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Application of Time-frequency Electromagnetic Method in The Exploration of Deep Geothermal Resources

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ABSTRACT

With “deep into the earth “proposed, the exploration of deep geothermal resources has become the forefront of geothermal resource exploration. As an important part of deep geothermal resource exploration, geophysical survey has the technical characteristics of greater depth, higher precision and efficiency, lower cost and so on. At present, due to the increasing depth of geothermal exploration and the constantly improved detection accuracy, the detection effect of ordinary electromagnetic method is obviously insufficient. Time-frequency electromagnetic method (TFEM) is widely used in petroleum, shale gas, coalfield and other exploration areas with its advantages of stronger anti-interference capability, greater exploration depth, combined time and frequency domain analysis, and obtained a variety of electrical parameters. Based on the exploration of deep geothermal resources in the Dongli lake area of Tianjin, TFEM has been used for the first time in the sedimentary basin of the north China plain. The result shows that TFEM can extract the real earth’s electromagnetic information under the condition of strong background noise, achieve effective exploration depth of 5 km, furthermore, divide stratigraphic structure and determine the fault location accurately combined with seismic, well logging, borehole drilling and other geologic information.

1. INTRODUCTION

The exploration of deep geothermal resources is one of the hot spots in the field of energy exploration today. The primary task to be solved is to explore the distribution of thermal reservoirs and geological structures. Due to the complex geological background of China, the buried distribution of deep heat-storage and the geological conditions of hydrothermal enrichment are complicated. The geophysical exploration of deep geothermal resources and geophysical characteristics of space distribution of thermal storage are undoubtedly the key and technical basis for resource investigation, evaluation and target selection. In addition, with the continuous development and utilization of geothermal resources, the mining depth is getting larger and the mining risk is increasing. Developers pay more and more attention to the preliminary geophysical exploration, which can not only improve the exploration effect of geothermal fields, reduce the cost, but also reduce the investment risk (Huang et al., 2004).

At present, seismic exploration, magnetotelluric sounding (Li et al., 2009), controlled source audio-frequency magnetotelluric (CSAMT) (Di et al., 2007) (Li et al., 2013) and imaging survey of natural seismic background noise (Zhang et al., 2017) are widely used in the exploration of deep geothermal resources. Seismic exploration is greatly restricted by the working area, and there are some problems such as low energy of vibroseis, which cannot reach the target exploration depth, distortion of data collection caused by traffic, human culture and power interference, as well as high exploration cost. Magnetotelluric sounding method needs to solve problems such as survey area selection, avoidance of electromagnetic interference, low vertical and longitudinal resolution, large deviation between local section inversion results and geological interpretation and actual geological situation caused by multiple solutions of spectrum curve, etc. (Li et al., 2009). In practical application, solving regional deep structure and stratum control may achieve better exploration results. CSAMT also has problems such as survey area selection and avoiding electromagnetic interference. Non-plane wave effects cause distortion of resistivity and phase in the "transition zone" and "near zone", and data processing problems such as identifying and suppressing shadow and field source additional effect also need to be solved urgently(Tang et al., 2015). In addition, the exploration depth is limited, and it is better to find out the formation structure and geological structure at a shallow exploration depth of 2km (Sun et al., 2015). Data acquisition of natural seismic background noise imaging survey must consider the strength of seismic activity, the number of seismic stations and long-term continuous high sampling records, and other factors. In the case of lack of accurate location of source or uncertainty of source parameters, it will bring great deviation to underground imaging. At the same time, because most natural earthquakes occur in specific areas, the distribution is very uneven, so the impact on imaging is great (Qi et al., 2007).

To solve the effective exploration depth, avoid electromagnetic interference, improve resolution, reduce cost and other issues as well, TFEM is used to detect deep geothermal resources of sedimentary basin in the north China plain for the first time, aimed at division of strata structure accurately, determining the fracture structure which influence or control the distribution of the deep geothermal resource. As the underground hot water, tectonic zone and fault zone, etc., have great electrical differences with surrounding rocks, and the electrical response characteristics of which are relatively low resistivity and high induced polarization (IP), so it has a better premise for electromagnetic method.

