Three-dimensional inversion of SQUID TEM data at Lalor Lake VMS deposit

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Summary

The combination of high fidelity and late time channels make SQUID magnetometers an attractive sensor for deep and highly conducting targets. Here we focus upon a data set acquired over the Lalor Lake VMS deposit. The deposit consists of a zinc zone between 700m and 1000m depth and a deeper gold/copper zone. The SQUID data set had previously been interpreted using the plate modeling to yield two conductors respectively corresponding to the zinc zone and the gold-copper zone. In this paper we invert these data with our 3D TEM inversion algorithm to produce a 3D voxel conductivity volume. Our 3D model recovers a shallow dipping conductor, which coincides well with the plate model of the zinc zone, as well as a large conductor below 1000m depth. Our inversion is done without incorporating prior knowledge and there is always the potential that large features at depth can be an artifact of the inversion algorithm. To investigate this, and to have confidence, or not, in the existence of the deep body, we carry out a hypothesis analysis where we attempt to find a model that does not have a high conductivity at depth. Forward modeling and subsequent inversion confirms that there must be another conductor below the zinc zone. Much of the concentration of conductivity lies near the region indicated by the initial blind inversion, but the amplitudes and distribution are different. Nevertheless, despite lack of knowledge about geometric details, there is some highly conductive material at depth and it would warrant a drill hole. In a final analysis we look at the relative merits of using B or dB/dt for the particular geometry of this survey. We generate synthetic B and dB/dt data based on our inversion model of Lalor Lake deposit. While the B-field data inversion recovers the correct locations and geometries of the two compact conductors, the dB/dt inversion shows the shallow conductor in a distorted geometry and the deep conductor as a blurred conductive region with conductivity much smaller than the true model. This demonstrates that B-field data can be are superior to dB/dt data for this survey in which we have surface transmitters and receivers.

Introduction

Most time-domain electromagnetic (TEM) surveys measure the time derivative of the B field using induction coils. However, with SQUID (Superconducting Quantum Interference Device), B-field data of unprecedented quality are now available. It has been shown that the SQUID data have several advantages over the coil data (Chwala, et. al., 2001; Osmond, et. al., 2002; Leslie, et. al., 2008): (1) They have much higher signal-to-noise ratio. This allows SQUID to measure the B field at very late time so that weak signals from deep targets or targets under conductive cover can be detected.
(2) They are sensitive to good conductors. The off-time dB/dt data may fail to see highly conductive targets due to the slow decay of the B field, while a good conductor is distinctive in B-field data.

Currently the most popular interpretation method of the SQUID data from a ground loop survey is the plate modeling, which assumes the EM responses are caused by some discrete conductive plates in free space. The plate modeling is fast and easy to implement, and it has many practical successes accredited to it, however it may suffer from over-simplification if the true model is complicated. In this paper we carry out rigorous 3D inversion of a SQUID data set from a VMS deposit and show how 3D inversion technique can interpret the SQUID data.

Background of the Lalor Lake deposit and SQUID data

The Lalor Lake is located in the Chisel Basin portion of the Flin Flon Greenstone Belt, and about 8km west to Snow Lake in central Manitoba, Canada. The deposit, discovered in 2007 within the meta-volcanics, meta-sediments and granitoids of the Churchill province, is believed to be the largest VMS ever found in this area. An extensive drilling program has confirmed three mineralization zones at different depths (Figure 1). Due to the deep burial below more than 1000m, the gold/gold-copper zone at bottom is not well sampled by the drill holes and its extension is still unclear. However, drill holes have intercepted some high grade copper and gold in that area. This indicates that a more economically interesting target may exist at greater depth and is worth a further investigation.

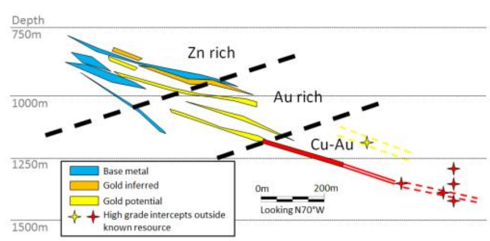

Figure 1: Lalor Lake VMS deposit.

A time-domain EM survey using the HTS SQUID sensors was carried out at Lalor Lake with the expectation of seeing the deeply-buried targets. The SQUID sensors are JESSY HTS working at high temperature (69 degree Kelvin) and cooled with liquid nitrogen. Two large loops were used to

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energize the ground and for each of them two lines of three-component B-field data were collected. The station spacing varied between 100m and 200m (Figure 2). The transmitter for the large loop (Loop 1) used a ramp-off waveform at the base frequency of 1.667Hz, while the small loop (Loop 2) data had a base frequency of 0.5Hz. The transmitter was the Phoenix TXU-30 and the data were recorded using the EMIT SMARTem24 receiver at 34 time channels (0.1 to 126ms) for the large loop and 39 time channels (0.1 to 371ms) for the small loop.

