Research on the Geothermal Resource Exploration in Igneous Rock Areas by Comprehensive Geophysical Methods

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Abstract

Geothermal resource has considerable development potential and utilization value. In order to have a clearer understanding and understanding of geothermal resources, it is very important to carry out geological exploration of geothermal resources before mining. In Igneous rocks, ground water is heated by deep magmatic rocks and Igneous rocks to form geothermal resources, but their communication is poor and the depth of burial is generally large. The traditional geophysical method, such as the excitation polarization method, is difficult to reach the effective detection depth, and the precision is poor. In this paper, the comprehensive geophysical method based on CSAMT and TEM is applied to geothermal exploration in igneous rock area, which makes up for the shortcomings of single method and achieves good detection effect, which provides reliable geological basis for further development and utilization of geothermal resources.

Introduction

As a green, low-carbon clean energy, geothermal resources have huge reserves and are widely distributed in my country. However, my country's currently utilized geothermal resources are less than 5‰ of the reserves, and further development and utilization of geothermal resources have broad prospects (Shi 2005). The buried depth of geothermal resources is generally large, most of which have exceeded 2000m, and the risks taken during mining are great. In order to have a clearer understanding and understanding of geothermal resources, it is necessary to conduct a geological survey of geothermal resources before mining to find out the depth, location and reserves of geothermal resources. In the exploration of geothermal resources, geophysical methods are an effective method (Wang et al. 2000; Yang 2017; Kang 2018).

Among the geophysical methods, the controllable source audio frequency magnetotelluric sounding method (CSAMT), transient electromagnetic method (TEM) are relatively effective methods for the exploration of geothermal resources, but each method has It has its own limitations (Munoz et al. 2004; Yin et al. 2007; Di Q et al. 2008; Spichak et al. 2009; Yang et al. 2009; Zhao et al. 2015). In recent years, comprehensive geophysical exploration methods (mainly CSAMT, supplemented by TEM) have been used to explore geothermal resources in igneous rock areas, and relatively ideal exploration results have been achieved.

Geophysical Characteristics Of Geothermal Resources In Igneous Rock Areas

Different rock formations have different conductivity. Generally speaking, in most igneous rock regions, due to the ancient diagenesis age, after long-term metamorphism, the formation is compact and complete, and the fractures are not developed. The resistivity is relatively uniform in the horizontal direction, and gradually increases with the increase of the depth in the vertical direction, which is not conducive to Looking for geothermal resources (Li 2010).

In some igneous rock areas, the pore water of the overlying loose layer, after receiving the vertical infiltration replenishment of atmospheric precipitation and the intermittent leakage replenishment of surface water, can flow into the deep igneous rock and the fissures of the igneous rock basement through the fault fracture zone and rock fissures. Thermal storage aquifers form underground hot water and are stored in igneous rock formations. The resistivity of eruptive igneous rocks (such as basalt, rhyolite, etc.) is generally low (20–500Ω•m), which is lower than that of granite (greater than 500Ω•m), but the resistivity of igneous rocks is generally greater than that of sediments Surrounding rock. Therefore, the difference in resistivity values between igneous rocks and sedimentary surrounding rocks can be measured by geophysical prospecting methods to determine the location of igneous rocks and igneous rocks, and then to search for geothermal resources (Zhang et al. 2012; Zhang et al. 2016).

Table 1
Statistical table of rock resistivity in Igneous area

Lithology	Resistivity (Ω·m)	Lithology	Resistivity (Ω·m)
Sand	60–100	Conglomerate	50–200
Silty clay	14–25	Limestone	100–300
Basalt	20–500	Igneous rock	>1000
Granite	500–2000		

On the other hand, in areas where faults are developed, the resistivity value will change. The activity of the fault may cause a fracture zone near the fault, and the fault will lead to the hydraulic connection between the upper and lower strata, thus forming a low-resistivity anomaly area near the fault that is close to the dip angle of the fault. Such low-resistance anomalies are in the resistivity. Generally, the cross-sectional view is relatively steep. By looking for such a steep anomaly with low resistivity, it can reflect the existence of faults, and then search for geothermal resources (Li and Liao 2002; Garyet et al. 2006)On the other hand, in areas where faults are developed, the resistivity value will change. The activity of the fault may cause a fracture zone near the fault, and the fault will lead to the hydraulic connection between the upper and lower strata, thus forming a low-resistivity anomaly area near the fault that is close to the dip angle of the fault. Such low-resistance anomalies are in the resistivity. Generally, the cross-sectional view is relatively steep. By looking for such a steep anomaly with low resistivity, it can reflect the existence of faults, and then search for geothermal resources (Li and Liao 2002; Garyet et al. 2006).

Brief Description Of The Characteristics Of Each Working Method

CSAMT

The controllable source audio magnetotelluric sounding method (CSAMT) is developed on the basis of the magnetotelluric sounding method (MT). This method overcomes the shortcomings of MT using natural field sources as emission sources, and uses artificial controllable The field source is used as the emission source to emit electromagnetic signals with a certain frequency width. The horizontal component Ex of the electric field and the horizontal component Hy of the magnetic field are observed in areas far from the field source, and the apparent resistivity is calculated (Shi 1999).

