Geothermal resource exploration by using Numerical simulation and comprehensive geophysical method

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Research Article

Keywords: Geothermal Exploration, Numerical simulation, CSAMT, TEM, Geophysical exploration

Posted Date: August 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-828808/v1

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Geothermal resource exploration by using Numerical simulation and comprehensive geophysical method

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Abstract:
Geothermal energy is an important renewable clean energy resource with high development and usage potential. Geothermal resources, on the other hand, are buried deep below, and mining hazards are significant. Geophysical investigation is frequently required to determine the depth and location of geothermal resources. The Transient Electromagnetic Method (TEM) and the Controlled Source Audio Frequency Magnetotellurics (CSAMT) have the highest detection efficiency and accuracy of all electromagnetic exploration methods. This article initially explains the algorithm theory of the finite difference technique before establishing a simplified geothermal system resistivity model. Established on the simplified resistivity model, a simulation analysis of the ability of CSAMT and TEM to distinguish target body faults at different resistivities and dip angles was performed, and the effectiveness and difference of the two methods in detecting typical geothermal resource targets was verified. A complete exploratory research of CSAMT and TEM was conducted in Huairén County, Shuozhou City, Shanxi Province, China, based on theoretical analysis. Both approaches can reflect the geoelectric structure of the survey region, demonstrating the efficacy of the two methods in detecting genuine geothermal resources.

Key words: Geothermal Exploration, Numerical simulation, CSAMT, TEM, Geophysical exploration.
Introduction

As a green, low-carbon clean energy, geothermal resources have huge reserves and are widely distributed in China. However, currently utilized geothermal resources in China are less than 5‰ of the reserves, and further development and utilization of geothermal resources have broad prospects (Shi B, 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 G et al., 2000; Yang L, 2017; Kang F, 2018).

Among the geophysical methods, Controlled Source Audio-frequency Magnetotellurics (CSAMT), Transient Electromagnetic Method (TEM) are relatively effective methods for the exploration of geothermal resources, but each method has its own limitations (Muraoka H et al., 1998; Spitzer K, 1995; Yang Y et al., 2009; Wang L et al., 2018; Iqbal I et al., 2021). In recent years, comprehensive geophysical exploration methods (mainly CSAMT, supplemented by TEM) have been used to explore geothermal resources, and achieved good results (Munoz Gerard, 2004; Yin M et al., 2007; Di Q et al., 2008; Zhao X et al., 2015).

However, most of the past geothermal resource exploration focused on engineering applications, and there were few geophysical numerical simulation studies, that is why in this paper we focused to correlate the numerical simulation with geophysical field data applicability. The ability of taking topography into account in a forward solver greatly depends on the numerical method. The finite difference approach used to be a popular method in the past but it is restricted only to be used in areas with flat topography (Spitzer K, 1995; Mufti IR, 1976). Alternatively, the integral equation method is usually valid for simple structures (Dieter K et al., 1969; Okabe M, 1981). Including complex topography and substructures in the modelling remains difficult with such methods. The finite element
approach was first introduced in the resistivity problem by Coggon (1971) and later further developed by many other authors. It appears to be a flexible method to model both topography and possibly complicated geometries. Initially, finite element modelling codes including topography were defined on distorted grids, using quadrangular or hexahedral elements, and were thus limited to undulating topography. These approaches using block-oriented meshes are also limited regarding the possibility of effective mesh refinements. Only recently, codes have been developed on unstructured tetrahedral meshes; allowing for complex geometries and local mesh refinements, especially around source locations. In parallel, surface integral methods are also available, with the advantage of only discretizing the top interface.

