Application of TEM Based on HTS SQUID Magnetometer in Deep Geological Structure Exploration in the Baiyun Gold Deposit, NE China

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ABSTRACT: Exploration of deep mineralization, particularly where the mineralization of interest is covered by a conductive overlain, is still a challenge for the conventional transient electromagnetic (TEM) method, which measures TEM response using induction coils as the sensor. However, sensors such as fluxgate and superconductive quantum interfere device (SQUID) magnetometers can measure the B-field directly, which can provide more reliable deep information for mineralization exploration. In this paper, we report on the research and development of our newly developed high-temperature superconductor (HTS) SQUID magnetometer, which is cooled by liquid nitrogen at 77 K, and its application in TEM measurement for deep exploration in a gold deposit in China. This improved SQUID magnetometer version has a good performance with noise (50 fT/√Hz), slew rate (0.8 mT/s), dynamic range (100 dB), sensitivity (6.25 mV/nT), and bandwidth (20 kHz). To find deep and peripheral ore in the Baiyun gold deposit located in Liaoning Province, NE China, both the SQUID magnetometer and induction coil were used for TEM data acquisition. Results show that TEM can detect the distribution of local strata and the faults contained within them. Results also indicate that the SQUID magnetometer has superior response performance for response over geological targets with slower decay time when compared to the induction coil signals. The SQUID magnetometer is more sensitive at observing the induced-polarization effect which is closely related to the ore-controlling faults.

KEY WORDS: TEM, HTS SQUID magnetometer, B-field, deep exploration, the Baiyun gold deposit.

INTRODUCTION

The transient electromagnetic (TEM) method has been an important geophysical method for mineralization exploration (Xue et al., 2020a; Di et al., 2019; Chwal et al., 2015; Asten and Duncan, 2012; Wolfrum and Thomson, 1998). In traditional TEM exploration, the transmitter system generates a bipolar tapered wave in the loop laid out on the surface to induce a secondary magnetic field related with the target bodies. The decay of the secondary magnetic field can be recorded by a receiver during the off-time. The TEM response is a decaying signal with a wide bandwidth and a high dynamic range (Ji et al., 2016; Lee et al., 2001). Additionally, the complete appearance of decay curves can reflect the geoelectrical structure reliably. However, for the deep high conductive targets, a long recording time range (from tens of milliseconds to several seconds) is required (Xue et al., 2020b, 2014; Zhao et al., 2008). In this case, complete decay curves are not easily to be recorded by the traditional induction coils since the power spectrum of dB/dt field has less energy at low frequencies and the curves will decay rapidly at late times (Smith and Annan, 1998).

To overcome this problem, recorders, such as the fluxgate and superconductive quantum interfere device (SQUID) magnetometers, have played an increasing role in deep mineralization exploration (Le Roux and Macnab, 2007; Foley et al., 2006). These recorders directly measure the B-field, where the curve does not decay as rapidly as that of the dB/dt. Moreover, they have high sensitivity in low frequency, which means they can provide more reliable information for deep mineralization exploration (Le Roux and Macnab, 2007; Foley et al., 2006). Field and model results have shown that the TEM with a SQUID magnetometer has many potential advantages over that using induction coils (Chen et al., 2012a; Ari et al., 2007; Wang et al., 1999; Smith and Annan, 1998; Spies, 1989) and several TEM systems based on the high-temperature superconductor (HTS) SQUID magnetometer have been developed for deep exploration (Nagendra et al., 2017; Chen et al., 2012b; Chwal et al., 2010; Ari et al., 2017; Biek et al., 1999; Foley et al., 1999; Wang et al., 2000).

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The application research of HTS SQUID magnetometer was started in 1989 by the Institute of Geophysical and Geochemical Exploration (IGGE), Chinese Academy of Geological Science, and a series of research has been conducted since then. With the development of the radio frequency (RF) SQUID magnetometer intelligent control system (Zhao et al., 2002), the control system’s working efficiency and the accuracy and reliability of compensation are improved. The wide-band non-magnetic Dewar with a frequency band greater than 100 kHz makes the HTS magnetometer meet the bandwidth requirements of TEM (Chen et al., 2007). Slew rate is an important index, which represents the ability of the system circuit to track the external field without losing its lock. The improved SQUID magnetometer version can collect data in an interference environment with a slew rate of 0.8 mT/S (Chen et al., 2012a).

Many field tests have been completed using the HTS SQUID magnetometer in TEM, including key performance index tests (Chen et al., 2006) and the comparison experiment of induction coil probes, the application test on the long off-transient electromagnetic method (Wang and Wang, 2002; Wang et al., 1999), and on the central loop configuration (Zhi et al., 2020; Zhang et al., 2010; Chen et al., 2002). This current research is a collection of tests on the large fixed-loop configuration in a mining area with some electromagnetic interference.

