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The Distribution Characteristics and Favorable Exploration Zones of Karst Reservoirs in the Beijing-Tianjin-Hebei Plain

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ABSTRACT

The main part of the Beijing-Tianjin-Hebei Plain is located in the Jizhong Depression and the Cangxian Uplift of the Bohai Bay Basin, and is the main area for the development and utilization of the medium-to-deep geothermal energy in China. However, very few study has been done on plane distributions and forming mechanisms of the karst geothermal reservoirs in this area. In this paper, based on drilling data and seismic interpretations, a comprehensive analysis of the basin tectonic evolution and karst reservoir forming mechanism of the basin was carried out. The results show that the karst geothermal reservoirs that developed in the Wumishan Group of the Jixian System and the Ordovician System are the two main geothermal reservoirs in the Beijing-Tianjin-Hebei Plain area. Controlled by different denudation degrees from the Indosinian to Yanshanian periods, the plane distribution of the geothermal reservoir age is characterized by segmentation from south to north inside the Jizhong Depression, and zoning from east to west in the whole area. In the Jizhong Depression, main geothermal reservoirs are the Wumishan group and the Middle Ordovician in the middle and south parts respectively, and there areresidual Cambrian - lower Ordovician locally existing in the north part. The lithology of the Wumishan group is mainly composed of tidal-flat facies polycyclic deposited stromatolites with siliceous band dolomite, while the Ordovician system is mainly composed of leopard limestones, grainstones and micrites which were deposited during four third-level sea level eustacies. There had been four phases of karstification that determined the formation of karst reservoirs, the Caledonian, the Indosinian, the Yanshanian and the Himalayan periods. Two main types (epigenetic and buried) with six hypotypes of Karstifications are recognized. As a result, the reservoir space can be divided into three types: pores, caverns and fractures, which can be further divided into 9 subcategories. The karst geothermal reservoirs are characterized with multi-layer reservoirs, large effective thickness, good porosity and permeability conditions, and large geothermal water volume. Both the central basal bulge of the Jizhong Depression and the Cangxian Uplift are favorable karst zones and have relatively shallow-buried karst reservoirs. Therefore, they are the most favorable exploration zones for karst reservoirs in the Beijing-Tianjin-Hebei Plain area. The existed geothermal resource exploration results have confirmed that the geothermal resource conditions of the central basal bulge of the Jizhong Depression and the Cangxian Uplift are superior, with 55 to 110°C wellhead water temperature and 80 to 120m^3/h water volume. They are the potential areas for forming medium to large geothermal fields.

1. INTRODUCTION

As a kind of pollution-free energy, geothermal energy plays an important role in alleviating the pressure of energy supply and improving the ecological environment (Bahadori et al. 2013). At present, China has initially formed an integrated development and utilization system of geothermal resources (Zhao and Wan, 2014).

The Beijing-Tianjin-Hebei Plain is the main area for the development and utilization of medium-to-deep geothermal energy in China. According to incomplete statistics, by the end of 2017, geothermal energy space heating area had reached 75 million square meters. There are two types of geothermal reservoirs in this area: the sandstone thermal reservoirs (the Guantao Group of the Neogene), and the karst thermal reservoirs (the Middle and Upper Proterozoic and the Lower Paleozoic). Karst thermal reservoirs have become the favorable targets for geothermal resource development and utilization due to the advantages of large water volume, low salinity, easy recharge, and small environmental impact. Currently, four karst thermal reservoirs have been revealed (Table 1): the Ordovician Majiagou Group (such as in Tianjin) and the Mujunshan to Zhangxia groups of the Cambrian System (such as in Gucheng and Xinji, and the geothermal water is combined with the Ordovician water), the Wumishan Group of the Jixian System (such as in Xiongxian, Xianxian, etc.; Nindre et al. 2011), and the Gaoyuzhuang Group of the Changcheng System (such as in Rongcheng, and is a mixed production with the Wumishan Group water). These karst thermal reservoirs are mainly concentrated in the central basal bulge of the Jizhong Depression, Cangxian Uplift and places where the buried depth is relatively shallow (Fig. 1). The buried depth of the top surface of the karst reservoirs is 1,500-2,500m, the wellhead temperature is 55-90°C, and the water volume is 80-120m^3/h. According to the latest geothermal energy exploration, steam-water mixtures with 100°C wellhead temperature and above 100m^3/h water volume have been found under 4,000m within reservoirs of the Jixian Wumishan Group in Gaoyang, Boye and Nanmeng town of Bazhou. These exploration results show that the development and utilization of karst thermal reservoirs in the Beijing-Tianjin-Hebei Plain area has a broad prospect.

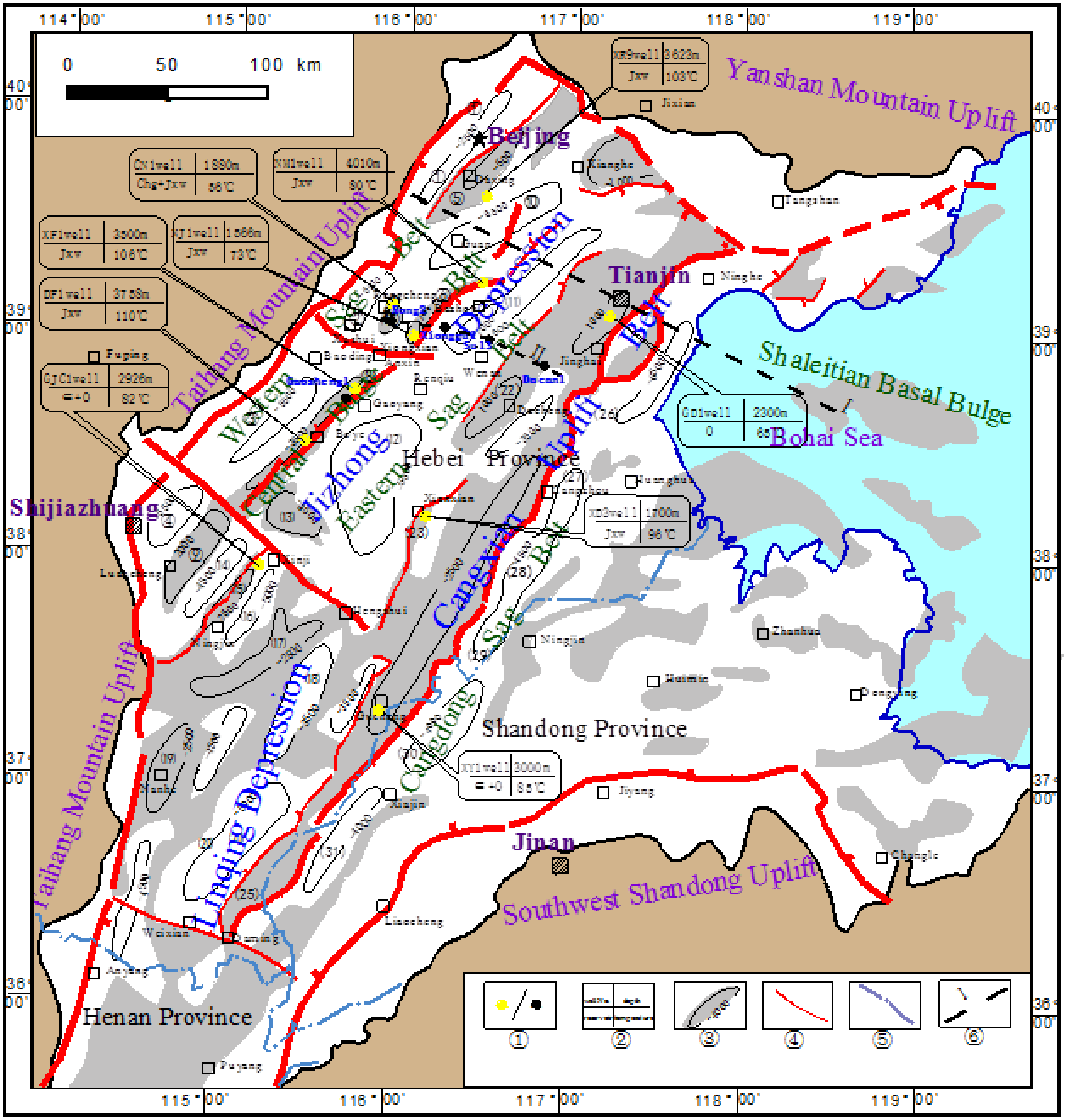


Figure 1. The exploration results of karst thermal reservoirs and tectonic map of the Beijing-Tianjin-Hebei Plain