Due to the manual controllable emission source, this method has the following advantages (Tang and He 2005):

(1) Large exploration depth;

(2) Strong ability to penetrate high-resistance shielding layer;

(3) The transmitting power is large, and the anti-interference ability is strong;

(4) It is more effective for detecting high-resistance basement formation;

(5) The polarization direction is obvious, and the signal-to-noise ratio is high.

However, this method also has certain limitations:

(1) Affected by the undulations of the surface or shallow terrain, the apparent resistivity distortion of the shallow part is caused, that is, "static displacement";

(2) Due to the large exploration depth, the vertical resolution of shallow strata is relatively reduced;

(3) The lateral resolution is limited, and the ability to detect faults and other structures is slightly weak;

(4) In actual construction, electrode pits need to be arranged during signal transmission, and the construction steps are more complicated.

TEM

The transient electromagnetic method (TEM) belongs to the time domain electromagnetic induction method. The detection principle is: lay a loop on the ground, and supply a current pulse square wave to the sending loop. At the moment of the falling edge of the square wave, a primary magnetic field that propagates to the ground is generated. Under the excitation of the primary magnetic field, the geological body The eddy current will be generated, the size of which depends on the degree of conductivity of the geological body. After the primary field disappears, the eddy current will not disappear immediately, it will have a transition (decay) process. This transition process produces an attenuated secondary magnetic field that propagates to the surface, and the receiving device on the ground receives the secondary magnetic field. The change of the secondary magnetic field will reflect the electrical distribution of underground geological bodies. If the secondary induced electromotive force V(t) is measured according to different delay times, the characteristic curve of the secondary magnetic field decay with time is obtained. According to the secondary field potential and sampling time, the apparent resistivity values of different depths can be calculated, and then the underground geology can be understood based on the secondary field potential and the inverted resistivity characteristics (Wang et al. 2018; Yang et al. 2019).

The observation time of TEM is in the gap between the primary field of the next pulse after the primary field is turned off. The observation data has nothing to do with the size of the primary field, and can be separated from the primary field in time, which is called temporal separability ;According to the passage of sampling time, the secondary field signals received at a certain time node are transmitted from different exploration depths. After processing the collected secondary field signals and resistivity, the geological information at each depth can be obtained, Called the separability in space (Zhang and Pan 2004).

Based on these two separability, TEM has the following characteristics (Xu et al. 2006):

(1) Less affected by terrain;

(2) The number of construction methods is relatively simple, and the work efficiency is high;

(3) The vertical resolution is high in the shallow layer of the surface, and the detection ability of the low-resistance formation on the surface is strong;

(4) The lateral resolution is high, and low-resistance bodies such as water-conducting fault structures are sensitive.

This method also has some shortcomings:

(1) Slightly poor anti-interference ability;

(2) The exploration depth is small;

(3) The deep data error is large;

(4) There is a certain blind zone.

Comparison of electromagnetic field propagation characteristics between CSAMT and TEM

CSAMT is a frequency domain method, while TEM is a time domain method. The difference between the two methods in this respect is directly reflected in the source waveform. The difference in source waveforms makes CSAMT and TEM different in the way of data observation. CSAMT transmits and receives through a single frequency point in the frequency domain to obtain a response signal. TEM transmits wideband signals in the time domain and collects the wideband response, and signals at all frequency points can be obtained with only one transmission. From the perspective of data collection efficiency, TEM is higher than CSAMT. However, in the CSAMT transmission mode, the energy of a single frequency point in the source signal is greater than the energy of a single frequency point in the transient electromagnetic transmission mode, so that CSAMT can obtain a higher signal-to-noise ratio at each frequency point than the TEM method. However, due to the actual mutual conversion relationship between the frequency domain and the time domain, in addition to the signal-to-noise ratio and data collection efficiency, the difference in the form of data presentation will not cause the difference in the resolution capabilities of the two methods (Fig. 1).

The difference in resolving power between CSAMT and TEM is mainly caused by the different types of emission sources of the two methods. The return line sources TEM and CSAMT respectively use ungrounded return lines and grounded long wires to send signals to the ground, resulting in essential differences in the electromagnetic fields used by the two methods. Under the excitation of a long ground wire, due to the existence of the ground term, there will not only be a horizontal current induced by induction in the earth, but also a vertical induced current, so that the electromagnetic field excited by the long wire source not only contains the component of the TE mode, but can also produce the TM mode. Weight. And the non-grounded loop device can only generate horizontal current, so there is only TE mode electromagnetic field (as shown in Fig. 2.1). Because the TE mode is sensitive to low-resistance objects but not to high-resistance objects, the loop-source transient electromagnetic exploration method has poor resolution capabilities for high-resistance targets.

On the other hand, CSAMT measures electric and magnetic field components, and TEM measures magnetic field components. When the target fault of the local thermal system is covered by a shallow low-resistance layer, the abnormal response generated by the layer boundary charge accumulation will submerge the low-resistance target fault, making the target fault difficult to distinguish. In fact, the influence of layer boundary charge accumulation on electric field is much greater than that on magnetic field. On this basis, the loop source TEM can produce a better resolution of target faults in this environment. In actual exploration, since the complexity of underground media is far greater than that of geophysical analysis and modeling, comprehensive exploration using CSAMT and TEM can undoubtedly provide more information and evidence for distinguishing target faults and other geological bodies.

