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# Study on the geothermal reservoir of Cambrian-Ordovician carbonate rocks in the north of North China Plain and its significance

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## ABSTRACT

Since geothermal resources are clean, renewable, and have substantial reserves, they are crucial for China to accomplish the "Double Carbon" target. Beijing, Tianjin, Hebei, Henan, Shandong, Jiangsu, Anhui, and other provinces and cities that are part of the North China Plain have developed economies, dense populations, and high energy demands. The North China Plain region has three primary groups of geothermal reservoirs: Tertiary sandstone, Cambrian-Ordovician, and Jixian System Wumishan. The Cambrian-Ordovician geothermal reservoir is the least utilized due to its complicated distribution and significant drilling risk. The degree of exploitation of each group of formation carbonate rocks varies greatly. This research of the Cambrian-Ordovician geothermal reservoir is based on the practice of geothermal development and use in the Wuji-Gaocheng region. The research demonstrates that in the North China Plain, the favorable target areas for the Cambrian-Ordovician carbonate are primarily distributed in the secondary uplift and slope areas of the depressional area; the effective geothermal reservoir is primarily developed in the lower plate of the fracture and the tectonic high part; the geothermal gradient is controlled by the uplift and the deep fault cutting through the basement; The enormous fracture in front of the mountain is used to convey the atmospheric precipitation-recharged geothermal water to converge in the tectonic high region of the carbonate geothermal reservoirs.

In order to effectively reduce drilling risks and maximize resource production, it is important to analyze the distribution range, burial depth, reservoir thickness, and water temperature of the three sets of geothermal reservoirs in the North China Plain area. The development of the Cambrian-Ordovician carbonate geothermal reservoirs should be prioritized, while the other sets of geothermal reserves should be taken into consideration.

## 1. INTRODUCTION

The North China Plain area extends from Yan Mountain in the north to Huai River in the south, Taihang Mountains in the west, and the Bohai Sea and the Yellow Sea in the east, with a total area of about 300,000 square kilometers, geographically spanning seven provinces and cities, including Beijing, Tianjin, Hebei, Shandong, Henan, Suzhou, and Anhui. The North China Plain is a Cenozoic fault zone on the North China Platform, and its bedrock is dominated by Paleozoic Carboniferous, Permian, Mesozoic Jurassic, and Cretaceous strata, with local distribution of Lower Paleozoic metamorphic systems and Paleozoic Cambrian and Ordovician strata, and the bedrock is covered by huge thick Tertiary and Quaternary accumulations (Zhao et al., 2002; Lei et al., 2018; Ma et al., 1990).

Tertiary sandstones and dolomitic carbonates of the Jixian System Wumishan Formation constitute the majority of North China's geothermal reservoirs (Ma et al., 1990; Wang et al., 2021; Wang et al., 2020). The Tertiary sandstone, which is deeply buried and has a large thickness, contains a greater quantity of water at elevated temperatures. This set of geothermal reserves is widely dispersed and has the highest utilization rate, but as the geothermal field mining time is extended, the reservoir's reinjection capability becomes increasingly difficult. In general, the Jixian System Wumishan Group carbonate bedrock geothermal reserve is deeply buried and heterogeneous. The interior water has a higher temperature and a constant volume. The reservoir is simple to reinject, but drilling is expensive. Numerous successful applications of this geothermal reservoir have been documented.

The Cambrian-Ordovician carbonates in the North China plain region are developed primarily in areas of regional uplift and depression (Wang et al., 2021; Wang et al., 2020; Zhang et al., 2008; Wang et al., 2021; Sui et al., 2020) (Figure 1. Distribution map of favorable Cambrian-Ordovician carbonate geothermal reservoir areas) This geothermal reservoir has a complex distribution, large thickness variations, and strong inhomogeneity, and its development and utilization are minimal. In 2019, the geothermal resource development in the Shijiazhuang Wuji-Gaocheng area with the Jixian System Wumishan Formation also considers the development of Cambrian-Ordovician geothermal reserves. Four geothermal wells have been successfully implemented, achieving a breakthrough in the geothermal exploration of Cambrian carbonate rocks in the Hebei plain area.

