge-migration mode of geothermal water in the karst geothermal system has the characteristics of two-way, near-source and rapid. The time from the recharge area to the basin pressure area is only 2000 a, and the type of hydrochemistry changes from HCO_3-Ca type to HCO_3-Ca•Mg type, then to SO_4-Ca type with the increase of their salinity. (5) According to the method of geothermal reservoir volume evaluation, the total geothermal resources of the karst geothermal system in Taiyuan Basin are estimated to be 8.303 billion GJ, which is equivalent to million tons of standard coal. The annual exploitation of geothermal resources can meet the heating area of 15 million square meters with broad prospects for development.

1. INTRODUCTION

The concept of geothermal system includes two connotations. One is the effectiveness of the geothermal system (Helgeson, 1968), that is, geothermal system is a relatively independent geological unit in heat and fluid circulation, with sufficient geothermal enrichment to constitute energy resources (Rybach,1981;Wang,2015); the other is the specific research content of the geothermal system, that is, the study of a geothermal system requires that while dissecting the four geological genetic factors of "source (including heat source and water source), reservoir, pathway, caprock", more attention should be paid to the analysis of the geological process of "heat transmission, storage, preservation and loss" (Arnorsson ect.,1995;Fauldsect.,2010;Deonect.,2012;Moeck, 2014；He ect.,2017；Zhang ect.,2017). Previous studies of geothermal system mainly focus on the high-temperature convective geothermal system at the active edge of the plate, mainly used for geothermal power generation (Arnórsson, 1995). Those researches, however, contain little discussion of the low-and medium-temperature conductive geothermal system mainly used for urban heating in the sedimentary basin, especially the genetic model of the karst geothermal system in the intermountain fault basin.

The Taiyuan Basin is a Cenozoic intermountain fault basin in the northern extension of the Jinzhong Rift, located in the middle part of the Fen-Wei graben system-an extensional faulting belt with a length of 1000 km in North China Plate. The basin contains Cenozoic sedimentary areas from the north of Qingxu County to the south of Yangqu County, Taiyuan City. The width of the basin is about 20 km in EW direction, and the length is about 50 km in SN direction, with a total area about 1000 km^2 (Fig.1). The urban area of Taiyuan City is basically the same as the outline of Taiyuan Basin, with a permanent population of 4.42 million and a potential geothermal heating demand of 30 million m^2. The research on karst geothermal reservoirs in Taiyuan Basin before 2014 was relatively low. Based on the data of more than ten wells constructed in the basin only, the hydrochemical types, geothermal geological conditions and karst water recharge have been discussed (Ha Chengyou et al., 1989; Han Hangrui et al., 1993; Han Dongmei et al., 2006). While the genetic mechanism of the karst geothermal system, the heterogeneity of the karst geothermal reservoir and the evaluation of the overall resources in the whole basin are seldom involved.

Since 2014, Sinopec has exploited 54 geothermal wells (by the end of 2018) of lower-Paleozoic karst reserves in Xiwenzhuang uplift (also known as Xiwenzhuang geothermal field), Taiyuan Basin. Most of the wells have a water temperature of 61~74℃, and single well water volume of 79~150 m^3/h. The realization of heating capacity of 3.5 million square meters shows good development prospects. Based on the latest geothermal drilling data and test materials, combined with previous exploration and research results of karst geothermal reservoirs in Taiyuan Basin (Ma Teng et al., 2005; Ma Rui, 2007; Han Ying, 2009; Ma et al., 2009), this paper has established the genetic model of the karst geothermal system, compared spatial distribution differences of karst geothermal reservoirs in different secondary tectonic units, evaluated the amount of geothermal resources, and defined the exploration and development prospects of the karst geothermal reservoirs in Taiyuan Basin.

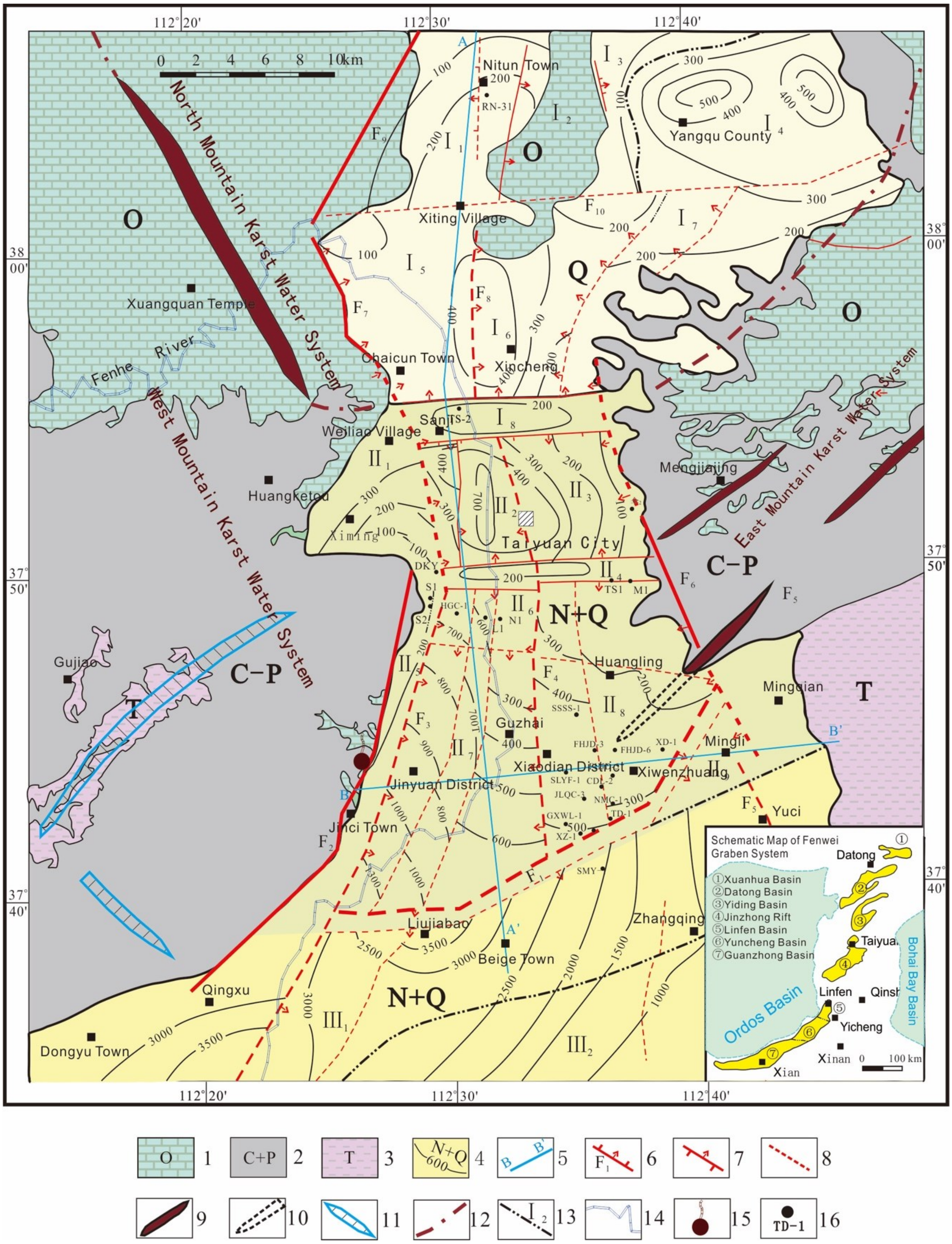

Figure1: Tectonic zoning and karst water system in Taiyuan Basin

1-Ordovician; 2-Carboniferous-Permian; 3-Triassic; 4-Cenozoic and thickness; 5-section location; 6-normal fault; 7-reverse fault; 8-hidden fault; 9-anticline; 10-depression anticline; 11-syncline; 12-karst water system boundary; 13-tectonic unit boundary; 14-river; 15-hot spring point; 16-geothermal well. F_1-Tianzhuang Fault Zone, F_2-Jinci Fault, F_3-Nanyan Fault, F_4-Fenhe Fault, F_5-Mingqian Fault, F_6-Dongbianshan Fault, F_7-Daliu Fault, F_8-Xincheng Fault, F_9-Guankou Fault, F_{10}-Shanglan-Donglingjing Fault; I_1-Nitun Fault Terrace, I_2-Qizishan Horst, I_3-Mapotou Horst, I_4-Yangqu Depression, I_5-Xizhang Faulted Terrace, I_6-Xincheng Depression, I_7-Nanshe Fault Terrace, I_8-Sangi Horst; II_1-Ximing Fault Terrace, II_2-Urban Depression, II_3-Chengdong Fault Terrace, II_4-Yanxian Horst, II_5-Xibianshan Fault Terrace, II_6-Chengnan Uplift, II_7-Jinyuan Depression, II_8-Xiwenzhuang Uplift, II_9-Mingli Depression, III_1-Qingjiao Depression, III_2- Qixian Fault Terrace.

2. EVOLUTION OF KARST GEOTHERMAL SYSTEM

The Taiyuan Basin shows an obvious structural pattern of the north- south segmentation and the east- west zonation in the plane (Guan and Li, 2001). Due to the differential tectonic subsidence of the extensional fault blocks in the Cenozoic, the basin was divided into three parts in the north- south direction by the nearly EW-oriented Sanji horst and the NE-oriented Tianzhuang fault. These three parts are the northern part, the central part and the southern part with the Cenozoic thickness of less than 500m, 300~1000m, and 1000~3500m, respectively. In the east- west direction, the basin was divided into 19 second-grade tectonic units by 3~4 nearly SN-oriented faults (Fig.1).

The geologic configuration of the Taiyuan Basin consists of 5 structural layers vertically (Figure 2): the Precambrian metamorphic basement; the Lower Paleozoic dominated by the platform-type marine carbonate buildups; the Upper Paleozoic dominated by the coal-bearing strata developed in transitional facies; the Mesozoic dominated by terrestrial clastic rocks; and the Neogenes dominated by poorly cemented or semi-diagenetic sediments. The maximum thickness of the sedimentary cover bed above the basement is over 6000m. In the basin, karst geothermal reservoirs developed in the Lower Paleozoic, overlying cover beds of the reservoirs developed in the Upper Paleozoic, and the regional cover bed developed in the Neogenes.