In order to confirm the above analysis, the electromagnetic field under the two modes of grounded line source and ungrounded return line source in a uniform half space was simulated. Since only the electromagnetic field propagation characteristics are compared here, and the difference between the time domain electromagnetic field and the frequency domain electromagnetic field is not compared, the calculation here is the diffusion of the underground current over time after the step source is turned off, as shown in Fig. 2 and Fig. 3.

Figure 2 shows the underground current distribution excited by a 400m ground wire source. The positions of the two ground electrodes of the emitter are (-700m, 0m) and (-300m, 0m), and the current intensity is 1A. It can be seen from the figure that the ground line source is excited to produce horizontal current and vertical current. On the ground, the current field is distributed axisymmetrically with respect to the ground line source. Below the source, the current gradually spreads downward and outward over time. There is an area of minimum current under the source, which spreads downward over time and the range gradually increases.

Figure 3 shows the current distribution excited by a square loop with a side length of 20m, and the center point of the loop is (0m, 0m). Different from the ground line source, the current field excited by the loop is symmetrically distributed on the ground with respect to the source position, and the current excited by the underground is distributed horizontally without vertical current.

The lack of vertical current in the electromagnetic field excited by the loop source makes the loop source transient electromagnetic exploration method lack the ability to distinguish high-resistance horizontal layers. However, because the energy is concentrated on the horizontal current, this method is extremely sensitive to low-resistance targets. On the other hand, the CSAMT method based on the grounded line source may be better than the loop source TEM in the resolution of high-resistance targets, while the resolution capability of the low-resistance target is not as good as that of the loop source TEM.

Advantages of comprehensive geophysical methods

In a certain survey area, there are great variability in geological conditions and interference conditions. The use of a single geophysical method for exploration will inevitably be affected by factors such as topography, surface construction difficulty, shielding layer, noise current, and effective exploration depth. Restrictions, there are certain limitations.

In order to overcome the limitations of a single method, the comprehensive geophysical exploration method with CSAMT as the main and TEM as the supplement is used to conduct geothermal resource exploration in the igneous rock area. Several methods can complement each other in a targeted manner and achieve relatively ideal results (Zhang et al. 2012; Wu 2016):

(1) CSAMT has a large exploration depth and insufficient resolution for shallow layers, while TEM exploration depth is relatively small and has a good detection effect on shallow layers. Several methods are integrated After exploration, it can have a relatively reliable detection effect on the shallow and deep parts (Huo et al. 2011; Chen et al. 2013).

(2) CSAMT has stronger anti-interference ability than TEM, and comprehensive exploration is adopted in the section with strong electromagnetic interference signal, which can improve the accuracy of data collection;

(3) CSAMT has higher requirements for signal transmission and data collection, while the data collection of TEM is relatively simple. Comprehensive exploration in a complex construction environment can reduce the impact caused by construction;

(4) CSAMT has obvious response to high-resistance bodies in deep basement formations, and can be used to detect high-resistance geological bodies such as igneous rock intrusion, while TEM has a better detection effect on low-resistance bodies such as water-conducting fault structures. The method can

increase the exploration resolution in the vertical direction, adopt comprehensive methods for exploration, and effectively detect both high-resistance bodies and low-resistance bodies in the vertical direction.

Project Example

Project Overview

In order to verify the effect of comprehensive geophysical methods on geothermal resources exploration in igneous rock areas, a geothermal resource exploration with comprehensive geophysical methods was carried out in a place in Huairen County, Shanxi Province, China.

This area is located in the uplift belt on the west side of the central part of the Sanggan River New Rift in the Datong Basin. It straddles the Huairen Sag and the Huanghualiang Sag uplift from west to east. Martial, Lower Ordovician, Carboniferous, Permian, and Cenozoic (Q + N) strata, with Archean granite and Late Tertiary basalt intrusions locally, among which basalt and deep igneous rocks of the Wutai Group are underground thermal Good storage of water.

This area straddles two structural units, the Huairen Graben and the Huangliang Horst, which are secondary structures of the New Rift of Sanggan River. A series of NE-strike fault structures develop in the area. The development of fault structures provides a better connection channel for various underground aquifers.

As shown in Fig. 4, 4 CSAMT survey lines are arranged in the exploration area.

In the CSAMT detection, the instrument used is the GDP32□ multifunctional electrical method workstation. The transmitting pole distance AB = 1500m, the transmitting current is 14-16A, the transmission distance is 6km; the receiving point distance of line 59 and 64 is 50m, the receiving point distance of line 10 and line 60 is 100m, and the signal frequency range is 0.125- 8192Hz.

In the TEM detection, the instrument used is also the GDP32□ multifunctional electrical method workstation, and the center loop device is used for measurement. The transmitting wire frame is a 600m×600m single-turn loop, powered by a generator, the fundamental frequency of the transmitting source is 16Hz, and the transmitting current is 15A; the distance between the measuring points is 50m.