The development practice in the Wuji-Gaocheng region demonstrates that the Cambrian-Ordovician geothermal reserve in the North China Plain is governed by tectonic location, degree of weathering erosion, and fracture development. This geothermal reservoir carries a high development risk, but once a breakthrough is made, it has substantial development value. We should expand the study of the Cambrian-Ordovician geothermal reservoir in this region, identify favorable target areas, and consider developing this

geothermal reservoir system when the Tertiary sandstone and dolomite of the Wumishan Group are the primary development strata.

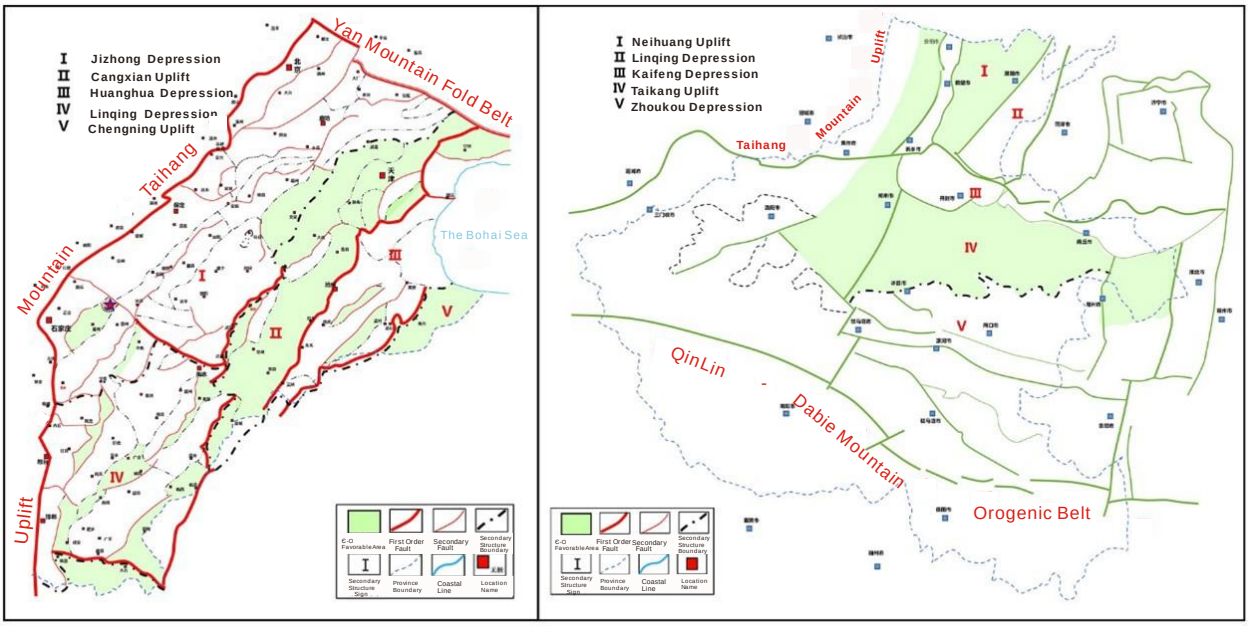


**Figure 1: Distribution map of favorable Cambrian-Ordovician carbonate geothermal reservoir areas (The left is the Hebei Plain area; The right is the South of North China Plain area)**

## 2. THE SECONDARY UPLIFT AND SLOPE AREA WITH CAMBRIAN-ORDOVICIAN STRATA DEVELOPED IN THE DEPRESSION, WITH MODERATE BURIAL DEPTH, GOOD COVER, AND SATISFYING THICKNESS CONDITIONS, IS A POTENTIAL TARGET AREA FOR CAMBRIAN-ORDOVICIAN GEOTHERMAL RESERVOIR DEVELOPMENT.

