Combination use of gravimetry, CSAMT and SOTEM methods in geophysical prospection of a polymetallic silver-copper deposit: Case studies in the Inner Mongolia, China

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Abstract Geophysical methods, which use physical properties to reveal the structure of the underground spaces, have been widely applied in geological exploration. However, a single geophysical approach only reflects the distribution of a kind of physical property and therefore has its limitations. To improve the reliability of geophysical methods in actual geological exploration, in this paper, we are trying to combine the use of a variety of geophysical exploration methods, such as gravity, control source audio magnetotelluric method (CSATMT) and electrical source short offset transient electromagnetic method (SOTEM), to a specific metal in Inner Mongolia. Firstly, the gravimetry method is applied to figure out the anomalous area, and then the CSAMT method is adopted to probe the deep electrical distribution. Finally, the SOTEM method is applied for further auxiliary verification. Results show that the underground structure is well revealed by combing the use of these methods. This paper can be used as a reference for the exploration of concealed ore bodies in polymetallic ore deposits.

1. Introduction
Recent years have witnessed rapid development of geophysical exploration technology and the important role it played in mineral resource exploration (Yan Jiayong et al., 2008; Cao Lingmin, 2011; Lu Qingtian, 2015; Liu Jianxin, 2016; Lu Qingtian, 2019). Despite the many geophysical exploration methods, each method has its advantages, limitations and multiplicity of solutions when applied to exploration of mineral resources (Yu Peng, 2006; He Zhanxiang, 2019). Therefore, it is the ultimate goal of geophysical prospecting engineers and a hot research topic to make effective combination of different methods, reduce multiplicity of solutions, give full play to advantages of each method and reach the optimal drilling effect (Ding Xurong et al., 1980; Liu Guangding, 1995). In order to make up for the shortcomings of single geophysical prospecting methods and realize secondary space
prospecting of deep and marginal edges of crisis mines, lots of geophysical methods are combined for joint interpretation (Tu Guanghong et al., 2008; Cui Minli et al., 2010; Qu Ting, 2016; Qu Xiaoyi, 2018). Some researchers have proposed multi-parameter joint inverse analysis methods (Yang Hui et al., 2002; Jing Rong Zhong, 2004; Yu Peng et al., 2006; Chen Jie et al., 2007; He Weihui, 2009; Wang Jun, 2013; Xu Guifen, 2019). Liu Hongtao et al. (2004) used the very-low-frequency method (VLF method) and the continuous conductivity imaging method, combined with the Controlled-source Audio-frequency Magnetotellurics (CSAMT) method, to measure and jointly interpret the Chifeng Chaihulanzi Gold Mine. Chen Weijun (2009), by using multiple geophysical methods, discovered polymetallic mines of silver, lead and zinc in Zhaojiaweizi, Inner Mongolia. Xue Ronghui et al. (2011) used induced polarization, CSAMT, and magnetic methods to discover ores in Shaoguan, Guangdong, and conducted a comprehensive geophysical interpretation. Sun Yan et al. (2011) achieved good results in the prospecting of a polymetallic mine by using integrated geophysical methods. Lin Fangli et al. (2016), by using high-precision magnetic measurement, induced polarization, and CSAMT, studied the distribution characteristics of magnetic susceptibility, polarizability, and resistivity in the study area, and verified the important role of integrated electromagnetic method in exploration of porphyry polymetallic deposits. Wang Zhenliang et al. (2019) used gravity, magnetism, magneto-electric staircase, and CSAMT to find hidden ore bodies, and summarized comprehensive exploration technologies of hidden ore bodies in covered regions. Zhang Gang et al. (2019), through numerical simulation in the lab, collected data from the intermediate gradient device in a metal mine in Gansu. In summary, the combined use of multiple geophysical methods has achieved satisfactory results in mineral resource exploration (Li Jingchao et al., 2002; Zhou Liguo et al., 2009; Tian Wenfa et al., 2010; Yuan Guiqin, 2013; Du Ruiqing, 2013; Wang Zhenliang et al. 2019), and comprehensive interpretation of multiple geophysical prospecting methods will also be a dominating trend of geophysical prospecting of deep and marginal areas of mines.

