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Research Progress of Deep Geothermal Exploration in Dongli Lake Area, Tianjin, North China

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ABSTRACT

Chinese government put high emphasis on geothermal development and utilization. In order to enlarge the amount of exploitable geothermal resources, improve the status of geothermal resources in energy structure, and to meet the demand of clean heating in the north area, China Geological Survey are launching deep geothermal exploration program in the recent years and focusing on new reservoir exploration in the depth of 3 to 6 km underground. Geothermal exploration in Dongli Lake area in Tianjin city is among this program. Through regional geological research and analysis, two types of reservoirs were confirmed existing in the study area, such as porous reservoir and karst reservoir. Porous reservoir has two sub-reservoirs, one is in Minghuazhen formation and the other in Guantao formation. Both of them belong to Neogene era. Karst reservoir has three sub-reservoirs in Ordovician, Cambrian and Jixian systems. Among these reservoirs, section 4 and 3 in Wumishan formation of Jixian system is the main development reservoir in current period. Induced seismic and high power time-frequency electromagnetic methods were used in deep geophysical detection and got good results in description of the underground cap rocks, reservoirs and faults within 5 to 6 km. Furthermore, 3D geological structure model was built with geostatistical method for resources assessment use. Based on the preliminary work above, deep drilling work was implemented and finally section 2 in Wumishan formation of Jixian system was found in the depth of 3715m. Fortunately, reservoir production test shows that this new reservoir has enormous resources prospect. This research is of good significance not only in support of local geothermal development, but also in demonstration of geothermal exploration in sedimentary basins.

1. INTRODUCTION

Tianjin is one of the four municipalities under the direct administration of the Central Government of the People's Republic of China. It is located in the northeast of the north plain, near the Bohai Gulf. It is an economic center and industrial city of northern China, and has an extremely important strategic position in China's economic development. Due to the geologic condition, Tianjin has relative scarcity of mineral resources, which restricts the city's economic development to some extent. Fortunately, it is rich in geothermal. Former exploration results show huge low-to medium- temperature geothermal resources reserves underground. 8 geothermal fields have been discovered in the south plain area. Total area of the 8 fields is about up to 2300 km^2, which is about 1/4 of the plain and 1/5 of the total city (Figure 1).

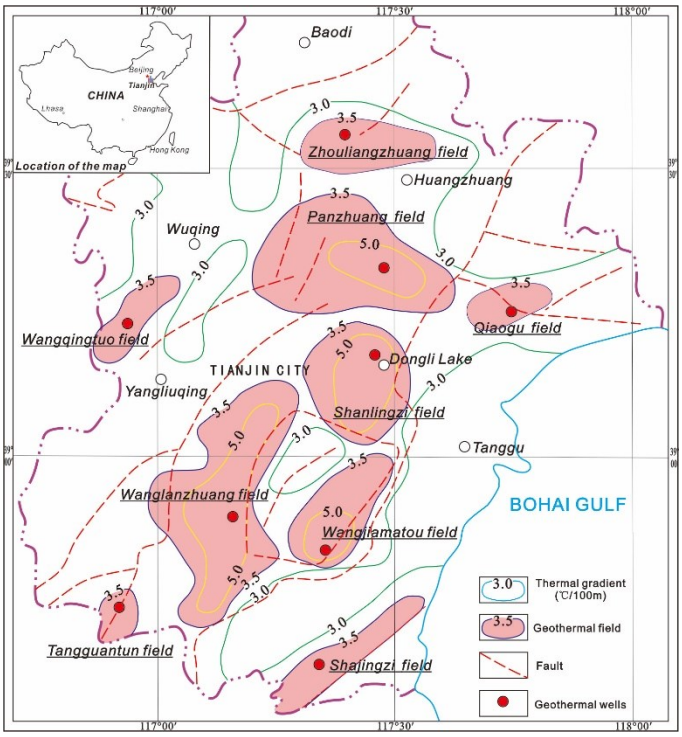

Figure 1: the distribution map of geothermal fields in Tianjin, with average geothermal gradient of cap rocks greater than 3.5°C/100 m (Zhang, 2006)

According to former assessment, recoverable reserves of geothermal fluid with temperature higher than 25°C within 3,000 meters depth is 7607×10^4 m^3/a, and the exploitable thermal energy is 1.30×10^{16} J/a, equivalent to 44.3×10^4 tons of standard coal per year. The geothermal resources in Tianjin are widely used, universal form, developed early, with the largest urban space heating area. By the end of 2017, 683 geothermal wells reservoirs were drilled in the whole city, including 466 for production and 217 for reinjection. Nowadays, total annual exploitation of geothermal fluid is 51.8×10^6 m^3/yr while reinjection is 27.9×10^6 m^3/yr with reinjection rate 53.9%. Among the annual exploitation, 82% is used to heat 35.0×10^6 m^2 buildings in winter time supported by 230 projects.

