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The Application of Comprehensive Geophysical Methods on the Geothermal Exploration in Northwest Piedmont Area in Huairou, Beijing

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ABSTRACT

The Northwest piedmont regional geologic structure is complex, and the water circle alternate is intensive in Miaocheng town, Huairou District. The dolomite is part of the Wumishan formation and the Jixian system is a geothermal reservoir in this area. Based on geological, hydrogeological and geophysical data, the methods of gravity, microseism and CSAMT are implemented in geothermal exploration. According to the identification of geology structure, strata combinative characteristics and related geothermal conditions, the optimum site of geothermal exploration was determined. The geophysical interpretation was shown to be accurate by drilling of the JH-1 geothermal well. The reservoir is composed of carbonate rocks from the Wumishan formation and the bottom of Cambrian formation. The results from the JH-1 well shows that the yield is 616.12 m³/d and the temperature is 45℃.

1. INTRODUCTION

Geothermal resources have become one of the most indispensable and important resources in Beijing. The history of development of geothermal development is more than 50 years old. With further development, geothermal exploration is gradually expanding to the surrounding areas which are still considered inadequate in order to find more geothermal anomaly areas.

The exploration area is located in the northwest piedmont in the town of Miaocheng, Huairou District, Beijing. The identification of the geothermal geological conditions in this area is based on several geophysical exploration results and wells. Geophysical prospecting and drilling are commonly used in geothermal exploration. The main role of geophysical exploration is to delineate the regional distribution of water-bearing fractured zones and find the efficient thermal reservoirs (Chen Zhonghou, 1996; Li Anning, 2001; Zheng Dongming, 2005; Xu Guanghui, et al, 2005). Based on geological, hydrogeological and geophysical data collection, three geophysical exploration technologies are implemented; this includes the gravity method, microseism method and controlled source audio-frequency magneto telluric method (CSAMT). According to the comprehensive geophysical interpretation, the geothermal, geological and deep geophysical characteristics, and the geothermal geological analysis, the JH-1 geothermal well was successfully drilled. The production is 616.12 m^3/d and the temperature is 45℃.

2. GEOLOGICAL SETTINGS

The exploration area is located in the mid-east part of Changping-Huairou dome fault which is part of the Yanshan platform folding zone. The regional geologic structure is complex. Geomorphology, sediments and the buried bedrock is obviously controlled by faults.

2.1 Stratum

The Quaternary cumulative thickness increases from northwest to southeast. The strata exposed in the northwest mountains is Cretaceous with some magmatic rocks and small dykes; Ordovician-Cambrian rocks are exposed in the relic mountain of the Zhengzhongshan-Erzhangying area in the south; Magmatic rocks are concealed in the Northeast where the lithology is dominated by granite and granodiorite (Figure 1). Due to the influence of Yanshanian's movement, the bedrock strata are generally distributed from NE to SW and is in accord with the NE-trending tectonic line.

2.2 Structure

The structures are mainly NE-trending or NS-trending. The NE-trending structures are the Huangzhuang-Gaoliying fault, the Fengshan East fault and the Zhengzhongshan syncline. The NS trending structures are the Huairou-Niulanshan fault zone, the Qiaozi-Qianxinzhuang fault and the Wolonggang-Fengshan syncline. The EW trending structure is the Qiaozi-Miaocheng fault and the NW trending structure is the Maxinzhuang-Miaocheng fault (Beijing Geological and Mineral Bureau, 1991).

2.3 Geothermal geological conditons

The thermal is conduct by the Huangzhuang-Gaoliying and Qiaozi-Miaocheng faults in the exploration area. The caprock is comprised of Quaternary, Cretaceous and Cambrian systems. The carbonate fissured rock of the Jixian system constitutes the thermal reservoir.

Four geothermal wells have been drilled around the exploration area and the results are shown in Table 1. H-3 and H-5 are relatively close to the exploration area which can be used for reference purposes.