Legends: (1) geothermal(yellow color point) and oil (black color point) wells, (2) geothermal well parameters, (3) buried-hills and buried contours of bedrocks, (4) faults, (5) provinces boundaries, (6) position of the profile. Tectonic Units: (1)Beijing sag; (2)Xushui sag; (3)Baoding sag; (4)Shijiazhuang sag; (5)Daxing basal bulge; (6)Niutuozhen basal bulge; (7)Rongcheng basal bulge; (8)Gaoyang low basal bulge; (9)Wuji-Gaocheng basal bulge; (10)Langgu sag; (11)Baxian sag; (12)Raoyang sag; (13)Liucun basal bulge; (14)Jinxian sag; (15)Ningjin basal bulge; (16)Shulu sag; (17)Xinhe basal bulge; (18)Nangong sag; (19)Jize basal bulge; (20)Qiuxian sag; (21)Shuangyao basal bulge; (22)Dacheng basal bulge; (23)Xianxian basal bulge; (24)Minghuazhen basal bulge; (25)Guantao basal bulge; (26)Banqiao sag; (27)Cangdong sag; (28)Nanpi sag; (29)Wuqiao sag; (30)Dezhou sag; (31)Guanxian sag.

The main areas of the Beijing-Tianjin-Hebei Plain are the Jizhong Depression and the Cangxian Uplift which are two secondary tectonic units of the Bohai Bay Basin. The Bohai Bay Basin is a large-scale Mesozoic-Cenozoic fault basin that developed on the foundation of shallow sea carbonate platform sedimentary environment that formed during the middle-late Proterozoic and Early Paleozoic, and through strong compression during the Indosinian and Yanshanian period (Zhang et al. 2001; Qiao et al. 2002; Dong et al. 2013). The Beijing-Tianjin-Hebei Plain show the characteristics of zoning from east to west, segmentation from south to north (Wu et al. 2007; Yang, 2009; Lao et al. 2010). In the deepest area of the fault depression, the thickness of the Cenozoic Layer exceeds 8,000m. Geothermal resource systems are different from the closed, static and irreversible systems of oil and gas resource, they are open, flowing and renewable systems. The production layers of oil and gas systems are generally less than 10 meters, much thinner than the geothermal ones which are usually 500 to 800 meters. Previous study of carbonate reservoirs in this area were mainly concentrated on local buried-hill hydrocarbon reservoirs at places such as Renqiu and Qianmiqiao (Wu et al. 2007; Wu et al. 2010; Wu et al. 2015; Li and Sun, 2015). It was believed that the reservoir type belongs to the karst weathering crust type (Carbonate rock can be divided into 4 types: marginal biohermal type, karst weathering crust type, dolomite type and grain beach type) and is mainly composed of buried-hill karst reservoirs that was formed during the Himalayas rifting (Zhao et al. 2007; Luo et al. 2008; Jiao et al. 2009). However, studies on geothermal resources in the Beijing-Tianjin-Hebei Plain are still rare, especially on the distribution law of the karst, the karstification stage as well as the target of karst thermal reservoirs' distribution and key controlling factors (Zhou et al. 1989; Yan and Yu, 2000). Based on the drilling and seismic data, this paper used the stratigraphic stripping method to recover the different denudation degrees in different tectonic zones before the Cenozoic deposition, in order to research the distribution laws of karst thermal reservoirs and the types of reservoir space. Under the study of tectonic evolution (Liu et al. 1999; Liu et al. 1997), sedimentary and diagenesis, the stage and the type of karstification will be understood. On the basis of above study, the favorable karst facies zone and the physical property of reservoirs will be checked out, and the favorable exploration targets will be selected by the different Cenozoic buried depths.

Table1. Statistics of geothermal wells that drilled in karst thermal reservoirs in the Beijing-Tianjin-Hebei plain

Typical well	County	Structural Location	Depth (m)	Reservoirs	Depth of top surface(m)	Wellhead Temperature(°C)	Volume (m^3/h)	Geothermal gradient (℃/100m)
XR9	Daxing	South slope of the Daxing Bulge	3,350-3,620	Jxw	3,000-3,200	103-117	80-100	3.43
NJ1	Xiongxian	Southern part of the Niutuozhen Bulge	1,300-2,000	Jxw	700-1,200	65-80	100-130	4.62
NM1	Bazhou	Northern part of the Niutuozhen Bulge	3,260-4,050	Jxw	2,500-3,300	110-114	90-120	4.50
GD1	Tianjin	Shuangyao Bulge	2,000-2,200	O	1,200-1,500	60-70	80-120	3.78
CN1	Rongcheng	Rongcheng Bulge	1,200-2,000	Chg+Jxw	500-1,000	45-60	80-130	4.13
XD3	Xianxian	Xianxian Bulge	1,800-2,100	Jxw	1,200-1,500	75-90	80-90	3.89
XY1	Gucheng	Cangxian Uplift	3,000-3,600	∈+O	2,100-2,700	59-80	74-140	3.51
GJC1	Xinji	Shulu Depression	2,800-3,200	∈+O	2,200-2,500	72-86	72-101	2.98
XF1	Gaoyang	Gaoyang Low Bulge	3,500-3,700	Jxw	3,200-3,400	100-106	50-70	3.12
DF1	Boye	Gaoyang Low Bulge	3,600-3,760	Jxw	3,300-3,500	110-114	71-100	3.32

2. THE PLANE DISTRIBUTION OF GEOTHERMAL RESERVOIRS

Karst thermal reservoirs in the Beijing-Tianjin-Hebei Plain are mainly developed within the Middle-Upper Proterozoic and the Lower Paleozoic strata, and are mainly composed of North China platform type carbonate rocks with an original thickness of approximately 5,000m. The overlying strata are the coal-bearing marine-terrigenous Upper-Paleozoic formations that were deposited in the Carboniferous-Permian period, with a thickness of 300-800 m. Under the multiple tectonic movements, especially the strong compression and uplift during the Indosinian and Yanshanian period, different tectonic belts went through different denudation, thus the carbonate rocks in the second and third order of tectonic unit in different basins have big differences in strata, thickness and elevation. It can be seen from the east-west evolution profile (Fig. 2) that the compression deformation during the Indosinian and Yanshanian periods was strong in the west and weak in the east. The Jizhong depression was the highest point during the Indosinian and Yanshan periods and went through strong denudation and the strata were eroded to the Jixian System. The stripped strata included the Carboniferous, Permian, Cambrian, Ordovician, and upper part of the Middle-Upper Proterozoic strata, with a thickness of at least 3,000m. While in the Himalayan period, due to the strong fault depression, the bedrock of the Jizhong Depression was deeply buried into the lower part of the structure. In contrast, the tectonic movement was relatively weak in the Cangxian Uplift during the Indosinian and Yanshanian periods, and mainly formed moderate folds. The denudation rate of anticline of Paleo Cangzhou-Tianjin complex syncline was relatively strong, and the middle Ordovician system was denuded, with a denudation thickness of about 1,000m. While in the faulted-depressed period of early Himalayan, the rotation and tilt caused by large tensional faults such as the Dacheng Fault and Cangdong Fault resulted in the collapse of Cangzhou-Tianjin complex syncline. The rising plate of the normal fault (the Cangdong fault) was further uplifted and denuded, with Jixian System exposed at some structural high points. During the Himalayan Depression period, the rising plate buried shallow and was at the structural high point relatively, which formed the Cangxian uplift. However, the downthrown side of the Cangdong Fault continued to decline during the Himalayan period, and the carbonate reservoirs were buried deep, forming the Cangdong Depression belt (including the Huanghua Depression).