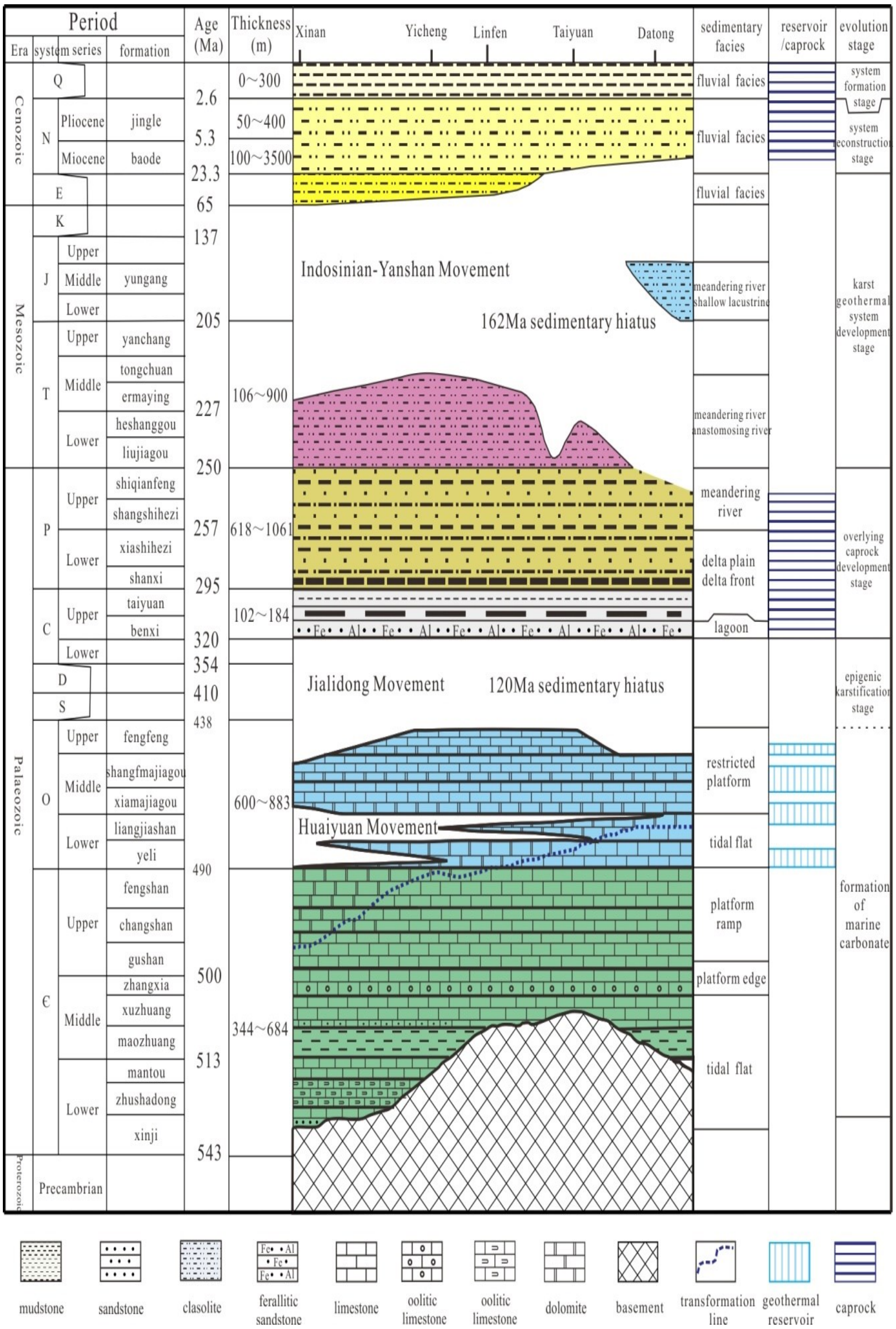

Figure 2: The structure-strata framework in Taiyuan basin and its adjacent area.

According to the controlling effect of regional tectonic evolution on the formation of genetic elements of karst geothermal system, the evolution process of karst geothermal system in Taiyuan Basin is divided into the following five stages. (Fig. 3).

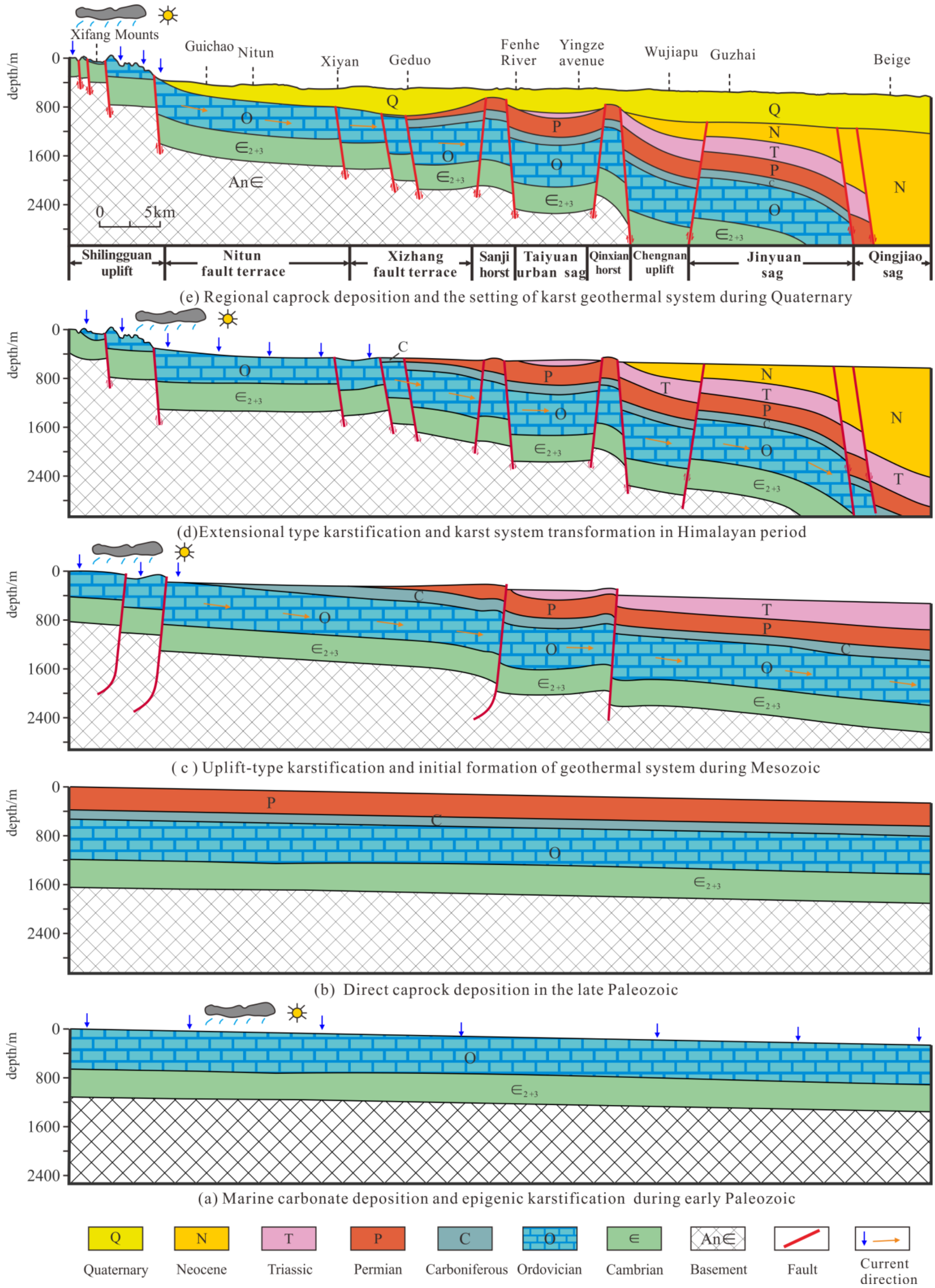

Figure 3: The evolution of karst geothermal system in Taiyuan Basin.

(1) Marine carbonate deposition and the epigenic karstification of the stable uplift during early Paleozoic (Fig. 3a). In the southwestern part of North China Platform, the platform-type sedimentation from Middle to Neoproterozoic was gradually overlying from south to north along the Jin-Henan fracture trough and reached the study area in the late Middle Cambrian. Therefore, above the basement ，Taiyuan Basin only developed the Middle Cambrian-Ordovician widespread carbonates with a total thickness of 1200m. During this period, two tectonic movements, the Huaiyuan Movement and the Caledonian Movement, dominated by overall lifting happened. The Huaiyuan Movement, dominated by episodic lifting, happened in late Cambrian- Early Ordovician (Song, 2001), and the Caledonian Movement, dominated by regional uplift, happened in the Late Ordovician with a depositional hiatus of about 120Ma. As a result, three disconformity surfaces and three dolomite-limestone cycles of sedimentation could be identified in the Ordovician (Fig. 2). Dolomite is favorable for geothermal reservoirs, and argillaceous limestone and argillaceous dolomite is favorable for high-

quality interlayer. At the same time, the depositional hiatus and flattened karst paleogeomorphology, formed by multipahse tectonic movements, resulted in the interlayer karst, forming karst caves and dissolutional pores, which distributed along the layer surface (Luo et al., 2008).

(2) The direct caprock deposition in the late Paleozoic (Fig. 3b). The Silurian-Lower Carboniferous didn't develop in the study area. Until the Late Carboniferous, the overall settlement of North China Plateform resulted in the deposition of the transitional facies coal-bearing strata with a thickness of about 800-1200m, forming the overlying caprock of the Ordovician karst geothermal reservoir.

(3) The uplift type karstification and the initial formation of karst geothermal system during Mesozoic (Fig. 3c). The tectonic movements of the Mesozoic Indosinian and Yanshanian Movement caused the regional strata to be strongly compressed and uplifted, and formed the modern NE-oriented structural pattern. The study area was located in the southern flank of the Wutaishan anticlinorium formed during the period. The regional karst topographic feature showed the buried hill-type karst, the Wutaishan anticlinorium core developed the karst highland facies with an outcrop of the Archaeozoic crystalline basement, the Qinshui Basin developed the karst depression facies (the Triassic residual thickness here is about 1000m), and the study area developed the karst slope facies. The strata of the study area was gently dipping, and from north to south the Middle Ordovician, the Carboniferous-Permian and the Lower Triassic were outcropped respectively. A relatively uniform karst geothermal system was formed under the continuous leaching of atmospheric precipitation in carbonate exposed areas.