Dongli Lake area is a typical site in Tianjin for geothermal development. Located in the Shanlingzi geothermal field, it is abundant in geothermal resources with thermal gradient of cap rock 3.0~5.4°C/100m. There are two types of reservoirs discovered in this area such as Neogene sandstone pore-controlled and karst dolomite fissure-controlled ones. The pore-controlled reservoir has two sub-reservoirs, one is in Minghuazhen formation and the other in Guantao formation. Both of them belong to Neogene era. The karst dolomite fissure-controlled reservoir has three sub-reservoirs in Ordovician, Cambrian and Jixian systems. Among these reservoirs, section 4 and 3 in Wumishan formation of Jixian system is the main development reservoir in current period. Even in the whole city, section 4 and 3 in Wumishan formation of Jixian system is also the main production reservoir (Lin, 2007; Wang, 2013).

In order to enlarge the amount of exploitable geothermal resources, improve the status of geothermal resources in energy structure, and to meet the demand of clean heating in the north area, China Geological Survey has been launching deep geothermal exploration program in Dongli Lake area in the recent years and focusing on new reservoir exploration in the depth of 3 to 6 km underground. This program has been started since 2017.

2. EXPLORATION HISTORY

As one of the earliest cities in China to develop and utilize the geothermal resources, the history of geothermal production in Tianjin is over 80 years. In the 1930s, the French drilled the first Neogene geothermal well in Tianjin, which is the starting flag of the geothermal mining history. In the 1970s, with the advocacy of Chinese famous geologist expert Li Siguang, Tianjin started a series of large-scale exploration of geothermal resources. United Nations Development Program (UNDP) also provided drilling equipment aid in the 1980s, and to the late 1990s Tianjin stepped into the large-scale development phase. The cumulative drilled depth reached nearly 9×10^6 m over nearly 50 years, and the maximum depth of single-well exploration is up to 4046 m. Tianjin has become a "geothermal city" of the highest research degree, the largest development scale and the highest utilization level in China (Wang, 2008; TGEDDI, 2000). Geothermal energy plays an important role in alleviating the local energy shortage situation and promoting economic development. The resources are widely used in various aspects of the national economy and people's lives: space heating, textile washing, greenhouse cultivation, aquaculture, medical rehabilitation, tourism, mineral water, etc. A variety of utilization systems have formed, achieving significant social, economic and environmental benefits.

Dongli Lake area is not only a famous resort of Tianjin, but also a “geothermal town” of China. Since exploration started in1980s, five reservoirs have been discovered within the depth between 500m to 3200m such as Minghuazhen, Guantao, Ordovician, Cambrian, and 3-4 section of Wumishan formations (Wang, 2010). The exploitable amount of geothermal fluids is about 224.36×10^4 m^3/a, equivalent to 20.3MW_{th}.of thermal energy, which is similar to a mid-scale geothermal field. At present, there are 34 geothermal wells in the area including 18 reinjection wells with reinjection amount about 185.57×10^4 m^3/a (reinjection rate is about 83.07%) .Production capacity of the wells is between 60m^3/h to 200 m^3/h. With the help of 11 heat centers, buildings of 2.46×10^6 m^2 in this area is heated by geothermal.

In 2017, China Geological Survey started to carry out deep geothermal exploration program focusing on new reservoir exploration in the depth of 3 to 6km in Dongli Lake area. Efforts has been taken through geological analysis, geophysical exploration and geothermal drilling to prove that there would be a new reservoir under the main development one.(section 4 and 3 in Wumishan formation of Jixian system, Jxw_{3+4}) . Two wells named CGSD-01 and CGSD-02 have been under drilling since November 20, 2017 Both of the wells are aimed to reach the depth of 4000m.