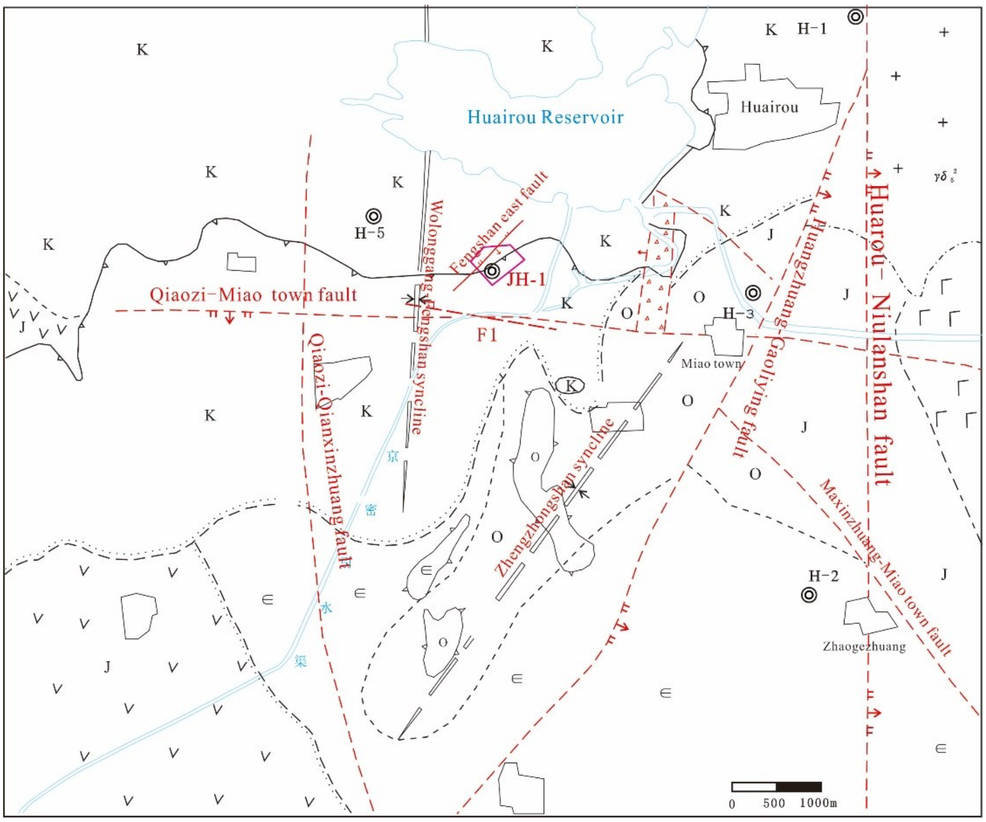

Figure 1: Geological structure map in exploration area

Table 1: List of known geothermal wells around the work area

Well No.	Temperature (℃)	Capacity（m^3/d）
H-1	Bottom hole temperature 36	Uncompleted
H-2	< 20	Large amount of water
H-3	40	603
H-5	42	1268

3. GEOPHYSICAL CONDITIONS AND LAYOUT OF COMPREHENSIVE GEOPHYSICAL METHODS

3.1 Geophysical conditions

The strata in the exploration area are mainly Quaternary, Cretaceous, Jurassic, Ordovician, Cambrian and Jixian systems. The physical characteristics of strata in the above-mentioned are collected and counted (Table 2). According to the collected data, there are some physical differences among strata of different ages which provide a good geophysical precondition for using gravity, magnetic, CSAMT in the exploration area and its surrounding areas to carry out preliminary exploration.