Independent of the numerical scheme, a resistivity forward solver consists of solving the electrical boundary value problem for every source location. The solution of such a system of linear equations shows a singularity at the source location. This leads to significant numerical errors in the vicinity of the electrode position. The singularity removal technique introduced to splits the potential into a singular part, related to the source, and a residual part taking into account a possible non-homogeneous conductivity model. The singular part is defined analytically for flat topography. For non-flat topography, the singular component is usually computed numerically. Even with local mesh refinement around the sources, a highly accurate solution is however difficult to be obtained as the objective is to estimate a singular function (Günther T et al., 2006). With a thorough description and history of TEM and its modeling, we discovered that TEM has never been utilized for geothermal research, and if it has been used, it has never been coupled with numerical simulation. This research will demonstrate the relationship and significance of numerical simulation and physical investigation in their respective fields of study. Furthermore, it is not required in any investigation that numerical simulation produce equally exact and matched results with field data, but it does provide a hint for future exploration in the field that is the subject of this study. We primarily simulate and evaluate the anomalies induced by changes in the resistivity, inclination, and width of the low-blocking layer in the simplified model of the geothermal system's resistivity using CSAMT and TEM. Evaluate the anomalies induced by changes in
the resistivity, inclination, and width of the low-blocking layer in the simplified model of the geothermal system's resistivity using CSAMT and TEM (Spichak et al., 2009).

Numerical simulation of electromagnetic method based on finite difference

The finite difference time domain (FDTD) method is applied in the numerical simulation. The finite difference time domain technique solves Maxwell equations directly in the time domain, bypassing the procedure of first calculating the frequency domain answer and then getting the time domain response using the inverse Fourier transform. The Maxwell equations in uniform, unconsolidated and passive media can be expressed as:

\[
\begin{align*}
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}(\mathbf{r},t)}{\partial t}, \\
\nabla \times \mathbf{H}(\mathbf{r},t) &= \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E}, \\
\n\nabla \cdot \mathbf{E}(\mathbf{r},t) &= 0, \\
\n\nabla \cdot \mathbf{H}(\mathbf{r},t) &= 0.
\end{align*}
\]

(1)

Whereas, \( \mathbf{E} \) is the electric field intensity, \( \mathbf{H} \) is the magnetic field intensity, \( \mathbf{B} \) is the magnetic flux density, \( \sigma \) is the electrical conductivity, \( \varepsilon \) is the dielectric constant, and \( t \) is the time. Taking the curl of Faraday's law of electromagnetic induction in equation (1), and considering Coulomb's law, the homogeneous damped wave equations of electric and magnetic fields can be obtained:

\[
\nabla^2 \mathbf{E} - \mu \varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} - \mu \sigma \frac{\partial \mathbf{E}}{\partial t} = 0.
\]

(2)

After disregarding the displacement current, Maxwell's equations (2) in the active medium must contain the source current term, which is amended as follows;

\[
\nabla \times \mathbf{H}(\mathbf{r},t) = \varepsilon \frac{\partial \mathbf{E}}{\partial t} + \sigma \mathbf{E} + \mathbf{J}_s.
\]

(3)

Where, \( \mathbf{J}_s \) represents the source current density. At this time, according to the Yee unit cell format and the coordinate system discrete grid, the equation (3) can be spatially discrete. At the same time, since only electric or magnetic fields are sampled at the same time, on the time axis, electric and magnetic fields are sampled alternately.
Therefore, a uniform time grid is sampled, and the sampling interval is half a time step. When the grid form and time sampling method are adopted, equation (3) can be expressed as:

\[
\frac{\partial H_x}{\partial y} - \frac{\partial H_y}{\partial z} = \gamma \frac{\partial E_x}{\partial t} + \sigma E_x + \begin{cases} J_{sx} & \text{if } x, y, z \text{ are valid} \\ 0 & \text{otherwise} \end{cases}
\]

\[
\frac{\partial H_z}{\partial x} - \frac{\partial H_x}{\partial z} = \gamma \frac{\partial E_y}{\partial t} + \sigma E_y + \begin{cases} J_{sy} & \text{if } x, y, z \text{ are valid} \\ 0 & \text{otherwise} \end{cases}
\]

Since the excitation source current is in the xoy plane, there is no z-direction component of the source current, and only J_sx and J_sy components exist in the equation.