Based on previous study (Yan and Yu, 2000), combined with relevant oil drilling and seismic interpretation data, the plane distribution map of karst reservoirs in the Beijing-Tianjin-Hebei Plain is compiled (Figure 3). It can be seen from the figure that: (1) Due to the difference of denudation degree, the karst reservoirs showed the characteristics of old in the western part and new in the eastern part while old in the middle part and new in the Southern and Northern part, which was correlated with the Northeast distribution of basin which is zoning in East-West direction and subdistricting in North-South direction in the plain. Among them, the middle part of the Jizhong Depression was denuded strongest and Wumishan Group of Jixian System was exposed while the denudation rate was relatively week in the Northern and Southern part, Cambrian to lower Ordovician system and middle Ordovician system was exposed respectively. In the same way, the eastern part of the Cangxian Uplift was denuded strongly, and the Wumishan Group within the Jixian System was exposed while the denudation rate was relatively week in the eastern and western part, with the Lower Paleozoic strata still existed. (2) With the exception of the Gaoyuzhuang Formation of Changcheng System and the Cambrian strata was exposed, in most areas, the Wumishan Group and the Ordovician System are the main karst reservoirs in study areas. The Wumishan Group of Jixian System reservoirs are mainly distributed in the northern part of the Xinji-Hengshui line of the Beijing-Tianjin-Hebei Plain. The Ordovician System reservoirs are the most widely distributed weathering crust reservoirs in the study area. Except for the central and northern parts of the Jizhong Depression and the northeast-trending structural belt in the eastern part of the Cangxian Uplift, the Ordovician System reservoirs are widely distributed in the southern part of the Jizhong Depression and Cangxian Uplift and they are almost the only reservoir system in the southern part of the Xinji-Hengshui area.

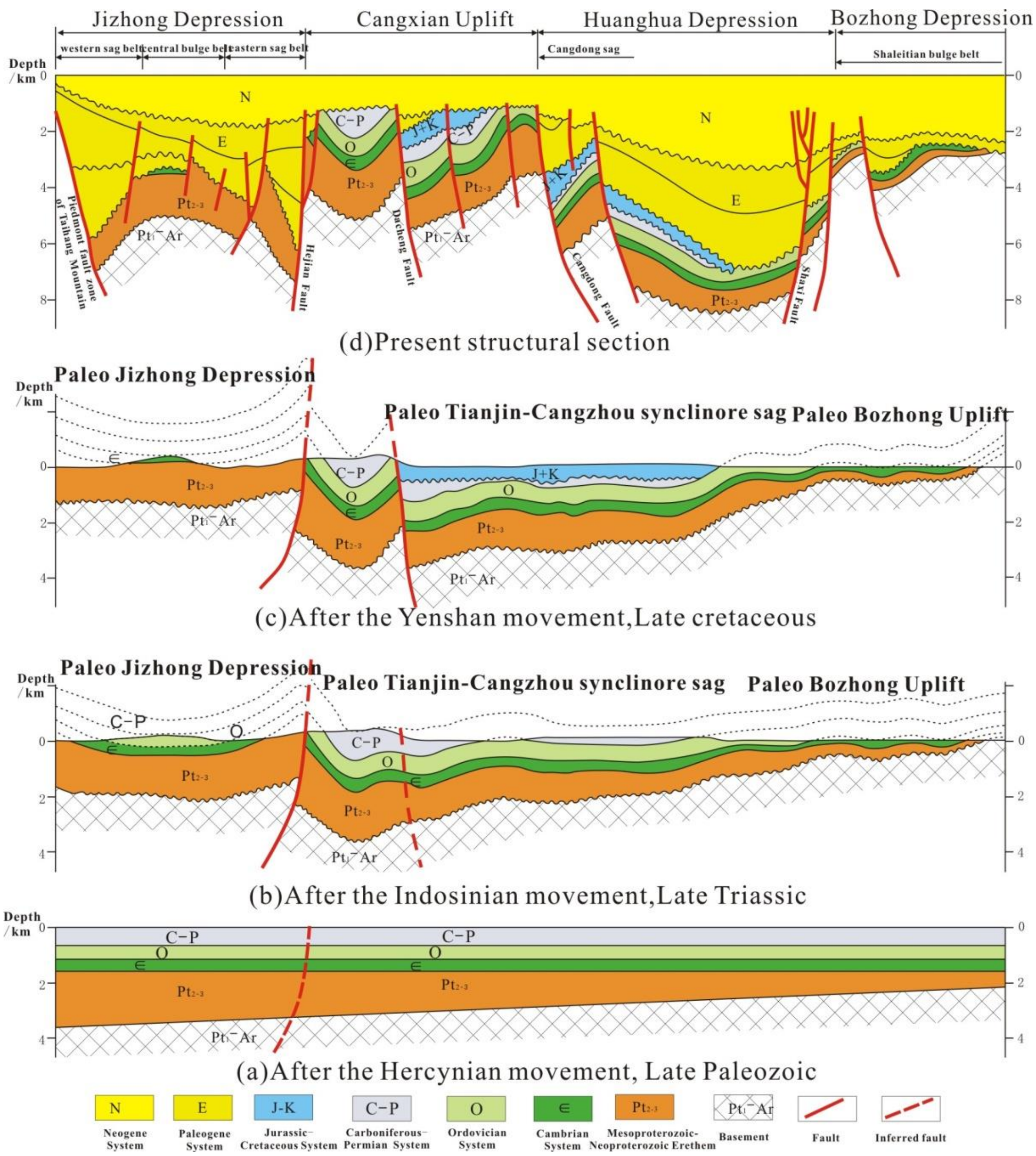


Figure 2. The Geological profile and its inversion profile of the Beijing-Tianjin-Hebei Plain in the East-West direction (the location of the profile can be seen in Fig.1)

3. THE CHARACTERISTICS OF RESERVOIR LITHOLOGY

Reservoirs in the Wumishan Group of Jixian System is mainly composed of various dolomite rocks, including stromatolite dolomite, algal dolomite, grain dolomite, mud crystalline dolomite, and silicified stromatolite dolomite, etc. Among them, stromatolite dolomite has various types, including lamellar, wavy, pyramidal, columnar, and spherical stromatolites, etc. The lithofacies palaeogeography was high in the southern part and low in the northern part, and the depositional environment was changed from the supralittoral zone, upper part of intertidal zone where dolomite and algal deposit in the Southern part of Cangzhou to lower part of intertidal zone and upper part of subtidal zone where reef deposit and lower part of subtidal zone where dolomite deposit in the north. The residual thickness of strata varies greatly, and the thickness has an increasing trend from south to north. For example, the thickness of Wumishan Group revealed by Gaoshen No.1 Well which locates in the middle of Gaoyang Low basal bulge is 1,262.5m. Compared with the 3,416m revealed on the standard section (which has 4 depositional cycles) of the Jixian System in Tianjin, the result shows that the fourth part or more parts of Jixian System were eroded strongly (Mei et al. 1999; Zhou et al. 2006).