Table 2: Physical parameters of strata in different ages

Stratum	Physical parameters			
	Magnetic susceptibility（10^{-5}SI）	Bedrock resistivity（Ω.m）	Density (g/cm^3)	Wave velocity（m/s）
Quaternary	weak	5—140	1.75—2.01	＜1000
Cretaceous	medium	11.5—21.7	2.37—2.50	1000—1300
Jurassic	medium	71—174	2.41—2.72	1100—1500
Ordovician	weak	800—1500	2.66—2.73	1500—1800
Cambrian	weak	254—608	2.56—2.72	1500—2000
Jixian system	weak	540—1000	2.69—2.80	＞2500
Magmatic rock	middle	＞400	2.52	1600—2900

The concluded physical characteristics of the rock are as follows:

Density characteristics: The density of strata decreases from old to new. The difference between Quaternary and Mesozoic Cretaceous is the maximum density layer interface.

Magnetism characteristics: The Cretaceous-Jurassic volcanic rocks and the magmatic rocks in the area have medium magnetism. The Quaternary, Ordovician, Cambrian, Qingbaikou and Jixian systems have weak magnetism.

Electrical characteristics: The resistivity varies greatly ranging from several ohms to thousands of ohms which can be divided into categories of high resistance, medium resistance and low resistance.

Wave velocity characteristics: The difference of wave velocity can be divided into categories of high-speed, medium-high-speed and low-speed.

3.2 Arrangement of comprehensive geophysical methods

In order to collect hydrogeologic and geophysical data, comprehensive geophysical prospecting was arranged and carried out (Figure 2).

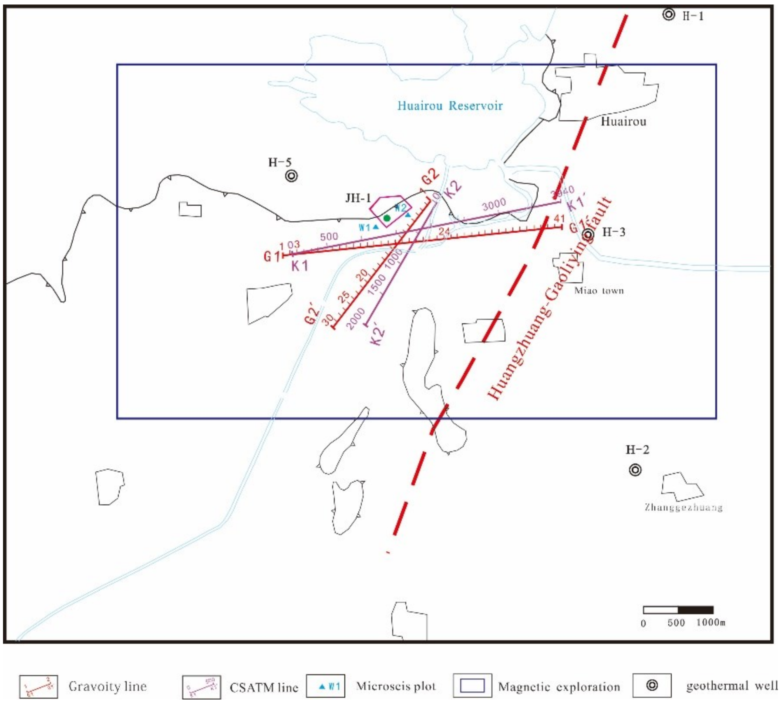

Figure 2: Layout of geophysical prospecting work

(1) Gravity exploration

Gravity exploration is based on the density difference between rocks and ores in the crust. It is a method to find geological structures by observing and analyzing the variation law of surface gravity fields. The rock density of Quaternary units is 2.00 g/cm^3, Cretaceous and Jurassic units have density values higher than 2.5 g/cm^3, Ordovician-Cambrian units have a value 2.70 g/cm^3 and the Jixian system has a value 2.8 g/cm^3. The density difference between Quaternary and bedrock is 0.5-0.8 g/cm^3. Based on the density characteristics of strata, the undulating state of bedrock and the location of fault distribution can be identified.

High Precision Gravity Survey: Two precise gravity profiles with a total length of 6.3 km, scale of 1:10,000 and point spacing of 50 m are laid out. The main purpose is to find out the characteristics of structures in the exploration area using a scale of 1:10,000 and a point spacing of 50 m. CG-5 automatic gravity gradiometer is used in field work.