This paper shows that the application of the HTS SQUID magnetometer based on the TEM system (Chen et al., 2012a, b, 2006, 2002; Wang et al., 1999; Zhang et al., 2010) for deep exploration in the Baiyun gold deposit, which is located in the Liaoning Province, China. The original decay curves and inversion results are compared between the Crone induction coil and the SQUID magnetometer.

1 HTS SQUID BASED TEM SYSTEM

1.1 Transmitting System

In our experiments, the PEM system (Crone Company of Canada) was used, which contains a 4.8 kW transmitting system and a receiving system. The transmitting system consists of a 5 kW generator, a rectifier, a transmitter and the loop laid on the top surface of earth surface. The 220 V alternating current generated by a generator was converted into DC voltage after rectification. The transmitter can generate a bipolar trapezoidal wave in the loop according to the acquisition parameters of the DC voltage. The maximum power of the transmitter is 4.8 kW, and its maximum voltage and current are 230 V and 30 A, respectively. The synchronous mode of the transmitting system and receiving system includes a cable and quartz clock for the 4.8 kW transmitter.

1.2 Receiving System

The receiving system consists of a PEM receiver and two sensors. The PEM induction coil and the HTS SQUID magnetometer, developed by IGGE, were used as sensors for the measuring. The PEM induction coil’s effective area is 3 850 m², and its bandwidth is 10 kHz.

The improved HTS SQUID magnetometer version has a good performance with noise (60 fT/√Hz ) (see Fig. 1), slew rate (0.8 mT/S), dynamic range (100 dB), sensitivity (6.25 mV/nT) (see Fig. 2), and bandwidth (DC-20 kHz), which ac-

Figure 1. B-field noise of the HTS SQUID magnetometer.

Figure 2. Frequency-amplitude response curves of the HTS SQUID magnetometer.
Previous data shows that the Gaixian Formation has medium to high resistivity, ranging from 2 800 to 6 000 Ω·m. Three parts of the third member of the Dashiqiao Formation are obviously different due to different lithology. Marble has a high resistivity, with the average being 3 500 Ω·m. The average resistivity of diopside diorite schist and graphite bearing marble is 227 and 702 Ω·m, respectively. For the remaining lithological units, quartz porphyry has an average resistivity of 4 300 Ω·m, silica-potassic altered rock has an average resistivity of 2 300 Ω·m, gold-bearing alteration rock has an average resistivity of 1 800 Ω·m. The silicified zone generally shows medium to high resistivity, and the typical value is larger than 1 000 Ω·m. The distribution of graphite in the area has a great influence on the rock resistivity.

2.2 Field Collection

To find deep and peripheral ore in the Baiyun gold deposit, the TEM method was applied to the exploration of ore-bearing strata and ore-controlled structures. Both the HTS SQUID magnetometer and induction coil were used in field data acquisition with a fixed-loop configuration. Several profiles were finished from March to December, 2019. More than 600 physical points were measured, and the total survey line reached 40 km. The TEM survey lines are basically coincident with the geological exploration lines in the NS direction, and previous line numbers were used. In this paper, L011 which is located in the western part of the Baiyun gold deposit, was chosen to show the application effect of HTS SQUID based on the TEM system. Figure 3 shows the geological map and the survey line.

The TEM response was collected along several NS-trending profiles in the Baiyun District, as illustrated in Fig. 3, with the Canadian PEM system. Fixed-loop configuration was used in the field data collection. In order to pursue a magnetic moment, a 4.8 kW high-power transmitter was used for measuring. The station interval was 50 m. A 400 m×900 m transmitter loop was powered with 20 A using the Crone transmitter with a 5 Hz base frequency (time base is 50 ms). The ramp time is 500 μs, stack time ranged from 128 to 256, and a quartz clock synchronous mode was chosen. The time channels are shown in Table 1.

3 RESULTS AND DISCUSSION

Figure 4 shows the measured TEM response profile curves of L011, and the curves of SQUID and coil can be seen in Fig. 4a and Fig. 4b, respectively. The profile curves are divided into three groups according to time channels. The characteristics of the two sets of curves are similar. Two high-value abnormalities appear obviously at both ends of the line, while a low-value abnormality appears in the 2 600–2 900 section of the third group of curves. In general, a high value corresponds to the marble of the Dashiqiao Formation, while a low value corresponds to the schist and granulite of the Gaixian Formation. The two high conductivity anomalies between station 800 and 1 200 and between station 2 600 and 2 900 were caused by the diop-
side diorite schist exposed on surface of a steep dip. More detail changes can be seen from the 1 500 to 2 500 section in the third group of the SQUID curves than from the coil curves.