(4) Extensional faulting-block type karstification and karst system transformation in Himalayan period. The large scale NE-oriented rift basin formed under the control of the NS-oriented stress field during the Himalayan (Zhang, 1990). Due to the differential tectonic subsidence of the extensional fault blocks, the early relatively uniform karst geothermal system was damaged. The Tianzhuang fault zone were contemporaneous faults, the karst geothermal reservoirs south of the fault zone gradually subsided, while in the north of the fault zone, sediments overlapped gradually to the north, and the reservoirs developed concealed-exposed epigenetic karstification (Fig. 3d).

(5) The regional caprock deposition and the setting of karst geothermal system during Quaternary. Due to the Quaternary depression of the Taiyuan Basin, the sediments overlapped from south to north on the Nitun-Yangqu area north of the Sanji horst, and as a result, the regional cover bed formed. At the same time, the mountains on both sides of the east and west were tilted, and the basin was severely stretched and subsided. This tectonic pattern made the atmospheric precipitation flow from mountains to the foreland and the basin, then gather and accumulate in the carbonate reservoirs in the basin, forming the current karst geothermal system (Fig. 3e).

3. GENESIS ELEMENTS OF KARST GEOTHERMAL SYSTEM

3.1 Geothermal source analysis

3.1.1 Dynamic mechanism of geothermal anomalies in the deep basin

The high geothermal flow generated by the Cenozoic rifting provides a good geothermal source for the Taiyuan Basin, which belongs to the anomaly area of high thermal flow (Deng Qidong et al., 1999; Luo Huanyan et al., 1988). Its geothermal flow value exceeds 1.7 HFU (71 mW/m^2) (Fig. 4a), which is much higher than the global average geothermal flow value of 1.47 HFU. It can be seen from the Curie isothermal surface depth map of the five major fault basin groups in Shanxi Province (Fig. 4b) that there is a NE-trending belt distribution convex belt on the Curie isothermal surface of the Jinzhong Rift, which is about 60 km long, 20 km wide, less than 20 km deep and much less than 32 km in the surrounding mountainous areas (according to Wang Xiwen, 1989, cited from Li Shizhong et al., 1994). The Curie isothermal surface located in the upper crust has characteristics of low velocity, high conductivity and high temperature (600 °C). It is a physical surface to indicate and judge the thermal state of the crust. The thermal flow distribution in the Jinzhong Rift is exactly the same as the distribution of the Curie isothermal surface, indicating that the thermal anomalies in shallow crust are mainly controlled by deep structures.

The sedimentary range of the Cenozoic faulted basin group in Shanxi is basically the same as the Curie isothermal surface uplift zone (or high thermal flow anomaly zone), but the distribution characteristics are obviously different (Fig. 4). In Xinding Basin and Datong Basin in the north of Shanxi, the anomaly zones of high thermal flow are mainly located in the middle of the basins, and they have symmetrical distribution characteristics. In Yingcheng Basin, Linfen Basin and Jinzhong Rift in the south of Shanxi, the anomaly zones of high thermal flow are located at the western boundary of the basins and have asymmetrical distribution characteristics. The origin of symmetrical and asymmetrical distribution is related to the different dynamic mechanism of fault basin formation.

The dynamic mechanism of the formation of faulted (or rift) basins generally includes pure shear model and simple shear model (Haakon Fossen, 2010), in which pure shear model forms a symmetrical rift with hot spots in the central part of the rift basin, while simple shear model is generally dominated by a low-angle shear zone and produces an asymmetric rift, with hot spots located at the edge (or even the periphery) of the rift basin. It can be inferred that the dynamic mechanism of Xinding basin and Datong basin in northern Shanxi is a pure shear model, while that of Yingcheng basin, Linfen basin and Jinzhong rift in southern Shanxi is a simple shear model (Zhang Hongwei and Deng Qidong, 1992) (Fig. 5a).

To sum up, the heat source of Taiyuan basin comes from the high earth heat flow (> 1.7HFU) of Cenozoic asymmetric fault basin, and its dynamic genetic mechanism is a simple shear model under the background of crustal extension. This can also be evidenced by the tectonic form of the Cenozoic sedimentary pattern in Taiyuan Basin, which is faulted in the west but overlapped in the east, and the largest subsidence center located on the west side of the basin (Fig. 1).

3.1.2 Crustal structure model of geothermal anomalies in the basin

According to the interpretation results of magnetotelluric sounding profiles in Shanxi, the former researchers divided the crust-upper mantle geological structure into five electrical layers, and the high-conductivity layer exists in the middle crust and upper mantle. The high-conductivity layer is thick and shallow in the basin. The burial depth of high-conductivity layers in crust and upper mantle are mirrored with Cenozoic thickness of the fault basin (according to Xing Jishan et al., 1989, cited from Li Shizhong et al., 1994).

On the basis of summarizing these research results, this paper has compiled a schematic diagram of the crustal section of Jinzhong Rift. Among them, the deep crust thickness of the basin is about 43 km and the depth of Curie is about 20 km. The high-conductivity layer in the middle crust plays a decisive role in the thermal anomaly distribution in the shallow crust of the basin. The buried depth is about 14 km, the resistivity is 2 ~ 5 Ω m and the thickness is 4km. The buried depth becomes larger, the thickness gradually becomes thinner and even disappears towards the mountain areas on both sides, with steep in the west and gentle in the east. The abnormal high point is located on the western boundary of the basin. These determine the asymmetric distribution pattern of fault basins in the shallow crust under the action of mechanical mechanism of simple shear model(Fig. 5b).

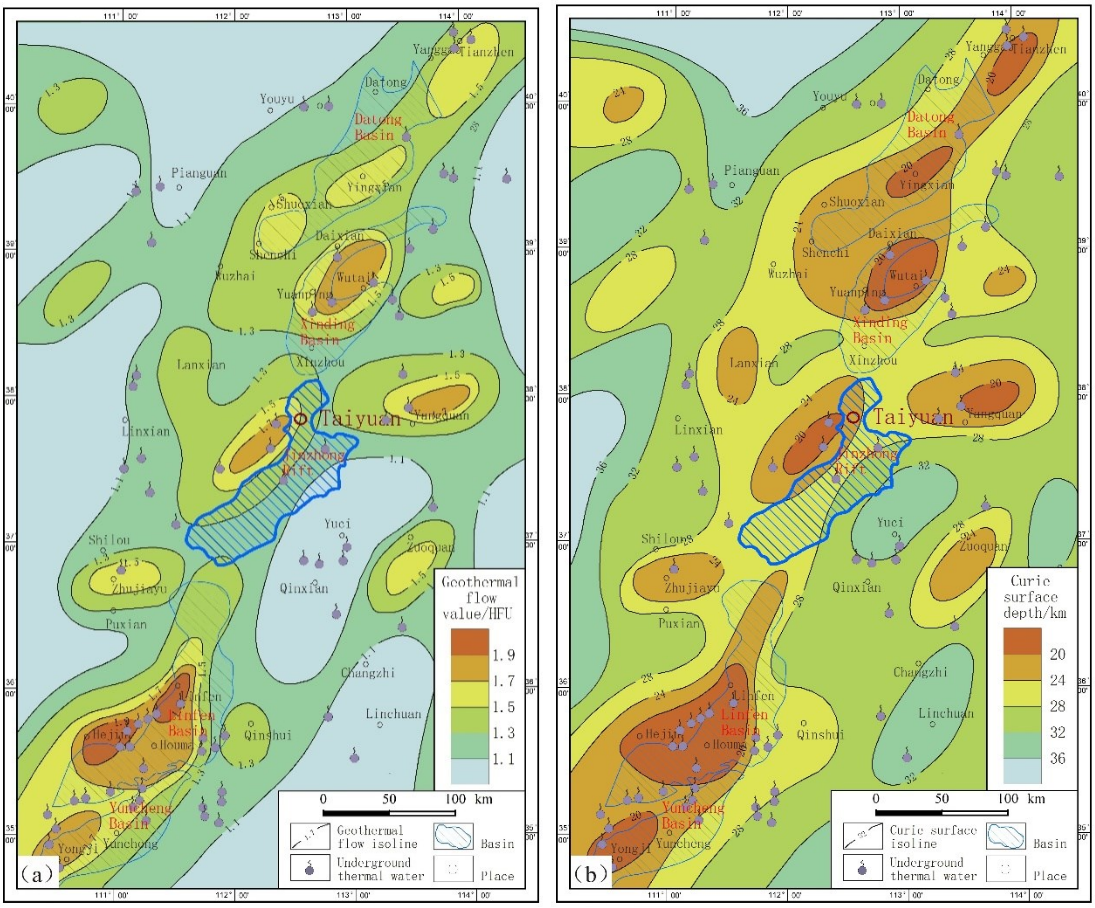

Figure 4: Distribution map of terrestrial heat flow (a) and Curie surface depth (b) in the fault basins of Shanxi province (Slightly modified from Wang, 1989, cited from Li et al., 1994).

3.1.3 Thermal transfer modes in the shallow level of the basin

As a Cenozoic faulted basin with three sides surrounded by mountains and relatively narrow area, the shallow geothermal field of Taiyuan Basin is inevitably affected by deep faults in the basin margin and groundwater activities, resulting in a variety of thermal transfer modes in different secondary tectonic units in the basin. Based on the relationship between the geothermal gradient of thermal reservoir and caprock revealed by the stratigraphic temperature-depth curves of geothermal wells in different tectonic units of Taiyuan Basin (Fig. 6), the thermal transfer modes in Taiyuan Basin are divided into two distinct types: convection type and conduction type. Among them, the convection type can be sud-divided into two types: the recharge water convection type and the deep thermal flow convection type.

Recharge water convection type

It mainly distributes in the northern part of the basin, north to Sanji Horst. Because of the short distance from the recharge source area, the fast runoff speed, the thin geothermal caprock (< 400m) and the poor geothermal sealing performance, the strong geothermal convection reduces the temperature of the upper caprock, which results in that the karst water in the area basically maintains the temperature of the surface source area, or the temperature increase is very small, the water temperature increases by 13.0 ~ 17.0 ℃, and the caprock geothermal gradient increases by 0.5 ℃/100m. For example, well RN-31 in Nitun Fault Terrace is 460m deep, the wellhead temperature is only 16.0 ℃. Well TS-2 on Sanji Horst is 823.33m deep, the wellhead temperature is only 17.1 ℃. (Fig. 6). The karst geothermal system in the northern part of Taiyuan Basin is ineffective, because the geothermal water temperature is less than 25 ℃, which can not meet the basic conditions for the utilization of geothermal resources.