After the CSAMT measurement is completed, a TEM measurement line is arranged near the 60 line where the CSAMT resistivity is more obvious, which is used to more accurately delineate the low resistance fracture zone, and combined with the CSAMT and TEM results.

Verified situation

In the processing of the measured data, we first use the data preprocessing software of GDP32□ to sort the collected data and remove the dead pixels, and then use the CSAMT-2D software and TEM-1D software based on the OCCAM algorithm to invert the data. The inversion results of CSAMT and TEM resistivity profiles are as follows (Fig. 6):

In general, the morphology of the resistivity profile of CSAMT and TEM is basically the same, and both show that the resistivity is medium-low resistance in the medium and shallow layers, and the resistivity gradually increases as the depth increases, and the deep substrate shows high resistance.

Comparing the detection effects of CSAMT and TEM, the differences are:

(1) TEM is better than CSAMT in the detection effect at shallow depths on the surface. CSAMT is affected by topography, the low-resistance shielding interference of the Quaternary muddy sand and clay layer is relatively large, which shows abnormal medium resistance, and the resistivity curve presents characteristics such as distortion, which reduces the resolution of shallow layers to a certain extent. Although there is a blind zone with a depth of about 100m in TEM, the low-resistance shielding layer at the shallow surface is less interference, and the resistivity value shows obvious regularity at the shallow surface, which is consistent with the actual geological characteristics.

(2) CSAMT is better than TEM in the detection effect at large depths. In the 4500–10000 point section, CSAMT has better data stratification in the deep part, while the TEM resistivity curve in this section is slightly confused, and the TEM shows a circle of the resistivity curve in the 9000–9500 point section. Closed high-resistance abnormal value. This high-resistance abnormal value should be a false abnormality caused by interference. The secondary field potential of the late TEM measurement track also fluctuates greatly in this section, lacking regularity, indicating that CSAMT has better anti-interference ability TEM.

(3) TEM and CSAMT have their own advantages in the detection of water-conducting fault structures.

Since the pure TE field mode of TEM is especially sensitive to low-resistance targets (Xue et al. 2013), this is more obvious in the reflection of F1 fault. CSAMT hardly reflects the F1 fault in the low-resistance area in the shallow part, but there is obvious low-resistance anomaly on the TEM profile. It can also be seen from the TEM secondary field potential multi-channel map that there is an obvious abnormal high value of the secondary field potential in this area.

The advantage of CSAMT for fault detection is mainly reflected in the detection of deep high-resistance basement interruption layer. In the sections of 5000m-5700m and 9500m-10000m, it is inferred that the buried depth of the Quaternary and Tertiary loose deposits is about 500m. The lower part is the basement of igneous rock, and the resistivity reflects the characteristics of high resistance. In the CSAMT cross-section map, these two sections appear as steep gradient zones, which are inferred to be F2 and F3 faults, which can more intuitively distinguish the upper and lower walls of the fault.

(4) CSAMT is better than TEM for the detection effect of igneous rock basement. In the 5800m-9300m section, CSAMT has a very obvious high-resistance response to the igneous rock basement, while the

high-resistance response of TEM is not obvious at this position, and it does not highlight the igneous rock basement.

After the completion of the geophysical prospecting construction, the drilling verification was carried out at 3350 point. The borehole encountered underground hot water at 1610m; then a pumping test was carried out. According to the results of the pumping test, the unit output of underground hot water in this area was 233m3/d. The water temperature is 58°C. This result confirmed the occurrence of geothermal water in faults and igneous rock formations of the Wutai Group.

Conclusion

(1) CSAMT and TEM are all effective methods for geothermal resource exploration, but each method has its limitations and applicability. It is not possible to use only one method to complete all geological tasks. The comprehensive geophysical method is more reliable Effect.

(2) Comprehensive geophysical prospecting is not a simple combination and addition of single geophysical prospecting methods. Instead, the best method should be selected according to the principles and characteristics of each geophysical prospecting method according to the geological tasks and geological conditions of the exploration area. Give full play to the advantages of each method.

(3) Through the principle, characteristic analysis and engineering examples of different methods, it is shown that CSAMT is better than TEM in deep detection and igneous rock basement detection, while TEM is better than CSAMT in shallow detection and water-conducting fault structure detection.

Declarations

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Author contributions

Jie Zhu: Conceptualization, writing original draft preparation;

Sheng Jin: methodology and supervision;

Sanxi Peng: soft-ware, investigation, visualization;

Yang Yang: validation, data curation, software;

Tianyu Zhang: writing-reviewing and editing;

Weizu Zeng: validation;

All authors read and approved the final manuscript.

Availability of data and material

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing financial interest.