Secondary tectonic units include Shijiazhuang Depression, Wuji-Gaocheng Bulge, and Jinxian Depression, which is adjacent to Taihang Mountains Uplift in the west and southwest, bordered by Baoding Depression in the north, and separated from Ningjin Uplift by the Ningjin Fault in the east and southeast. Drilling and seismic data indicate that, prior to the Mesozoic, the basement morphology of the Shijiazhuang and Baoding depression was high in the north and low in the south, and that the Paleozoic was devoid of vegetation from south to north. The Jixian System Wumishan Formation is commonly developed in the Wuji-Gaocheng low Uplift, and the overlying Cenozoic boundary is over 800-1300m deep, thickening from south to north. The Paleozoic strata are eroded and extinguished from south to north, with the C-P remnant located south of the Gaocheng tectonic zone, the Ordovician remnant in the south-central region, and the Cambrian stratigraphic acute-extinction line near the Wuji tectonic zone. In the southern portion of the Baoding depression, the Cambrian is absent, and the Lower Tertiary directly overlies the Middle and Upper Paleozoic (Zhao et al., 2002; Sui, 2020). (Figure 2. Structure Map of the Shijiazhuang-Wuji Area; Figure 3. Geological profile through the Wuji-Gaocheng Low Uplift in the NNE direction)

From the perspective of strata distribution and burial depth, the Jixian System Wumishan Formation in the Wuji structure zone is a potential target for geothermal reservoir development; the exploitation of Cambrian-Ordovician strata is at risk due to denudation and thinning of bedrock, but as long as it is distributed, it is favorable targets for geothermal reservoir even if its thickness is not large.