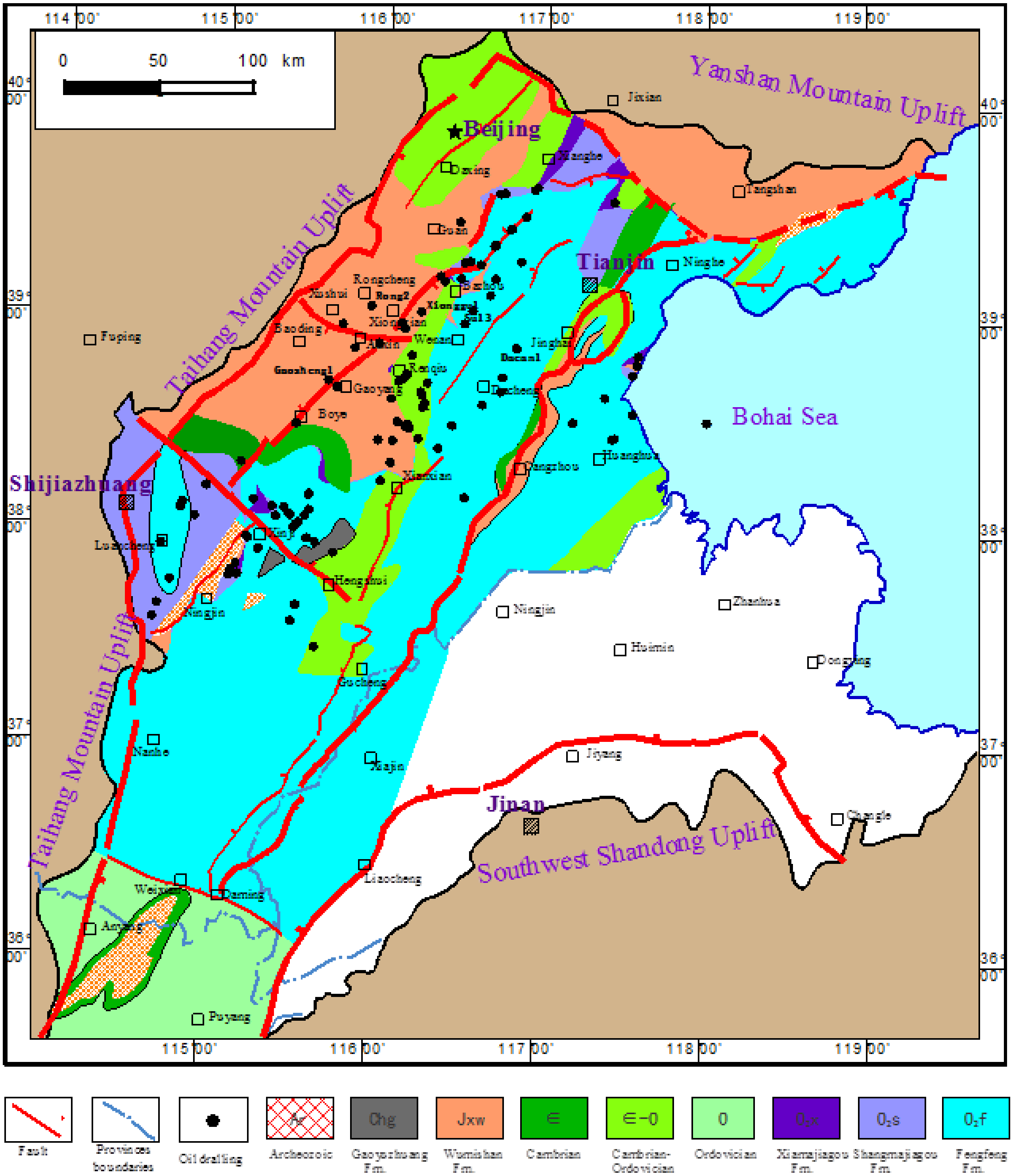


Figure 3. The distribution map of karst reservoir strata in the Beijing-Tianjin-Hebei Plain

The lithology of Ordovician reservoirs is dominated by limestone which was controlled by four third-order sea level fluctuations. The sea level fluctuation in early-Ordovician: Yeli Group was characterized by a huge thick layer of leopard-like limestone and mudstone limestone which deposited in the low-energy environment of supralittoral zone and intertidal zone. The Liangjiashan Group is characterized by medium-thick layer of chert tuberculosis limestone with some edgewise limestone which developed in the open sea environment of the subtidal zone. The three third-order sea level fluctuations in the Middle and Late Ordovician corresponded to the deposition of the lower Majiagou Group, the Upper Majiagou Group, and the Fengfeng Group, respectively. Each stage experienced the process from the transgression (from the evaporation dolomitic plateau to supralittoral zone to subtidal zone) to regression and lithology are grain limestone, mud crystalline limestone, with some gypsum dolomite (Liu et al. 1997; Liu et al. 1999; Zhao et al. 2016). The residual thickness of Ordovician system is 200-800m, and the upper part of the Upper-Ordovician Fengfeng Group was the main eroded stratum.

4. KARSTIFICATION AND KARST FACIES

4.1 Types of Karstification

Combining the diagenesis process and evolution model of karst reservoirs (Figure 4) of the Proterozoic and Ordovician strata in the study area, two types of karstification can be identified in the Beijing-Tianjin-Hebei Plain: weathering crust type karst and buried type karst (Qian et al. 2007).

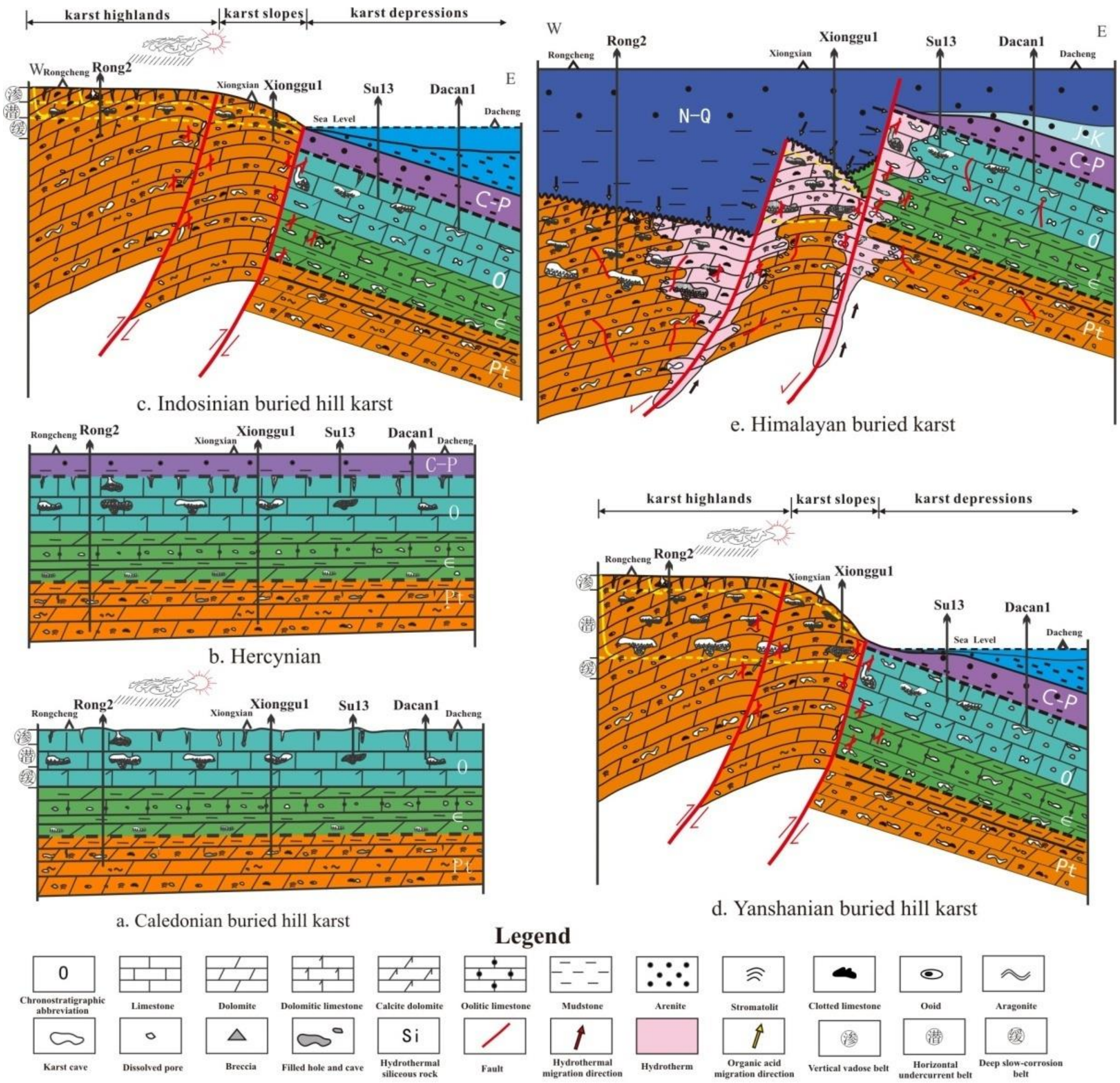


Figure 4. The evolution model of karst reservoirs in the Beijing-Tianjin-Hebei Plain