(2) Magnetic exploration

Magnetic prospecting is based on the magnetic difference between different rocks and ores. It is a method to find out the geological conditions by analysis of the variation law of the surface magnetic field. The contour plane maps of regional anomaly $\triangle Z$ magnetic are collected.

(3) Controllable Source Audio Magnetotelluric Method exploration (CSAMT)

Controllable Source Audio Magnetotelluric Method (CSAMT) is an electromagnetic sounding method which uses a finite length of ground electric dipole as the field source and simultaneously observes the parameters of electric and magnetic fields at a certain distance from the center of the dipole. In this exploration, the equatorial dipole device is used for scalar measurement. The horizontal component Ex parallel to the field source and the horizontal component Hy orthogonal to the field source are also observed. Then the electric field amplitude Ex and magnetic field amplitude Hy are used to calculate the impedance resistivity ρs. The electric field phase Ep and magnetic field Hp are observed to calculate the impedance phase φs. The resistivity parameters are calculated by joint inversion of impedance resistivity and impedance phase. Finally, the inversion resistivity is used for geological inference and interpretation.

Controllable Source Audio Magnetotelluric Method (CSAMT): There are two sections in this area, the total length of which is 5.9 km. The main purpose is to determine the distribution of characteristics of fault structures and the spatial distribution characteristics of strata in this area. Controllable Source Audio Magnetotelluric (CSAMT) can effectively detect the location of faults related to the formation of groundwater, determine the location of hidden faults, and provide a basis for geothermal drilling. For field work, the GDP-32 multifunctional electrical meter produced by Zonge Company of the United States is used. The point spacing is 50 m, and quality inspection completed 0.46 km which accounts for 7.80% of the total workload.

(4) Microseis exploration

Microseis or microtremor are small daily tremors on the earth's surface. They are different from "mega-shocks" with a specific source and seismogenic time, and can be observed at any time and place. Fretting displacement ranges are generally several microns. Frequency variation ranges from 0.3 to 5.0 Hz. The spatial autocorrelation (SAC) method is used to extract Rayleigh wave dispersion from fretting. By calculating the vertical distribution of wave velocity, the burial depth of strata in different ages can be inferred according to the wave velocity difference of different lithologic strata in different ages.

Microseis: A total of two observation points are laid out for the estimation of the burial depth of strata at different times.

4. ANALYSIS OF COMPREHENSIVE GEOPHYSICAL PROSPECTING RESULTS

4.1 Analysis of plane geophysical prospecting

(1) Magnetic measurement

Across the △Z magnetic anomaly contour map (Figure 3), the magnetic survey value near the exploration area is relatively high. The maximum magnetic survey value is 400 nT. The magnetic survey value of the western exploration area is relatively low. Based on the regional geological data, it is inferred that magmatic rocks may be hidden deep in the eastern exploration area. Thus, the well location should be as far away as possible in order to reduce drilling risks.