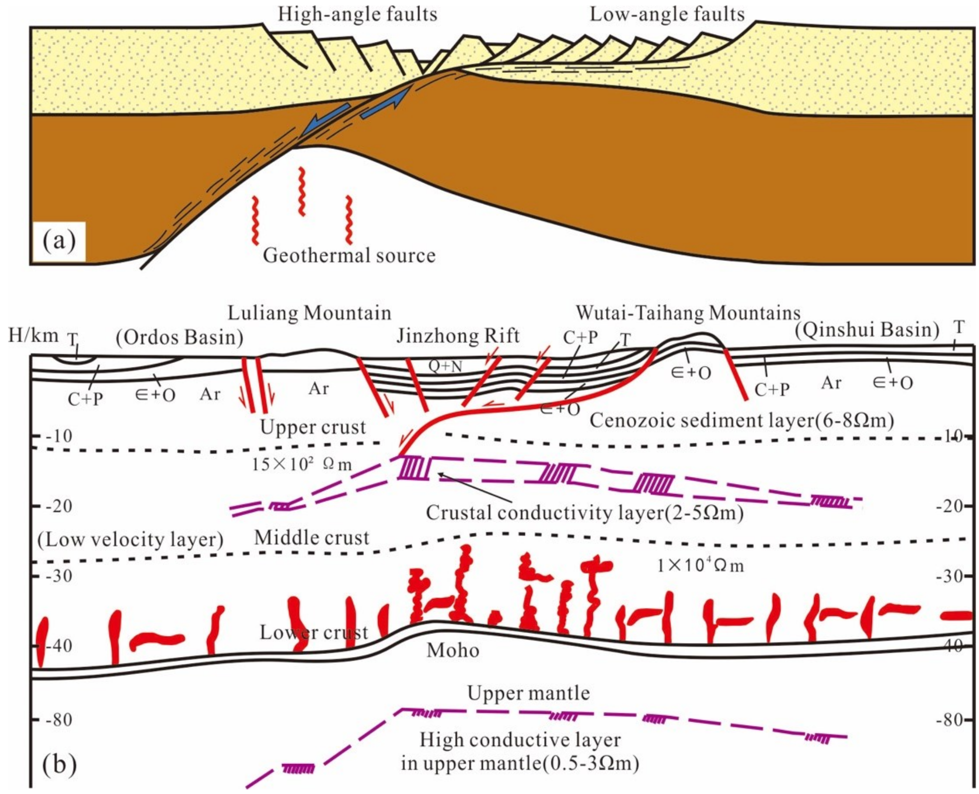

Figure 5: Comparison of simple shear model of crustal extension(a) and crustal section model of Jinzhong Rift (b) (Slightly modified from a: Haakon, 2010; b: Wang, 1989; cited by Li et al., 1994).

Deep thermal flow convection type

It mainly occurs in Xibianshan Fault Terrace in the western part of the basin. Because the thermal anomaly zone in the deep level of the basin is located in the secondary tectonic zone, and the Jinci Major Fault connects the deep geothermal source, it leads to strong geothermal convection heating. For example, well S2 located in Xibianshan Fault Terrace has a well depth of 801.18m and the geothermal reservoir temperature of 45℃. The geothermal convection in the geothermal reservoir accelerates the thermal transfer rate and reduces the geothermal gradient by about 2.17 ℃/100m. Correspondingly, the thermal aggregation of the upper caprock makes the average geothermal gradient reach to 4.69 ℃/100m (Fig. 6c). In addition, similar karst reserves convective thermal transfer and shallow caprock thermal aggregation phenomenon exist in well TD-1 near Tianzhuang Fault Zone. Due to the upward vertical movement of karst water in the deep fault, the geothermal gradient of the Ordovician karst geothermal reservoir and Carboniferous-Permian direct caprock has been homogenized, with the geothermal gradient difference is less than 1.40 ℃/100m. The high geothermal gradient section with rapid temperature increase mainly occurs in Cenozoic regional caprock, and the geothermal gradient is greater than 7.0 ℃/100m (Fig. 6d).

Normal conduction type

This type of thermal transfer mainly occurs in the middle part of the basin south to Sanji Horst and north to the Tianzhuang Fault. Its characteristic is that the temperature of the caprock increases linearly with normal (or slightly lower) geothermal gradient as the depth increases. For example, well SSSS-1 and well SLYF-1 in the Xiwenzhuang Uplift have an average gradient of 2.0 ~ 2.5 ℃/100m (Fig. 6e-f).

3.2 Characteristics of thermal reservoir

3.2.1 Residual Thickness and Top Burial Depth of Thermal Reservoir

The residual thickness of thermal reservoirs is the basis for the development of hot water reservoirs as well as an important parameter for resources evaluation. Because the original sedimentary environment of Ordovician thermal reservoir is a stable shallow sea platform, the initial thickness of the reservoir varies little, ranging from 600 m to 800m. Therefore, the thickness difference of the remaining Ordovician is mainly related to the denudation degree caused by the later tectonic movement. The foregoing study shows that the structural position of Taiyuan Basin during Mesozoic denudation period is on the wing of wide and gentle anticline, and the overall denudation degree is not strong (Fig.3c), which results in little difference in the remaining thickness of thermal reservoir. In the basin area north of Sanji horst, most of the area is exposed to the Upper Ordovician, and the thickness of thermal reservoir is about 550-600m. In the basin area south of Sanji horst, the Ordovician is not exposed, and the initial thickness

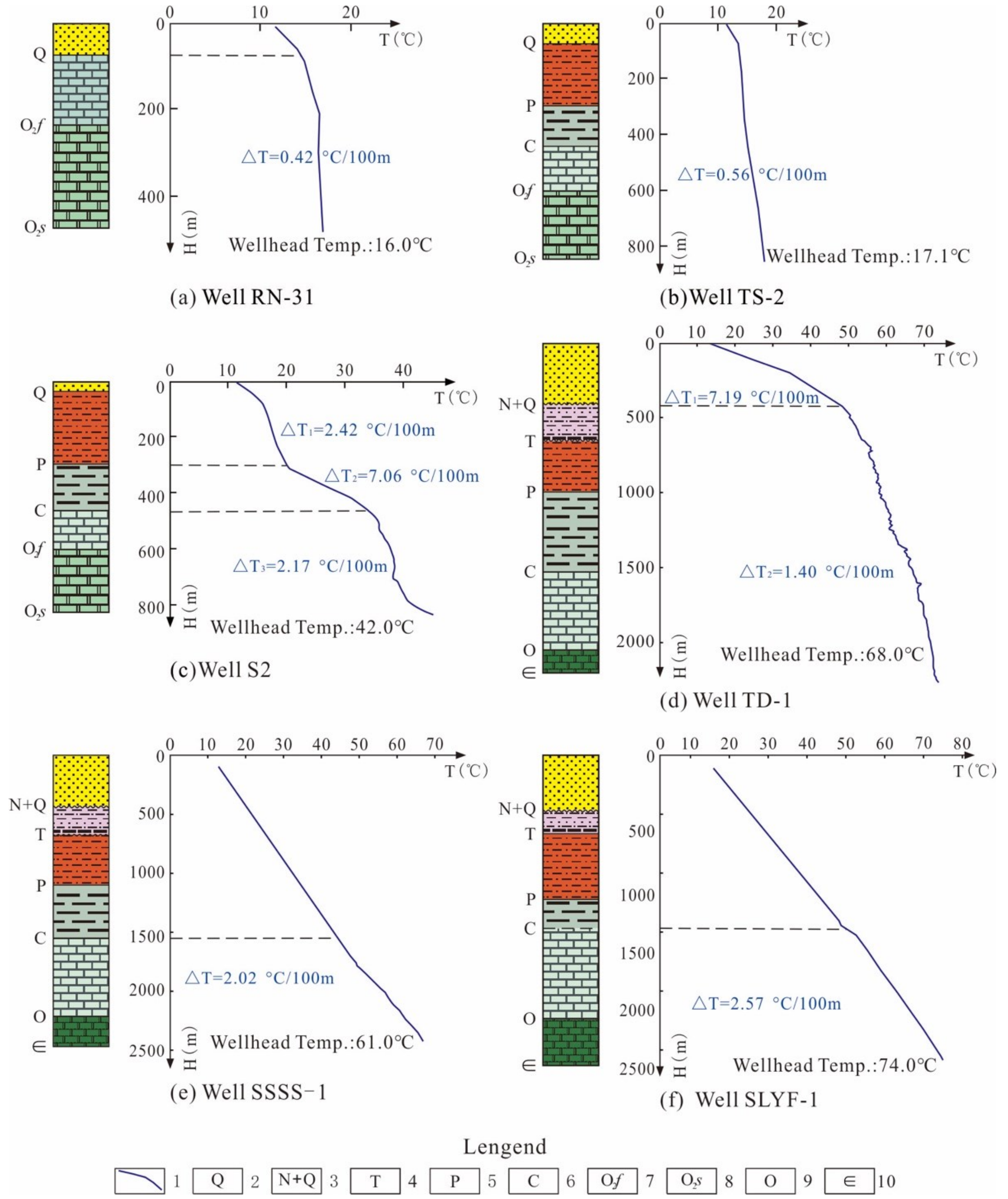

Figure 6: Typical drilling depth–temperature curves in the Taiyuan basin. (1) Depth–temperature curve, (2) Quaternary, (3) Neogene and Quaternary, (4) Triassic, (5) Permian, (6)Carboniferous, (7) Fengfeng formation, (8) Upper Majiagou formation, (9) Ordovician, (10) Cambrian.

3.2.2 Temperature of Geothermal Reservoir and Geothermal Gradient of Caprock

Temperature of Thermal Reservoir This paper refers to the measurement temperature of geothermal fluid at the wellhead, which is actually the mixing temperature of geothermal water in different depths of reservoirs (neglecting the heat loss during pumping), and can be regarded as the average temperature of thermal reservoirs. It is one of the main parameters for evaluating the quality of geothermal resources. According to the geothermal fluid temperature (Ma, et al., 2011; Ma Teng et al., 2012) of existing geothermal wells and the latest 54 geothermal wells in Taiyuan Basin, the temperature distribution map of karst thermal reservoirs in Taiyuan Basin is compiled (Fig. 6-b). This map shows that the temperature of karst thermal reservoir is obviously controlled by its top burial depth and geological structure. It is mainly manifested in three aspects：(1) Because of the thin thermal cover, the temperature of karst water is less than 25℃, the basic condition of geothermal resources utilization is not reached in Sanji horst and the basin area north of it. (2) In the middle segment which located from the south of Sanji horst to the north of Tianzhuang fault zone, the karst thermal reservoir temperature increases gradually from south to north, from the edge of mountainous areas on the east and west sides to the center of the basin with the increase of the thickness of the caprock, ranging from 30℃ to 75℃. (3) The high temperature distribution area of karst thermal reservoir is located in the southwest of Xiwenzhuang uplift to the east of Jinyuan depression. The temperature range from 65℃ to 75℃. It is a high-quality geothermal resource development area for geothermal heating utilization (Fig. 7c).