3. GEOLOGICAL EXPLORATION

3.1 Geological Settings

Tianjin is located in the north east of the North China Plain near Bohai Gulf, west of the Pacific Ocean, the lower reaches of Haihe River valley, with The Bohai Sea to the east and Yanshan Mountain to the north. Tianjin Geothermal field is located in a sedimentary-fault basin in the North China Platform and is divided into a northern and a southern part by the Ninghe-Baodi fault (Figure 2). Most of the area is covered by Quaternary strata. The outcrop of the base rock is limited to the mountain area in the north of Jizhou District. The northern part belongs to the secondary tectonic unit; the Jibao Upfold, in the Yanshan platform orogen. The southern part lies in the Bohai Gulf Basin. From west to east, the southern part constitutes three tectonic units; the Jizhong depression, the Cangxian upfold, and the Huanghua depression, that are cut into numerous tectonic blocks by several east-west, northwest and northeast trending fractures (Chen, 1988). On the whole, the center part is uplifted with the low-lying part in the east and west. The anticline structure is the main regional trend. The main faults are the Tianjin Fault in the west, the Cangdong Fault and the Baitangkou Fault in the east, and in the middle there are the Haihe and Chenglinzhuang faults. Several faults accompany them. Most of the geothermal fields are located in the Cangxian uplift. The Dongli Lake area is seated in the Panzhuang Uplift, surrounding by the Cangdong Fault, Tianjin Fault, Hangu Fault and Haihe Fault (Wang, 2008).

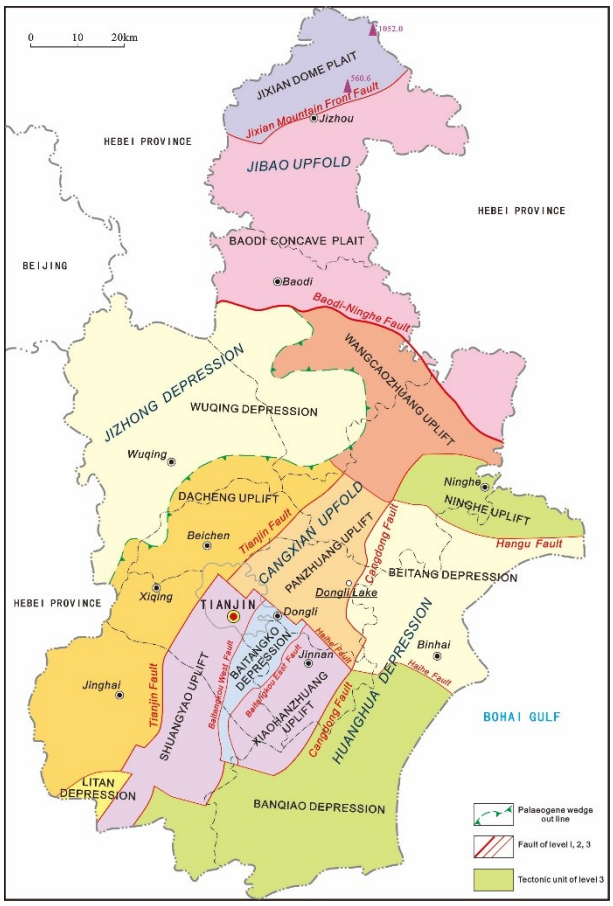

Figure 2: the sketch of geological tectonics in Tianjin

3.2 Geological Structures

Based on geological data collection (TBG, 1992; Zhao, 2006) and analysis, a 3D geological model is built to describe the structures underground in the depth of 0～4000m (Figure 3). From the model we can see that there exists, from top to bottom, the Quaternary, Neogene, Ordovician, Cambrian, Qingbaikou, Jixian Formations. As mentioned above, there are two types of reservoirs discovered in this area. Of those, Minghuazhen and Guantao formations belong to Neogene system, of Cainozoic era. Besides, there are also Ordovician, Cambrian systems belonging to late Proterozoic era. What is more, there is Wumishan formation buried in the depth of 1800 m or so. The Wumishan formation can be divided into 4 sections, of which section 4 and 3 are the proven high capacity reservoirs with geothermal fluids of 96-108℃. According to geological laws, section 2 and 1 should also be a reservoir of high capacity because they are composed of dolomites, which have similar characteristics with that of section 4 and 3, but has never been proven.