The weathering crust type karst was mainly controlled by paleo-geomorphology which was the result of tectonic movements. This type of karst can develop in various carbonate rocks and is non-selective. According to the dissolution status of parent rock, weathering crust type karst can be divided into four types: intra-layer karst, buried-hill karst, faulted karst, and bedded karst. Combining with the mechanical properties of tectonic movement, weathering crust type karst can be classified into 3 deformation patterns: stable uplift pattern, compression uplift pattern, and extensional fault block pattern. The background of interlayer karst was a relatively flat paleo-geomorphology formed by the overall uplifting movement, which include the Qinyu, Jixian and Caledonian movements. The strata that develop interlayer karst include the Tieling Group within the Upper Jixian System, the Jingeryu Group within the Upper Qingbaikou System, and the Middle Ordovician System. The karst caverns and solution pores are mainly developed along the layers (Figure 4a). The buried-hill karst was developed on paleo-geomorphology differences which formed by compression or extension. Among them, compression uplift type buried-hill karst mainly developed in the Indosinian and Yanshanian period (Fig. 4c-d), while the extensional fault block type buried-hill mainly developed in the early Himalayan period (Fig. 4e). Both type of buried-hill karst show the characteristics of lateral zoning and vertical layering. Laterally, the buried-hill karst can be divided into three karst facies: karst highlands, karst slopes, and karst depressions, while vertically it can be divided into: vertical vadose belts, horizontal underflow belts and deep corrosion belts. Vertical vadose belts and horizontal underflow belts are the main intervals that developing karst reservoirs. The vertical solution fissures, solution grooves and ponors are mainly developed in vertical vadose belts while large bedded caverns are mainly developed in horizontal underflow belts. Faulted karst reservoirs are developed on the faults that formed during compressional or extensional periods and the formed caverns are distributed along the faults. Bedded karst is associated with the fault karst, which means that the meteoric freshwater is not only infiltrates along the fault, but also flows to the hidden high-porosity and high-permeability rock formations through the fault and form bedded distribution caverns (Fig. 4e).

The buried-type karst can be divided into 2 types: the hydrothermal dissolution type in the late Cretaceous and the organic acid dissolution type in the late Paleogene. The developing area of buried-type karst are limited and mainly controlled by fault migration. The dissolution happens along the existing caverns and fractures (Fig. 4e). The organic acid dissolution is mainly developed in oil and gas distribution areas, where due to exist of oil and gas are not good reservoirs for geothermal water. However, in the late stage of oil field development, organic acid dissolution provides spaces for geothermal water. The hydrothermal dissolution has a constructive effect for reservoirs due to the hydrothermal activity is widely distributed and the newly added hydrothermal dissolution pores can provide space for geothermal water.

4.2 The phases of karstification

The above analysis shows that the physical properties of the Jixian Wumishan Group and the Ordovician System depend on four phases of karstification, namely, the overall uplift in the Caledonian period when the interlayer karst developed, the compressional uplift in the Indosinian and Yanshanian periods when buried-hill type karst developed, and in the Himalayan period when fault-related buried-type karst developed (Fig. 4). The Ordovician karst reservoirs developed in the Caledonian period, strengthened in the Indosinian and Yanshanian periods, and reformed in the Himalayan period; while the Wumishan karst reservoirs formed in the Indosinian period, strengthened in the Yanshanian period, and adjusted in the Yanshanian Period. In comparison, the development of Wumishan Group karst reservoirs was later than that of the Ordovician reservoirs. However, in the Indosinian and Yanshanian periods, the overlying strata of the Wumishan Group were eroded much heavier than that of the Ordovician System, and were uplifted much higher, which resulted in deep degree of karstification and more effective thickness.

4.3 Karst facies

In this paper, under the constraints of tectonic evolution and strata denudation degree (Figure 2), sedimentary analysis, residual thickness method, and balanced section technology were used to restore the karst paleo-geomorphology in different periods of the study area and tried to analyze the distribution law of karst facies (Figure 5). The main features are:

(1) The karst paleo-geomorphology of the late Caledonian (namely, the top of the Pre-Carboniferous system) was affected by the overall uplift of the earth's crust. The topographic relief was small and the fault system was not developed. The overall performance was a karst platform, with high micro-topography in local areas. Places like Beijing, Gu'an, Xinji, Gucheng, Cangzhou West, Huanghua, Nanpu, etc.

(2) During the Indosinian period (namely, the top of the Pre-Jurassic system), the karst paleo-geomorphology was controlled by compression deformation, and also showed the characteristics of Northeast distribution and uprising adjacent downfalling. It shows that: In the northwestern part of the study area, like Langfang, Guan, Bazhou, Renqiu, and West of Raoyang area, karst highlands were developed; Places like Tianjin, Cangzhou, Tangshan and Xinji are where the karst sub-highlands developed; Areas like Baodi, Wuqing, Laoting, from Raoyang south to Hengshui, and Gucheng are where the karst slopes were developed. The karst basins are mainly developed in places where northeast distribution and weakly deformed like central part of Beijing, southern Wuqing, Luancheng, southern Hengshui to Weixian, and Congdong area, etc (Figure 5).

(3) The karst paleo-geomorphology of the Yanshanian period (namely, the top of the Pre-Tertiary) inherited the karst paleo-geomorphology of the Indosinian period, and only changed locally. For example, Baoding was a karst highland in the Indosinian period, however, during Yanshanian period, it evolved into a karst basin due to the movement of the Gaoyang fault and mainly deposited the Jurassic-Cretaceous system. Due to the differential subsidence, Baodi, Wuqing, Nanpu, and Laoting areas evolved from the karst slopes in the Indosinian period to the karst basins in the Yanshanian period, mainly accepted the deposit of Jurassic-Cretaceous strata.

From the above analysis, it is known that the areas in the central and northern parts of the Jizhong Depression, like Langfang, Guan, Bazhou, Renqiu, and West Raoyang, and the east part of the Cangxian Uplift like the east of Tianjin, Cangzhou are the places where karst highlands of the Indosinian Period superposed with karst slopes of the Yanshanian Period. Thus, they are the most favorable karst facies in the study area.

