Application of integrated geophysical methods in geothermal exploration: a case in Zhangjiakou

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Abstract. Geothermal energy has become increasingly important in our energy structure as it is a kind of clean and sustainable resource. Zhangjiakou, along with Beijing, is the host city of Winter Olympic Game 2022 and has the demand of geothermal resources. In the central-south part of Zhangjiakou area, integrated geophysical exploration was carried out in 2019, including regional and local high-precision gravity, magnetotelluric (MT), controlled source audio magnetotelluric (CSAMT) and seismic measurement. Combined with geothermal geological survey, new secondary faults, the contour maps of depth of geothermal reservoir and basement are achieved, which plays a vital role in delineating geothermal anomalous area. Based on the analysis of geophysical interpretation results, geological and hydrological information, the geothermal favorable zone and drilling target areas are determined. The work done in the year of 2019 is the beginning and basis of this geothermal resource survey project, and will provide technical support for the drilling work.

1. Introduction
The implementation of geothermal resource survey and comprehensive evaluation can accurately serve the construction of the renewable energy demonstration zone in Zhangjiakou, and provide geotechnical support and effective services for local green development. In order to realize the target, gravity, electromagnetic and seismic data acquisition, processing and interpretation were carried out to further ascertain the characteristics of the geothermal system in Xuanhua-Huaihui area. Locations, occurrences and extension patterns of thermally-controlled faults, depth of reservoir layers, cap rock lithology and thickness and characteristics of concealed rocks. Combined with geothermal geological information, the results are used to determine the favorable area for geothermal resource exploration and the optimized drilling locations. The achievements also provide geophysical basis for further drilling work and research on geothermal reservoir formation mechanism and sustainable utilization of geothermal resources.

The working area is in central Zhangjiakou with longitude 115.10 E ~ 115.93 E and latitude 40.24 N ~ 40.68 N. The area, topographically, is surrounded by mountains and an intermountain basin distributes roughly east-west. Accordingly, the geothermal anomalous area and sites mainly spread over the basin, in which the research of Houhaoyao geothermal field is on a high level. In 1990, a line survey on the 12 discovered geothermal anomalous sites was implemented. The covering area is 2500...
km², and completed temperature measurement of 39 boreholes (springs), field verification of 6 faults and 25 sampling analysis. The geothermal field is identified as a type of ‘graben basin-volcanic heat’ in terms of the interpretation results. According to “Preliminary Investigation of Geothermal Resources in Xuandong Geothermal Anomalous Zone, Jiajiawan, Xuanhua, Hebei Province” completed in 2013, a 1301.13-meter-deep geothermal borehole was drilled and logged. The information of strata and thermal reservoir obtained would provide reference for geophysical work deployment and data interpretation. In 2018, the investigation and evaluation of geothermal resources in Huailai expanded the exploration area [1-3]. The geological and geophysical results established foundation for the surrounding condition of underground geologic structures. Through the analysis of the temperature measurement, soil geochemical elements, CSAMT and high-precision magnetic measurement, the results of Han can be used for reference in geothermal investigation in similar geological conditions [4].

2. Application

2.1. Geological background

The working area is located in the North China Plate and consists of three consecutive intermountain basins from west to east, namely Zhang-Xuan Basin, Huai-Tong Basin, Yan-Fan basin. According to the disclosure of boreholes in the surrounding mountain areas and basins, the strata distributed in the working area range from the Archean to Cenozoic, besides the Lower Paleozoic Upper Ordovician, Upper Paleozoic Silurian, Devonian and Carboniferous-Permian. The strata distribution is shown in Figure 1.

![Figure 1. The strata distribution in working area.](image-url)
The strata in this area generally experienced strong multi-stage fold deformation, and the formation of most folds is closely related to the thrusting fault. The folds in NEE direction mainly include the Zhaojiafang-Xinglinbao anticline, Huailai syncline, and Laojunshan anticline. Volcanic or magmatic rocks are usually distributed on the axis of the syncline. The NW folds are mainly south Huazhuang syncline and Jiuzhuangwo anticline. The faults in the area can be roughly divided into three groups: NW-NWW, NE-NNE, and EW. The majority of the faults are shear structures with strike-slip characteristics, and some of them have both normal and reverse property.

The magmatic activity in the working area is strong, and it is part of the Daxinganling-Taishan Mountain tectonic magmatic active zone. The main activity time is the Mesozoic, and, it is strong in the middle and late Mesozoic. The magmatic rock geological mass formed during this period have the characteristics of large scale, wide distribution range, complex and diverse shapes, and significant mineralization. It mainly produces batholites, stocks, dykes, apophysis, lava beds, rock mats, and talus cone with varied scales. The magmatic intrusion and volcanic eruption are controlled by the great Henan-Chicheng deep fault spreading from NE-NNE.

2.2. Geophysical methods

2.2.1. Gravity. The gravity measurement includes 1:100,000 and 1:10,000. From the regional Bouguer anomaly and isostatic anomaly, a couple of predictions can be made. The gravity value in this area extends high to low from southeast to northwest with a floodplain-like trend. In the area of Zhuolu-Guanting, the gravity value of the northeast direction is about 20 kilometers wide. This indicates that the crust gradually thickened from southeast to northwest under the effect of NW direction stress in the early stage of the area. Due to the NW fault on the south side and the NWW fault on the north side, the crystalline basement in this area rose up as a whole, showing a relatively high gravity value. During the Yanshan period, it was mainly NNE and NE direction rift valley growing. In the area of Zhuolu-Guanting, a NE rift valley was formed, and along the rift valley there was magmatic rock intrusion and strata deposition. It showed low gravity value. The inherited lifting movement to the Cenozoic developed again, forming a Cenozoic fault depression basin.