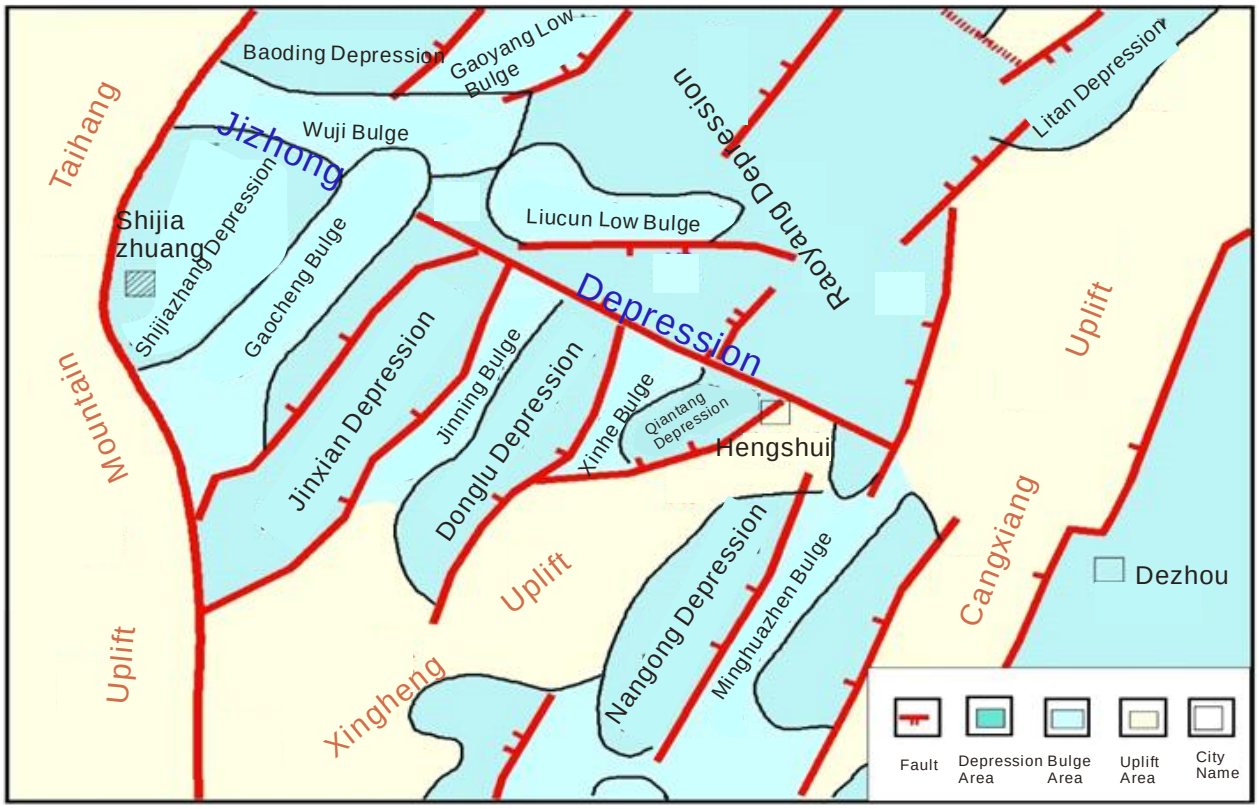


**Figure 2: Structure Map of Shijiazhuang-Wuji Area**

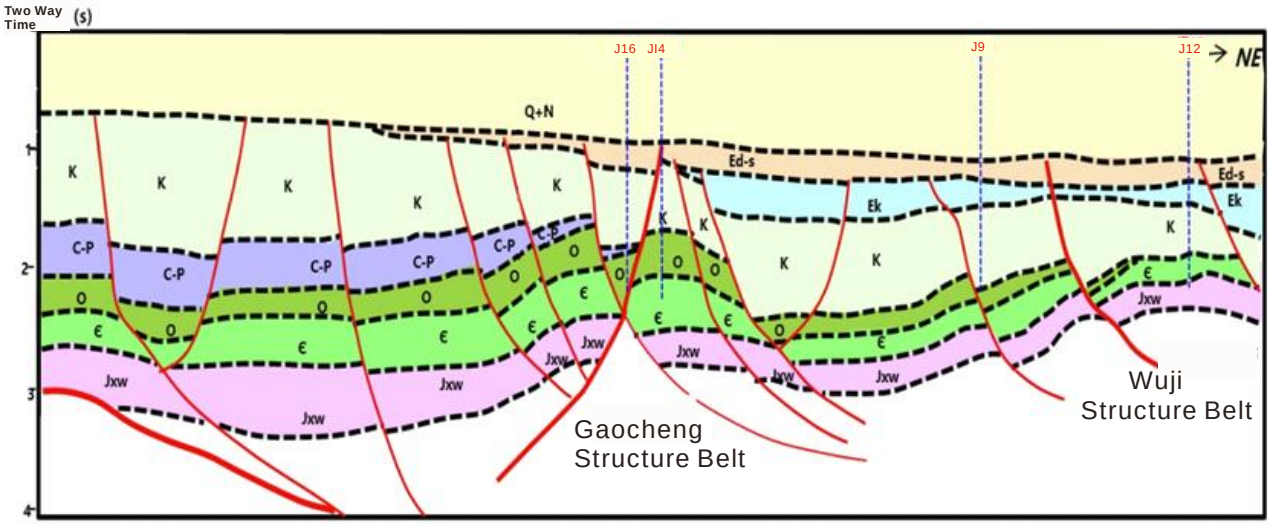


**Figure 3: Geological profile through Wuji-Gaocheng Low Uplift in the NNE direction**

**3. WITHIN THE POTENTIAL TARGET AREA, THE CAMBRIAN-ORDOVICIAN (INCLUDING THE JIXIAN SYSTEM WUMISHAN FORMATION) FAVORABLE TARGET AREA IS THE TECTONIC HIGH PART, FRACTURE RISING BLOCK, THE STRATUM SUFFERS FROM LONG-TERM WEATHERING AND STRIPPING, THE CARBONATE ROCK DEVELOPS PORES, CAVES, FISSURES SHOWED GOOD PHYSICAL PROPERTIES.**

In a region where carbonate geothermal reservoirs have been developed, the favorable tectonic location and drilling target area are situated. In the high part of the Wuji tectonic zone (see Figure 4. pre-Mesozoic tectonic map of the target area), the lower plate (rising plate) of the Wuji fault is missing the Carboniferous-Permian and Ordovician systems, and based on the analysis of the logging data of the J12 well, the main storage space of the Cambrian dolomite thermal reservoir in this area fractures, with uneven fracture development in the vertical. Microfracture is developed in the Jixian System Wumishan Formation, which portends good physical properties of the weathered crust (Shen et al., 2014) (see Figure 5, the results of the comprehensive interpretation of well logging of J12).