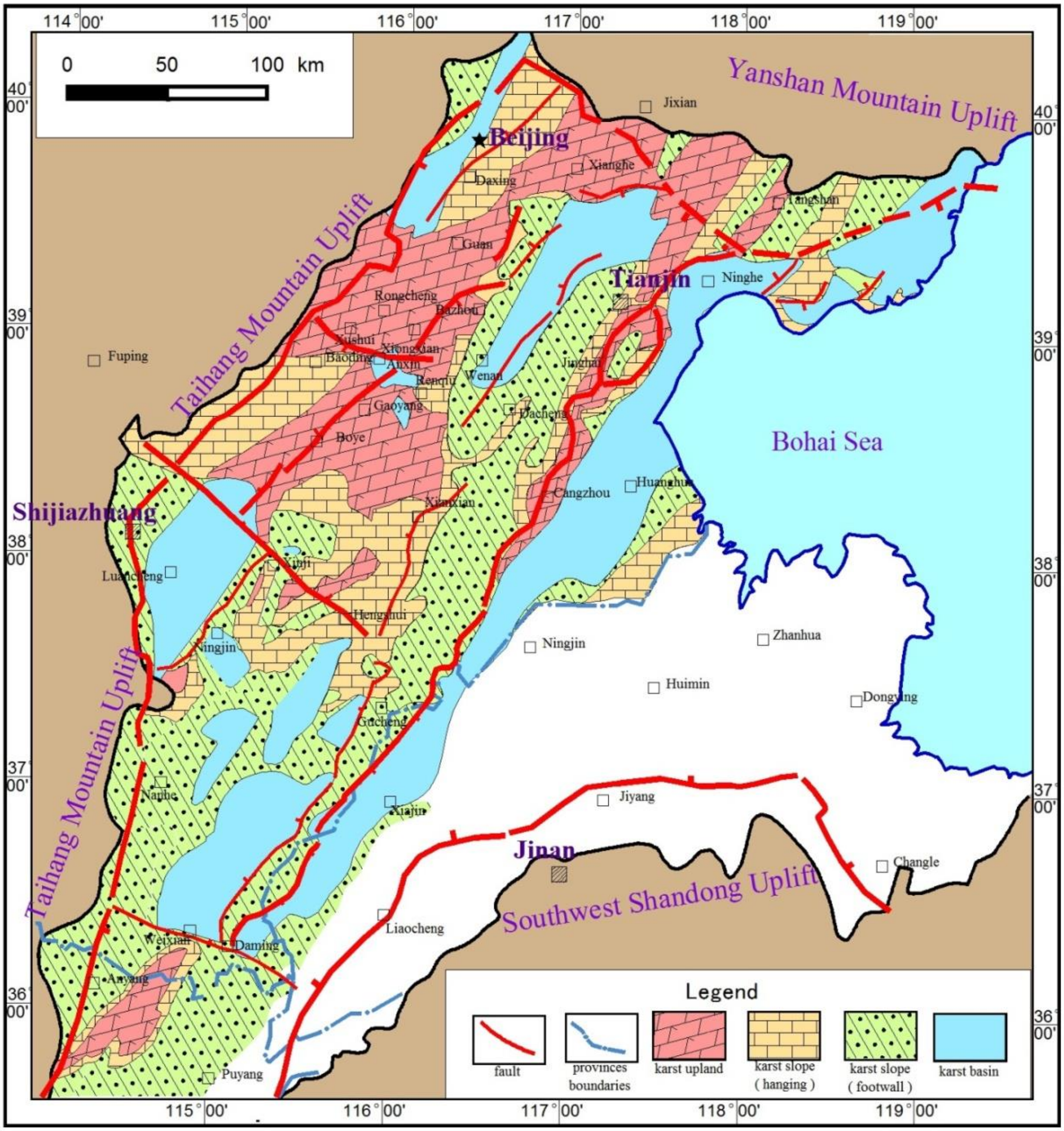


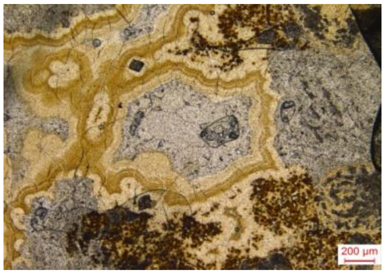
Figure 5. The distribution of karst facies in Beijing-Tianjin-Hebei Plain during the Indosinian toYanshanian period

5. RESERVOIR CHARACTERISTICS

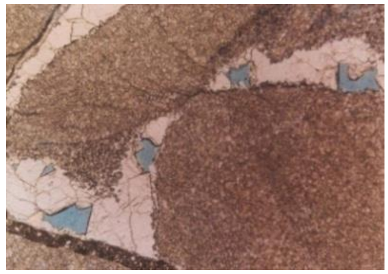
5.1 Reservoir space type

According to the core and microscopic observations, the space type of the karst reservoirs in the study area can be classified into three types: pores, caverns and fractures, which can be further divided into 9 subcategories(Figure 6).

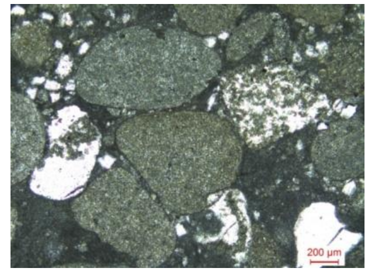
Pores: Pores mainly includes algae frame pores, intergranular pores, dissolved pores in grains (mould pores), and inter-crystalline pores (inter-crystalline dissolved pores). Algae frame pores and intergranular pores are primary pores. Algae frame pores are common in algal clot dolomite and stromatolite dolomite (Fig. 6A). Intergranular pores are mainly found in grain dolomite (Fig. 6B), with various particle types, including gravel, algae, nucleus, cerebella and bio-fragment, and the porosity can reach up to 20% to 30%. The dissolved pores in grains (mould pores) and inter-crystalline pores (inter-crystalline dissolved pores) are secondary pores. The dissolved pores in grains (mould pores) are mainly developed in grain dolomite (limestone) and clot dolomite. The dissolved pores in grains are pores eroded in grains while mould pores formed when particles were completely eroded, leaving only the appearance of grains (Figure 6C). The inter-crystalline pores (inter-crystalline dissolved pores) are widely developed in dolomite crystalline. They exist in euhedral or subhedral fine crystalline dolomite and microcrystalline dolomite during the dolomitization process, mainly show as inter-crystalline dissolved pores (Figure 6D).



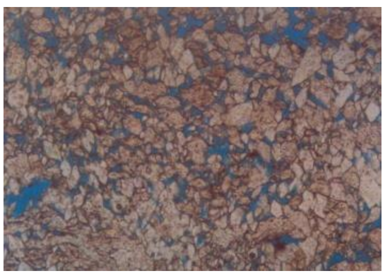
A. Jixxian field section, Wumishan Fm, algae- clot fine dolomite, algae-skeleton pore



B. Ren 266 well, Wumishan Fm , sand-clastic dolomite, intergranular pore was half filled by quartz and fluorite



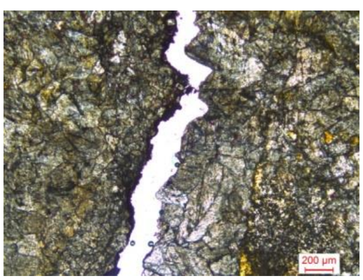
C. Jixxian field section, Wumishan Fm, sand-clastic dolomite, dissolved intra-grain pore and moldic pore



D. Chang 3 well, Wumishan Fm, dolomite intercrystal pores and solution pore

E. Beijing Zhuanghuwa field section, Wumishan Fm, cone stromatolite dolomite, karst pore

F. Renshen 2X well, Wumishan Fm , karst cave was filled by breccias with karst pore



G. Jixxian field section , Wumishan Fm, fine-crystal dolostone, tecetnic dissolution fracture

H. Ren 813 well , Xiamajiagou, inter crystalline fracture in a calcite vein inside muddy dolomite

I. Ren 813 well , Xiamajiagou , argillaceous half filled stylolite in shaly dolomite

Figure6. The space types of karst reservoirs in the Beijing-Tianjin-Hebei Plain

Caverns: Caverns mainly refers to dissolution holes and dissolution caves. Dissolution holes developed in various lithologies, and usually bedded distribution. The size and shape of dissolution holes are often related to the composition and structure of strata. The dissolution pores that developed in grain dolomite, algal clot dolomite, and stromatolite dolomite are related with the grain size, shape, and stromatolite morphology (Figure 6E). The shape of the caverns are usually long strip or irregularly round, with different sizes. The diameter of the largest cavern can reach several tens of meters. Most of the caverns are half filled with collapsed breccia, terrigenous clastic, calcite and dolomite, etc. (Figure 6F). According to the field observations, caverns are mostly developed in the middle and upper parts of the Wumishan Group, the upper and lower parts of the Majiagou Group, and the upper and lower parts of the Fengfeng Formation. Caverns are formed from the dissolution of cracks and developed along layers, with bead distribution.