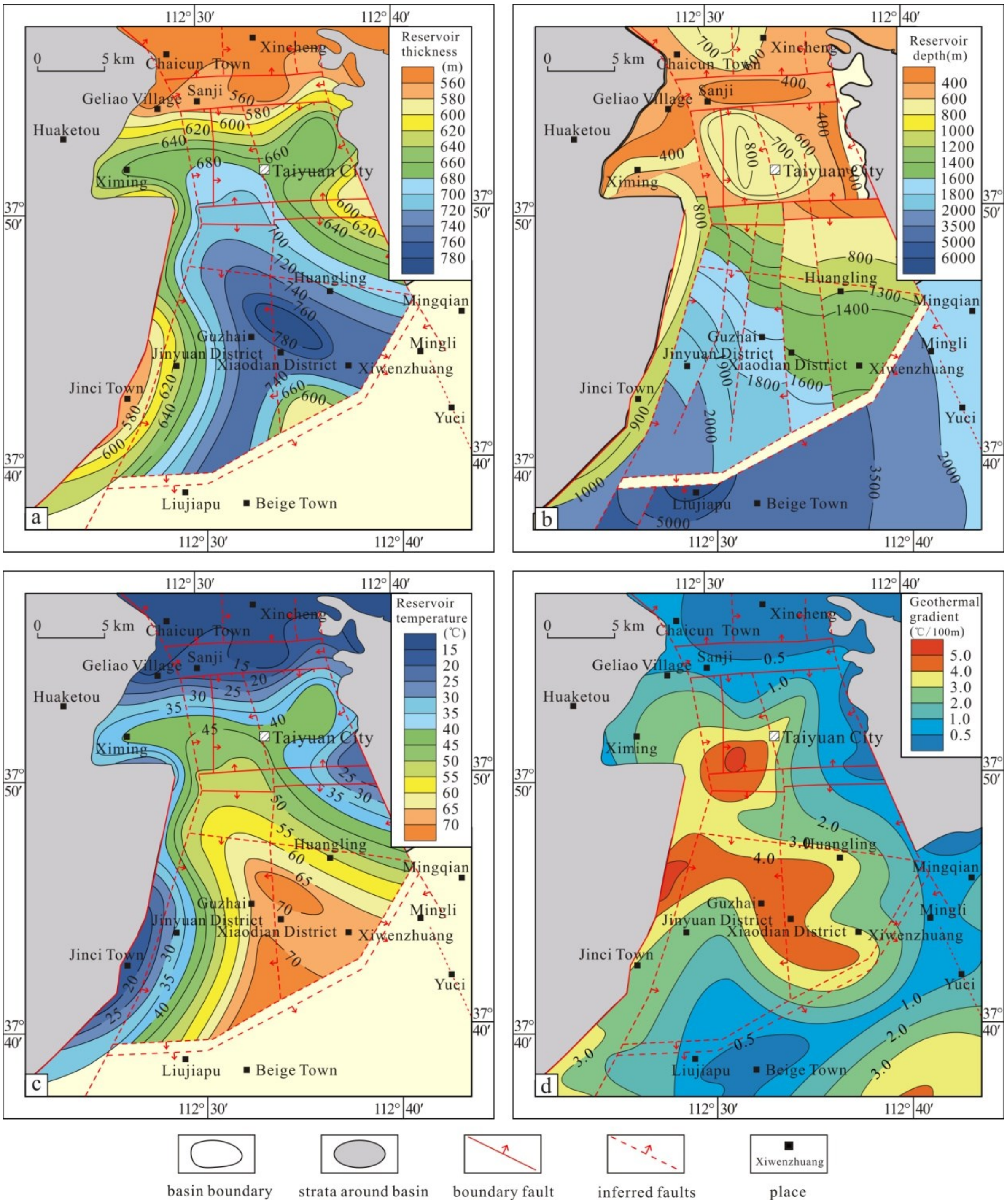

Figure 7: Description of Ordovician karst reservoir in the Middle part of Taiyuan Basin. a) Reservoir residual thickness; b) Buried depth of reservoir; c) Reservoir temperature; d) Geothermal gradient of the caprock.

Geothermal gradient of caprock

The geothermal gradient of the caprock in the basin is a comprehensive reflection of the temperature of the karst thermal reservoir, the thickness of the overburden and the mode of heat transfer. It is also one of the important parameters for optimizing the exploration target area. In the basis of the temperature of karst thermal reservoir and the burial depth of the top surface, the geothermal gradient distribution map of the caprock (Fig. 7d) shows that: (1) The geothermal gradient of the cover layer is less than 0.5℃/100m in the basin area north of Sanji horst, which is the result of intense convection of the recharge water. (2) In the middle segment of the basin to the south of Sanji horst and north of Tianzhuang fault zone, the geothermal gradient value gradually increases from the negative anomaly area in the basin margin (< 2.0 C/100m) to the normal area uplift area in the basin (~3.0 C/100m), and then to the positive anomaly area on the basement uplift zone in the basin(>4.0 C/100m). (3) The positive anomaly of the geothermal gradient in the northern part of the western mountain fault terrace (> 5.0 C/100m) is related to the local thermal convection caused by deep faults.

Based on the analysis of thermal reservoir characteristics, the Chengnan uplift zone and the Xiwenzhuang uplift zone, that be seated in the middle part of the basin are the most favorable exploration targets for karst thermal reservoirs because of their relatively shallow burial depth (800-1700m) and high thermal reservoir temperature (50-75℃).

3.2.3 Reservoir heterogeneity

Reservoir heterogeneity refers to the uneven changes in spatial distribution and internal attributes of reservoirs due to the influence of sedimentation, diagenesis and tectonics during the formation process. The reservoirs in the study area are karst thermal reservoirs in the lower Paleozoic, which go through longer in geological period and have a long evolutionary history. Influenced by tectonic and weathering effects in the later stage, the reservoirs have many types and strong heterogeneity. It is rare that the researches on the heterogeneity of carbonate reservoirs in this area. Based on the productivity test and well interpretation results of the geothermal wells in Xiwenzhuang uplift, Taiyuan Basin, this paper intends to analyze the differences between the horizontal distribution and vertical stratification of reservoirs.

(1) Horizontal zoning of reservoirs

The inhomogeneity of karst thermal reservoirs in the study area is mainly manifested in the following aspect: in the same geothermal field within a geothermal system, the water volume of single well varies greatly. Taking the water test results of 43 geothermal wells in Xiwenzhuang geothermal field of Taiyuan Basin as an example (Fig. 8). The depth and the water-intaking sections of these 43 wells is basically similar, which is about 2500 meters deep and 600-800 meters long. The water-intaking horizons include the Ordovician and the Fengshan formation in the upper Cambrian. Although most of the effluent temperatures are concentrated in the range of 60-70℃, the water quantity of a single well varies greatly. According to statistics, there are 20 wells whose water volume is more than 110 m^3/h, accounting for 46.51%; 11 wells whose water volume is 50 m^3/h to 110 m^3/h, accounting for 25.58%; 12 wells whose flow rate is less than 50 m^3/h.

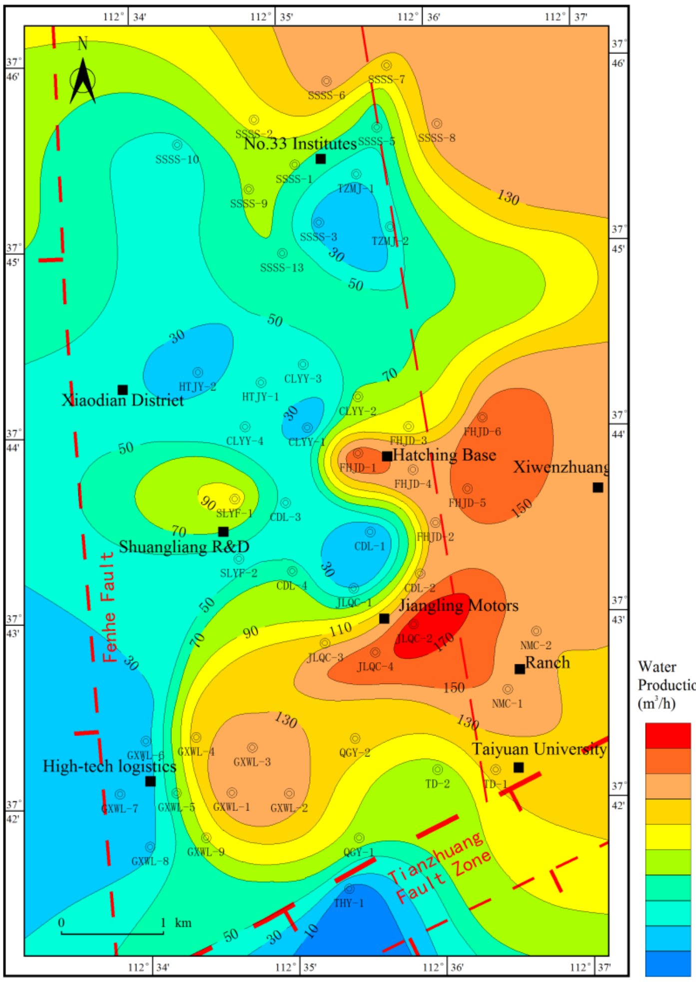

Figure 8: Distribution of water yield of single well in Xiwen Zhuang geothermal field in Taiyuan Basin.

It can be seen from the contour map of total water volume in Xiwenzhuang geothermal field (Fig. 8)：(1) In the southeastern area of Xiwenzhuang uplift (FHJD—JLQC—the east of GXWL—NMC), there exists a high water volume zone with NE direction. The water volume of a single well is more than 100 m3/h, and the highest is 178 m^3/h (JLQC-2). (2) The water production in the north (SSSS) and south(TD) of Xiwenzhuang uplift is the second, about 60-100 m3/h. (3) The water production in the central (SLYF) and the southwest part (west of GXWL) is relatively low, less than 60 m^3/h. The lowest well is THY-1, which is only 8.7 m^3/h.