Based on the company’s scientific research project, this study selects easy-to-implement geophysical methods with large detection depth and strong resistance to interference according to the different physical properties of mineral resources exploration in polymetallic mining areas. The study area is located in the south of the Neocathaysian tectonic system in the Greater Khingan Mountains, where the fault structure is relatively developed. The polymetallic ore bodies, subject to the local geological structure, are mainly produced in the northwest-oriented structural fissure and the polymetallic deposit is a fissure-filling hydrothermal deposit. Historical statistics on physical properties of this area shows that the average density of granite in this area is 2.6 g/cm³, and the Linxi Formation assumes gravity high. Sandstone formation density of Linxi Formation is 2.7 g/cm³, and the remaining density difference is 0.1 g/cm³. Therefore, there are significant density differences, and gravity measurement is proposed. At the same time, the measurement area is affected by the construction of the mine and is subject to severe electromagnetic interference. In order to resist interference, an active source method is adopted; through comprehensive comparison, this study made a combined use of three methods – gravity measurement, CSAMT and the short-distance transient electromagnetic method of electrical source (Xue Guoqiang, 2013; Wang Xianxiang, 2016; Xue Junjie, 2017; Zhou Cong, 2019) for verification.

2. Theoretical analysis and numerical simulation
The CSAMT method and the gravity method are is already mature methods that have been widely adopted in different fields, but the electrical source transient electromagnetic method is rarely studied in China due to its complexity. Therefore, the theoretical analysis mainly introduces the short-distance transient electromagnetic method of electrical sources. The detection device of the electrical source short offset transient electromagnetic method is characterized by a relatively fixed field source, and data distributed on one or both sides of the field source are acquired; the transmission and reception distance is close to or less than the target detection depth, and the receiving positions are distributed within a certain range on both sides of the line source AB; the GDP32 receiver is used to receive magnetic or electric field signals; both single-point or point-by-point measurement methods can be
used, and multiple channels can be arranged simultaneously.

2.1 Calculation of transient electromagnetic forward response
On the basis of the Helmholtz equation satisfied by the electromagnetic field and the given the boundary conditions satisfied by the surface, due to the rotation relationship between the electromagnetic vector potential and the magnetic field, a uniform half-space galvanic source can be derived and the formula for vertical components of frequency in the frequency domain at any point is obtained, as Eq. (1) shows.

\[
H_z(\omega) = \frac{i|d|}{2\pi} \sin(\phi) \int_0^\infty \frac{\lambda^2}{\lambda + \mu} e^{i\lambda z} J_1(\lambda r) \frac{1}{r^2} d\lambda,
\]

(1)

where \(I\) represents the current intensity, \(dl\) is the length of the electric dipole, expressed as \(\mu_i = \sqrt{\lambda^2 + \kappa_i^2}\). If the displacement current is not considered, \(\kappa_i^2 = i \omega \mu \sigma\), represents the wave number of the medium.

The magnetic field strength in the \((Z)\) direction is expressed in Hz; the transmitting dipole length is expressed as \((AB)\), and \(I\) is the transmitting current; \((r)\) is the transmitting and receiving distance; \(\theta\) is the angle between the electric dipole \((AB)\) and the transmitting and receiving distance \((r)\).

Under the condition of ideal layered medium, the magnetic field in the frequency domain is expressed as Eq. (2).

\[
\varphi = \frac{2}{\pi} \int_0^\infty \text{Im} \left[ \frac{1}{2\pi} \int_0^\infty \frac{\lambda}{\lambda + \mu} / R_1 \cdot j_1(\lambda r) d\lambda \right] \cos(\omega t) \frac{d\omega}{\omega} dt
\]

(2)

When a step wave is used as the transmission waveform, the magnetic field in the frequency domain undergoes numerical transformation, and the expression of the magnetic field in the time domain can be obtained, as Eq. (3) shows.

\[
H_z(t) = \frac{1}{2\pi} \int_{-\infty}^\infty H_z(\omega) e^{i\omega t} d\omega
\]