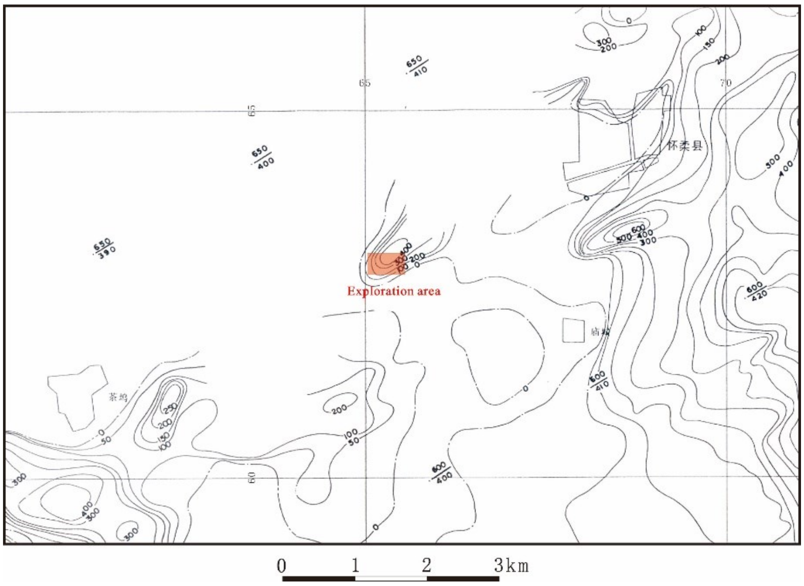

Figure 3: ∆Z magnetic anomaly contour map

(2) Gravity exploration

Based on the plane map of Bouguer gravity anomaly contour (Figure 4), the Bouguer gravity value in the northeastern corner of the exploration area is relatively low, and it is relatively high in the southwestern part. It indicates that the thickness of Quaternary system is relatively thin, and the depth of bedrock is shallow in the southwestern part of the area; this reflects the trend that the thickness of Quaternary system is getting thicker from southwest to northeast.

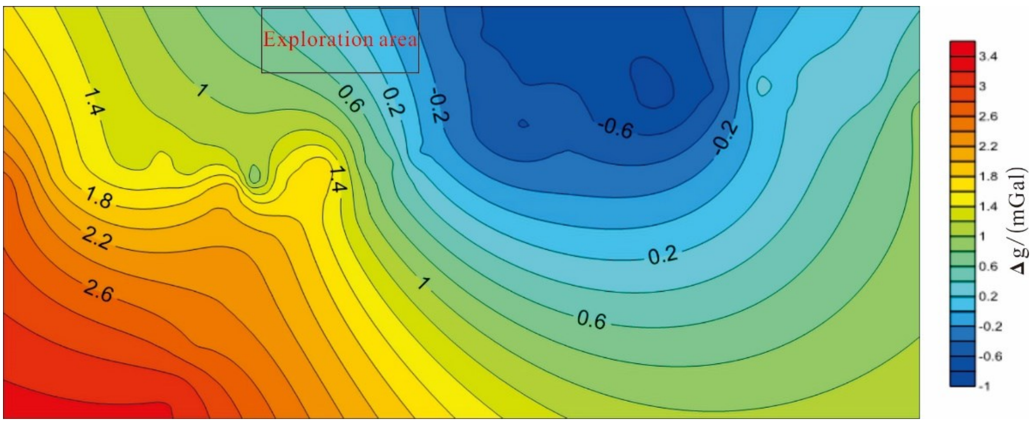

Figure 4: Bouguer gravity anomaly contour map

Two high-precision gravity profiles: the Bouguer gravity value in the southwest section of the profile is obviously higher, which proves that the depth of the bedrock in this area is shallow and deeper in the northeast side (Figure 5 and 6).