TFEM is a kind of electromagnetic exploration method developed by Bureau of Geophysical Prospecting INC., China National Petroleum Corporation based on CSAMT and Long Offset & Window Transient Electromagnetic Method (LOTEM) (Zhang et al., 2015). At present, it is widely used in the field of oil and gas exploration, and its exploration field is still expanding. It has also been applied in the study of water-rich limestone in coalfield (Zhou et al., 2013), dynamic monitoring of complex oil and gas target exploitation (Suo et al., 2007), rapid identification of shale gas "sweet spot" target (Zhou et al., 2015) and other aspects.

Compared with passive source electromagnetic exploration, the data collected under electromagnetic field stimulated by high power artificial field source has a higher signal-to-noise ratio under the strong background noise interference, which is helpful to distinguish the IP anomaly characteristics. In the time series data collection, zero square wave is adopted, and there are various combinations, continuous stimulation ranging from high frequency to low frequency, and each frequency is repeatedly stimulated for several times, the data quality and reliability are high. The exploration depth is related to the excitation period, the length of transceiver distance and the excitation current, and the longer the excitation period is, the deeper the exploration depth will be (Zhao et al., 2014). With the advantages of both frequency domain method and time domain method, there can be two processing methods in time domain and frequency domain. The exploration accuracy is effectively improved by using various means to study the petrophysical properties of various fields comprehensively.

2. OVERVIEW AND ELECTRICAL RESPONSE CHARACTERISTICS OF THE STUDY AREA

2.1 Geothermal conditions

The Dongli lake area in Tianjin has good geothermal geological conditions, and two types of heat storage are developed from top to bottom, the upper Minghuazhen Formation (Nm) and Guantao Formation (Ng) of Neogene (N) with sandstone and conglomerate as the pore type thermal storage, and the lower Changping Formation and Wumishan Formation (Jxw) of Ordovician (O) and Cambrian (Є) with limestone and dolomite as the karst fissure type thermal storage. The development and utilization of bedrock thermal reservoirs are mainly the thermal reservoirs of the Jxw of Jixian (Jx) System, and the lithology is mainly carbonating rocks. It is the main mining layer with the deepest mining layer, the largest mining intensity and the highest fluid temperature in Tianjin area (Li et al., 2007), followed by the O thermal reservoir.

2.2 Background of geological structure

The tectonic location of the study area is located on Panzhuang uplift. Panzhuang uplift tectonic area belongs to the third level tectonic unit of Cangxian uplift, which is located in the north of Cangxian uplift. On the plane, it is a long and narrow fault block with NE orientation. In the northeast, Hangu fault is the boundary and it connects with Wangcaozhuang uplift. The southern boundary is bounded by Haihe fault and connected with Shuangyao uplift and Baitangkou depression. Northwest and southeast are bounded by Tianjin fault and Cangdong fault respectively, and are adjacent to Dacheng uplift and Beitang depression. In general, it is an asymmetrical hora extending in the northeast, and it is partially raised or sunken. The Pre-Cenozoic basement belongs to the two wings of the residual semi-anticline above, which is of high south-western and low north-eastern distribution. The strata are mainly composed of the Mesozoic, Paleozoic, and Meso-Neoproterozoic, and the upper Cenozoic is about 1400~1900m thick, without the N. There are mainly Cangdong fault and Tianjin fault.