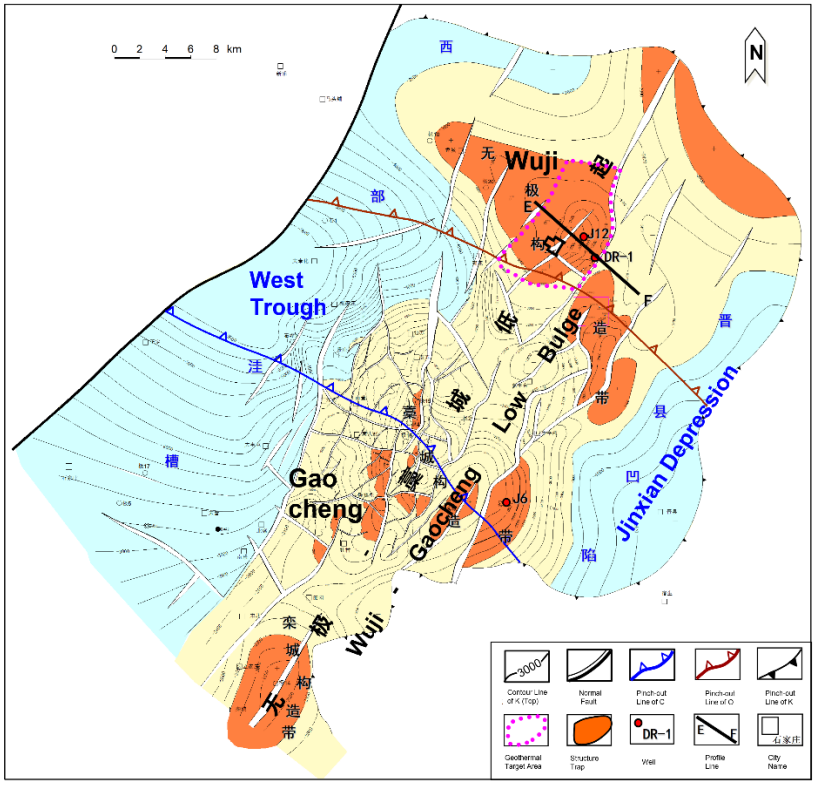


**Figure 4: Pre-Mesozoic tectonic map of the target area.**

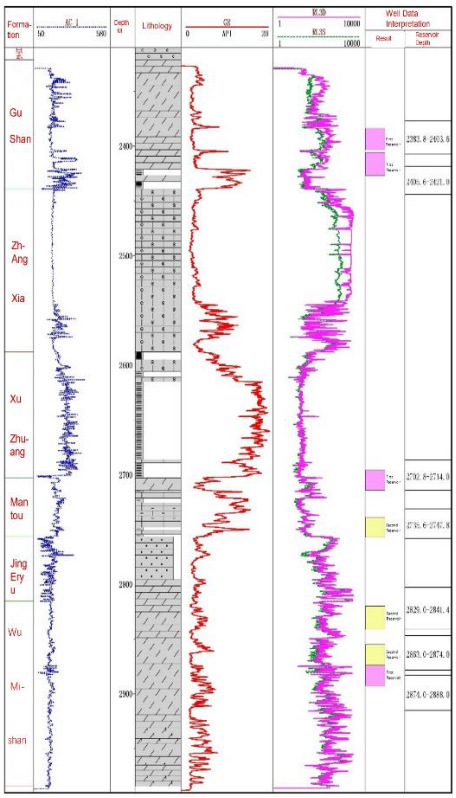


**Figure 5: Results of the comprehensive interpretation of well logging of J12.**

**4. THE GEOTHERMAL GRADIENT IN THE NORTH CHINA PLAIN IS GOVERNED BY THE UPLIFT ZONE AND THE DEEP FRACTURES THAT CUT THROUGH THE BASEMENT. MANY DEEP AND LARGE FRACTURES CUT**

**THROUGH THE BASEMENT AROUND THE HIGH GEOTHERMAL GRADIENT ZONE, AND THESE FRACTURES PLAY AN ESSENTIAL ROLE IN THE CONVERGENCE OF HEAT FLOW.**