(3)

2.2 Definition of full-domain apparent resistivity
According to Eqs. (1), (2) and (3), the functional relationship between resistivity and electromagnetic wave propagation is complicated, as expressed by Eq. (4) after simplification.

\[
\varphi(x, y, t, \rho, \lambda_0, I_0) = \frac{2}{\pi} \int_0^\infty \text{Im} \left[ \frac{1}{2\pi} \int_0^\infty \frac{\lambda}{\lambda + \mu} / R_1 \cdot j_1(\lambda r) d\lambda \right] \cos(\omega t) \frac{d\omega}{\omega} dt
\]

(4)

where the coordinates of the surveying point is \((x, y)\), the sampling time is \((t)\), the true resistivity of the medium is \((\rho)\), the step current is \((I_0)\), \(\varphi()\) is the function between the electromagnetic response and the parameters of the electrical source device parameters (line source length, emission current, observation point position coordinates, model device parameters, etc.).

Because it is difficult to solve Eq. (4) using analytical methods, the explicit inverse function between resistivity and the field cannot be obtained for the time being. However, numerical simulations in the laboratory have verified that the functional relationship between the electromagnetic wave response and the model parameter resistivity is monotonic, so the iteration method is used to find its inverse function value, so as to replace the inverse function expression.

First, we build a stable iterative format, determine the initial value of the electrical ancestor, and perform the Taylor expansion in the neighborhood of the initial value of the resistivity \((\rho_0)\), as Eq. (5) shows.
\[ \varphi(\rho, \text{const}) = \varphi(\rho_0, \text{const}) + \varphi'(\rho_0, \text{const})(\rho - \rho_0) + \frac{\varphi''(\rho_0, \text{const})}{2!}(\rho - \rho_0)^2 \]
\[ + \ldots + \frac{\varphi^{(n)}(\rho_0, \text{const})}{n!} (\rho - \rho_0)^n + R_n(\rho) , \quad (5) \]

We ignore the second-order and higher-order terms, shift the terms, and obtain the iterative format, as Eq. (6) shows.

\[ \rho_1 = \frac{\varphi(\rho, \text{const}) - \varphi(\rho_0, \text{const})}{\varphi'(\rho_0, \text{const})} + \rho_0 \quad (6) \]

At the same time, we set the judgment conditions for iteration termination, and when the iteration error is within the given error range \( \varepsilon \), the iteration is terminated.

\[ \left| \frac{\partial B - \varphi(\rho, \text{const})}{\partial B} \right| < \varepsilon , \quad (7) \]

where \( (\partial B) \) represents the position of the receiving point and the intensity of the magnetic field at the receiving time, \( \varphi(\rho_1, \text{const}) \) represents the field value of the geoelectric model with a resistivity \( (\rho_1) \) at a given location and a given time. By setting the conditions for iteration termination, the full-domain apparent resistivity of the electrical source transient electromagnetic field can be calculated.

3. Full-domain apparent resistivity

Apparent resistivity is a parameter used to reflect the electrical changes of rocks and ores. By using the Eqs. (4) ~ (7), the full-domain apparent resistivity of the transient electromagnetic field of the electrical source is calculated. The apparent resistivity is not subject to influence of the time or distance, and iterative algorithms are used to more intuitively display the physical characteristics of the strata. Through forward modelling of the response curve of the geoelectric model, the full-domain apparent resistivity is obtained.

