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TEM measurement in a low resistivity overburden performed by using low temperature SQUID

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ABSTRACT

Exploration of areas with thick low resistivity overburden is still a challenge for time domain transient electromagnetic method (TEM). We report modeling of a sandwich-layered earth by simulating the *B* field response with different conductive target layer thicknesses, thus obtaining a relationship between the resolution of the *B* field and the exploration depth. A low temperature Superconducting Quantum Interference Device (SQUID) is an ideal sensor for measuring the secondary magnetic field *B* in TEM measurements, because its sensitivity of several fT/√Hz is independent of frequency. In our TEM experiments, we utilized two different coils as receivers, a simple SQUID system, and a large transmitter loop of 200×200 m^2 to compare the detected decay curves. At some measurement points, a decay signal of more than 300 ms duration was obtained by using the SQUID. Apparent resistivity profiles of about 9 km length are presented.

Contents

1. Introduction

Time domain transient electromagnetic method (TEM) is traditionally used for deep exploration, for stratigraphic application (Spies, 1989), saltwater detection (Auken et al., 2010) and further applications. The central-loop configuration sounding system consists of a large square transmitter loop and a receiver placed at the loop's center

Abbreviations: TEM, time domain transient electromagnetic method; SQUID, Superconducting Quantum Interference Device; LT SQUID, a low temperature Superconducting Quantum Interference Device; IGBT, Insulated Gate Bipolar Transistor.

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(Mitsuhata et al., 2006). The transmitter magnetic moment is an important factor for the resolution of the exploration (Auken et al., 2010). One usually uses the central-loop configuration to record the whole vertical component of the response in a horizontally layered earth (Spies et al., 1988). A double signal synchronous stacking method is usually employed to suppress the environmental noise (Spies et al., 1988).

TEM is an active method used for geo-exploration. The transient response is a decaying signal over time with a wide bandwidth [from DC to several tens of kHz] and a high dynamic range. Conventionally, the resulting secondary magnetic field at the surface is measured during off-time by a voltage induced in a receiver coil. There is a trade-off between the detection bandwidth and the receiver coil sensitivity due to the coil inductance. A large inductance is an important factor to improve the receiver sensitivity (Faraday's law), but it limits the bandwidth of the receiver system, thus making it difficult to detect layers close to the surface; on the other hand, deep layers can hardly be detected with a low inductance coil. In brief, a coil is not optimally suited for detecting the transient signals in a bandwidth spanning a few tenth of a hertz to tens of kHz.

When using a coil receiver, the depth of investigation is proportional to the 1/5 power of the source moment and of ground resistivity. If the receiver sensor directly measures the magnetic field, e.g., a low temperature Superconducting Quantum Interference Device (LT SQUID), the depth of investigation is not only proportional to the 1/3 power of the source moment, but also no longer a function of resistivity (Spies et al., 1988). Using a *B*-field sensor rather than a *dB/dt* sensor also improves the estimate of conductance (Smith, 2014). Thus, a *B*-sensor is very well suited for TEM measurements.

A SQUID is an ideal sensor for measuring the secondary magnetic field *B* of TEM because its sensitivity of only a few fT/√Hz is independent of frequency, at least above a few hertz. Furthermore, the SQUID system exhibits a wide bandwidth into the MHz range so that the whole decay signal can be recorded without distortion. It is expected that the observable decay time detected by a SQUID is much longer than that measured by an induction coil, especially in areas with thick overburden of low resistivity. During the past half century, the complexity of SQUID systems and the requirement to cool the SQUID device to very low temperatures 4.2 Kelvin (K) prevented LT SQUIDs from being widely used for TEM measurements (Clarke and Braginski, 2004). High temperature (HT) SQUIDs that need to be cooled with liquid nitrogen only, have become a production tool in mineral exploration (Chwala et al., 2010; Arai et al., 2004). Due to a high operation temperature, the higher thermal noise level of HT SQUID systems as compared to their LT counterparts limits their application, however. In the last ten years, TEM measurements with LT SQUIDs made enormous progress, e.g., IPHT Jena firstly applied a large loop source to SQUID-based TEM. Here, the transmitter was a Geonics TEM 57 MK2, and the receiver was a combination of a Protem unit and a LT SQUID sensor with a typical system noise level of 20–30 fT/√Hz@10 kHz (Chwala et al., 2011). In a recent paper (Chwala et al., 2015) they review the use of LT SQUID systems in geophysical applications.