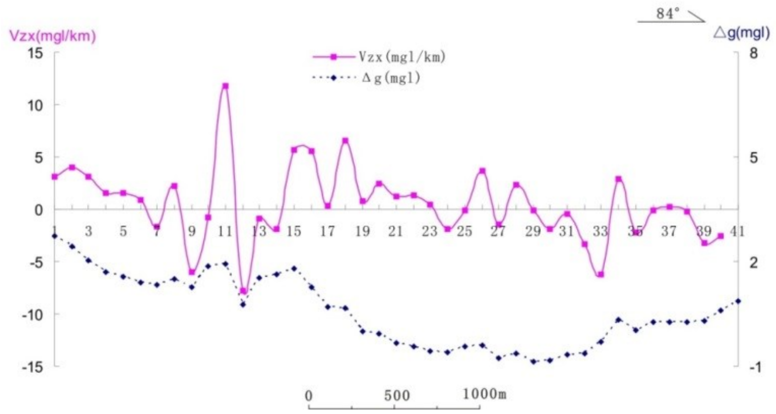

Figure 5: Gravity exploration G1—G1' line profile

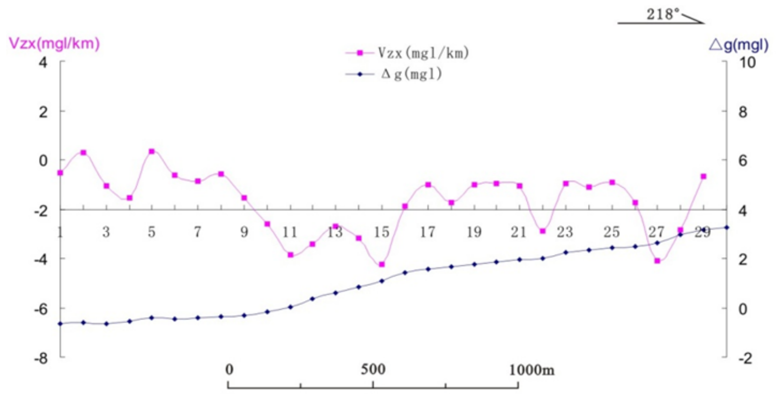

Figure 6: Gravity exploration G2—G2' line profile

4.2 Analysis of plane geophysical prospecting

(1) Microseis, W1 point: The wave velocity varies between 983-1565 m/s and increases with time in a depth range of 0-1783m. It is an indication of the Mesozoic Cretaceous system in combination with regional geological data. The wave velocity of underlying bedrock is more than 2000m/s, and it is presumed to be the reflection of the Ordovician-Cambrian system.

W2 Point: The wave velocity varies between 1050-1223 m/s and is not high and relatively stable in the depth range of 0-910m. It can be inferred as an indication of the Mesozoic Cretaceous units. The wave velocity of underlying bedrock is greater than 1788 m/s with values rising to 2014 m/s, and it is the reflection of the Ordovician-Cambrian units.

(2) Controlled Source Audio MagnetoTellurics Sounding (CSAMT)

The inversion resistivity profile of the K1-K1' line (Figure 7) shows that the single-point curves of the profile are generally the HK-type. The shallow resistance value is relatively low and reflects the Quaternary system. The deep apparent resistivity is relatively high, and it is inferred as bedrock. High resistivity anomaly values are found in the deep part from the measuring point of 2000 to 2500m. It is presumed to be the reflection of magmatic dikes in combination with magnetic data. The apparent resistivity curves fluctuate and bend around at the measuring point of 500 m, forming a dense band of resistivity curves that are inferred to be the indication of F1 fault.

The inversion resistivity profile of the K2-K2' line (Figure 8) shows that the single-point curves of the profile are H-type. The lower resistivity in the shallow part reflects the Quaternary system. The higher resistivity in the deep part reflects the bedrock. A high resistivity body is found in the deep part of the section which might reflect the same magmatic dike in K1-K1'. The apparent resistivity curve fluctuates and bends greatly at the measuring point of 1000m. It is presumably conjectured that it is showing the F1 fault.