According to the forward model and the “D” and “G” geoelectric models, forward response values are calculated to obtain the full-domain apparent resistivity curves, as shown in Figure 1 ~ 4. Figure 1 is the apparent resistivity curve of a geoelectric model where the first layer has a resistivity of 200 \( \Omega \cdot m \) while the second layer has different resistivity. In Figure 1, the shapes of the apparent resistivity curves are basically the same when the value of \( \rho_2 \) varies. Early apparent resistivity is consistent and approaches \( \rho_1 \); the lower the second layer resistivity, the earlier the apparent resistivity curve moves upwards. When the second layer resistivity is 200 \( \Omega \cdot m \), the model is a uniform half-space model, and the apparent resistivity calculation is the same as the forward model. When the resistivity of the second layer is lower than that of the first layer, it is a D-type model. This model can well respond to the low-resistance body under the high-resistance ground electrical section of the two underground layers, thus having good effect. Figures 2 and 3 show the D-type apparent resistivity curves of different \( H_1 \) thicknesses. These curves indicate that the first layer thickness is small, the resistivity of the first branch is subject to the influence of the second layer, while the tail branch largely remains consistent. When the thickness of the first layer reaches a certain value, the apparent resistivity of the first branch tends to be consistent, and the time delay of the tail branch tends to be consistent. Figure 4 shows the G-type apparent resistivity curves of different thickness. The curves show that the first low-resistance layer is affected by the second high-resistance layer, and as the thickness varies, the point where the curve moves upwards differs, and the tail branch remains consistent.
When different values are assigned to $h_2$, the apparent resistivity curves are basically the same, and a minimum value is formed at the low resistance value of $\rho_2$, which reflects the three-layer “K” and “H” geoelectrical sections with significant effects. As $h_2$ increases, the time when the apparent resistivity curve shows a minimum value is delayed, because the increasing thickness leads to more time for the transient field to penetrate the formation. The layer thickness of the second formation can
be calculated based on the time of delay. The first branch of the apparent resistivity curve is less affected by the value of $h_2$, which basically overlaps with the changes in time, and the tail branch will be affected by $h_2$ to varying degrees, but the effect is not significant, and will gradually approach the set value of $\rho_3$ as the time increases.

4. On-site verification

4.1 General geological conditions of the study area

The polymetallic silver-copper deposit in an area of Inner Mongolia is a medium-temperature fissure-type filling hydrothermal deposit associated with subvolcanic rocks. Its ore-controlling structure is a rotating tectonic system and this rotation produced ore-controlling effects during the ore-forming process. A series of supporting structural fissures generated by the tectonic stress during the Yanshan tectonic movements period led to time differences in the formation of rock veins and ore veins, so the type of mineral deposits is rare. The veins of this polymetallic deposit are mainly filled along the structural fissure penetration, the fractures between the vein body and the same layer show a small angle of intersection, and some of them are penetrated along the fissure between the layers, and both are trans-tensional. Tensile veins are important industrial veins of this polymetallic mine; gently torsional veins, another type of important industrial veins in the region, are longer and less thick than the tensile veins, but their extension is more stable. Steep torsional veins are generally small in scale. On the profile, the torsional slow veins limit the tensile steep veins, featuring a staircase shape that tracks the steep veins. From 1982 to 1994, the North China Nonferrous Geological Prospecting Bureau organized a geophysical exploration team to carry out geophysical prospecting and evaluation work in the periphery and near-periphery area of the current polymetallic mine.

The geological characteristics of this polymetallic silver-copper deposit indicate that there may still be another type of deposit and a second ore-bearing space in the deep and periphery of the mining area. Currently, the ore bodies under mining are concentrated in the strata 500 m below the surface, and the deep and peripheral sides of the mine has large ore prospecting space. In terms of methods and technology, the geophysical characteristics of the mines show that there are significant differences in density and resistivity between the mineral (fossil) rocks and surrounding rocks, and there are good geophysical prerequisites for using gravity and electromagnetic methods to detect and predict their deep resources. A lot of data and facts show that gravity and electromagnetic methods are also a common combination of geophysical methods for deep mine exploration.

4.2 Research ideas and technical methods

In order to avoid the limitations brought by using a single geophysical method, this project will give full play to the advantages of multiple geophysical methods. In this geophysical survey, various geophysical exploration methods such as gravity measurement method, controllable source audio frequency electromagnetic sounding method and electrical source transient electromagnetic method were used to verify the abnormal area. The instrument model used by the gravity method is a CG-6 AutoGravity relative gravimeter, with a reading resolution of 0.1uGal, and a reading repeatability of 5uGal, and the data sampling rate is 10Hz. The instrument used in the controllable source audio magnetotelluric method is a GDP 32 multifunctional electromagnetic instrument, the sampling frequency range of which is 1Hz ~ 8192Hz, the location of the emission source is 9km, and the emission current is 15A. The electrical source transient electromagnetic method uses a GGT-30 transmitter with a transmitting current of 12A, a TEM/3 magnetic probe with a receiving area of 10000m$^2$; the receiver uses a GDP 32 multifunctional electromagnetic instrument.