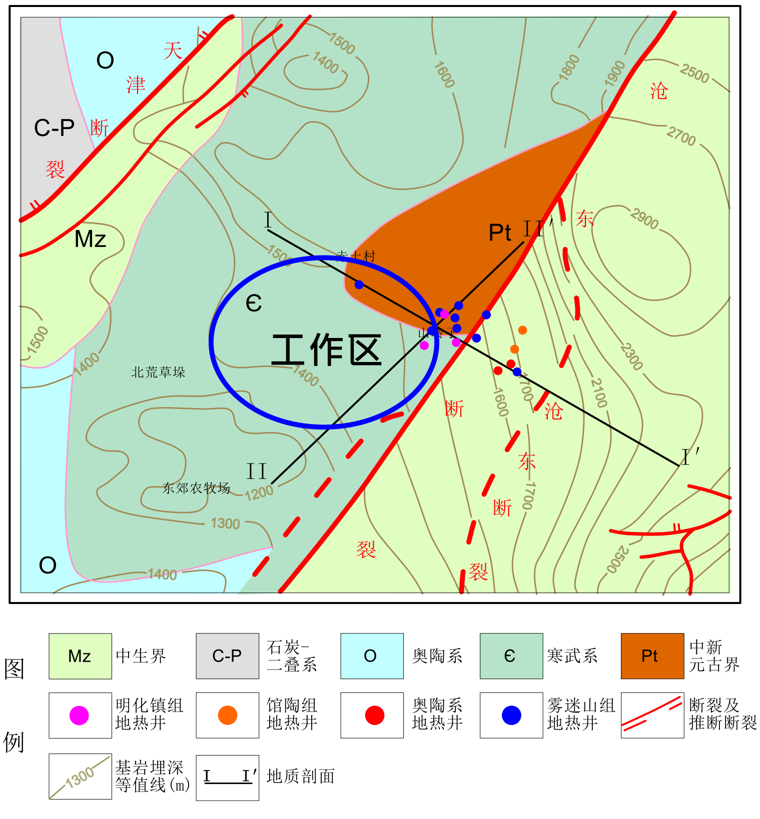

Figure 1: Geological map of bedrock in Dongli lake area in the south of Panzhuang uplift

Cangdong fault is an important buried fault that controls the geological formation of Cangxian uplift and Huanghua depression. The fault is deep at the bottom of the upper crust and the upper middle crust, and tends to extend for 10km in the horizontal direction. Due to the influence and control of Cangdong fault and its secondary fault, the upper crust can transfer the upper thermal energy of the lower reservoir to the shallow part in the form of thermal convection, the influence scope decreases with distance from the fault zone (Wang et al., 2013). On the whole, the fault zone and the two disk rock bodies have strong ability of conducting water and thermal from the northeast to the southwest (Zhao et al., 2006), but there are some local differences.

Tianjin fault is a multi-stage active fault, which is the internal fault of Cangxian uplift, also the boundary between Dacheng uplift and Shuangyao uplift, Dacheng uplift and Panzhuang uplift. It has played a great role in geological history, forming dislodge of Paleozoic, which is the growth fault of Paleozoic. It controls the distribution of Ordovician, and the lower Paleozoic in the west is thicker. The drilling results show that the Tianjin fault plays a certain role of water insulation for the thermal storage of Jxw.

2.3 Electrical response characteristics

The difference among the geophysical characteristics of underground stratum is the precondition of geophysical exploration. On the basis of a lot of previous geophysical exploration (Yang et al., 2009) (Wang et al., 2010) (Li et al., 2010), the corresponding relationship between electrical abnormal layers and geological strata is established through the understanding and qualitative analysis of the macroscopic vertical electrical structure of strata in Dongli lake area of Tianjin, as shown in table 1.

Table 1: The statistical table between formation lithology and its electrical response characteristics in the study area

Stratum	Apparent resistivity (Ω·m)	Lithology	Characteristic description	Remarks
Quaternary (Q)	5～12	Sand and clay interlayer	Low resistivity, uneven electrical properties	Cap rock
Neogene (Nm_2)	0～80	Mainly sandstone, mudstone, siltstone and fine sandstone interbedded	Relatively high resistivity and unclear boundary with Quaternary	Geothermal reservoir
Neogene (Nm_1)	4	Mudstone, fine sandstone interbedded, sandwiched with more siltstone and calcareous nodules	Low resistivity	Geothermal reservoir
Neogene (Ng)	6	Mainly gravel sandstone, sandwiched with mudstone and silty mudstone	Low resistivity, higher than Nm_1	Geothermal reservoir
Neogene(E_3d)	15	Mudstone, mudstone and sandstone interlayer	Relatively low resistivity	Geothermal reservoir
Neogene (E_2s_1)	5	Mudstone, intercalated limestone and siltstone	Low resistivity	Geothermal reservoir
Neogene (E_2s_2)	15	Mudstone interbedded with siltstone	Relatively low resistivity	Geothermal reservoir
Before the Carboniferous (AnC)	＞100	Mainly coarse conglomerate, with a small amount of mudstone	High resistivity	Cap rock
Cambrian (€)	125	Mainly dolomite, containing brecciferous limestone, intercalate mudstone and shale	Relatively high resistivity	Geothermal reservoir
Qingbaikou (Qb)	100	Mainly argillaceous limestone in the upper part, quartz sandstone in the lower part	Relatively high resistivity	Cap rock
Jixian (Jxw)	＞300	The third and fourth member: mainly dolomite, mixed with mudstone, calcareous mudstone and dolomite limestone, with 2～5 layers of red-brown mudstone at the bottom	High resistivity	Geothermal reservoir
		The first and second member: mainly dolomite, with a small amount of sand-bearing mudstone and argillaceous limestone		Geothermal reservoir