Combined with regional tectonic analysis, the pre-Cenozoic bedrock of Xiwenzhuang uplift is a broad anticline structure, which is the plunging(extension) part of the NE-trending Dongshan anticline in the basin（Fig.1）. The strata involved in anticline are Cambrian-Triassic. The ridge line in the core of the anticline is exactly in the high-yielding water zone along the NE-trending strip. It can be inferred that the hidden NE-trending ridge line belt in the Dongshan anticline is the most favorable channel for karst water migration and the best water-rich reservoir in the basin. On the flanks of the core zone of the anticline, the water-enrichment of thermal reservior decreases; at the turning end of the disappearance of the concealed anticline, the water-enrichment of reservoir is poor.

(2) Vertical stratification of reservoirs

There are thirteen geothermal wells in total at the Xiwenzhuang geothermal field of Taiyuan Basin have been tested for fluid production profiles, which are distributed in the northern, central, southwestern and southern parts of Xiwenzhuang uplift. Comprehensive analysis of productivity profile shows that there are four main aquifers in Ordovician in the study area from top to bottom: the lower member of Fengfeng Formation to the upper member of Shangmajiagou Formation, the lower member of Shangmajiagou Formation, the upper member of Xiamajiagou Formation, the lower Liangjiashan Formation to the upper Yeli Formation, these constitute four sets of geothermal fluid reservoir-cap assemblages in Ordovician（Wang Xinwei, et al 2019）. However, the main aquifer of the four sets of reservoirs in the Ordovician vary in different structural positions, sometimes transiting to the Fengshan Formation on the top of the Cambrian. For instance, the No.33 institutes in the north of Xiwenzhuang uplift, the main aquifer is Fengshan Formation of Cambrian and the second is Fengfeng Formation. The hatching base block in the central part of Xiwenzhuang uplift regards the Shangmajiagou Formation and Liangjiashan Formation as the main aquifers and the lower member of Fengfeng Formation and Xiamajiagou Formation as the secondary aquifers. In the high-tech logistics area in the southwest of Xiwenzhuang uplift, the main aquifers are Xiamajiagou Formation and Yeli Formation, and the secondary aquifers are Fengfeng Formation and Liangjiashan Formation. Taiyuan University area lies in the south of Xiwenzhuang uplift, the main aquifer is Liangjiashan Formation, and the next is Xiamajiagou Formation. The whole Lower Paleozoic can be regarded as a large reservoir, it can be divided into three or four main water-bearing sections, where the main aquifer is prone to "overflowing" phenomenon in the process of migration.

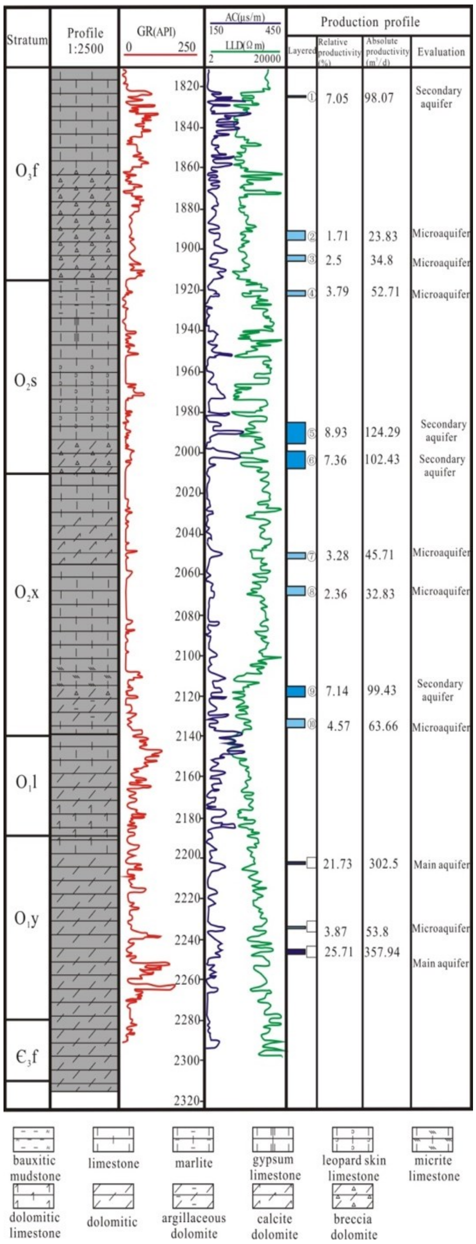

Figure 9: Log curve interpretation and productivity test of GXWL-2 well in Taiyuan Basin.

Taking GXWL-2 well in the southwest of Xiwenzhuang uplift as an example to illustrate the vertical zoning features of reservoir.

Productivity profile analysis of GXWL-2 well (Fig. 8, Table 1): (1) Thirteen aquifers with different thickness can be identified in the reservoir section, and the total effective thickness is 28.5m. According to the three dolomite-limestone sedimentary cycles, it can be classified into 4 sections. From new to old, the sequence is the Fengfeng Formation to the upper member of Shangmajiagou Formation, the lower member of Shangmajiagou Formation, the upper member of Xiamajiagou Formation and the Yeli Formation. The average porosity is 3.7%, 6.5%, 3.7% and 7.1%, respectively. (2) Yeli Formation is the main aquifer, with productivity accounting for 51.31% of the total. The other three layers are secondary production layers, accounting for 15.05%, 16.29% and 17.35% of the total respectively from new to old. (3) The effective water production thickness of Yeli Formation is only five meters, but it contributes more than half of the production capacity, which may be related to its relatively high permeability (average 0.33 mD).

Table2: Corresponding tables for log interpretation of GXWL-2 well in Taiyuan Basin.

Number	Aquifer formation	Depth range(m)	Thickness (m)	Acoustic (μs/m)	Deep Lateral (Ω•m)	Porosity (%)	Permeability (mD)	Lithology	Relative productivity (%)	Absolute productivity (m^3/D)	Interpretation and evaluation	Comprehensive capacity
1	Up O_2f	1824.75～1825.55	0.8	190	525.2	4.7	0.13	breccia dolomite	7.05	98.07	secondary aquifer	15.05%
2	Lw O_2f	1891.60～1897.40	5.80	186.8	204.6	3.8	0.07	breccia dolomite	1.71	23.83	microaquifer	
3	Lw O_2f	1902.30～1905.40	3.10	177.9	236.6	2.7	0.04	leopard skin limestone	2.5	34.8	microaquifer	
4	Up O_2s	1920.85～1923.45	2.60	188.6	307.7	4.5	0.09	leopard skin limestone	3.79	52.71	microaquifer	
5	Lw O_2s	1985.10～1995.40	10.3	198.1	406.1	6.2	0.31	breccia dolomite	8.93	124.29	secondary aquifer	16.29%
6	Lw O_2s	1999.30～2007.55	8.25	220.1	150.6	8.9	1.19	lime dolomite	7.36	102.43	secondary aquifer	
7	Up O_2x	2048.50～2052.30	3.8	188.5	623.8	4.8	0.12	limestone	3.28	45.71	microaquifer	17.35%
8	Up O_2x	2064.45～2070.90	6.45	174.2	685.2	2.7	0.04	breccia dolomite	2.36	32.83	microaquifer	
9	Lw O_2x	2114.30～2120.90	6.60	187	202.7	4.3	0.1	dolomite	7.14	99.43	secondary aquifer	
10	Lw O_2x	2131.85～2137.65	5.80	180.2	297.1	3	0.05	dolomite	4.57	63.66	microaquifer	
11	O_1y	2202.40～2204.00	1.60	194.5	603.5	5.5	0.22	gravel dolomite	21.73	302.5	main aquifer	51.31%
12	O_1y	2234.50～2235.50	1.00	214.3	599.7	7.8	0.39	coarse-grained dolomite	3.87	53.8	microaquifer	
13	O_1y	2242.20～2244.60	2.4	212.4	885.3	8.1	0.38	coarse-grained dolomite	25.71	357.94	main aquifer	

Note: The productivity profile test used turbine flowmeter. The absolute water production and relative water production of each water producing horizon are calculated quantitatively according to the flow value measured at the point and the flow data measured continuously, and the systematic comparative analysis is carried out with open hole logging data. The total water yield was 1,392 m^3/d in the test..

3.3 Analysis of water source and transport channel

3.3.1 Hydrogen and oxygen isotopes analysis

Hydrogen and oxygen isotopes are the most commonly used stable isotopes. The linear correlation between the hydrogen-oxygen isotope compositions in meteoric precipitation in a particular region is called the meteoric precipitation line. As the geothermal water enters the basin from the recharge mountainous area, it gradually deviates from the meteoric precipitation line as the water-rock interaction progresses. Because of the different effects of different regions, it is possible to distinguish between different fluid systems and to track the direction of fluid transport. Three points of understanding can be drawn from the$\delta 2H$-$\delta 18O$ plot of different layers of the Taiyuan Basin (Fig. 10): (1) The isotope composition of the karst water in the East and West Hills has a similar trend with the current Fen River, reflecting the overall composition of the isotope is affected by the current meteoric precipitation isotope and isotope exchange with the sedimentary layer. (2) The isotope composition of karst water in the East and West Hills does not have obvious distinguishable structure, indicating that the karst geothermal system in the central part of the Taiyuan Basin has been recharged from the karst water from the East and West Mountains. (3) The hydrogen and oxygen isotope composition of the Permian pore water has obvious isotope depletion phenomenon, and its change trend is obviously deviated from the isotope variation trend of the Fen River. This indicates that as a karst thermal reservoir caprock, the formation pore water is not homologous to the underlying Ordovician karst water and may be older than deep karst water. At the same time, it also reflects the good sealing effect of the Carboniferous-Permian coal strata on the karst geothermal system.

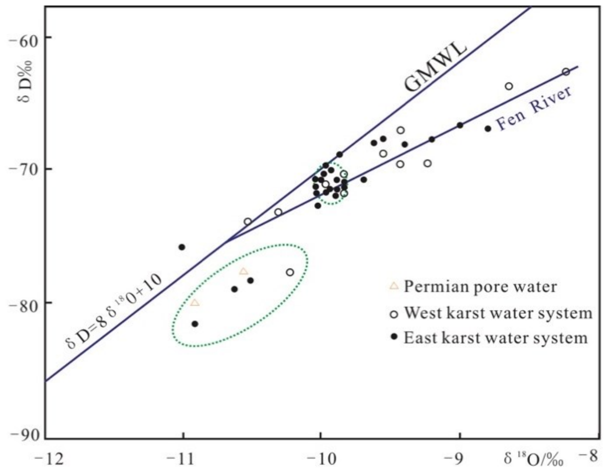

Figure10: Map of hydrogen and oxygen isotopic composition of geothermal water in Taiyuan Basin (Modified from Zhao & Cai, 2009.)