The prospecting survey includes the following parts:

a) First, the working target area is determined based on the geological conditions of the metal mining area, surface geological surveys and collected data;

b) Secondly, in the working area of the polymetallic mining area, the high-precision gravity relative instrument CG-6 is used for surface scanning;
c) The CSAMT method and the electrical source transient electromagnetic method are deployed in key parts of gravity anomalies to conduct focused exploration of gravity anomalies and further assist the interpretation of anomalies;

d) Last, the geological background, geological conditions, and known rock mass outcrops are combined to verify the results of geophysical anomalies.

4.3 Gravity measurement and anomalies

The survey area is located at the southern end of the Xinhuaxia structure in the Greater Xing'an Mountains. The fault structure in the mining area is relatively developed. Most of the metal ores, subject to influence from the structure, are produced in north-westward structural fractures. Therefore, metal ore deposits are fissure-filling hydrothermal deposits. Historical statistics of physical properties shows that the average density of granite in this area is 2.6 g/cm$^3$, and the Linxi Formation often assumes gravity high. The formation density of the sand plate rock of Linxi Formation is 2.7 g/cm$^3$, and the remaining density difference is 0.1 g/cm$^3$.

Figure 10 shows that the northwest gravity of the polymetallic mine is distributed on the gravity gradient belt, the gravity anomaly is low in the northwest and high in the southeast. According to regional gravity anomalies, three measuring lines are arranged at a north-west azimuth of 131 °, and the number of measuring lines is G1, G2, and G3. There are 4 measuring lines at 41 ° northeast, numbered K-19, K49, K66, and K77, respectively. The K49 measuring line is 7 km long and K66 is 9 km.

The K49 and K66 lines are parallel, the two lines are parallel, and the distance between the lines is 340 m. After calculation of the Bouguer gravity anomaly, the Bouguer gravity anomaly curves of the two survey lines are similar in shape. The side proves accuracy of the measurement results. An abnormal peak appears in the range of 1600 m of the lines K49 and K66. It is presumed that the gravity anomalies of these two measuring lines are controlled by the same structural fracture zone.
According to geological conditions, it is inferred that the anomalous transition of the two measuring lines is caused by the same structural fracture zone, but the specific anomalous characteristics need to be verified through other geophysical methods. Therefore, based on the obtained gravity anomaly locations, in order to further investigate the electrical characteristics of the gravity anomaly locations, the CSAMT method and the electrical source transient electromagnetic method are used.

4.4 CSAMT and electrical characteristics

Geological data show that a polymetallic silver-copper deposit in Inner Mongolia is a series of supporting structural fissures caused by tectonic stress during the Yanshan formation period, which provides favorable conditions for the formation of rock veins and mineral veins. The mineral veins are mainly filled along the structural fractures.

According to the position of gravity anomaly, we carry out the CSAMT method in the range of 1000 m ~ 2000 m of Line K49 and Line K66. The measuring line is 1 km long and the line orientation is 41°, which coincides with the gravity measuring line. The apparent resistivity cross-sections of Lines K49 and K66 show that the electrical characteristics of Line K49 at the locations of 1450m ~ 1600m and 1850m ~ 1950m show low-resistance body anomalies, and high-resistance body anomalies...
between 1600m ~ 1800. On the gravity anomaly map, the gravity value becomes larger, which is presumed to be caused by the surrounding rock mass (Figure 14). There is also a low-resistance body at the position of 1450m ~ 1550m on Line K66 (Figure 15). Significant differences in surrounding geological bodies. The electromagnetic sounding of the low-resistance body abnormal result is consistent with the gravity abnormal result. Therefore, based on the gravity anomaly and the controllable source audio frequency magnetotelluric low-resistance body anomaly, combined with geological data, it is initially determined that there is a fault fissure zone in the range of 1450m ~ 1550m in the vertical survey lines K49 and K66, which is a fissure-filled hydrothermal deposit.