Fractures: Fractures can be divided into 3 types: structural (dissolution) fractures, inter-crystalline fractures and stylolites. Structural (dissolution) fractures are formed under tectonic stress, and are along or perpendicular to the layer’s strike. 4 to 5 sets of fractures with different occurrence can be found in field. In the initial stage, structural fractures are straight, smooth, and uniform, however, after dissolution, the dissolution fractures are irregular and the fracture width changes greatly (Fig. 6G). The fracture width is generally 0.2 ~ 3mm, and the maximum can up to 5mm. Inter-crystalline fractures are commonly found in the mud-sized crystalline dolomite of the Lower Majiagou Group and microcrystalline dolomite and fine crystalline dolomite in the middle and upper parts of the Wumishan Group. Microscopically, inter-crystalline fractures show reticulate, dendritic, polylineous and usually filled by dolomite and calcite. They have features of fine cracks, good connectivity, and large plane porosity (Fig. 6H). Stylolites are mostly found in muddy dolomite and dolomite with mud, and can be found in all layers, with polygonal distribution and along layers. Stylolites are usually filled with mud or dark matter, thus, their contribution to reservoir space are limited. (Figure 6I).

5.2 Reservoir Properties

5.2.1 Wumishan Group of Jixian System

The properties of karst reservoirs of the Wumishan Group are good, with high porosity and permeability. The geothermal wells are characterized with high water temperature and large water volume, which can meet the resource conditions for space heating. Take the BZC5 well in Xiongxian as an example, which is located at the southern part of the Niutuozhen Basal Bulge. The well was completed in 2016 with a well depth of 1,810m and the water intake section was 1,005 to 1,810m. The wellhead water temperature was 65° C and the water volume was 114m3 / h. After heat exchange, it can meet the heating demand of 83,000 m2. In the water intake section, 17 layers of aquifers can be identified and the effective reservoir thickness can reach 207.9m (Table 2). The lithology was mainly medium-fine crystalline dolomite and breciated dolomite. The porosity was 1.4% to 6.7%, with an average of 3.55% while the permeability was 0.1 to 1.16mD, with an average of 0.65mD.

Table 2 The logging interpretation results of BZC5 well in Xiongxian

No.	Beginning Depth(m)	Termination Depth(m)	Thicknes s(m)	Specific Resistance(Ω·m)	Interval Transit Time(us/m)	Porosity (%)	Permeability ($10^{-3}um^2$)	Grade of the Fracture Layer
1	1,060.7	1,069.6	8.9	163.22	188.46	5.05	0.35	Secondary
2	1,069.6	1,099	29.4	216.77	184.7	3.67	0.13	Third class
3	1,195.7	1,215.1	19.4	248.07	182.03	3.75	0.24	First-class
4	1,221.4	1,238.9	17.5	344.66	175.34	1.4	0.1	Third class
5	1,258.9	1,268.6	9.7	352.48	174.55	1.64	0.1	Third class
6	1,313.6	1,317.3	3.7	314.79	177.56	1.79	0.1	Third class
7	1,445.6	1,469.1	23.5	291.28	178.87	2.86	0.11	Third class
8	1,492.4	1,496.5	4.1	319.61	176.47	2	0.96	Secondary
9	1,514.8	1,544.4	29.6	319.6	209.94	7.8	7.43	Secondary
10	1,552.4	1,560.8	8.4	181.77	187.14	4.69	0.34	First-class
11	1,563.1	1,570.4	7.3	274.11	180.01	3.42	0.14	Secondary
12	1,594.9	1,600.8	5.9	234.28	183.05	4.05	0.15	Secondary
13	1,610.1	1,613.2	3.1	200.52	185.93	4.01	0.15	Secondary
14	1,670.4	1,681.4	11	251.8	181.62	3.86	0.18	First-class
15	1,702.4	1,706	3.6	224.69	187.93	4.44	0.22	First-class
16	1,716.5	1,723.5	7	267.17	183.36	4.06	0.22	First-class
17	1,768	1,783.8	15.8	431.77	173.31	1.82	0.11	Third class

At the meantime, 235 porosity data and 230 permeability data of karst reservoirs of the Wumishan Group of the Jixian system were analyzed in this paper (Figure 7). The results showed that the porosity was mostly within 6.0%, accounting for 85.9%, of which porosity from 1 to 6% accounts for 61.3%. The maximum porosity was 22.4% while the average porosity was 3.39%. The distribution range of permeability was relatively large, ranging from 0.01 to 1,000mD. The permeability between 0.01 to 100 mD was more common, accounting for 87.8%. The maximum permeability was 4,419mD while the average permeability was 82.38mD.

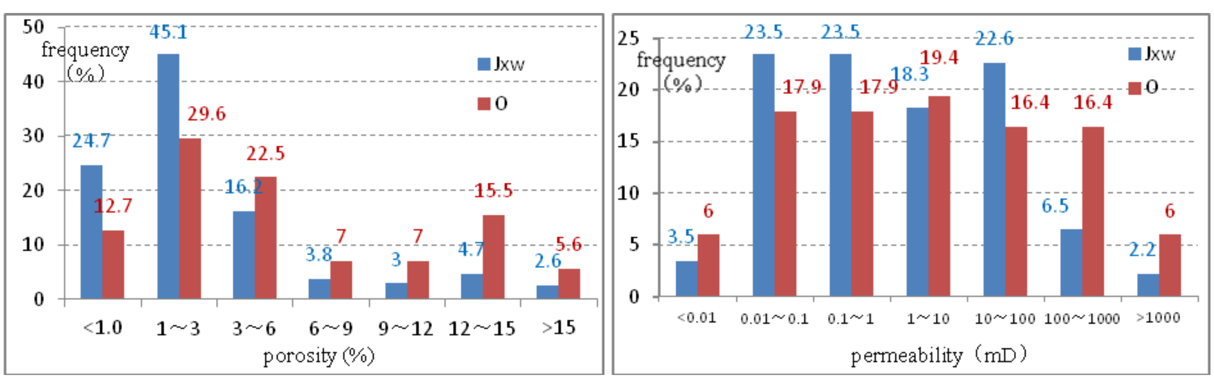


Figure7. The statistical analysis of physical properties of karst reservoirs of the Jixian Wumishan group and the Ordovician System in the Beijing-Tianjin-Hebei Plain

5.2.2 Ordovician System

The Ordovician karst reservoirs also have good physical properties, and also belong to high-porosity and high-permeability reservoirs. They have similar geothermal resource conditions to the Wumishan karst reservoirs. Take the XY1 well in Gucheng as an example, which is located at the Wucheng Basal Bulge (Southern of the Cangxian Uplift). The well was completed in 2014 with a well depth of 3,000m, and the water intake section was 2,096 to 3,000m. The wellhead water temperature was 85°C, and the water volume was 74m3 ／h. The XY1 well can meet the heating demand of 90,000 m2. In the water intake section, 11 layers of aquifers can be identified and the effective reservoir thickness can reach 142m (Table 3). The lithology was mainly mud crystalline limestone and intra-clastic limestone. The porosity was 1.3% to 10.9%, with an average of 4.46%. The permeability was 0.14 to 36.32mD, with an average of 6.52mD.