Exploration of areas with thick low resistivity overburden is still a challenge for TEM. In this paper, we report on modeling of a sandwich-layered earth by simulating the *B* field response with different conductive target layer thicknesses. From the simulation, we obtained a relationship between the minimum resolution in the *B* field and the exploration depth. The dependence of detection depth on transmitter magnetic moment will also be discussed. In our TEM experiments performed on an island near Shanghai, we utilized two different coils as receiver, a simple LT SQUID system specially developed for TEM, and a large transmitter loop of 200×200 m^2. TEM decay curves detected by the LT SQUID and by the coils are compared. At some measurement points, a decay signal of more than 300 ms duration was obtained using the SQUID, corresponding to an interpreted depth of 2500 m. We also present apparent resistivity profiles of about 9 km length. The results show that an exploration depth of 1400 m can be routinely reached in the profiles.

2. Simulations and calculations

2.1. B field response of a sandwich structure in homogeneous layered earth

Our survey area is a part of the island created by land reclamation in recent years. According to the Shanghai Marine Geological Survey, our survey area is a zone of the island created by land reclamation these years. The arrangement of the geological structures is Quaternary system (Q4), tertiary Pliocene series (N2) and upper Jurassic from the top down. The main ingredients of Q4 are variegated: gray clay, sandy gravel and deposition of transitional faces. It exhibits the lowest resistivity in this sandwich structure. The mid layer is made up by gravel, fine sand, coarse sand and gravel. Thickness of the mid layer is more than 480 m, its resistivity is only tens of Ω·m. The bedrock is upper Jurassic, mainly volcanic rocks and pyroclastic rocks. Its resistivity is several hundreds of Ω·m.

According to the above descriptions of this survey area, we model a sandwich-layered earth with the central loop configuration to simulate the *B* field response. Poddar et al. gave the general expression for the vertical magnetic field produced by a horizontal rectangle transmitter loop carrying a current $Ie^{i\omega t}$ (Poddar, 1983). In our simulation, a rectangular transmitter loop (200×200 m^2) is adopted and the transmitter current is set to be 50 A peak. We assume that the sandwich structure consists of a sequence of low-medium-high resistivity layers. The 1st layer is a 30 Ω·m low resistivity layer with $h_1 = 400$ m thickness, the 2nd layer (conductive target layer) is 50 Ω·m medium resistivity layer with a thickness ranging from $h_2 = 500$ m to 3000 m, and the 3rd layer is a 300 Ω·m high resistivity layer. With Poddar's expression, the simulation results are shown in Fig. 1a. The *B* field response of the sandwich structure varies over the thickness of the conductive target layer (h_2). At early times (<20 ms), the *B* response is independent on h_2, then the different *B* responses appear. From measurement times of > 100 ms onward, we can distinguish the *B* responses for different h_2. For measurement time of more than 300 ms, the *B* responses for different thicknesses h_2 are clearly separated. When assuming our measurement sensitivity of 10–20 fT, the valid measurement time should be limited to a maximum of 1 s.

2.2. The relation between detection depth and the sensitivity of B receiver under different transmitter magnetic moments

According to the smoke ring theory (Spies, 1989) for a single layer geophysical model, the expressions of the maximal detection (diffusion) depth *d* and the diffusion time *t* are given in Eqs. (1) and (2), where μ_0 denotes the free space permeability, σ is the conductivity of the single layer, *I* is the transmit current, B_z is the vertical *B* response and a is the transmitter edge length. When substituting Eq. (2) into Eq. (1), we get an approximate empirical Eq. (3) (Spies, 1989), which describes the relation between the diffusion depth *d* and the maximal sensitivity of the receiver B_z' under a certain transmitter magnetic moment *M*. Spies introduced the depth of penetration d_p which often equals 0.71 of the diffusion depth *d* (see Eq. (4)). In fact, the practical depth of investigation depends not only on the sensitivity and accuracy of the instrumentation, but also on the complexity of the geologic section, and the environment. The empirical coefficient $K < 1$ should be introduced to correct the relationship between the practical depth of investigation d' and the penetration depth d_p. Finally, we obtain Eq. (5). One finds that d' is independent on *t* and σ.

$$d = \sqrt{2t/(\sigma\mu_0)} \tag{1}$$