The constant temperature zone in the North China Plain is approximately 30 meters deep and 15 degrees Celsius. The average ground temperature gradient in the plain is greater than 3°C/100m and increases with increasing cover thickness. The high-value zone of the geothermal gradient is located primarily in the uplifted area and the low bulge area in the depression area, and the average geothermal gradient is approximately 3.5°C/100m, with the maximum reaching 5°C/100m (Ma, 1990; Chen et al., 1990; Fu et al., 2004; Wu at al., 1988; Zhang et al., 2007; Niu et al., 2001). These fractures play a critical role in the convergence of heat flow in the high-value zone of the geothermal gradient (Figure 6. Map of geothermal gradient and regional fault in the North China Plain area). Along the Wuji-Gaocheng low bulge, the geothermal gradient can reach 3.5-4.0°C/100m, and the Cambrian geothermal reservoir in the study area is presumed to be 95-105°C.

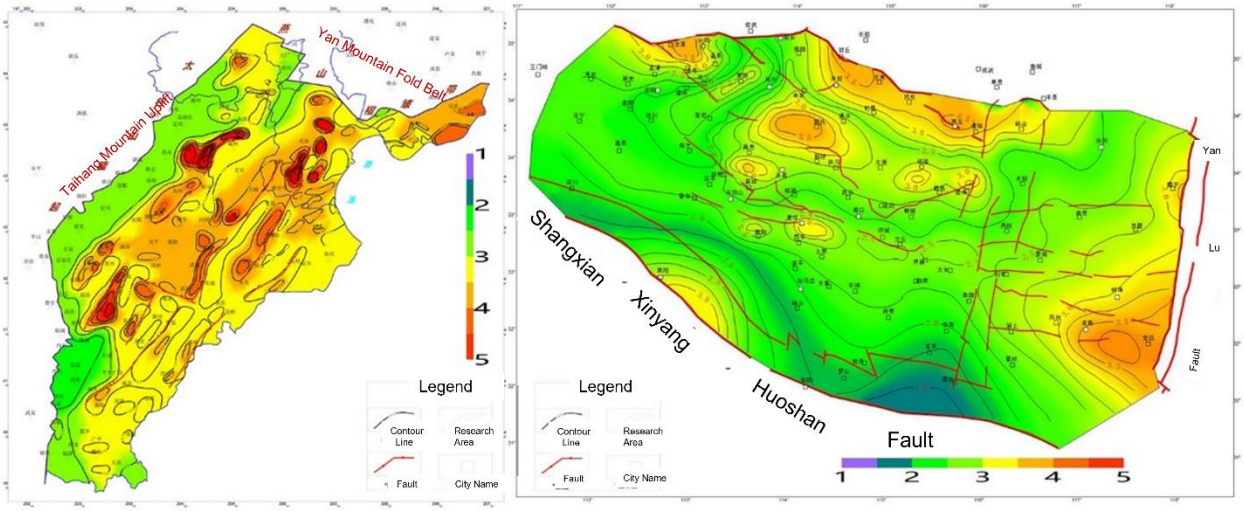


**Figure 6. Map of geothermal gradient and regional fault in the North China Plain area (the left figure is Hebei Plain area, right figure is South of the North China Plain area).**

**5. GEOTHERMAL WATER RECHARGE COMES FROM THE SURFACE PRECIPITATION OF THE TAIHANG AND YANSHAN MOUNTAINS IN THE WEST AND NORTH, WHICH IS TRANSPORTED ALONG THE BIG FRACTURE IN FRONT OF THE MOUNTAINS TO CONVERGE AT THE HIGH PART OF THE CARBONATE GEOTHERMAL RESERVE AND IS DEEPLY CIRCULATED.**

The overlying Cenozoic and Mesozoic strata and Paleozoic Carboniferous-Permian sand-mudstone are the cover of the Cambrian-Ordovician carbonate geothermal system in the North China Plain region; the geothermal reservoir is Paleozoic carbonate rocks, with well-connected fissures and fractures forming fluid channels; and the heat energy is primarily derived from the heat conduction of the upper mantle. The geothermal water is replenished by precipitation from the Taihang Mountains in the west and the Yan Mountains in the north. The geothermal water is then transported along the large fractures in front of the mountains and converges in the high portion of the carbonate geothermal reserve to form a favorable geothermal water discharge area. The geothermal water undergoes a profound circulation (Wang et al., 2020; Zhang et al., 2008; Wang et al., 2021; Sui, 2020; Wang et al., 2017; Jia, 1993) (Figure 7. Depicts a model of the origin of the deep carbonate reservoir geothermal system in the North China Plain region.)