4.5 Electrical source transient electromagnetic method and electrical characteristics
Among all metal ore exploration methods, the electrical source transient electromagnetic measurement method has higher resolution in shallow electrical characteristics. Based on the obtained gravity anomalies and the audio frequency magnetotelluric anomalies in the deep controllable source, further development of electrical source transient electromagnetics for auxiliary measurements is conducted to further verify that the anomalies are indeed electrical anomalies. In view of the actual geological conditions of the mining area, this study uses the electrical source transient electromagnetic full-domain apparent resistivity processing method to process the data and obtain the apparent resistivity section diagram. In Figure 16 and Figure 17, the electrical source transient electromagnetic full-domain apparent resistivity section diagrams show that the overall apparent resistivity section well matches the gravity anomaly curve. The obvious low-resistance anomaly sags downward at the 1500m ~ 1800 m of the measuring line, and it is a low-resistance anomaly in the same formation. Because the two measuring lines use the same parameter for time-depth conversion, but the measuring line offset is different, the detection depth is different. The offset of the measuring line K66 line is 300m. It is speculated that the detection depth is shallower than that of Line K49.

In Figure 16, there is a high-resistance trap at a horizontal position of 1700 m and an altitude of 500 m, and it is about 300 m away from the surface. At the same time, there is a high-resistance anomaly at 2000 m and 700 m above sea level. The anomalous curve appears as a local bump, and the side proves the detection effect of the electrical source short offset transient electromagnetic method. As shown in Figure 17, the horizontal distance of Line K66 is 1300m-1960m. The cross-sectional view of the apparent resistivity of the transient electromagnetic field of the electrical source basically matches the Bouguer anomaly curve. There is a low-resistance anomaly zone in the apparent resistivity at a horizontal distance of 1100 m, and there is no gravity depression in the Bouguer anomaly curve. Field surveys show that a high-voltage line is energized at a horizontal position of 1080 m. This transient electromagnetic low-resistance anomaly may be a false anomaly caused by high-voltage line interference.

5. Conclusions
1. It is important to choose a suitable method according to the physical property parameters. Gravity
measurement is greatly affected by terrain fluctuations, so it is better to perform the measurement in a flat terrain area. The flat terrain of this study area provides good conditions for gravity measurement.

2. Compared with the loop source transient electromagnetic method, the electrical source short offset transient electromagnetic method has a higher detection depth and is easier to implement. However, most domestic and foreign studies use the center loop processing method, and the detection effect is not significant. In this study, electrical source full-domain apparent resistivity processing method is adopted. The obtained apparent resistivity profile is consistent with the line of gravity fluctuations, regardless of time or space. However, the electromagnetic method is generally susceptible to interference by high-voltage lines, so it is necessary to avoid interference. The measured data show that the high-voltage lines are seriously affected by the high-voltage lines within 50 m.

3. The electrical source short offset transient electromagnetic method is a type of time-domain electromagnetic method. 16HZ frequency is set as the parameter to achieve the best detection result and the offset distance is similar to the detection depth. The test results are in the range of 300 m to 600 m, with the best quality.

4. The controlled source audio magnetotelluric exploration method can explore in deep areas, but the sampled is weak, so the resolution is not enough, which is suitable for detecting large geological structures, faults, etc.

5. The field geophysical exploration work is conducted. The abnormal position is delineated according to the gravity anomaly measurement, and the audio frequency magnetotelluric method of the controllable source is used to find out the characteristics of electrical differences in the deep part. Finally, the electrical source transient electromagnetic method is used for auxiliary verification. After drilling, it is verified that there is a deep ore-conducting structure. Therefore, the multi-method verification work idea and its technical route can give full play to the advantages of each method and verify each other; moreover, it proves the reliability of the electrical source short offset transient electromagnetic method.

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