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Figures

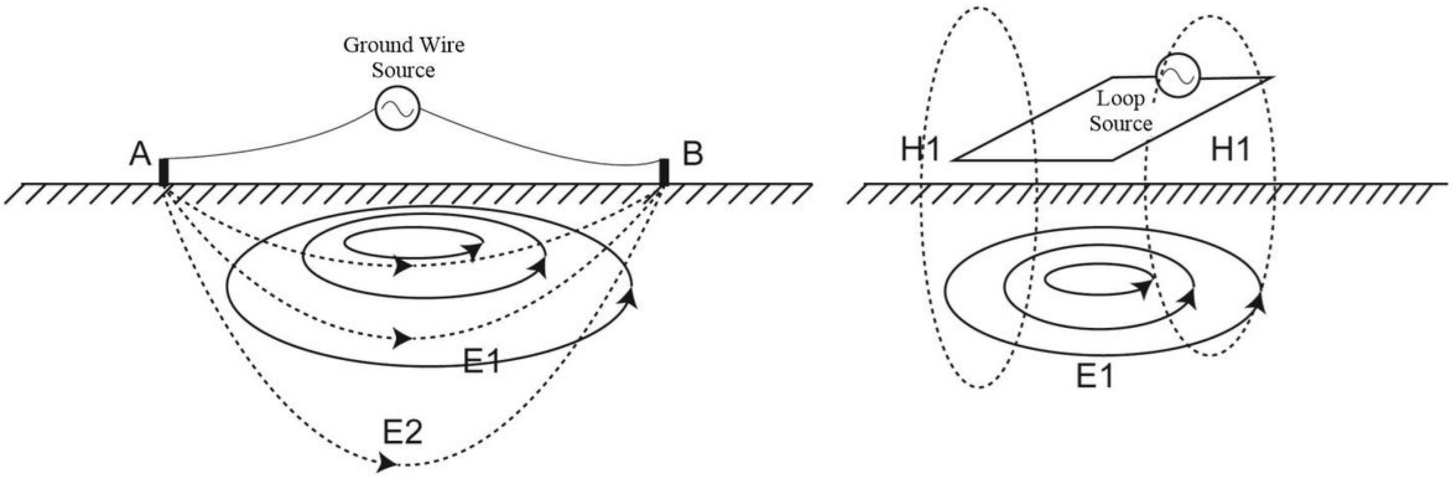


Figure 1

Contrast diagram of underground current distribution excited by ground line source and return line source in a uniform half space