3.3.2 Water chemical analysis

The karst water temperature at edge of Taiyuan Basin is low (15~25°C) and the mineralization is small (558~1199mg/L). The composition of water chemical ions is relatively scattered (Ma et al., 2012; Li et al., 2006; Zhang, 1990). According to Shukalev classification method, the water chemistry can be classified into three types: HCO_3-Na type, SO_4-Ca·Mg type, and HCO_3-Ca·Mg type. It reflects the characteristics of the diverse sources of geothermal water at the edge of the basin (Fig. 11a).

The water chemical data analysis of 34 geothermal wells in the Xiwenzhuang geothermal field in Taiyuan Basin indicates that: (1) the wellhead water temperature of karst geothermal reservior is higher (51~74°C), the mineralization degree is higher (1592~3279mg/L), the pH values are weakly alkaline (6.34~8.31). (2) The water chemistry type is dominated by SO_4-Ca type, and the smallest part is SO_4-Ca•Mg type, Cl•SO_4-Ca•Mg type and SO_4-Ca•Na type (Fig. 11b). (3) With the increase of TDS, the concentration of cation Ca^{2+} and the concentration of anion SO_4^{2-} increased significantly and showed a good linear relationship. It indicates that the water-rock interaction in the Ordovician limestone groundwater is dominated by the dissolution of minerals containing Ca^{2+} and SO_4^{2-} ions (Fig. 12).

The change of salinity and ion content of karst geothermal water provides an important basis for studying the flow direction of geothermal water and the process of water rock interaction (Zhang, 1990; Li et al., 2009). Comparing the mineralization degree and water chemistry type of the karst water in the East and West Mountain Faults on the edge of the basin and the Xiwenzhuang geothermal field in the central part of the basin, it can be inferred that the geothermal water transport process of the karst geothermal system in the Taiyuan Basin is: The karst water in the exposed areas of the east and west mountains of the basin is recharge along the deep fault and the karst unconformity, it gradually migrates and accumulates to the Xiwenzhuang uplift in the middle of the basin, the water and rock interaction in the transport process is mainly the dissolution of carbonate rock and gypsum minerals. It reflects the change law of HCO_3→HCO_3+SO_4→SO_4 type from the recharge area to the basin confined zone (Hou, 2002).

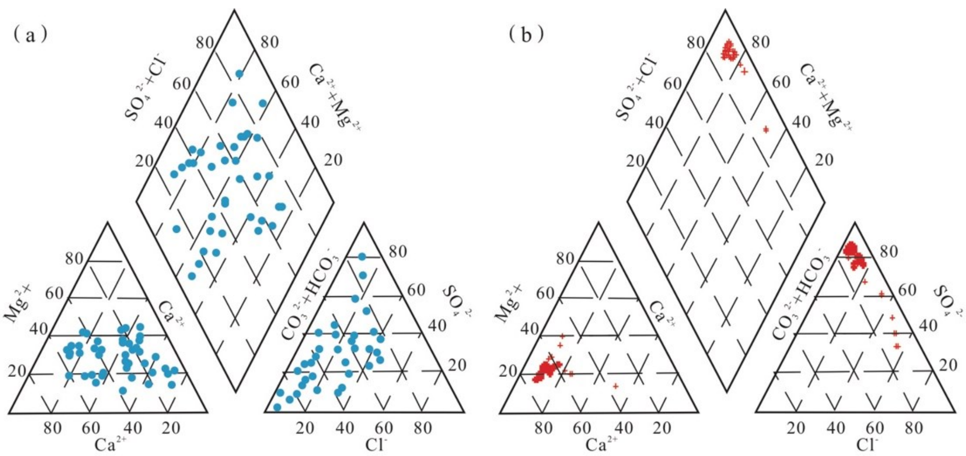

Figure 11: Piper diagram showing comparison of geothermal water between the edge of Taiyuan Basin (a) and Xiwenzhuang geothermal field (b).

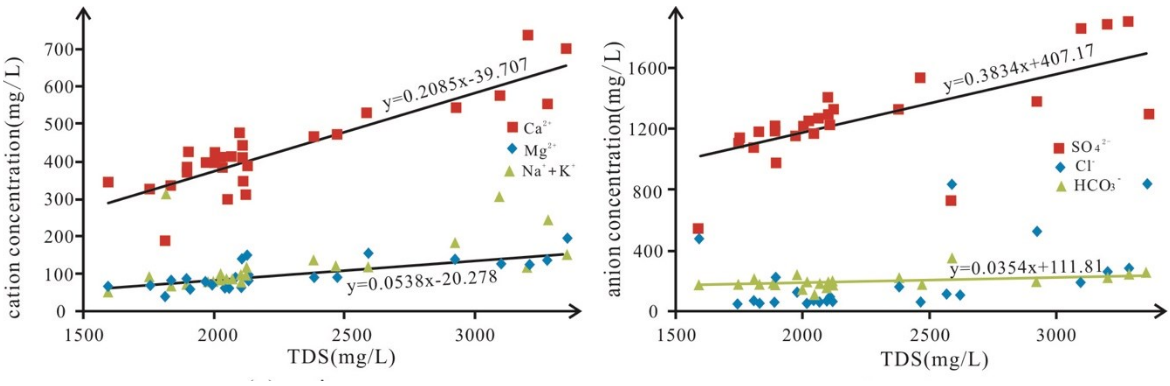

Figure 12: Relationship between ionic concentration and TDS in Ximenzhuang geothermal field, Taiyuan Basin.

3.3.3 ^{14}C age analysis

The ^{14}C age of geothermal water reflects the time when geothermal water is infiltrated from the recharge area, through deep circulation, runoff in the reservoir, and transported to the sub-structural belts of the basin. This paper synthesizes the ^{14}C dating results of previous predecessors (Ma, 2007; Li et al., 2006), and compiled a distribution map of the geothermal retention time in Taiyuan Basin (Fig. 13). On the whole, the retention age of geothermal water in Taiyuan Basin is obviously controlled by the structure of the basin, and it has the characteristics of short transport distance, fast recharge speed and younger retention age. The specific performances are as follows: (1) From the runoff of the east and west mountain recharge areas to the edge of the basin, the retention age of geothermal water is less than 500a, which is very fast for the distance of the runoff distance of 40 to 50km. For example, the ^{14}C relative age of karst geothermal water in the Jinci fault zone is 318a. (2) In the east and west of the Bianshan fault zone, an obvious age gradient zone is formed, with an age range of 500-1000a, reflecting the vertical movement of karst geothermal water along the edge of the basin and towards the deep basin. For example, the geothermal age of the TS_1 well is 978a. (3) The age of the fluid in the basin is about 2000 a, and the seepage velocity is relatively fast. (4) In the core section of the Xiwenzhuang uplift in the main confined area, the age of geothermal water retention is relatively old, exceeding 10 ka. Such as the ^{14}C age of Xiaodian area is 11330 a.

4. TRANSPORT MODEL OF KARST GEOTHERMAL SYSTEM

The thermal reservoir temperature in the northern part of Taiyuan Basin is less than 25 °C, the resource conditions cannot reach the requirements for development and utilization. Therefore, the study object of the karst geothermal system refers only to the Lower Paleozoic between the Sanji horst-Tianzhuang faults zones in the middle section of Taiyuan Basin. Through the above-mentioned research on reservoir performance, water recharge source, transport channel and heat transfer mode of karst geothermal reservoir, the transport model of karst geothermal system in Taiyuan Basin can be summarized as: Under the background of high geothermal flow in asymmetric rift basin, the meteoric precipitation recharge into the karst water system from the exposed areas of the karst in the East and West Mountain, gradually transport into the basin area along the karst unconformity surface and fault as the transport channel, and drain to deep basin through the basin deep fault, thus entering the hidden reservoirs in the basin. During the flow process, the karst water continuously absorbs the heat of the surrounding rock mass and gradually increases the temperature. The average temperature of the karst geothermal reservoir in the core of the Xiwenzhuang uplift zone can reach 65~75 °C. At the same time, the Upper Paleozoic-Mesozoic sand, shale and Cenozoic clay rocks in the basin provide a good thermal insulation cap for thermal water, forming a medium-low temperature conductive karst geothermal system that can be used for heating (Fig. 13). Part of the karst thermal water is blocked in front of the piedmont fault zone, moves upwards, and mixes with the shallow cold water to form a convective low temperature spring (such as Jinci Spring).

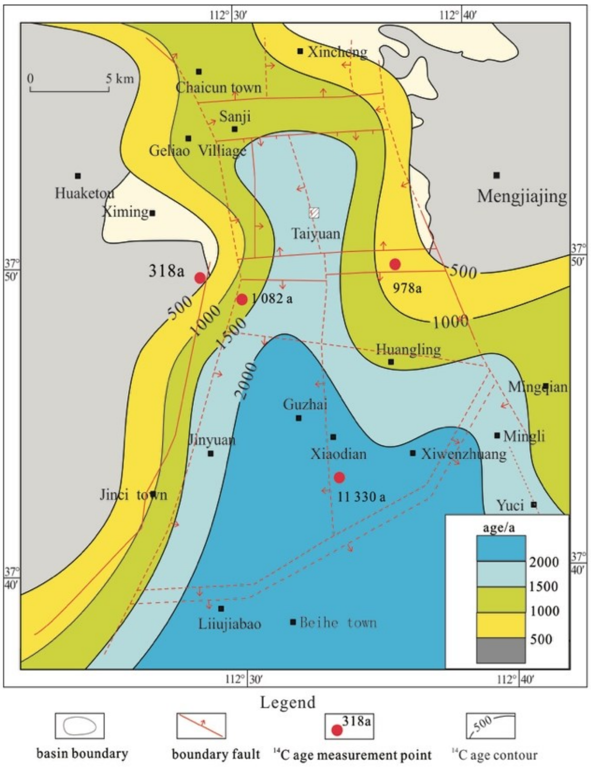

Figure 13: Distribution map of geothermal water retention time in Taiyuan Basin (ages in years).