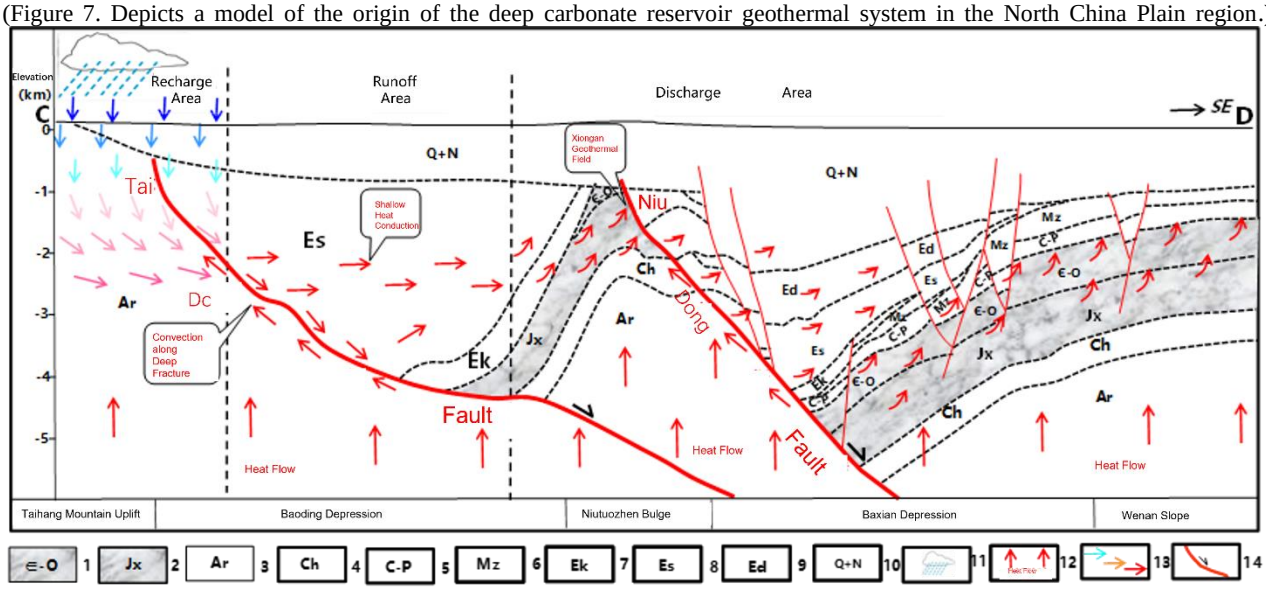


**Figure7: Depicts a model of the origin of the deep carbonate reservoir geothermal system in the North China Plain region.**