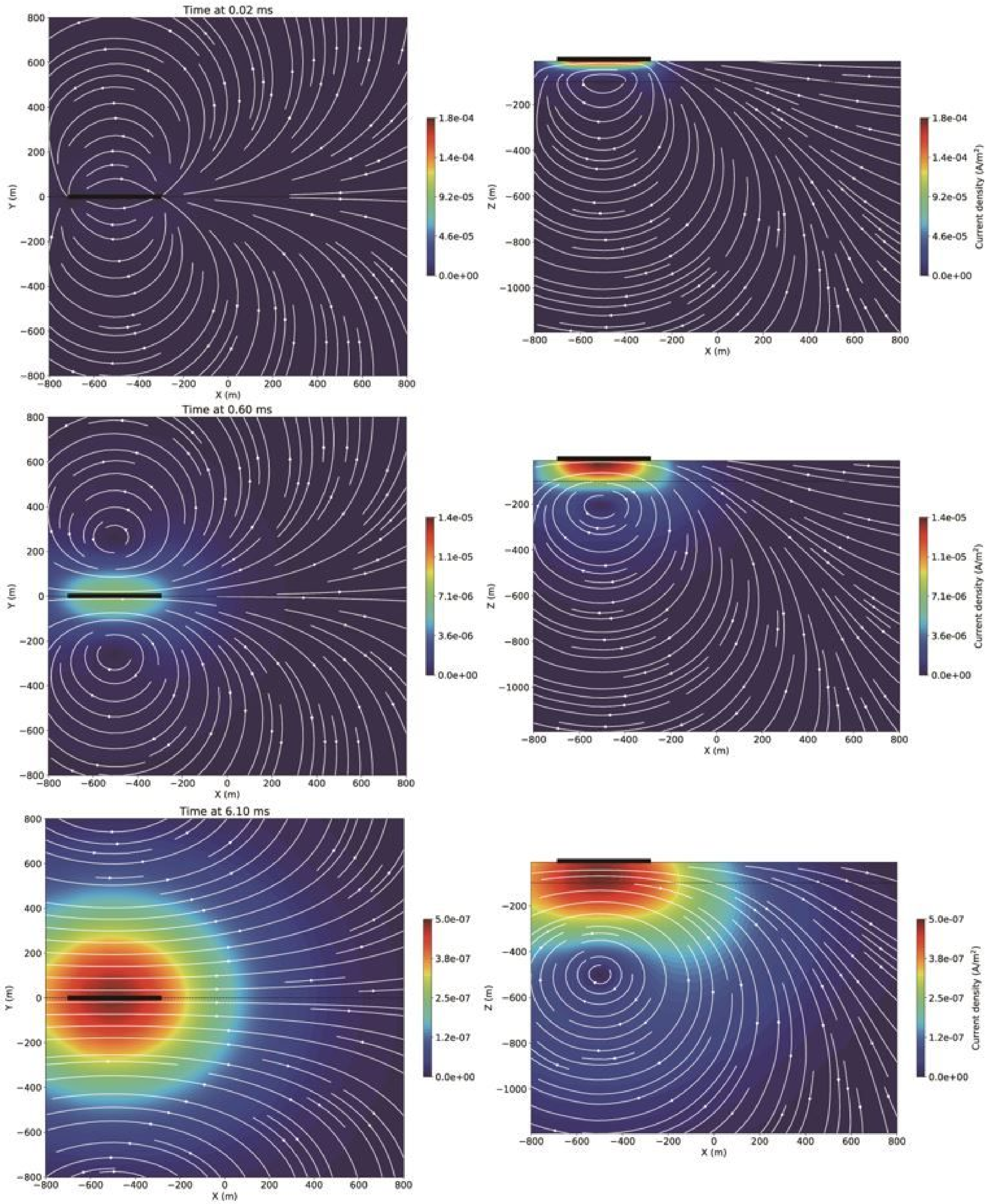


Figure 2

Comparison of underground current distribution of grounding line sources in a uniform half-space (from top to bottom, the distribution of underground current after the source is turned off for 0.02ms, 0.6ms and 6.10ms)

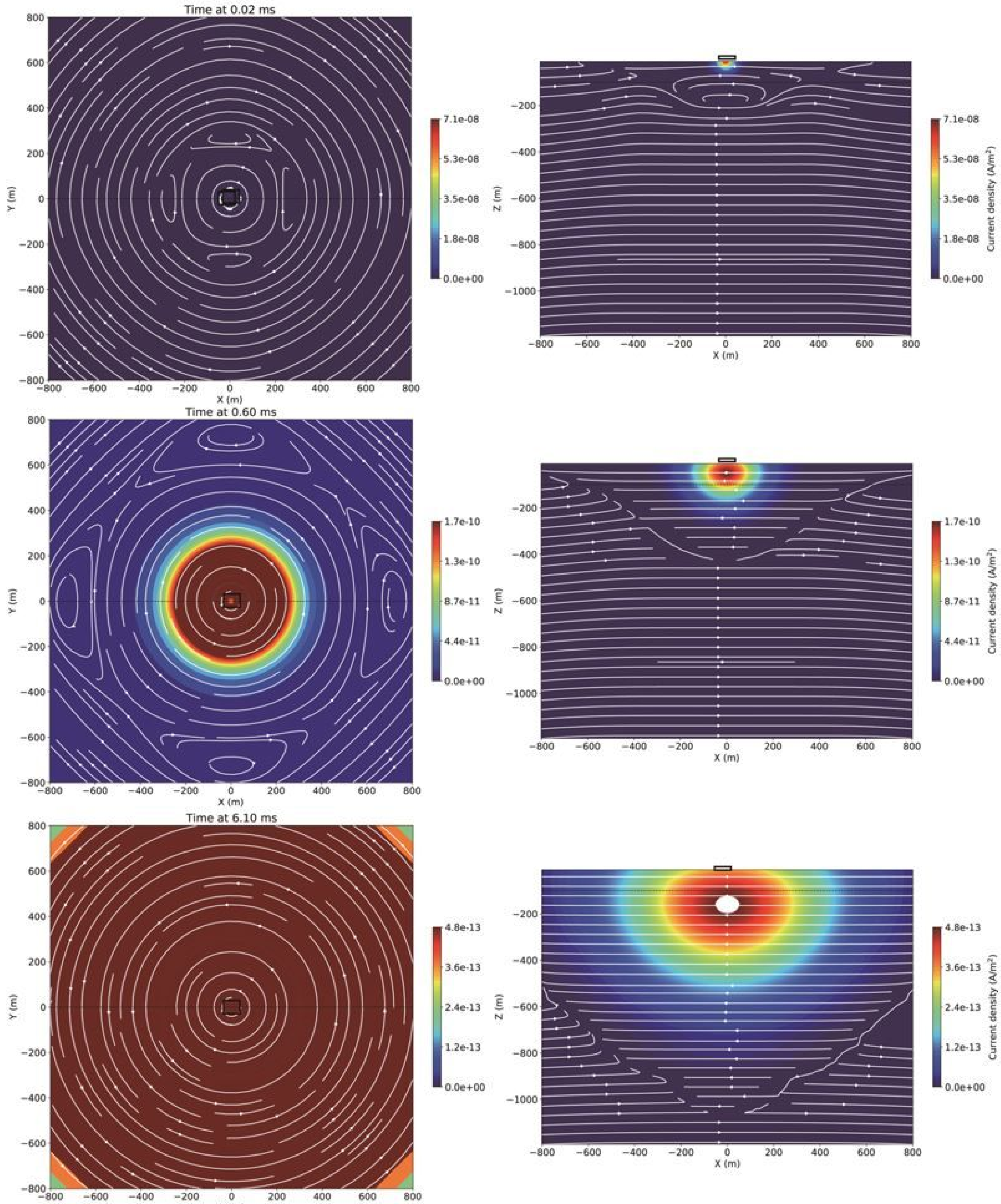


Figure 3

Comparison of the underground current distribution excited by the loop source in a uniform half-space (from top to bottom, the distribution of the underground current after the source is turned off at 0.02ms, 0.6ms and 6.10ms)