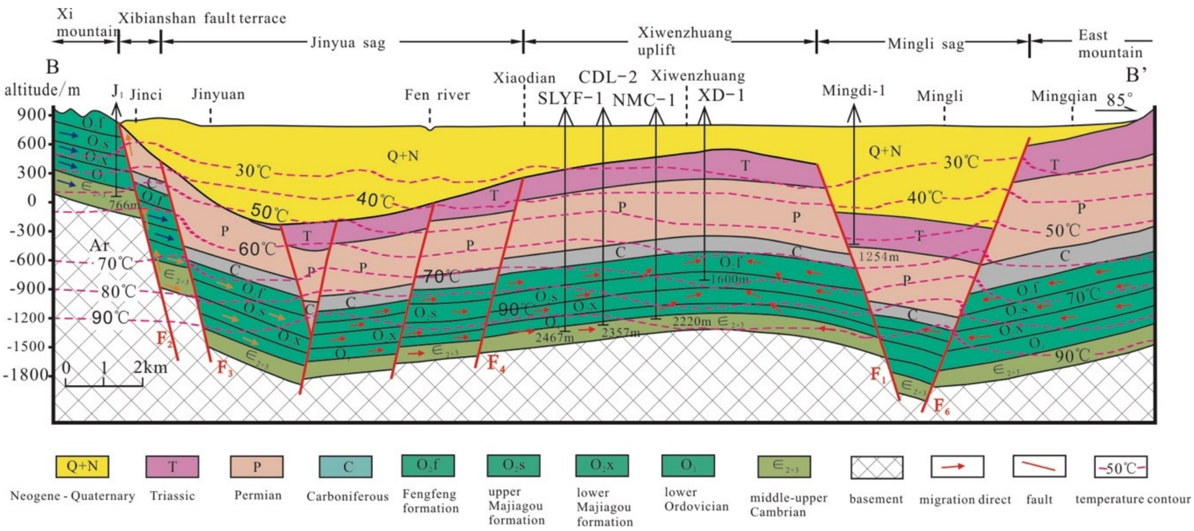

Figure 14: Geothermal water migration model map of karst geothermal system in Taiyuan Basin. ***F_1- Tianzhuang fault zone, F_2-Jinci fault, F_3-Nanyan fault, F_4- Fenhe fault, F_5-Mingqian fault, F_6-Dongbianshan fault***

5 EVALUATION OF GEOTHERMAL RESOURCES

The evaluation range of the geothermal resources of the karst geothermal system in Taiyuan Basin is Sanji Horst-Tianzhuang Fault Zone in the middle part of the basin. According to the division boundary of secondary structural units in the basin, it can be divided into eight units. From north to south, they are Urban Depression, Ximing Fault Terrace, Chengdong Fault Terrace, Qinxian Horst, Chengnan Uplift, Western Mountain Fault Terrace, Jinyuan Depression and Xiwenzhuang Uplift. The evaluated thermal reservoir is Ordovician.

5.1 Computational Formulas

The method of "thermal storage volume" is adopted in the evaluation. The calculation of "thermal storage volume method" includes two parts: the heat storage of rocks in thermal reservoir and the carrying heat of geothermal water. Its variable parameters are the evaluation area, effective thickness, porosity and thermal storage temperature of Ordovician karst geothermal reservoir, which can be determined by the research results mentioned above. Specific formulas are as follows:

$$Q = Ad\left[P_c C_c (1-\varphi) + P_w C_w \varphi\right](t_r - t_j) \tag{1}$$

where Q-geothermal resources, J; A-evaluation area, m^2; d-thermal reservoir thickness, m; t_r-thermal reservoir temperature, ℃; φ-rock porosity, %; t_j-reference temperature, ℃; P_c、P_w-densities of rock and water respectively, kg/m^3; C_c、C_w-specific heat capacity of rock and water respectively, J/(kg ℃).

5.2 Evaluation parameters of thermal storage

The accuracy of geothermal resource evaluation mainly depends on the reliability of the evaluation area, effective thickness, porosity and temperature of thermal reservoir. Among the eight secondary tectonic units to be evaluated in this paper, more than 60 geothermal wells have been drilled in the Xiwenzhuang uplift, so the evaluation of its resources is more accurate. The parameters of the other seven tectonic units may be estimated by comparison with those of the Xiwenzhuang uplift (Table 2). The specific steps are as follows:

(1) Evaluation area (A): The area of geothermal reservoir evaluation is the area of secondary tectonic units, that is, the area bounded by boundary faults of tectonic units. It can be calculated automatically by using the software of resource evaluation. For example, the area of Xiwenzhuang Uplift is 124.94 km^2.

(2) Geothermal reservoir effective thickness (d): In geothermal drilling and oil drilling logging data, the segments with porosity greater than 1.8% and permeability greater than 0.1mD are considered as effective aquifers. The sum of all aquifer sections is the effective thickness of karst geothermal reservoir revealed by the well. The average effective thickness of all geothermal wells can be a reliable evaluation parameter. The average effective thickness of 52 geothermal wells in Xiwenzhuang Uplift is 177.7 m. The average thickness of Ordovician strata is about 684 m, and the thickness ratio is 26.0%. As the initial sedimentary environment and karstification process of Ordovician in other tectonic units are basically similar, the average effective thickness of other evaluation units can be calculated according to the same thickness ratio. For example, the average thickness of residual strata in Jinyuan Depression is 673 m, and the effective thickness of aquifer is 175.0 m according to the same thickness ratio (Table 2).

(3) The average temperature of geothermal reservoir (t_r): This is a parameter most affected by the cold water in the supply area of geothermal water. The parameters of the eight evaluation units can be calculated by weighted average method of area according to the above-mentioned temperature distribution map of karst geothermal water (Fig. 5c). the average temperature of Xiwenzhuang uplift reservoir with the most abundant data is 68.8 C. Other calculation results are shown in Table 4.

(4) Porosity of geothermal reservoir: The average porosity of 52 geothermal wells in Xiwenzhuang uplift is 5.5%. Considering that the other seven tectonic units have the same tectonic evolution history and karstification process, the average porosity of other geothermal fields is 5.5%.

(5) Other parameters: The average annual temperature is 12.5℃, the density of geothermal water is 1000 kg/m^3, the density of rock is 2700 kg/m^3, the specific heat of water is 4180 J/ (kg. ℃), and the specific heat of rock is 920 J/ (kg. ℃).

5.3 Analysis of Evaluation Results

The karst geothermal system in Taiyuan Basin is calculated by eight evaluation units as shown in Table 4. The total amount of geothermal resources is 83.03×10^{8}GJ, which is equivalent to 2.83×10^{8}t of standard coal (29.3GJ of heat can be produced from 1t of standard coal). If the recovery rate of karst geothermal reservoir is 15%(GB/T 11615-2010), the recoverable resources of the karst geothermal system in Taiyuan Basin are 12.45×10^{8}GJ, equivalent to 4251.0×10^{4}t of standard coal. According to the calculation that the annual heat required for heating per square meter is equivalent to 0.0283 t standard coal, the heating area of the karst system can reach 15.02 million square meters. In view of the current built geothermal heating area of only 3 million square meters, there is a huge potential for resource development.

Table2: Summary of evaluation parameters and calculation results of geothermal resources for Ordovician in Taiyuan Basin.

Name of Evaluation Unit	Area of Evaluation Unit (km^2)	Average Effective Thickness (m)	Average Temperature (℃)	Average Porosity (%)	Geothermal Resources/10^{8}GJ	Resources Converted to Standard Coal/10^{8}t
Urban Depression	30.6	166.3	40	5.5	3.607	0.1231
Ximing Fault Terrace	43.77	158.8	37	5.5	4.389	0.1498
Chengdong Fault Terrace	65.19	160.0	43	5.5	8.199	0.2798
Qinxian Horst	10.68	162.5	38	5.5	1.141	0.0389
Chengnan Uplift	24.12	180.0	53	5.5	4.532	0.1547
Xibianshan Terrace	59.61	157.5	30	5.5	4.234	0.1445
Jinyuan Depression	128.92	175.0	55	5.5	24.712	0.8434
Xiwenzhuang Uplift	124.94	177.7	68.8	5.5	32.215	1.0995
Total	487.83				83.029	2.83

6. CONCLUSION

(1) The strata of karst thermal reservoir in Taiyuan Basin are mainly the Ordovician system of Lower Paleozoic, which is widely distributed in North China Plate. And the evolution of its karst geothermal system has gone through five stages, i.e. the epigenic karstification at the end of the early Paleozoic, the direct caprock deposition in the late Paleozoic, the initial formation of the karst geothermal system during Mesozoic, the transformation during Himalayan and the final setting during the Quaternary.

(2)The heat source of the karst geothermal system in Taiyuan Basin comes from the high terrestrial heat flow in asymmetric fault basin (> 1.7HFU). Influenced by the genetic mechanism of the intermountain fault depression basin, the heat transfer mode can be divided into two categories: strong convolution type and heat conduction type, which can be further divided into three sub-categories: the strong convolution type of recharge water supply in the weak area of basin margin caprock, the deep thermal convolution type of basin margin deep fault zone and the heat conduction type of layered thermal reservoir inside the basin.

(3) The residual thickness of Ordovician of geothermal reservoir is 600~750 m. Controlled by the geological structure of the basin with the western faulting and the eastern overlying, the burial depth of its top surface is larger in the west than that in the east, varies between 400~1900 m, and the temperature of the thermal reservoir is 30~75 ℃. The heterogeneity performance of geothermal reservoir is mainly controlled by the hidden structure in NE direction on the plane. In the longitudinal profile, the effective reservoir section of 15~ 20 layers with about 160 m cumulative thickness is identified, and it can be divided into 3~ 4 main water-bearing sections, where the main aquifer is prone to "overflowing" phenomenon in the process of migration.

(4) Controlled by the structure and geomorphology of the intermountain fault basin, the recharge-migration mode of the karst geothermal system in Taiyuan Basin has the characteristics of two-way, near-source and rapid. The migration distance of the karst water from the exposed Ordovician area to the basin pressure area is about 30 km, the migration time is about 2000 a. In the meantime, the type of hydrochemistry of geothermal water changes from HCO_3-Ca type to HCO_3-Ca•Mg type, then to SO_4-Ca type with the increase of their salinity (558~1199mg/L→1592~3279mg/L).

(5) The total geothermal resources of the karst geothermal system in Taiyuan Basin are estimated to be 8.303 billion GJ, which is equivalent to million tons of standard coal. The annual exploitation of geothermal resources can meet the heating area of 1502 million square meters with broad prospects for development.

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