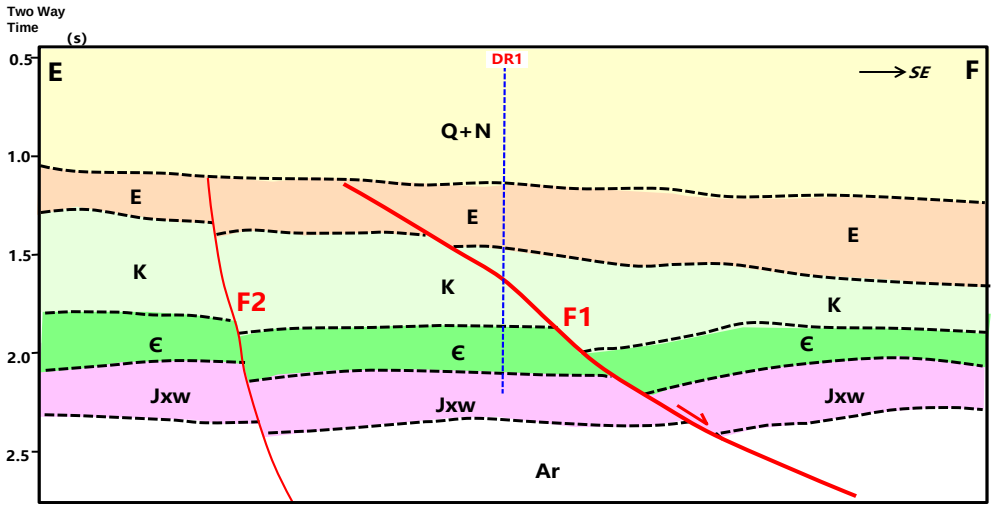


**Figure8: Geological section through DR1 well**

## 6. RESULTS OF CARBONATE GEOTHERMAL RESERVE DEVELOPMENT IN THE WUJI-GAOCHENG AREA

In accordance with tectonic analysis and heat demand, the location of the geothermal well was chosen on a fault block sandwiched between three faults in the northern portion of Wuji County (Figure 8. Geological section through DR1 well). Two important water and heat conducting faults (F1 and F2) traverse the Cambrian and Middle-Upper Paleogene strata and have a northeast direction and a southeast inclination. The J1 well is adjacent to fault F1, which is located in the fault's lower plate, a favorable tectonic location.

Based on the aforementioned research findings, the first carbonate geothermal well (DR1 well) was installed in this region; the target geothermal reservoir is dolomite of the Jixian System Wumishan Formation; and the Cambrian System is also being investigated. The geothermal well has a maximum depth of 3,850 meters. The well was completed on September 30, 2019, with a completion depth of 3,901 meters, the first 70 meters of the Wumishan Formation exposed, a bottom temperature of 125 degrees Celsius, a water output temperature of 108 degrees Celsius, and a volume of 110 cubic meters per hour.

During the logging of the J1 well, it was discovered that the weathering at the top of the Cambrian System was extremely severe and that there was mud leakage. The electric logging results also revealed that the Cambrian System fractures were relatively developed, and it was determined that the physical properties of the Cambrian System geothermal reserves in the area were favorable. Consequently, the J2 well was drilled to target the Cambrian System dolomite geothermal reserves. The J2 well was completed at a depth of 2,830 meters on October 27, 2019. At 2718m (oblique depth), the well was drilled into the Cambrian system and encountered a large cavern at 2726m. Due to a well leak, the wellhead lost return. Repeatedly plugging the leak had no effect. The output water temperature is 97 degrees Celsius, and the flow rate is 180 cubic meters per hour.

According to the heating demand and the successful drilling of the J1 and J2 wells, the J3 and J4 wells were successively drilled, and both yielded positive outcomes. The group of wells heated an area of 460 000 square meters.

The successful practice of geothermal exploration and development in the Wuji-Gaocheng area of Shijiazhuang marked a breakthrough in geothermal exploration in the Lower Paleozoic Cambrian carbonate rocks of the Jizhong Depression. This is the first time in China that high temperature and high yield geothermal water resources have been discovered in this region.

## 7. CONCLUSION

The geothermal development practice in the Wuji-Gaocheng area shows that the Cambrian-Ordovician geothermal reservoir in the North China Plain area has great development potential, and in the future exploration and development of this set of geothermal resources, the secondary uplift or slope area in the depression should be taken as a key area to find out the situation of Paleozoic carbonate strata in the high tectonic parts, fracture spreading, and analyze the water and thermal conductivity of fractures. These tectonic sites are strong in weathering and stripping due to fracture development, stratigraphic uplift, and other factors, with good reservoir physical conditions, fissures, and cavities. Moreover, the Jixian System Wumishan Formation and the Cambrian-Ordovician System in the North China Plain have similar geothermal geological characteristics, and the two sets of geothermal reservoirs should be developed in a balanced manner to maximize economic benefits and promote the scientific utilization and economic development of geothermal resources in the region.

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