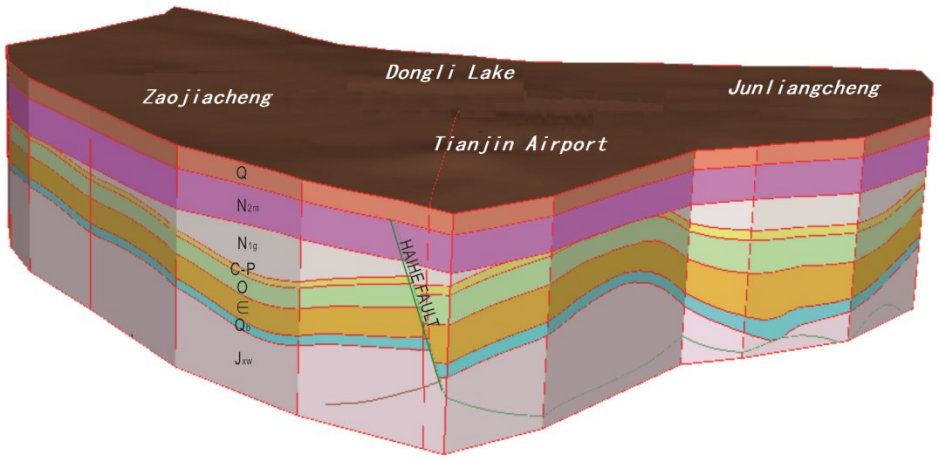

Figure 3: the 3D geological model for Panzhuang Uplift

4. GEOPHYSICAL EXPLORATION

Geophysical exploration methods were used to find out geological settings, characteristics of deep faults, location of deep reservoirs and to determine the locations of wells. To get amount of information from the deep in the environment with obvious electromagnetic interference, two kinds of methods were experimented including high power time-frequency electromagnetic method (TFEM) and 2D induced seismicity (Figure 4). Of which, high power time-frequency electromagnetic method (TFEM) was used in geothermal exploration for the first time.