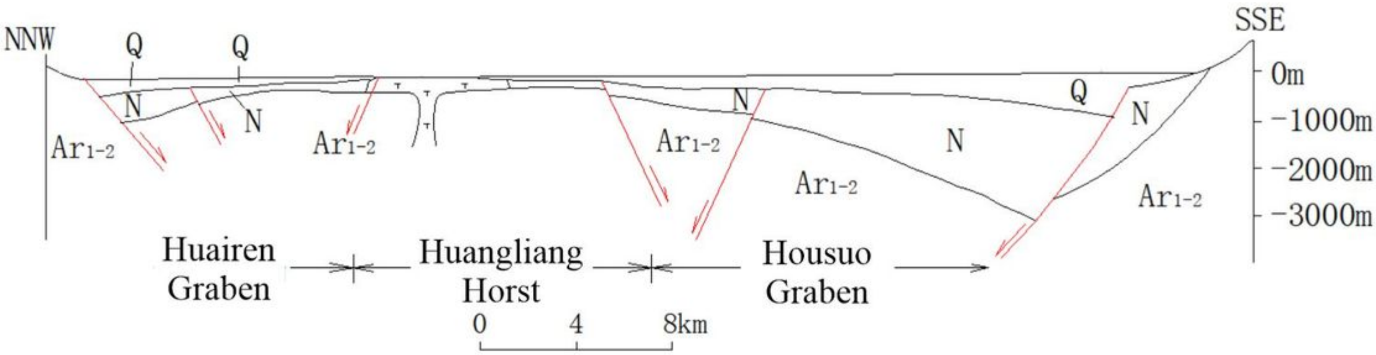


Figure 4

New rift of Sanggan River geologic section diagram

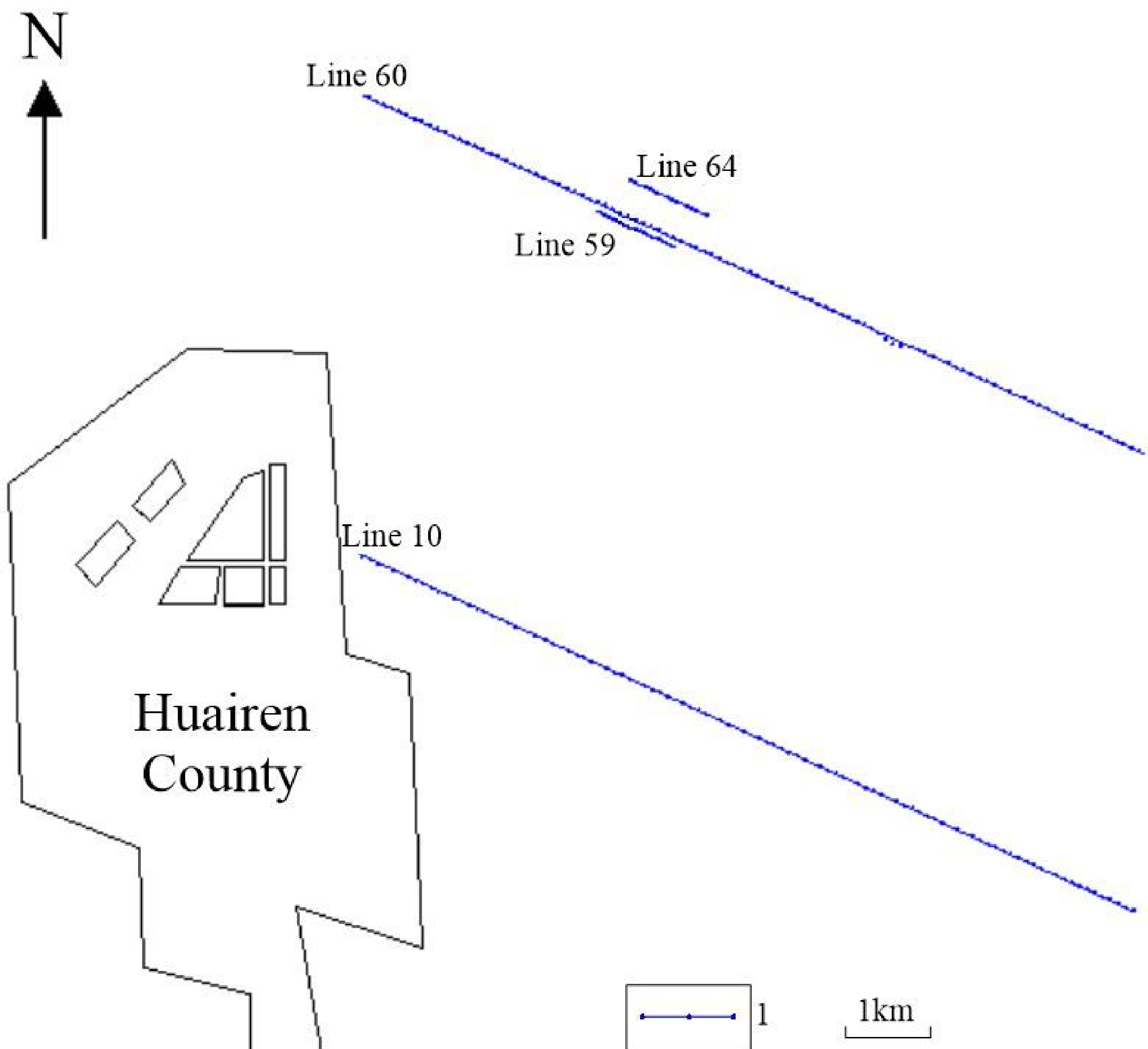
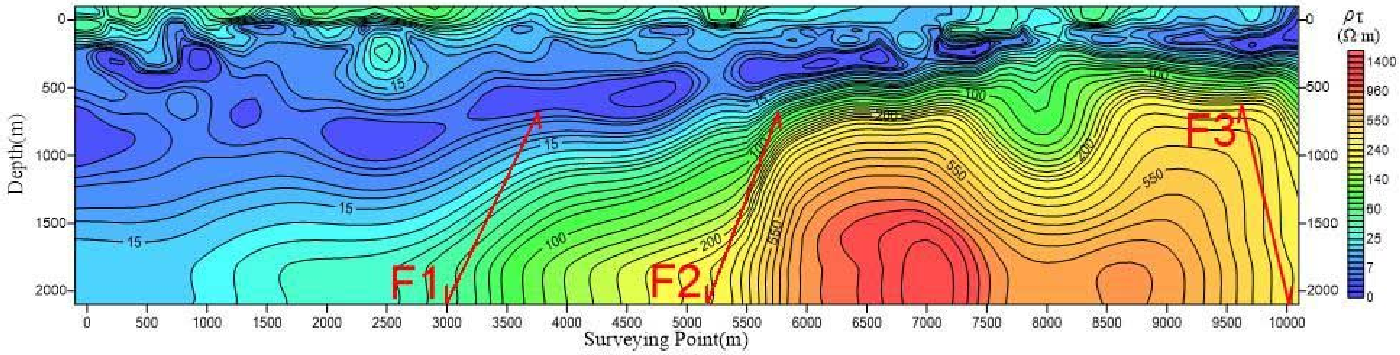
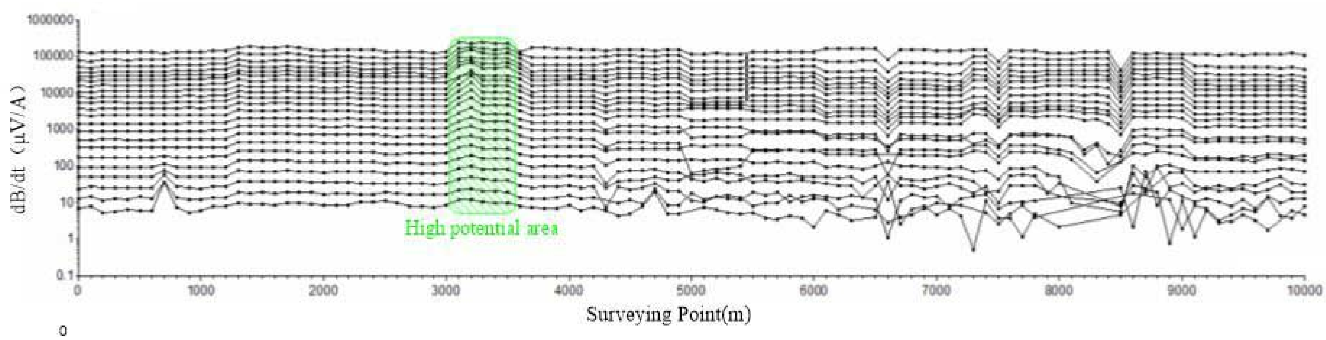