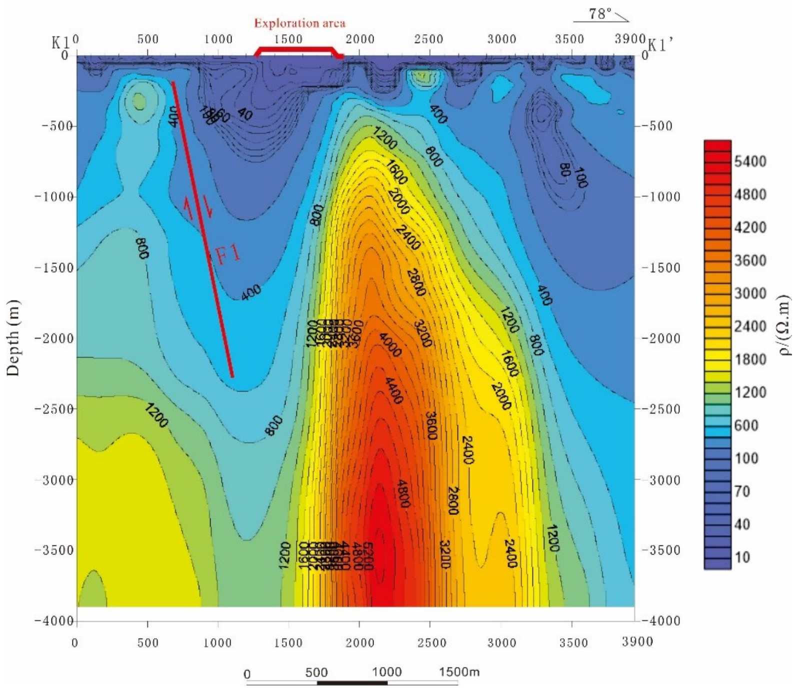

Figure 7: K1－K1'controlled source inversion resistivity section

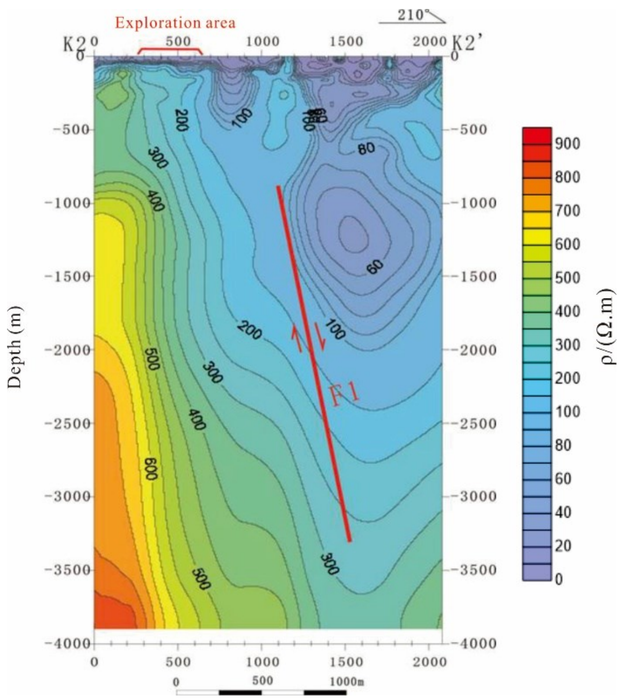

Figure 8: K2－K2'controlled source inversion resistivity section

Based on the results from the geophysical prospecting and geological data, a geological section map is plotted which has a same direction with K1-K1'line (Figure 9).

It is inferred that the thickness of Quaternary units near the exploration area varies from 0 to 100m, and the thickness of Cretaceous units varies from 1000 to1750 m. The trend of the thickness is ascending from East to west and north to south. The thickness variation of Cambrian units shows a similar trend. The bottom depth of the Cambrian system varies from 2500 m to 2900 m, and the underlying strata is the Jixian system.

The risk of drilling the concealed magmatic rocks in the southwestern part of the exploration area is low, and it is close to F1 fault which is conducive to heat and water transfer. Therefore, exploration well should be placed in the southwest of the exploration area.