Furthermore, the difference scheme of the electric field FDTD iteration in the active medium.

\[
E_x^{n+1}(i+1/2, j, k) = \frac{2\gamma - \sigma(i+1/2, j, k)\mathcal{V}_t}{2\gamma + \sigma(i+1/2, j, k)\mathcal{V}_t} \cdot E_x^n(i+1/2, j, k)
\]

\[
H_z^{n+1/2}(i+1/2, j+1/2, k) - H_z^{n+1/2}(i+1/2, j-1/2, k)
\]

\[
\frac{\mathcal{V}_y}{\mathcal{V}_z} \left[ H_x^{n+1/2}(i+1/2, j, k+1/2) - H_x^{n+1/2}(i+1/2, j, k-1/2) \right]
\]

\[
\frac{2\mathcal{V}_t}{2\gamma + \sigma(i+1/2, j, k)\mathcal{V}_t} J_{sx}^{n+1/2},
\]

\[
E_y^{n+1}(i, j+1/2, k) = \frac{2\gamma - \sigma(i, j+1/2, k)\mathcal{V}_t}{2\gamma + \sigma(i, j+1/2, k)\mathcal{V}_t} \cdot E_y^n(i, j+1/2, k)
\]

\[
H_y^{n+1/2}(i+1/2, j, k+1/2) - H_y^{n+1/2}(i+1/2, j, k-1/2)
\]

\[
\mathcal{V}_z \left[ H_x^{n+1/2}(i+1/2, j, k+1/2) - H_x^{n+1/2}(i+1/2, j, k-1/2) \right]
\]

\[
\frac{2\mathcal{V}_t}{2\gamma + \sigma(i, j+1/2, k)\mathcal{V}_t} J_{sy}^{n+1/2},
\]

The excitation source loading mode is only related to the x or y component of the electric field, so the iterative formula of Ez is the same as that of the passive region.

The radiation conditions are the regional boundary conditions, and the converging boundary conditions are the ground-air boundary and the stratum and anomalous body boundary. The connection criteria between the formation
and the aberrant body are automatically met in the Yee grid cell computation of FDTD, and no extra treatment is required. Therefore, the ground-air boundary conditions are mainly considered here.

The truncated boundary of the underground space is easier to meet the conditions of the far field, but it is not easy to meet the air area. In addition, there is a large difference between the aerial grid step length and the underground grid step length. According to the principle of canceling the scale, a considerable part of the calculation will be used in the non-key investigation area of the ground M-TEM. Therefore, a special solution is required.

In the quasi-steady state of the geophysical time-varying field, the air field satisfies the Laplace equation as:

\[ \nabla^2 \mathbf{B} = \mu_0 \nabla^2 \mathbf{H} = 0 \quad (7) \]

Based on this, the wave number domain equation can be derived as:

\[ B_x'(u, v, z = 0) = -\frac{iu}{\sqrt{u^2 + v^2}} B_z'(u, v, z = 0) \quad (8a) \]

\[ B_y'(u, v, z = 0) = -\frac{iv}{\sqrt{u^2 + v^2}} B_z'(u, v, z = 0) \quad (8b) \]

In the formula, \( B_x' \) and \( B_y' \) are the Fourier transform of \( B_y \) and \( B_y \), respectively, \( u \) and \( v \) are variables in the wavenumber domain, corresponding to \( x \) and \( y \) respectively.

3D uses the 2D Fourier transform used to process the ground-air boundary as follows

\[ F(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f(x, y) \exp[-i(ux + vy)] \, dx \, dy \quad (9) \]

From this, the, in formula (8) \( \widehat{B}_x^y \) and \( \widehat{B}_y^y \) can be extended upward to a grid in the air, namely

\[ B_x'(u, v, z = -h) = \exp(-h\sqrt{u^2 + v^2})B_x'(u, v, z = 0) \quad (10) \]

\[ B_y'(u, v, z = -h) = \exp(-h\sqrt{u^2 + v^2})B_y'(u, v, z = 0) \quad (11) \]

Substituting formula (8) into the above formula, we get

\[ B_x'(u, v, z = -h) = -\frac{iu}{\sqrt{u^2 + v^2}} \exp(-h\sqrt{u^2 + v^2})B_x'(u, v, z = 0) \quad (12) \]

\[ B_y'(u, v, z = -h) = -\frac{iv}{\sqrt{u^2 + v^2}} \exp(-h\sqrt{u^2 + v^2})B_y'(u, v, z = 0) \quad (13) \]
The Fourier transform on the ground-air boundary uses the fast Fourier algorithm. In order to meet the requirements of discrete Fourier uniform grids, different processing methods are adopted according to the characteristics of grid division.

1) Non-uniform grid. The uniform grid is interpolated by nonlinear interpolation algorithms such as cubic spline and five-point cubic smoothing, and after fast Fourier transform and inverse transformation continuation, the interpolation method is used to restore the original grid again.