Table 3 The logging interpretation results of XY1 well in Gucheng

No.	Beginning Depth(m)	Termination Depth(m)	Thickness(m)	Specific Resistance(Ω·m)	Interval Transit Time(us/m)	Porosity(%)	Permeability ($10^{-3}um^2$)	Grade of the Fracture Layer
1	2,202.8	2,212.7	9.9	446.42	168.83	2.17	2.47	Third class
2	2,238.7	2,261.7	23	259.72	191	5.68	11.98	Third class
3	2,297.4	2,306.5	9.1	414.28	171.47	2.16	0.14	Third class
4	2,319.2	2,333.7	14.5	442.72	181.78	4.36	5.89	Third class
5	2,358.2	2,363.7	5.5	339.23	170.98	2.96	1.86	Third class
6	2,473.2	2,490.2	17	318.38	176.74	3.48	0.98	Third class
7	2,641.2	2,647.4	6.2	158.07	227.7	10.96	36.32	Secondary
8	2,665.4	2,674.4	9	711.94	168.15	1.3	0.14	Third class
9	2,761.1	2,781.4	20.3	527.62	185.72	3.63	1.28	Third class
10	2,820.4	2,825.6	5.2	198.96	211.43	7.8	8.5	Secondary
11	2,839.9	2,862.2	22.3	278.55	196.01	4.63	2.16	Secondary

Similarly, 71 porosity data and 67 permeability data of karst reservoirs of the Ordovician system were analyzed in this paper. The results showed (Figure 7) that the porosity of the reservoirs was mainly distributed within 6.0%, accounting for 64.8%. In some local areas (favorable karst facies), the porosity was between 12 and 15%, accounting for 15.5%. The maximum porosity can up to 24.5%, and the average porosity was 6.04%. The distribution range of permeability was relatively large, ranging from 0.01 to 1,000mD, accounting for 88%. The maximum permeability was up to 4,916mD, while the average permeability was 256.04mD.

6. THE FAVORABLE EXPLORATION ZONES

The favorable exploration zones of karst reservoirs in the Beijing-Tianjin-Hebei Plain are mainly determined by two factors (Wang, 2015): One is the favorable karst facies during paleokarst (Figure 5), and the other is to have a relatively shallow buried depth (Figure 1). The former refers to places where karst highlands superimposed with karst slopes during the Indosinian and Yanshanian periods, and the latter refers to zones where the buried depth of the top of karst reservoirs are less than 3,500m after the fault depression in the Himalayan Period and structural elevation adjustment. According to this principle, the central basal bulge of the Jizhong Depression and the Cangxian Uplift are two favorable exploration zones (Figure 8).

The central basal bulge of the Jizhong Depression: The central basal bulge of Jizhong Depression went through intense compression deformation during the Indosinian and Yanshanian periods, especially the middle section, where were karst highlands. The middle section was strongly eroded and highly uplifted, with the middle-lower layer of the Wumishan Group exposed. The accumulated denudation thickness reached 4,000m. The karst highlands of middle section gradually transited to the karst slopes northwards and southwards and the exposed strata transited from Cambrian to Ordovician. During the extensional background of Himalayan, the structural elevation adjusted. The buried depth of the top of karst reservoirs in the northern, middle, and southern of the central basal bulge of the Jizhong Depression were 1,000–1,500 m, 3,000–3,500 m, and 2,000–2,500 m, respectively; while the buried depth of the top of karst reservoirs in the western and the eastern parts were more than 5,000m.

The Cangxian Uplift: Karst sub-highlands were developed within the Cangxian Uplift during the intense compressional deformation stage in the Indosinian and Yanshanian periods, with the upper layer of the Wumishan Group exposed in local places. The accumulated denudation thickness was about 2,000m. The karst sub-highlands of the Cangxian Uplift gradually transited to the karst slopes southwards and westwards and the exposed strata transited from Cambrian to Ordovician. During the extensional background of Himalayan, the structural elevation adjusted. The buried depth of the top of karst reservoirs of Cangxian Uplift was 1,000–2,500m while the buried depth of the top of karst reservoirs of Cangdong Depression was more than 4,000m.

In short, the central basal bulge of the Jizhong Depression and Cangxian Uplift are both favorable karst facies and the karst reservoirs have a relatively shallow buried depth. Therefore, they are the most favorable exploration zones for karst reservoirs in the Beijing-Tianjin-Hebei Plain. The existed geothermal resource exploration results have confirmed that the geothermal resource conditions of the central basal bulge of the Jizhong depression and Cangxian uplift are superior, with 55 to 110°C wellhead water temperature and 80 to $120m^3/h$ water volume. They have the potential to form medium to large geothermal fields.

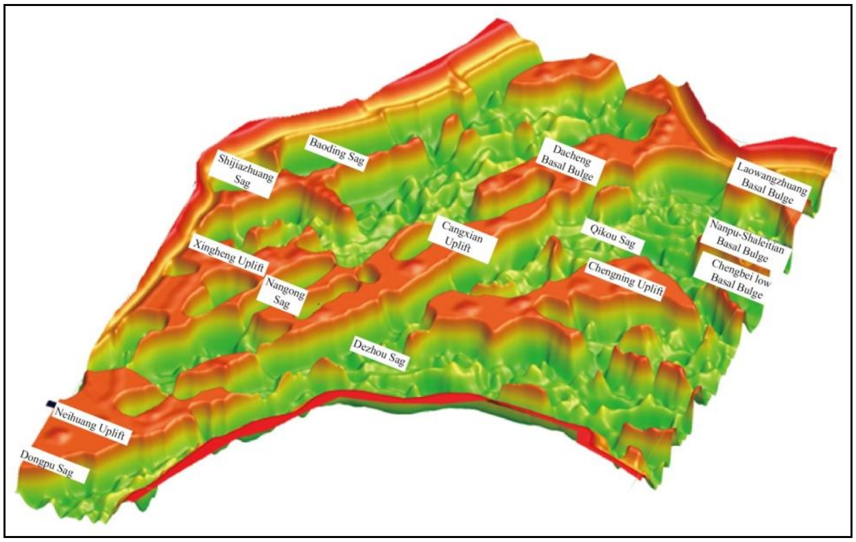


Figure8 Three-dimensional geological model of the karst geothermal reservoirs in Beijing-Tianjin-Hebei Plain

7. CONCLUSIONS

(1) Both the Wumishan Group of the Jixian System and the Ordovician System are the two main strata that developing karst reservoirs in the study area. Controlled by different denudation degrees from the Indosinian to Yanshanian periods, the plane distribution of the geothermal reservoir age is characterized by segmentation from south to north inside the Jizhong Depression, and zoning from east to west in the whole area. The age of the exposed stratum gets younger from the Jizhong Depression in the west to the Cangxian Uplift in the east. The Jizhong Depression has the highest denudation degree, the exposed strata are respectively the Wumishan Group in the centrel part, the Cambrian - lower Ordovician in the north part and the Middle Ordovician in the south part. Different residual strata in the secondary and third level structures determined the exploration target layers.

(2) The lithology of the Wumishan group is mainly composed of tidal-flat facies polycyclic deposited stromatolites with siliceous band dolomite, with a thickest total Original deposit thickness of more than 3,000 meters. The Ordovician system is mainly composed of leopard limestones, grainstones and micrites deposited during four third-level sea level eustacies, with the original deposit thickness of 600-800 meters. There had been four phases of karstification that determined the formation of karst reservoirs, the Caledonian, the Indosinian, the Yanshanian and the Himalayan periods. Two main types (epigenetic and buried) with six hypotypes of karstifications are recognized. The central and northern parts of the Jizhong Depression and the eastern part of the Cangxian Uplift are the superimposed areas of favorable karst facies belts in the geological time and have the most favorable karst geothermal reservoirs now.

(3) Pore spaces of karst geothermal reservoirs in the Wumishan Group of the Jixian System and in the Ordovician system can be classified into 3 types: pores, caverns and fractures, which can be further divided into 9 subcategories. The karst geothermal reservoirs are characterized with multiple reservoir intervals, large effective thickness, good porosity and permeability conditions, and large geothermal water volume.

(4)The central basal bulge of the Jizhong Depression and the Cangxian Uplift are both favorable karst facies and the karst reservoirs have a relatively shallow buried depth. Therefore, they are the most favorable exploration zones for karst reservoirs in the Beijing-Tianjin-Hebei Plain.

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