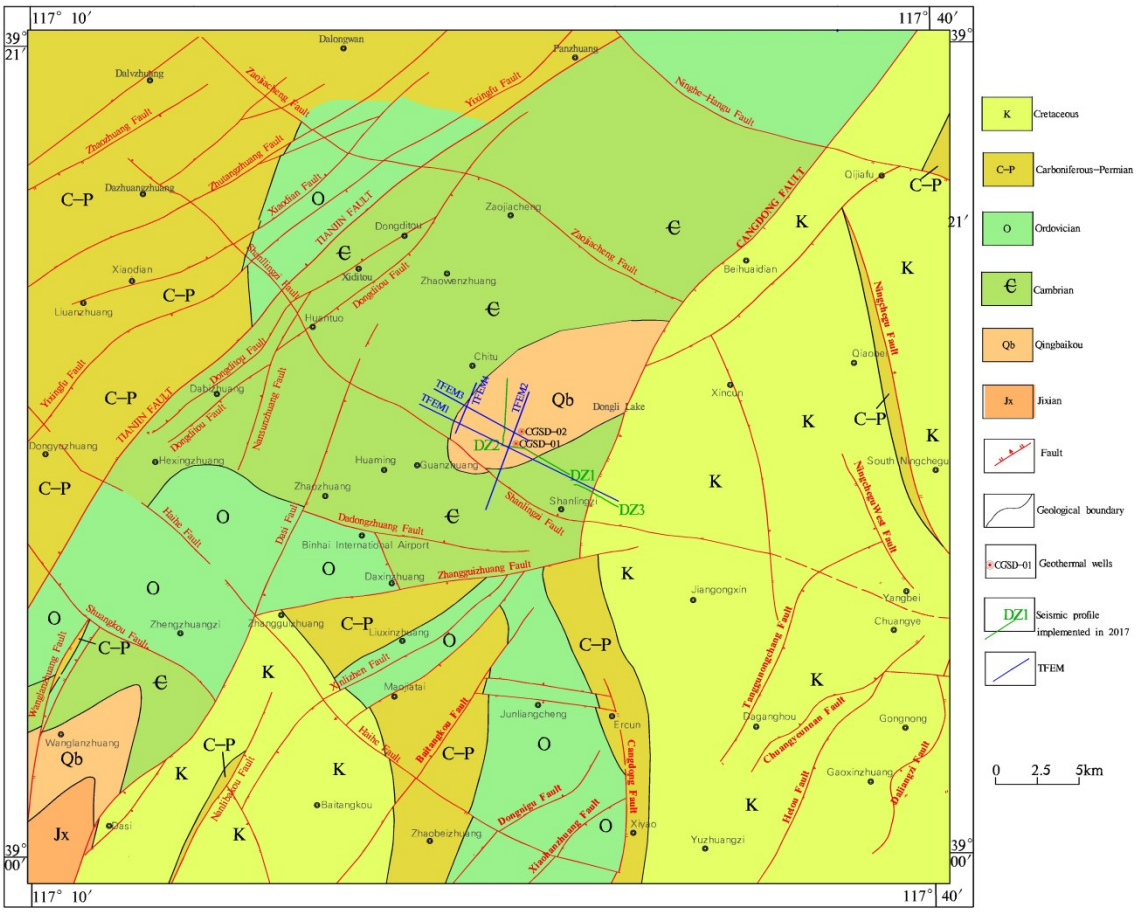

Figure 4: The location map of the deep geophysical profiles on a base rock map

4.1 Time-frequency electromagnetic method (TFEM)

Time-frequency electromagnetic method (TFEM) is widely used in petroleum exploration with its advantages of stronger anti-interference capability, greater exploration depth, combined time and frequency domain analysis, higher detection accuracy and obtained a variety of electrical parameters. In this case, it is tried to use for geothermal resources investigation for the first time,and it has enriched the geophysical method system; using high precision two-dimensional inversion and optimal stratification technology to divide the shallow stratum structure and fault features in the depth of 0~5km; confirming the effectiveness of the application of TFEM under strong background noise interference. It is concluded that TFEM has the anti-interference ability to explore a maximum depth of 10km (Dong, 2008; Zhou, 2013, 2015).

Results from TFEM-01 (Figure 5) show that geological characteristics underground in the study area is mostly controlled by nearly horizontal sedimentary stratums with several normal faults. In the west of F1 fault (the Cangdong Fault) on the Panzhuang Uplift, geological stratums from the top include the Quaternary (Q), Neogene (N), Cambrian (Є), Qingbaikou (Qb), Jixian Formations (Jx) systems. In the cross-section above 1500 depth, the apparent resistivity abnormities is quite continuously without distortion or disconnected phenomena. This shows the average thickness of Cenozoic stratums is 1300m and becomes thickened gradually from west to east. In the depth between about 1500 to 4000m, there are early Paleozoic and mid-late Proterozoic stratums buried with unconformable contact. The apparent distortion of apparent resistivity under point 141 shows the existence of the main regional fault F1 named Cangdong Fault. The other relatively weaker distorted phenomena uder points 113, 120, and 131 show the existence of three secondary faults. All the faults are normal and extension fractures. The main development reservoir Wumishan formation lies under the depth of 2200-2500m. The Jxw_4 lies between about 2300-3000m, and under which there is Jxw_{2+3} lying under 3000m. However, the boundary between Jxw_2 and Jxw_3 cannot be identified clearly due to the similarity of lithology and the lack of geophysical parameters. Considering information from regional standard geological cross-section showing the thickness of Jxw_3 is in the range of 500-700m, we can conclude that Jxw_2 should lie under the depth of 3500-3700m based on the TFEM results.