2) Non-uniform grid. If the nonlinear interpolation has excessive fluctuations that affect the calculation accuracy, you can change to the linear interpolation trial calculation.

3) Uniform grid. Fourier transform and inverse transform can be directly performed without interpolation, and a grid that is more suitable for discrete Fourier transform can be obtained by linear interpolation according to 2n interpolation.

In brief, when there is an issue with simulation accuracy, grid interpolation of the discrete Fourier transform, as a component of simulation software, can be used to enhance accuracy and identify a factor that influences accuracy. Through the iterative solution and the relationship between the electric field and the magnetic field, the response of the electromagnetic field at each time can be obtained.

**NUMERICAL MODELING**

According to the relative relation of the resistivity of the basic elements of the geothermal system, a simplified resistivity model of the geothermal system is designed for the common faults in the geothermal system that show low resistance due to water conduction.

The numerical simulation program is the open source code SIMPEG for writing papers on the Geophysical Tablet of the University of British Columbia, and the method is the finite difference method.
Considering the high resistance properties of deep intrusive igneous rocks that may occur, the resistivity of the basement in the model is set to high resistance. The basic model consists of four-layer models with shallow and deep resistivities of 100Ω•m, 200Ω•m, 500Ω•m and 1000Ω•m, as shown in the Fig. 1(a). Considering that faults will cause strata dislocation, on the basis of the basic model in the left Fig., the resistivity of each layer of the model is staggered along the fault, as shown in the in Fig. 1(b). The strata on the hanging wall of the fault move downwards, which is a common normal fault. The model design mainly highlights the low-resistance target properties of the broken and water-bearing fault zone, placing the fault zone in the layered, high-resistance surrounding rock.

Model assumptions for CSAMT Response

Based on the established simplified resistivity model of the geothermal system, the abnormal response of CSAMT apparent resistivity in the model with different fault resistivity values, inclination angles and widths was numerically simulated and analyzed. Since the emission source length and emission current are normalized during the calculation of apparent resistivity, the emission source length and emission current are no longer listed. In addition, in order to simulate the measured data as much as possible, Gaussian noise with a mean value of 3% of the response amplitude is added to the response obtained by the numerical simulation. In order to compare with the subsequent transient electromagnetic simulation more intuitively, noise is added to the electromagnetic field response obtained by the numerical simulation, and then the apparent resistivity is further calculated. Following are the parameters upon which our modeling is based on.

A) CSAMT Response to the faults with different resistivities

In the simplified resistivity model of the geothermal system established, the resistivity of the fault is 10Ω•m. usually in the stratum half-space, a fault can be regarded as an angularly inclined plate-like body extending downward from the ground. There are a large number of cracks in the fault zone, which are filled by particles such as breccia, and the resistivity of the filling is different, which determines Characteristics of fault resistivity. Therefore,
the resistivity of the fault is generally within a large range. We establish fault models with different resistivity values (fault dip angle 30°, width 70m, and fault resistivity values 10, 50, 100Ω•m), and perform forward simulation to obtain each response, then calculate its resistivity. All responses are shown in the Fig. 2 (a-c).

B) CSAMT Response to the faults with different dip angles

The dip of the fault is usually an important indicator of detection. Based on this, we establish fault models with different dip angles (fault resistivity value is 10Ω•m, width is 70m, dip angles are 30°, 45°, 60°) and forward modeling is performed, as shown in the Fig. 3(a-c).

Model assumptions for TEM Response

It is discussed above that, based on the numerical calculation of low-blocking layer models with different resistivities and inclination angles; the ability of CSAMT to identify low-blocking layers was analyzed. As a comparison, this section will carry out a numerical simulation analysis on the ability of the TEM method to identify low-blocking layers. Similarly, starting from the resistivity and inclination of the fault, analyze its influence on the TEM response. Because the apparent resistivity of the TEM method is divided into early and late stages, it is difficult to obtain a stable apparent resistivity calculation formula covering all time channels. Therefore, the TEM analysis is carried out for the derivative of the vertical magnetic field with respect to time (dB/dt).