The sedimentary strata of the study area develop Quaternary (Q), N, €, O, Qingbaikou (Qb) and Jx developed in from new to old (Gao, 2003). According to the electrical characteristics of the strata, it corresponds to five electrical layers. The apparent resistivity has the electrical response characteristics of "higher-lower-low-high-higher". The upper strata of the Nm show high resistivity, while the lower strata of Nm, Ng and Shahejie Formation (E_2S) are low resistivity. The Dongying Formation (E_3d) and the Second Member of E_2S appear low resistivity relatively, the resistivity of Pre-Carboniferous is more than 100 Ω•m, characterized by high resistivity as well. The apparent resistivity of € and Qb are between 100 and 125Ω•m, characterized by relatively high resistivity layer. However, the Jxw is higer significantly.

3. WORKING PRINCIPLE AND DATA PROCESSING OF TFEM

3.1 Working principle

TFEM combined time domain sounding with frequency domain sounding chooses different frequency and different types to excite the waveform according to the depth of exploration (Dong et al., 2008). Not only frequency sounding curves, but also multi-group excitation attenuation curves can be obtained by frequency division and time domain processing of different frequency signals in the process of data processing. TFEM is used to change the length and frequency of waveform for electrical sounding at different depths, rather than changing the geometric size. By introducing polarization effect into the inversion model, the Cole-Cole model can simultaneously research several parameters, such as electric field, magnetic field, resistivity, polarizability, multi-group phase and dual-frequency phase, which reflect different aspects of petrophysical characteristics (He et al., 2014).

3.2 Construction method

The field construction of TFEM adopts dipole equatorial array, which is divided into two parts: transmitting and receiving. The transmitting terminal is composed of horizontal finite length grounding wire source composed of several copper wires in parallel. High power transmitter is used to send a series of rectangular pulse currents underground at different frequencies. The receiving terminal measures the electrical component Ex through the grounding wire MN, and the vertical derivative of the magnetic induction component through the earth-free coil or the high-sensitivity magnetic bar (Sun and Shi, 2017). TFEM adopts the working mode of arranging to receive multiple measuring stations. Each measuring station is composed of electrical and magnetic collection stations. The signal receiving system synchronizes with the transmission through GPS and receives all signals repeatedly excited at each frequency. Field construction arrangement of TFEM is shown in figure 2 (Liu, 2003) (Wang et al., 2006) (He et al., 2010).

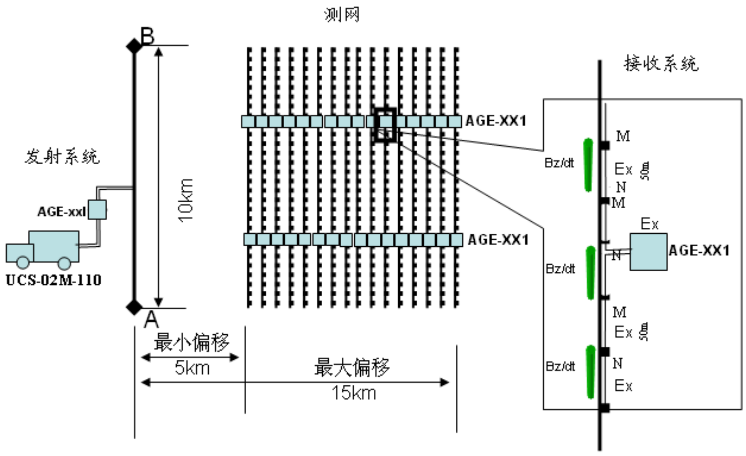

Figure 2: Layout diagram of field construction of TFEM

3.3 Data processing and inversion calculation

The data processing of TFEM has a fairly complete procedure, mainly including data preprocessing, obtaining geoelectric parameters and apparent resistivity inversion.

3.3.1 Data preprocessing

Firstly, time domain data preprocessing is carried out. The interference is serious when the data are collected in the field through railway, highway and high-voltage transmission line. The purpose of pretreatment is to eliminate or suppress the influence of interference factors, so that the signal can truly reflect the electrical characteristics of the formation.