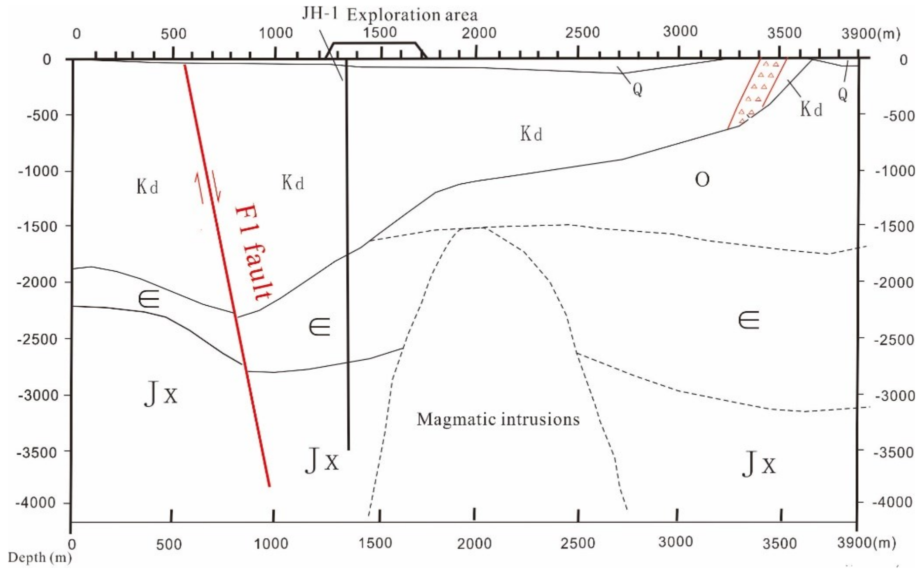

Figure 9: Inferential geological section

4.3 Contrastive Analysis of Previous Geophysical Exploration Demonstration and Drilling Results

The JH-1 well is designed with a 3000 m depth of and the final well depth is 3006 m. Geophysical logging data shows that the well temperature has reached 51 C at 2599.31m. The production rate is 616.12 m^3/d, and the water temperature is 45 C. The geothermal water can be used for heating, bathing and physiotherapy.

(1) Stratum

Based on the drilling data and cuttings, the thickness of the Quaternary units was found to be 15m. It shows that the physical properties of Quaternary units and bedrock are quite different, and geophysical exploration methods can be effectively used. The underlying strata of Quaternary units are Cretaceous-Jurassic units with a thickness of 1517 m. The bottom depth of the Cambrian limestone is buried at a depth of 2593 m which is underlain by the Jixian Wumishan Formation. In terms of stratigraphic sequence, thickness and burial depth, it basically coincides with the inferred stratigraphic sequence by geophysical prospecting.

(2) Fault

The F1 fault was interpreted by the CSAMT method. The F1 fault is located in the south of the exploration area. Combined with the regional geological structure map, it is considered that the F1 fault is the middle part of Qiaozi-Miaocheng fault.

(3) Concealed rock mass

Although intrusive rock mass was not drilled in JH-1 well, the gray, gray-white dolomite cuttings of Jixian Systems, which are below 2600 m deep, have been identified by grinding lens. The dolomite has been clearly oriented and marbled strongly, indicating the existence of hydrothermal activity. It may be caused by intrusive rock mass speculated by geophysical prospecting.

5 .CONCLUSIONS

The northwest piedmont in Miaocheng is an area with less geothermal exploitation and utilization. There is a certain risk of geothermal drilling. The JH-1 geothermal well was successfully drilled in the northwest piedmont area which is a preliminary breakthrough. Confidence is built up for further geothermal development and utilization.

(1) Through drilling verification, comprehensive geophysical methods are more accurate and feasible for geothermal exploration in this area. Geophysical prospecting plays an important role in avoiding risks and for drilling. Gravity data can point out the location of faults and the fluctuation of bedrock. Magnetic data can determine the distribution of volcanic strata and intrusive rock mass, Microseis sounding can determine the buried depth of thermal reservoirs, CSAMT can effectively determine the location of faults which helps understand the spatial distribution of deep thermal reservoir structures and can provide the basis for the location of geothermal drilling hole.

(2) The exploration area is located in the northwest Piedmont of Miaocheng where the Quaternary units are thinner. The main caprock is Cretaceous-Jurassic volcanic rocks with a thickness of about 1500 m. The thermal reservoirs are Cambrian limestone and dolomite from the Wumishan Formation of the Jixian System where the water abundance is better. The F1 fault is a deep circulation channel of heat and water. It is inferred that there are concealed magmatic rocks in the area, which is a geological risk in the future development of geothermal.

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