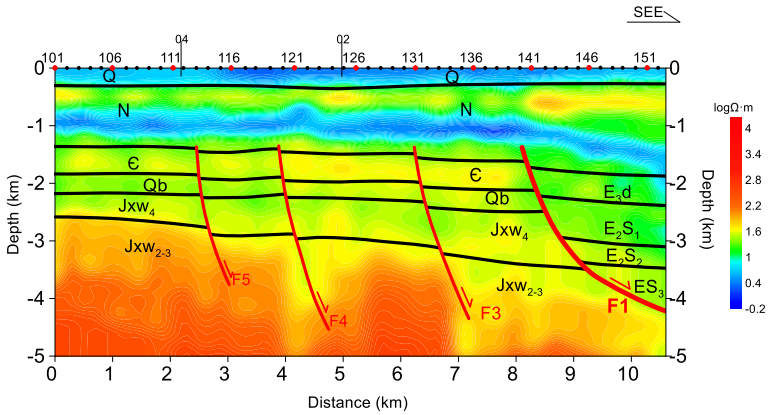

Figure 5: the Time-Frequency Electromagnetic Method profile TFEM-01

4.2 2D Induced Seismicity Exploration

To get more information and better understanding of the geological structure, 2D induced seismic exploration is adopted for exploration. And also more evidence needs to accumulate for drilling site section. Results from seismic exploration (Figure 6) give a lot of information in the depth of 0~4km. Geological stratums are composed of the Quaternary (Q), Neogene (N), Cambrian (Є), Qingbaikou (Qb), Jixian Formations (Jx) systems within 4000m. According to the distribution of reflecting interfaces, the bottom boundaries of the stratums can be divided as follows. Q is in the depth of 341-363m, N_{2m} is 1123-1160m, N_{1g} is 1347-1500m, Єm is 1758-2033m, Єch is 1856-2164m,as well as Qb is 2196-2444m. And what is more, the bottom boundary of Jxw_4 seems in the depth of 2802-3004m, and that of Jxw_3 seems in 3552-3726m which is the top boundary of Jxw_2. Though there is no more information to understand the deep structures in more detail, it gives confidence to reveal a new reservoir in Jxw_2 in the two proposed sites of geothermal wells CGSD-01 and CGSD-02

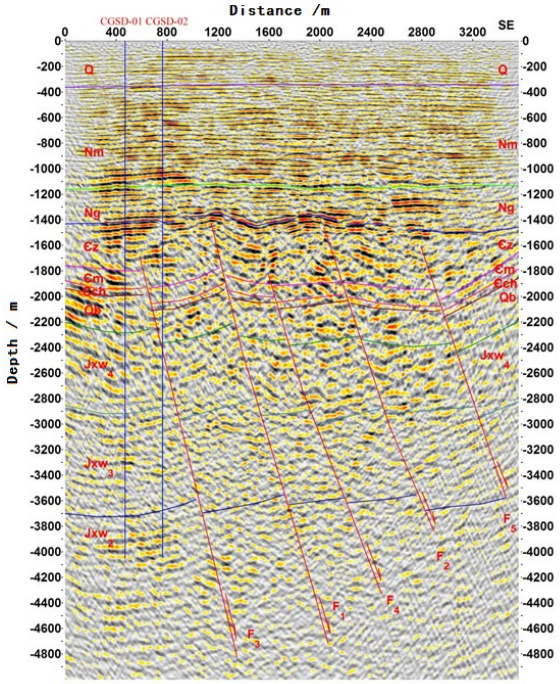

Figure 6: the 2D seismic profile DZ01

5. GEOTHERMAL SCIENTIFIC DRILLING

5.1 Deep Geothermal Drilling

The Dongli Lake area in Tianjin is one of the three key study areas in Beijing-Tianjin-Hebei region for deep geothermal research focusing on deep geothermal resources investigation and technology development carried out by CGS. China Geothermal Scientific Drilling No.01 (CGSD-01) is the first borehole of the two 4000m deep geothermal exploration boreholes implemented by CGS in 2017-2018. It is the deepest geothermal exploration drilling in the Dongli Lake of Tianjin. The purpose of the scientific drilling is to reveal the spatial distribution characteristics of deep geothermal reservoir, to identify the potential & availability of geothermal resources, to solve basic geological problems such as deep geothermal source forming mechanisms, and to guide the further exploration and development of clean geothermal energy in Tianjin. This 4000m deep CGSD-01 drilling is aimed to get through the Jxw_{3+4} stratums and enter the Jxw_2 formation.

In November 2018, the well reached 4051.68m finally, and became the deepest geothermal well in Tianjin area. It reveals Jxw_2 formation the first time in the depth of 3715m (Figure 7). The lithology of Jxw_2 is mostly white and black grey dolomite with layered solution cracks and fractures. Temperature of the bottom is up to 105℃. Well test shows that the production capacity can reach 130.2m^3/h with fluid temperature of 100℃ (Figure 8). This is a new reservoir in Tianjin and also proven to be a reservoir of significant for future development. Unfortunately, the well could not drill across the whole Jxw_2 strata in the depth of 4051.68m.

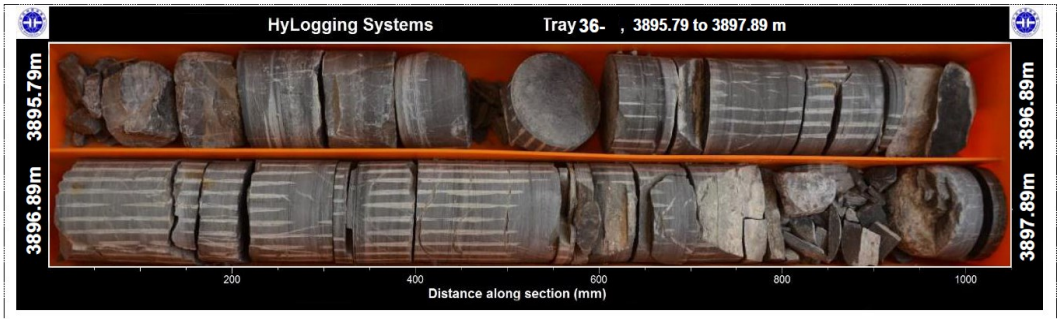

Figure 7: typical rock core of section 2 in Wumishan formation, Jixian system in CGSD-01