Then the amplitude and phase are extracted. The time series signals of each frequency need to be Fourier transformed to obtain the real and imaginary parts of each frequency and its three harmonic and five harmonic field components after the preprocessing is completed. Then, taking the period as the abscissa and the real or imaginary part of the field component as the ordinate, the curve of the field component in frequency domain was made.

Finally, geoelectric parameters are obtained. All kinds of interference are eliminated or suppressed through the above series of treatments, and the results are corrected caused by the corresponding characteristics of the instrument and the different parameters of the device. The actual observation results, observation field values and comprehensive geoelectric parameters are gathered into sections to generate a series of qualitative maps, which are used for qualitative analysis and interpretation.

3.3.2 Inversion calculation

Occam inversion method is used for 2D apparent resistivity inversion of TFEM. Occam inversion is a regularized inversion method, which requires the smoothest model while pursuing the maximum fitting between simulated data and the original measurement curve. Therefore, it is less affected by the initial model and can achieve stable convergence (Zhou et al., 2006). The apparent resistivity inversion section can give the objective laws of the variation of the resistivity of underground medium with depth, provide the quantitative variation law of the electrical property of the stratum in both directions, and can accurately reflect the law of the stratigraphic relief form and geoelectric structure of the stratum along the measured line. On the one hand, the apparent resistivity inversion section reflects the regional geological characteristics, on the other hand, the fault structure is an important basis for studying the regional geological characteristics and lithology and lithofacies.

4. ANALYSIS OF EXPLORATION RESULTS

In order to research the distribution of geothermal resources in the Panzhuang uplift tectonic area in Tianjin and find out the location, scale and characteristic of Cangdong fault and its secondary faults, four survey lines (124 coordinate points) has been deployed with a length of 24.40km and a point distance of 200m, as shown in FIG. 3. The starting instrument consistency test, the finishing instrument consistency test and the transceiver distance parameter test were carried out before the field data collection. 38 acquisition stations and 8 emission sources were arranged. The maximum and minimum values of the AB distance are respectively 6.820km and 6.098km, the maximum and minimum transceiver distance are 7.834km and 6.458km, and the maximum and minimum values of the supply current are 85A and 90A.

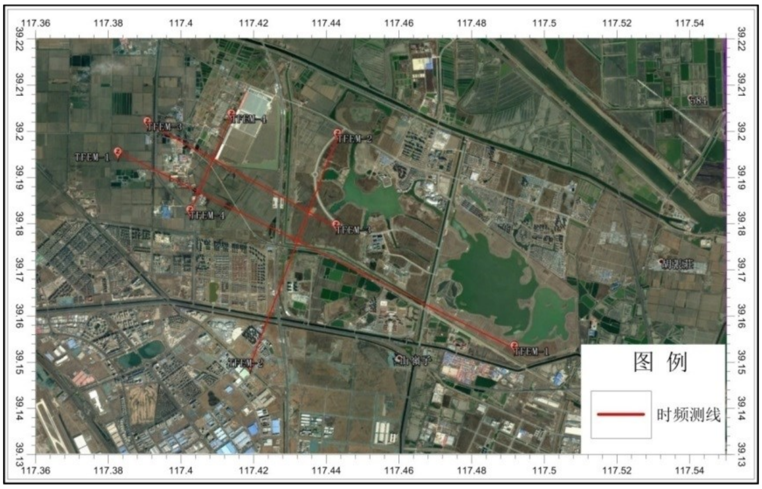

Figure 3: Deployment map of survey lines in Panzhuang uplift

4.1 Horizon calibration

Stratigraphic development on both sides of the fault is different due to the influence and control of Cangdong fault, the strata are demarcated in the eastern and western regions respectively.

4.1.1 Horizon calibration of western region

Combined with geology, seismic, borehole CGSD-1 and well-logging, horizon calibration of time-frequency apparent resistivity inversion profile has been carried out. Taking the TFEM 3 survey line as an example, there are five sets of electrical layers (FIG. 4), showing the abnormal response characteristics of "lower-high-low-high-higher" in the 2D apparent resistivity inversion profile. According to the existing petrophysical data, the main strata include Q, N, Є, Qb and Jx. The apparent resistivity of Q and N are generally low resistivity with uneven electrical properties. The relatively high resistivity is the response characteristics of the upper section of the Nm, which is given priority to with sandstone, mudstone, siltstone and fine sandstone, apparent resistivity in 30~80Ω•m. The apparent resistivity of dolomitic limestone in Є is about 125Ω•m, while it is as high as 300~400Ω•m in the Qb and Jx.