The comparison between SQUID and coil can be seen more clearly in the decay curves in late time (see Fig. 5). Figures 5a and 5b are the SQUID curves, where Fig. 5a shows some special decay curves chosen from the whole, while other normal decay curves are shown in Fig. 5b. Figures 5c and 5d are the special decay curves and normal decay curves of the coil data, respectively. In the special decay curves, such as at station 1 300, 1 550 and 2 700, the sign reversals (Yin et al., 2016; Spies, 2004; Panaitov et al., 2002) occur at late stage. According to the electrical characteristics in this area and the comprehensive logging data, the sign reversals are a typical induced-polarization phenomenon probably caused by the pyritization (Spies, 2004) enriched locally in the fault, which is related closely with ore bodies. From a comparison between Figs. 5a and 5c, more sign reversals can be seen in SQUID curves than coil curves, which implies the sensitivity of SQUID data at the late stage is higher than in the coil data. As the normal decay curves of SQUID (Fig. 5b) are compared with coil curves (Fig. 5d), the SQUID curves are shown to decay slower than its time derivative measured using the induction coil. While coil measurements at late times are subject to noise, the SQUID still measures more smoothly decaying transient in this region, which shows the advantages of SQUID magnetometer.

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Figure 4. TEM profile curves of L011. (a) SQUID profile curves; (b) coil profile curves.
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Figure 5. TEM decay curves of L011. (a) Induced polarization curves of SQUID; (b) normal decay curves of SQUID; (c) induced polarization curves of coil (d) normal decay curves of coil.

Figure 6. Comparison of TEM decay curves between SQUID and coil.

in deep exploration.

For a more detailed comparison, the TEM response data collected by the SQUID sensor and induction coil at four points are compared. The measured magnetic field of SQUID was differentiated and compared with the data from the induction coil. The comparisons at points 800, 1 000, 1 600, and 2 000 are shown in Fig. 6. In addition to the differences at the early stage, the shape and the decay character of the curves are basically same. The difference at the early stage was mainly caused by the different bandwidths of probe. The bandwidth of SQUID in the high frequency band is dozens of kHz, while that of the Crone induction coil probe is 10 kHz.

A pseudo-2D inversion method was adopted in the data processing and interpretation. This inversion method takes into account the lateral variation of adjacent measuring stations, which makes the calculation results more reasonable (Zhang et al., 2010; Zhi et al., 2015). Figure 7 shows a comparison of the apparent resistivity distribution of the SQUID data and coil data. Figure 7a is an inversion result of the coil data and Fig. 7b shows the SQUID results. High resistivity reflects the Gaixian Formation which mainly consists of schist and granulite. The conductive section can be explained as the comprehensive reflection of the diopside diorite schist, graphite bearing marble, and fracture zones of the Dashiqiao Formation. The geoelectrical structure of this profile reveals a typical nappe structure. The section from 1 200 to 2 700 can be explained as a nappe, and the Gaixian Formation is preserved mainly due to its location on the syncline axis. The faults caused by the extrusion of nappes are shown both clearly in the inversion results.

It is shown that the maximum depth of SQUID inversion result reaches 2 500 m. The two inversion results are similar regarding the whole electrical structure. However, there are some differences in detail. The differences between them are mainly shown in the range of the diopside diorite schist in the shallow part of the 800–1 200 section and in the lower part of the Gaixian Formation in the 2 600–2 900 section. In the deep part, the results from SQUID reflect the main sliding fault (F011-1) structural plane of the nappe structure more clearly than those of the coil results. The information of deep electrical structure change in the SQUID data inversion is more than from the induction coil.

The response of the HTS SQUID magnetometer to the magnetic field is independent of the signal frequency, while the response of the induction coil to the magnetic field is directly proportional to the frequency. Therefore, with a decrease of the frequency, the induction coil’s sensitivity drops rapidly. Since
the late stage TEM response is mainly composed of low frequency signals, so the HTS SQUID magnetometer is more sensitive to the electrical change than the induction coil. The SQUID magnetometer has more advantages in deep exploration than the induction coil.

4 CONCLUSIONS

A HTS SQUID-based TEM system suitable for deep exploration has been developed and applied. The self-developed HTS SQUID magnetometer was fabricated and integrated with the Crone PEM system. The system has been successfully used for the detection of ore-bearing strata and ore-controlled structure in the Baiyun gold deposit by recording the decay profiles.

Compared with the original curves of the induction coil, the B-field curves measured by HTS SQUID decay slower, and it has greater sensitivity in later stages, which characterizes it as being more suitable for deep exploration. In the inversion results, there were more electrical changes information than from the coil in deep part. With a transmitter magnetic moment of \(7.2 \times 10^5 \text{ Am}^2\) and 5 Hz base frequency (time base is 50 ms) in this work, the maximum depth in the inversion results of SQUID exceed 2000 m.

Field results show that the application of a HTS SQUID magnetometer to TEM can yield a better performance than coil sensors, especially in deep structure exploration.

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