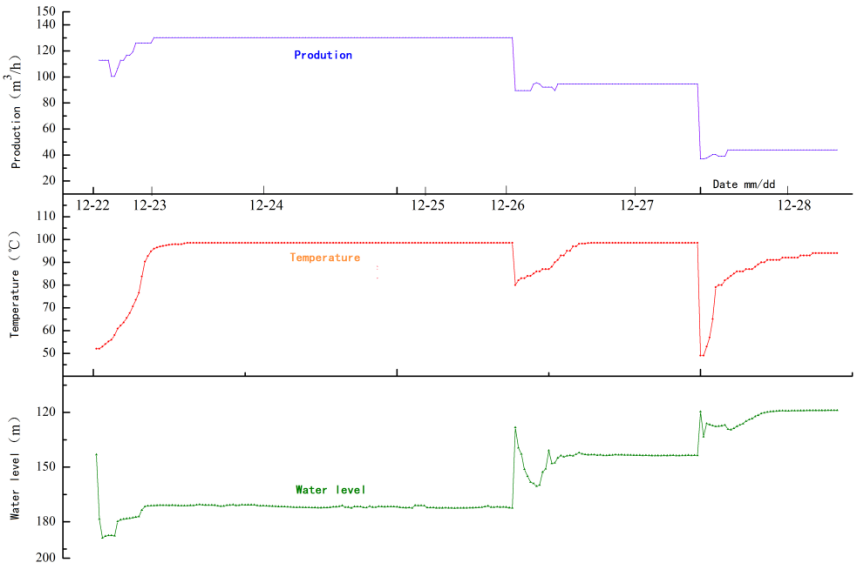

Figure 8: well test of CGSD-01

5.3 Stimulation Test in the New Reservoir

To know more about the new reservoir, stimulation test was used to know the largest production capacity of Jxw_2 strata. Based on indoor experiment, 100m^3 of 10% HCl and 60m^3 of water were injected into the well with injection rate of 0.5-1.0m^3/min under pressure no more than 10MPa. Well test was adopted to evaluate the effectiveness of the test. Results showed that the production capacity was increased obviously from 130.2m^3/h to 200.14m^3/h under the same water level drawdown. The capacity was improved by 53.7%. This can support the space heating demand of more than 30×10^4 m^2 of buildings in winter.

6. CONCLUSIONS AND OUTLOOK

A new reservoir is discovered and proven to be of considerable production capacity in section 2 of Wumishan strata in Jixian system (Jxw_2) in Tianjjin area. Because of the existence of solution cracks and fractures in dolomite karst strata, the new reservoir has similar characteristics with Jxw_3 and Jxw_4. Temperature of the reservoir is up to 105℃ and fluid production capacity of a single well can reach 130.2m^3/h.

Time-frequency electromagnetic method can be used in geothermal exploration. It has some advantages in the environment of strong background noise interference. Experiences show that it is effective to use for deep geothermal exploration combined with induced seismic method. The combined method is quite useful to get preliminary understanding for the deep geological structures and helpful for drilling site selection.

The new reservoir in Dongli Lake area is of significant for future development. Well test show that it can yield more 130.2m^3/h of 100℃ thermal water in a single well in only part of Jxw_2. Acid injection method can be used in reservoir stimulation. The production capacity can be improved obviously. In our case in CGSD-01, the capacity reached to 200.14m^3/h under the same water level drawdown. That was improved by 53.7%.

Geological analysis→geophysical investigation→well drilling→well test→stimulation is an effecive work flow for deep geothermal exploration. This work made a good progress in deep geothermal exploration and new reservoir discovery. However, it is only a start. To support future development, more detailed work should be done for resources characterizing in the deeper and larger space. The buried Jxw_1 and Jxg (Gaoyuzhuang formation) under Jxw_2 formation in Jixian system have similar lithology with Jxw_{4+3+2}. This means they also have large potentials and should be future research objectives.

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