2.2.2. Electromagnetic and seismic measurement. In our work, there are 12 survey lines for MT, 10 for CSAMT, and 5 for seismic exploration. Among them, there are 7 lines where MT and CSAMT overlap, and 4 between CSAMT and 2D seismic. Due to the shallow exploration depth of CSAMT (1.5km) and the large depth of MT and 2D seismic exploration (4km~10km), in the interpretation of comprehensive survey lines, the shallow layer is dominated by CSAMT, and the deep layer is dominated by MT and 2D seismic. Most overlapping line are consistent. Further combined with regional gravity and high-precision gravity gallery measurement data, the thermal and water controlling structures in the area were preliminarily clarified. In addition, we collected the geological survey data, coal field exploration data, active fault detection data, and drilling data to draw the contour of the basement depth and thermal reservoir depth. The above results would provide important support for delineating geothermal target areas.

2.3. Integrated interpretation results

Based on the integrated deduction of geophysical data, we drew a contour map of the basement depth (Figure 2a) in the Quaternary coverage area and the contour map of thermal reservoir depth (Figure 2b). Figure 2a reflects the characteristics of basement undulations in Huaiizhuo asin and Yanfan basin clearly. Basement depth of the Huaiizhuo Basin is the largest and the center depth is close to 2000 meters. As seen from Figure 2b, it is Jixian system dolomite thermal reservoir (Changcheng System in some area) and Archean thermal reservoir except for the Haituoshan, Nanwopu, Lujiaoyao-Yaojiapo, and several exposed rock masses around Duanjiabao. The Archean thermal reservoir is mainly distributed in the area of Liguanying-Houhaoyao-Wangshan, which includes the area of Houhaoyao
geothermal field. The Jixian system thermal reservoir is widely distributed in the working area, but in different regions, water abundance varies greatly.

Figure 2. (a) contour map of basement depth, (b) contour map of thermal reservoir depth.

Figure 3. The delineated geothermal target areas and optimized drilling points.

According to the integrated analysis, there are three main geothermal prospective zones for exploration and exploitation in the Xuanhua-Huailai area of Zhangjiakou: Donghuayuan zone (A, 36.1km²); Guozhuang-Dongbali zone in Zhuolu basin (B, 81.8km²) and east Gujiaying to west Dingfangshui (C, 45.6km²) (Figure 3). The appropriate locations for geothermal drilling within the above area are selected. The specific information the boreholes are listed in Table 1.

Table 1. The parameters of the optimized drilling sites.

| Borehole | Location               | Coordinate       | Designed depth /m |
|----------|------------------------|------------------|-------------------|
| NZ-01    | South-east of Xiaonanxin Village (X: 392776.30, Y: 4466425.98) | 2000             |
| NZ-02    | South-east of Donghuayuan Town (X: 398745.94, Y: 4468461.70) | 2000             |
| NZ-03    | South-west of Xinbaoan Town (X: 362370.19, Y: 4477438.93) | 3500             |
The reasons that determined the drilling sites would be illustrated with NZ-02 in three aspects (Figure 4):

1. The target area is located in NW side of the NE direction gratitude zone of regional gravity and aeromagnetic anomaly map, which indicate the position of fault.
2. The inversion results of line 6 of CSAMT and line 6 of MT reveal that the lateral resistivity varies evidently in this area. A significant low resistivity zone exists and extends below the depth of 3000 meters. This indicates that the deep karst is water-abundant with the influence of faults (Figure 4a, Figure 4b).
3. On seismic line 5, the event of CDP points 670-710 leaps obviously, which indicates that strata T2 dislocated Jixian System and the fault throw is roughly 500 meters (Figure 4c).

3. Conclusion

Based on the analysis of collecting data and focusing on the geothermal resource exploration target, we carried out gravity, electromagnetic and seismic data collection, processing, and interpretation in Xuanhua-Huaihai area.

1. Geothermal-related fault structures are roughly divided into three groups: near EW direction, NEE-NE-NNE direction, and near NW direction.

2. The reservoir lithology in east Xuanhua area is dolomite of Jixian and Changcheng System, with depth between 0 ~ 2200 meters. In the Huazhuo basin, the thermal lithology is dolomite of Jixian and Changcheng System on the south side of the fault, and on the other side, it is mainly Archean gneiss. In the Donghuayuan area, the thermal reservoir is dolomite of the Wumishan Formation, Jixian

![Figure 4. Integrated interpretation profile for NZ-02 optimization. (a) profile of contour map of CSAMT resistivity inversion, (b) profile of contour map of MT resistivity inversion, (c) profile of 2D seismic depth, (d) profile of integrated interpretation result.](image-url)
System. Close to Guanting Reservoir, the thermal reservoir depth becomes larger to about 1000 meters under the control of NE normal fault, and the reservoir thickness is also about 1000 meters.

3. Mesozoic magmatic activities in the working area are frequent. Many intrusive rock masses exist. Some of them outcrop in the mountain area, and some are buried in the basin.

4. In addition, the work petrophysical property is not abundant. We are also short of the thermal properties of deep-hole rocks and borehole (steady-state) temperature measurement data. Reference to adjacent area data brings errors to the temperature estimation of designed borehole. The lack of deep hydrogeological data would cause some problems in estimating the water-abundance of the reservoir based on the geophysical results.

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