The basic parameters of TEM numerical calculation are: the emission source is a 200m long single-turn square loop, the derivative of the vertical magnetic field with respect to time is received at the center of the loop, the emission waveform is a bipolar rectangular pulse, and the time range is 0.48ms-28.7ms, the number of time channels is 21, and the distance of the receiving point is 100m. The specific geoelectric model is the same as in the previous section. Similarly, in the transient electromagnetic response obtained by the simulation, random noise with a mean value of 3% of the response amplitude is added.

A) TEM Response to the faults with different resistivities
A simplified model of the geothermal system with the same fault angle of 30°, the same width of 70m, and different resistivity values of $10\, \Omega\cdot m$, $50\, \Omega\cdot m$, and $100\, \Omega\cdot m$ was established, and the voltage response was calculated. Due to the large buried depth of the fault, the anomaly of the response mainly appears in the late time channel of the transient electromagnetic response, and the early channel response is not greatly affected, as shown in the Fig. 4 (a-c).

B) TEM Response to the faults with different dip angles

A simplified model of the geothermal system with the same fault width of 70m, the same resistivity value of $10\, \Omega\cdot m$, and different fault inclination angles of 30°, 45°, and 60° was established, and the voltage response was calculated, as shown in the following Fig. 5(a-c).

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 L et al., 2012; Zhang Y et al., 2012; Wu L, 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 J et al., 2011).
(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 (Chen W et al., 2013);

(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.

Field Experimental example

Field Area 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, which formed a good storage area for geothermal resources.
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. The complete area map is shown in Fig. 6.

As shown in Fig. 7, four CSAMT survey lines are arranged in the exploration area. In the CSAMT detection, the instrument used is the GDP32II multifunctional electrical method workstation. The transmitting pole distance $AB = 1500\text{m}$, the transmitting current is $14-16\text{A}$, the transmission distance is $6\text{km}$; the receiving point distance of line 59 and 64 is $50\text{m}$, the receiving point distance of line 10 and line 60 is $100\text{m}$, and the signal frequency range is $0.125-8192\text{Hz}$. In the TEM detection, the instrument used is also the GDP32II multifunctional electrical method workstation, and the center loop device is used for measurement. The transmitting wire frame is a $600\text{m} \times 600\text{m}$ single-turn loop, powered by a generator, the fundamental frequency of the transmitting source is $16\text{Hz}$, and the transmitting current is $15\text{A}$; the distance between the measuring points is $50\text{m}$. 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.

**Geophysical characteristics of Field Area**

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 H, 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 Q et al., 2016).

Table 1. Statistical table of different rock’s resistivity in igneous area.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Resistivity</th>
<th>Rock Type</th>
<th>Resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>60-100</td>
<td>Conglomerat</td>
<td>50-200</td>
</tr>
<tr>
<td>Silty clay</td>
<td>14-25</td>
<td>Limestone</td>
<td>100-300</td>
</tr>
<tr>
<td>Basalt</td>
<td>20-500</td>
<td>Igneous rock</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Granite</td>
<td>500-200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 W et al., 2002; Garyet G et al., 2006).
In the processing of the measured data, we first use the data preprocessing software of GDP32II 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 shown in Fig. 8(a-c).

**Discussions**

The results show that the influence of the fault on the CSAMT response is mainly in the low frequency range, and the influence on the TEM response is mainly in the late stage. Because CSAMT low frequency band can still obtain high signal-to-noise ratio data, and the signal-to-noise ratio of the late TEM response is generally lower, so CSAMT has a stronger ability to distinguish low-blocking layers at this depth than TEM, and CSAMT can also distinguish faults. Upper and lower plate. On the other hand, the TEM response can clearly distinguish the abnormal response caused by the width of the fault, but the CSAMT response cannot be distinguished, which shows that the TEM has a stronger ability to describe the details of the target body in the fault with low resistivity than the CSAMT; In addition, the faults are mainly manifested as obvious resistivity dislocations on the apparent resistivity section of CSAMT, and the resistivity characteristics of the fault fracture zone cannot be directly judged through the apparent resistivity section.

Although both methods can identify the low-blocking layer of the model, the two methods show obvious complementarity in the detection depth and detail description ability, and are suitable for comprehensive application in the detection of geothermal resources.

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:
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.

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.