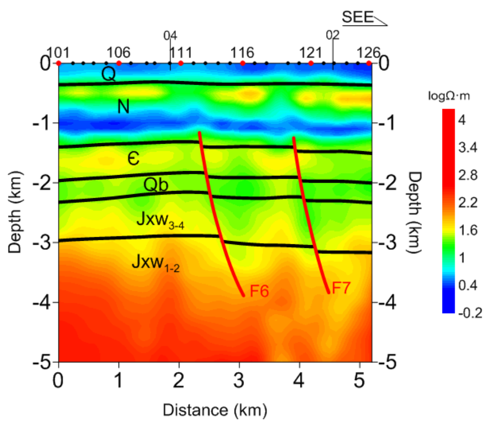

Figure 4: 2D apparent resistivity inversion profile of TFEM-3

4.1.2 Horizon calibration of eastern region

Take the TFEM-1 survey line as an example, the 2D apparent resistivity inversion profile is shown in figure 4, and the borehole CGSD-1 is located at the point 124. Electrical characteristics between no.101~141 points mainly show an abnormal feature of "lower-high-low-high-higher", which is similar to TFEM-3 survey line. The "lower-high-lower-low-high-higher" anomaly features are mainly observed at the 141~ 152 points and the main strata include the Q, N, E_3d, E_2S, and Jxw. The lithology in E_3d and E_2S is mainly mudstone, apparent resistivity of which is about 5Ω•m, characterized by obviously low resistivity. The deep high resistivity is the electrical response characteristics of the third member of E_2S, and the higher resistivity is Jxw.

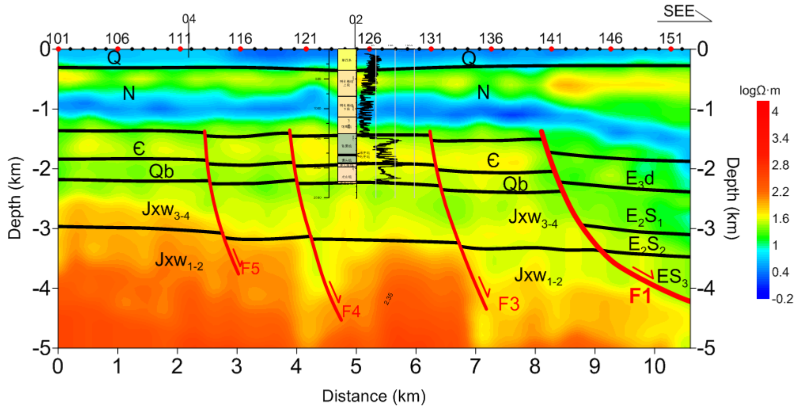

Figure 5: 2D apparent resistivity inversion profile of TFEM-1

4.2 Fault tectonic system

4.2.1 Fracture tectonic interpretation of TFEM-1

As can be seen from geological section map of TFEM-1 survey line (FIG. 6), the apparent resistivity is abnormal and continuous without distortion and dislocation at a depth of less than 1500m. The distortion and dislocation of apparent resistivity occur at point 141 at a depth of more than 1500m, which is speculated to be caused by transverse dislocation of the electrical layer due to the Cangdong fault. The abnormally high apparent resistivity between 101 and 140 points is mainly distributed at the depth between -1500m and -1800m and below -2800m, and the deep low resistivity layer between 141 and 152 points extends to -4000m, which is speculated to be caused by the thickening of N and Paleozoic strata to the east of Cangdong fault. In addition, the high resistivity layer at points 113, 120 and 131 has distorted and dislocated phenomenon in the longitudinal direction and the depth range is expanded, which is speculated to be the secondary influence caused by fault. Therefore, TFEM-1 mainly developed four faults, all of which were extensional normal faults. F1 shows a feature of steep shallow part and gentle deep part. F3, F4 and F5 faults leads to the gradual deepening of the top surface of E_3d in the SEE direction.

