Development of a TDEM Data Acquisition System Based on a SQUID Magnetometer for Mineral Exploration

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Summary

We report on the research and development of a TDEM data acquisition system (SQUITEM) by JOGMEC using a highly sensitive high-temperature superconductor (HTS) SQUID vector magnetometer cooled by liquid nitrogen, which is suitable for mineral exploration. JOGMEC has achieved stable long-term operation of all three channels during field tests. SQUITEM meets high requirements for slew rate (6.8mT/s), dynamic range (100dB) and bandwidth (DC – 100kHz). It offers deeper penetration of depth than the induction coil system because it can record the step response that decreases with time slower than the impulse response of the induction coil system. SQUITEM also performs horizontal gradient observations that can provide much better resolution of shallow conductive targets than conventional EM field component observations. We have obtained good reproducibility of SQUID data and correlation between the output signals of the reference induction coils and the derivatives of the SQUID signals in TDEM field tests.

Introduction

All commercial TDEM systems are based on an induction coil sensor to acquire the response from the ground. An induction coil outputs a voltage proportional to the time derivative of the magnetic field. Therefore, large responses will come from rapidly decaying magnetic fields and small responses from slowly decaying fields. Because the targets of interest in base metal exploration are generally conductive with slow decays, TDEM method using an induction coil sensor is considered to have an inherent weakness for this purpose. Concretely, the induction coil data are biased towards detection of less conductive and more rapidly decaying conductors. Therefore, a magnetometer will be more suitable for the detection of conductive targets in the presence of a conductive overburden because it does not have this bias. Furthermore, the slower decay of the magnetic field compared with dB/dt ensures better resolution at later time moments and therefore a large depth of investigation.

There are three solutions to improve detectability of more conductive targets and the signal-to-noise ratio at later time moments by the conventional TDEM instrument. The first solution is to obtain the equivalent magnetic field response by integrating the transmitter waveform such as UTEM system (Lamontagne, 1975). The second approach is to acquire the data measured with an induction coil and to deconvolve them to obtain the equivalent step response. However, this may be an unstable computation because the spectrum of the transmitter waveform does not have information at certain frequencies. Concretely, because an induction coil receiver cannot measure the whole waveform, it is impossible to determine the constant of integration (DC shift) which must be applied to the integrated data in integrating the equivalent magnetic field response from dB/dt data. The third method is to obtain the magnetic data directly using a high-frequency magnetometer. There are a few magnetometers such as a fluxgate magnetometer and a proton magnetometer to measure the magnetic field directly. However, their narrow bandwidth is not sufficient for mineral exploration to investigate at depth of several hundred meters.

A high-temperature (HTS) SQUID (superconducting quantum interference device) is a high-sensitive magnetic sensor that has wide bandwidth, and offers a high field sensitivity even at low frequencies. Therefore, we can notice the advantage of a SQUID magnetometer with higher sensitivity for slower decay of a conductive target in the presence of a more rapidly decaying response for a conductive overburden over an induction coil receiver.

Since 2001, JOGMEC (Japan Oil, Gas and Metals National Corporation; former Metal Mining Agency of Japan) has been developing a three-channel TDEM data acquisition system based on the SQUID magnetometer (SQUITEM) by contracting with Sumitomo Electric Hightechs Co., Ltd.. SQUITEM can measure three components of the magnetic field or the horizontal gradient of the magnetic field in order to achieve higher resolution of shallow part of the ground. In this paper, we present the outline of the SQUITEM and some results of field tests to check its performance and practicality.

SQUITEM

SQUITEM is a three-channel system to measure three components of the magnetic field simultaneously or one-component magnetic fields at two points and their horizontal gradient for ground-based TDEM application (Fig.1). SQUITEM has three SQUID magnetometers, one of which is the vector magnetometer, and the others are for horizontal gradient measurement. SQUITEM is characterized by the specification in Table.1. The SQUID magnetic field resolution is about 100fT/$\sqrt{Hz}$ above 10Hz in the field. The 3.3-liter dewar for three-component measurement has a dimension of 589 mm high and 190 mm in outer diameter (Fig.2). The 2-liter dewar for gradient measurement have a dimension of 353 mm high and 190 mm in outer diameter (Fig.1). All the dewars permit more than 9-hour continuous operation without liquid nitrogen refilling. The slew rate of the SQUID electronics (6.8mT/s) is sufficient to accurately respond to square-wave primary-field variation. The dynamic range of about 100dB and the frequency bandwidth from DC to 100kHz provides minimal distortion of the recorded signal. The SQUID is connected to a flux locked loop (FLL) circuit in order to linearize the SQUID response. Conceptionally a FLL is a feedback mechanism that attempts to maintain the output voltage of the SQUID (flux passing through the SQUID hole) at a constant value by application of a compensating field generated by a feedback coil. If the external magnetic field exceeds the feedback magnetic field, the SQUID will slip into the next period of the flux voltage characteristic and produce a jump in the FLL output signal. In order to prevent this flux jump, the FLL needs to have a slew rate enough to maintain the feedback signal to follow any change of the external magnetic field. For an idealized noise-free system, the slew rate of the SQUID system can be improved by increasing the bandwidth of the FLL electronics. However, because the SQUID is not noise-free, the achievable bandwidth of a FLL, and hence the maximum achievable slew rate, is determined by the level of noise of the SQUID (Lee et al., 2002).