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**

By numerical simulation, comparing the anomalies produced by the two methods on fault targets with different resistivities and dips, it shows that the two methods have differences in their ability to identify and describe the details of targets at different depths. Resolution of CSAMT for deep targets is stronger than TEM, and ability of TEM to describe the details of shallow targets and faults is stronger than CSAMT. Both methods are capable of identifying targets at different depths. However, in terms of depth of detection and ability to describe details, the two methods are obviously complementary, and they are suitable for comprehensive application in the detection of geothermal resources. Moreover actual detection results of CSAMT and TEM on the same survey line show that CSAMT is better than TEM in deep detection and magmatic rock basement detection, while TEM is better than CSAMT in shallow detection and water-conducting fault structure detection. The two methods of comprehensive survey overcome the limitations of a single method and have the effect of complementing each other and confirming each other. In the exploration of geothermal resources in Yunzhong Town, Huairén County, Shuozhou City, Shanxi Province, the following geological results were obtained: It is inferred that there are three faults F1, F2, and F3, and the fault layer F1 is the main conduction channel for underground hot water; The deep basalt basement or the mid-deep metamorphic rock basement of the Wutai Group is more likely to be a geothermal resource storage.
structure. This study verifies the respective advantages and disadvantages of CSAMT and TEM in geothermal resource
detection.

Declarations

Funding

This Research is sponsored by the Project of National Natural Science Foundation of China (41674075), co-funded by
Guangxi Natural Science Foundation Innovative Research Team Project (2016GXNSFGA380004), and partially supported
by the project Research on Shear Resistance and Water Resistance Performance and Law of Bottom Water-Resistant Layer
of Karst Aluminum Mine Discharge Reservoir with grant number (42062015).

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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.
Acknowledgements

We gratefully acknowledge the Editors and Reviewers for providing thoughtful and useful suggestions.

References


Fig. 1 (a) Simplified resistivity model of geothermal system with fault as the target body. (b) The model on the left is the background model, and the model on the right is dislocated along the fault.
Fig. 2 The model of fault resistivity is 10, 50, 100 \( \Omega \cdot m \) and the cross-section view of resistivity. Through the analysis of faults with different resistivity values, it can be seen that when the fault resistivity is small (10, 50 \( \Omega \cdot m \), less than the resistivity of the first layer of medium), the apparent resistivity curve near the fault is relatively smooth; As the fault resistivity increases, the apparent resistivity curve rises more and appears to be significantly higher. Generally speaking, the difference in resistivity in the fault zone can have obvious characteristics in the apparent resistivity profile.
Fig. 3 The model of fault dip angle is 30°, 45°, 60° and the cross-section view of resistivity from the above analysis, it can be seen that when the dip angle of the fault is 30°, 45°, 60°, "sags" will appear in the interrupted layer of the apparent resistivity profile; The greater the dip of the fault, the greater the degree of "sag" in the apparent resistivity profile; the dip reflected by the apparent resistivity in the apparent resistivity profile is greater than the dip of the actual fault.
The model of fault resistivity is 10, 50, 100 $\Omega\cdot m$ and the cross-section view of resistivity. It can be seen from the above analysis that when the resistivity of the fault zone is low, there is an obvious anomaly near the center of the fault, and the maximum value of the anomaly is located at the midpoint of the fault. The lower the resistivity, the more obvious the abnormal...
response. When the resistivity of the fault zone is 100Ω·m, the resistivity difference between it and the surrounding rock is small, and no large anomaly can be generated on the resistivity profile. This shows that when the resistivity difference between the fault and the surrounding rock is small, TEM is difficult to distinguish the existence of the fault.
Fig. 5 The model of fault dip angle is 30°, 45°, 60° and the cross-section view of resistivity through the above analysis, it can be seen that when the inclination of the fault with low resistivity in the geothermal system resistivity model is changed, the transient electromagnetic voltage response will change. With the increase of the dip angle of the fault, the width of the measuring point that can receive the abnormal response gradually decreases, and the amplitude of the abnormal response gradually increases, which shows that the transient electromagnetic exploration method is sensitive to the dip angle of the fault with low resistivity.

Fig. 6 New rift of Sanggan River geologic section

Fig. 7 Project layout (Surveying points and lines)
Fig. 8 (a) CSAMT resistivity profile of 60 Line

Fig. 8 (b) TEM secondary field profile of 60 Line

Fig. 8 (c) TEM resistivity profile of 60 Line