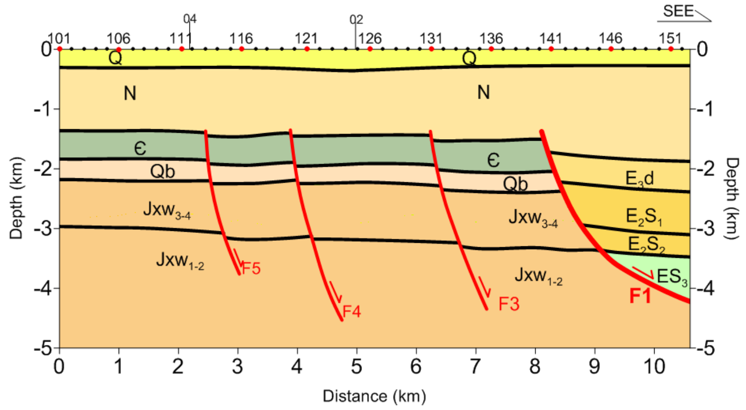

Figure 6: Geological map of TFEM-1

4.2.2 Regional fault tectonic system

The fault tectonic system in the Panzhuang uplift tectonic area is analyzed through data processing, 2D apparent resistivity inversion and geological interpretation of the original data of four survey lines. From fracture distribution map of top surface in three or four number of Jxw (figure 7), the working area is mainly explain 7 faults. The F1 being a NNE deep fracture, is Cangdong fault, and F2 is Shanlingzi fault, being a NWW cap fracture. The two main faults are extensional normal faults, while most of the others are NNE and NWW oriented.

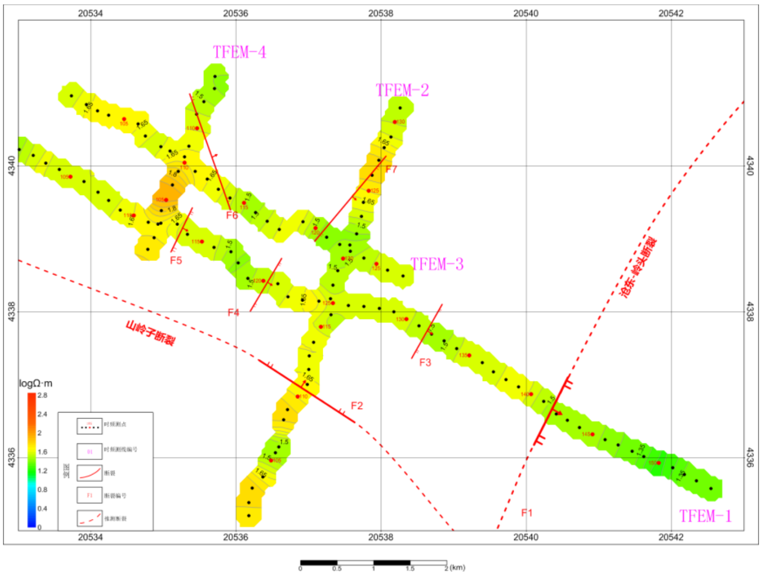

Figure 7: Fraction distribution of the top surface in the third and fourth Member of the Womeishan Formation

The faults cause the gradual subsidence trend from south to north. Meanwhile, the Cenozoic strata have gradually thickened from the west to the east due to the development of N strata to the east of Cangdong fault. The top surface gradually deepens affected by the development of F3, F6 and F7 faults in the northwest and the buried depth of the top surface gradually deepens was influenced by F4 and F5 faults in the east. Meanwhile, the N was also developed under the influence of Cangdong fault in the east. Affected by the F2 fault in the south, the buried depth of the top surface in the Jxw gradually deepens.

5. CONCLUSION AND SUGGESTION

The stratigraphic structure within a depth of 5km was accurately divided through TFEM survey in Dongli lake area, and NNE trending Cangdong fault, NWW trending Shanlingzi fault and five secondary extensional normal faults were identified. The application of TEFM to explore deep geothermal resources under the interference of strong background noise is effective and has certain significance of popularization and reference.

Due to the low vertical resolution, electromagnetic inversion results and geologic interpretation precision is not enough, it will make stratigraphic calibration and fracture structure interpretation more authentic and reliable if combined with well-known geological, geophysical, borehole drilling, well-logging and other related information in the data processing and interpretation to carry out deep geothermal resource exploration, and multi parameter constraint, joint inversion and the comprehensive information interpretation. In this way, the information of deep strata and structure information can be extracted effectively, and the spatial morphology and characteristics of deep thermal storage can be depicted profoundly.

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