Field tests

We have conducted field tests several times since 2002 in order to check performance and practicality of the SQUITEM. Here, we introduce the results of three field tests at Kamikawa and over two Cu-deposits inside Japan in 2003.

Table 1. Main specification of SQUITEM

Bandwidth	DC – 100kHz
White noise	100fT/$\sqrt{Hz}$ @10Hz (field)
Slew rate	6.8 mT/s
Liquid nitrogen hold time	more than 9 hrs.
Dynamic range	100dB
Volume of dewar	3.3l (3-component) 2l (gradient)
Dimension of dewar (3-component)	589mm(height) 190mm(diameter)
Dimension of dewar (gradient)	353mm(height) 190mm(diameter)

Fig.1 SQUITEM consists of three SQUID magnetometers, a PC, an A/D converter, a controller, and a battery unit.

Fig.2 SQUID magnetometer for three-component simultaneous measurement. It was surrounded by aluminum foil to dull the abrupt change of the magnetic field just after current interruption in order to inject large current into the transmitter loop.

Fig.3 and Fig.4 represent an example of the SQUID data and a comparison between the SQUID and the coil transient signals, respectively, which were recorded over Kannondo Cu-deposit (Kuroko-type deposit) at the northern part of Japan in November, 2003. In Fig.4, a good agreement is found between the time derivative of the SQUID data and the reference coil data. Notice that the SQUID magnetometer provides better signal-to-noise characteristics at later time moments than the induction coil, illustrating the advantage of the SQUID magnetometer over the coil receiver to increase the depth of investigation.

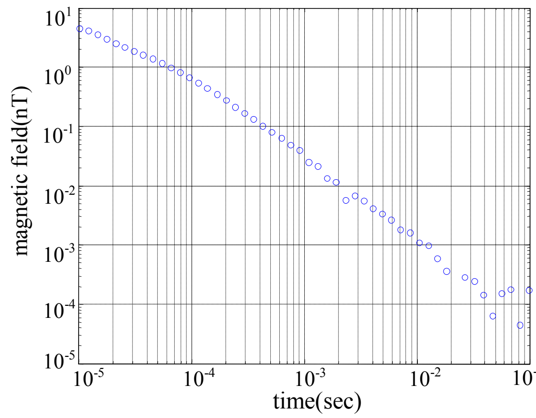

Fig.3 The magnetic field by SQUITEM over Kannondo Cu-deposit placed about 50m below the surface. The signal-to-noise ratio by the SQUID data is better than the reference coil data shown in Fig.4.

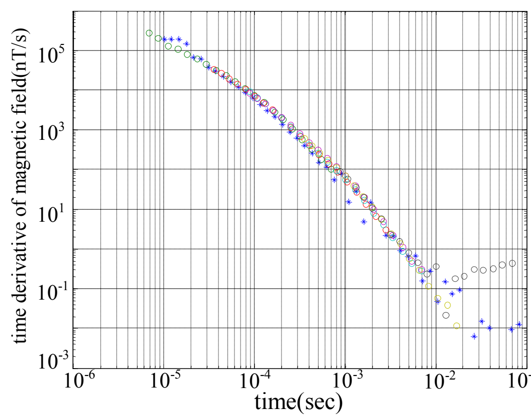

Fig.4 Comparison between the time derivative of the SQUID data in Fig.3 (*) and the reference coil data (o). A good agreement is found between them.

The function of electronic differentiation between two SQUID magnetometers was installed in order to obtain the horizontal gradient of the magnetic field between two points in the summer of 2003. Fig.5 shows the space derivative of z-component magnetic field acquired by the electronic differentiation (solid line) and those computed from the magnetic fields measured at two points (30m spacing) simultaneously (open circle) at Kamikawa in October, 2003. The purpose to measure the space derivative data is to achieve higher resolution at the shallow part of the ground. Our modeling using a two-layer resistivity model (the upper layer has a typical resistivity of 100 ohm-m in Japan) suggested that the space derivative data at about 1msec would be necessary to detect the target placed about 200m below the surface more distinctly than the induction coil data. However, the horizontal gradient data reach the system noise floor, about 1pT for 1,000 times stacking at about 0.2 msec in Fig.5. To obtain the horizontal gradient data untill about 1 msec, the system noise floor must be reduced to one bit resolution by 10 times amplification.