Figure 5

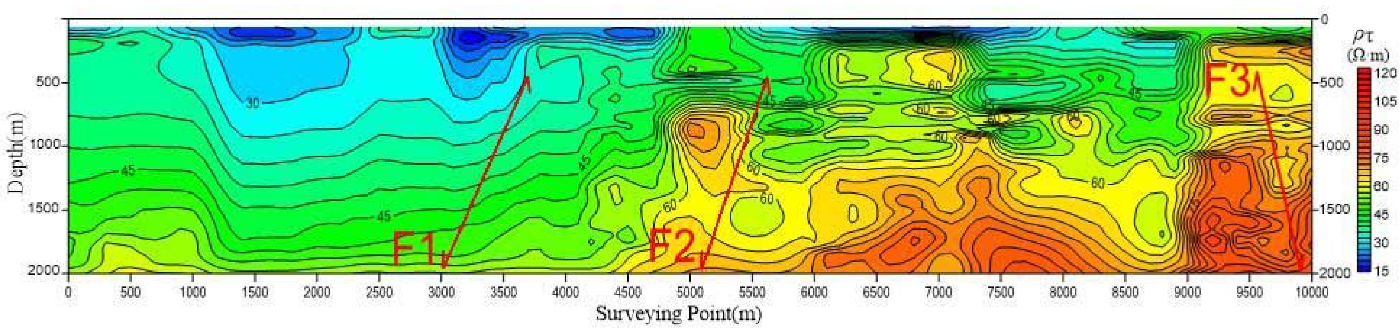
Project layout 1-Surveying points and lines



a.CSAMT resistivity profile of 60 Line



b.TEM secondary field profile of 60 Line



c.TEM resistivity profile of 60 Line

Figure 6

CSAMT and TEM contrast profile of 60 Line