Fig.6 represents the reconstructed resistivity distribution by 1-D inversion computation of the SQUID data acquired over Uwamuki No.4 Cu-deposit located at the Kuroko-area in the green tuff region at the northern part of Japan. Uwamuki No.4 deposit is a kuroko-type deposit (volcanogenic massive sulfides) of middle Miocene age, and placed about 300m deep below the surface. The thickness of the surface Quaternary volcanic ash fall is 80m to 100m. Neogene volcanics and pyroclastics is located 300m to 400m below the surface. The intrusive rhyolite occupies the left part of the section. The host tuff breccia and the foot wall dacite are intensively altered around the orebody which is already mined out located at the right side below the intrusive rhyolite (Hishida et al., 1992). The reconstructed distribution almost matches well to known geology by drilling, the result of the DC resistivity logging, and the 2-D resistivity distribution reconstructed from the DC resistivity tomography data. The Quaternary volcanic ash fall shows the higher resistivity in the upper layer and the lower resistivity in the lower layer. The intrusive rhyolite precisely corresponds to the high resistivity zone. The low resistivity at deeper portion might be due to the presence of intensively altered part around the orebody.

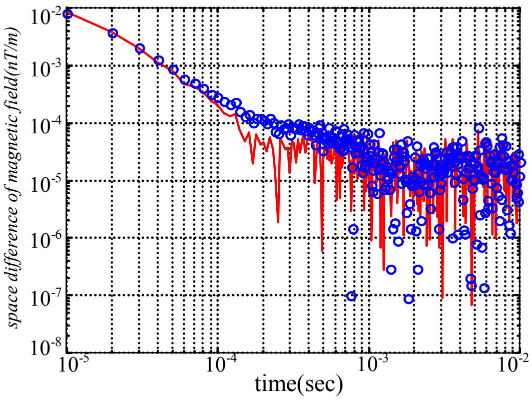

Fig.5 Space derivative of z-component magnetic field acquired by the electronic differentiation (solid line) and those computed from the magnetic fields measured at two points simultaneously at Kamikawa in October, 2003. A good agreement between the electronic differentiation and the computed differentiation suggests the electronics of differentiation operated well. However, the horizontal gradient data reach the system noise floor at about 0.2msec, which is not enough to investigate 200m below the surface.

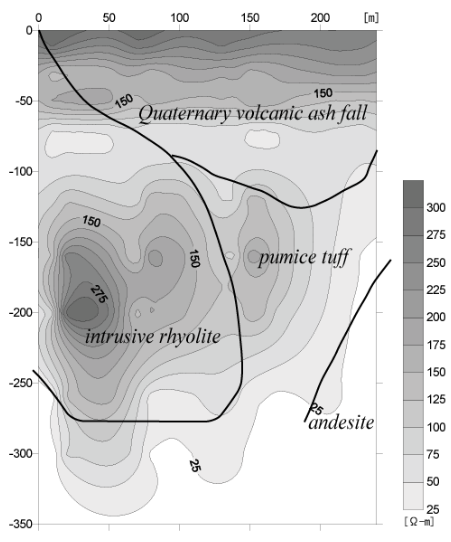

Fig.6 The reconstructed resistivity distribution by 1-D inversion computation of the SQUID data acquired over Uwamuki No.4 Cu-deposit. The SQUID data were acquired at a 10m spacing by four transmitter-loops. The orebody was placed just below the intrusive rhyolite. There is a low resistivity zone corresponding with argilic alteration.

Conclusions and future works

JOGMEC has been developing a three-channel TDEM data acquisition system using the SQUID magnetometer (SQUITEM) for mineral exploration. SQUITEM has two measuring modes for simultaneous data acquisition of three-component magnetic field, and simultaneous measuring of one-component magnetic fields at two points and the horizontal gradient between them. In several field tests, a good agreement was found between the time derivatives of the SQUID data and the reference coil data from early time to late time. The SQUID data generally have better signal-to-noise characteristics at later time moments than the induction coil data, representing the advantage of the SQUID magnetometer over the induction coil receiver.

However, we could not acquire the horizontal gradient data of the z-component magnetic field at time moments which included information around 200m deep in the field tests. This is because the gradient data were so small that they reached the system noise floor faster than the magnetic field. JOGMEC will improve the function of gradient measurement, and make an effort to make SQUITEM more robust in the field, and to reduce the period to adjust SQUID in order to raise the acquisition efficiency.

References

Lamontagne, Y., 1975, Applications of wideband, time-domain EM measurements in mineral exploration, Res. in Applied Geophys. 7.

Lee, J. B., Dart, D. L., Turner, R. J., Downey, M. A., Maddever, A., Panjkovic, G., Foley, C. P., Leslie, K. E., Binks, R., Lewis, C., and Murray, W., 2002, Airborne TEM surveying with a SQUID magnetometer sensor, Geophysics, 67, 468-477.

Hishida, H., Mimami, H., and Tsujimoto, T., 1992, Case study on resistivity tomography in mining districts, The 2nd SEGJ/SEG "Geotomography International Symposium" in Tokyo, 229-245.

Acknowledgments

The authors would like to thank Dowa Mining Co. Ltd., Hanaoka Mining Co. Ltd., and Unekura Mining Co. Ltd. for their presenting geological information and their helpful cooperation in the field tests.