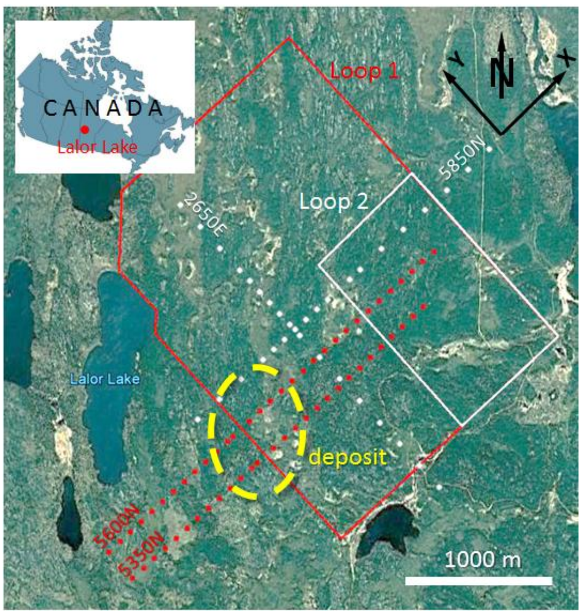

Figure 2. Layout of the SQUID TEM survey at Lalor Lake. Line 5350N and 5600N were collected with the transmitter Loop 1 (red) and Line 5850N and 2650E with the Loop2 (write).

Interpretation of plate modeling

The SQUID TEM data were first interpreted using the plate modeling of Maxwell (D. Bingham, et. al., 2010, Living Sky Geophysics Inc. and Discovery International Geophysics Inc., New generation JESSY HTS SQUID results over the Lalor deposit), in which a parametric inversion is implemented to find the plates with geometry and conductance so that the observed data can be reproduced. Only very late time channels were considered for the data fitting. Three plates were required to explain the data (Figure 3). The green plate buried at depth of between 700m and 1000m and slightly dipping north coincides with the zinc zone known from drilling. Another steeply dipping purple plate, continuing the trend of the zinc zone below 1000m, is also supported by the late time data. This models the gold and gold-copper zones. Both the green and purple plates have conductance greater than 600S, implying very high conductivity of sheet-like

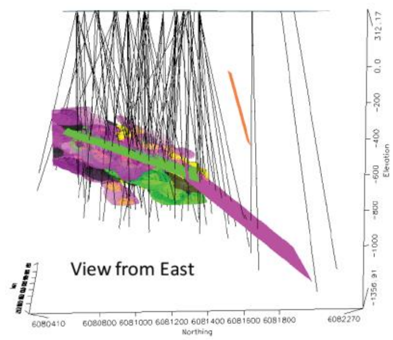

Figure 3. Plate modeling of the SQUID data for the deposit.

conductors. A small and shallow plate (orange) is required to fit the local variation in the data.

The plate modeling is fast and easy to implement. However, there are some limitations of the plate modeling:
(1) It is difficult to fit both early and late time channels;
(2) It does not model the host rock that may contribute background responses to the data;
(3) The plate may over-simplify the actual model;
(4) When data are complicated, one may have to work with an unmanageable number of plates.

Rigorous 3D inversion

A rigorous 3D inversion based on a voxel model can properly address the shortcoming of the plate model. Our 3D TEM forward modeling and inversion is based on finite volume method in space and time stepping in time (Oldenburg, et. al., 2008). It can invert B and dB/dt data to recover a 3D conductivity.

Our inversion mesh has 64×56×47 cells with the smallest cell size in the center being 100m horizontally and 50 m vertically. Data at time channels after 30ms from all SQUID stations in Figure 2 are included for the inversion. The standard deviation assigned to the data is 10% of each

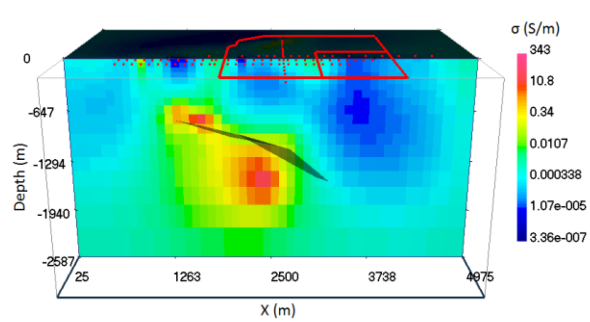

Figure 4. Conductivity model from the 3D inversion. The cross section on 5700N is shown. The plate models are indicated by the shaded surfaces.

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datum plus a small floor value. The inversion starts with an initial and reference model of 0.001S/m half-space. The target misfit is achieved after 28 iterations within 8 hours.

The inversion recovered two conductors at depth each having conductivity greater than 10S/m. The small conductor is located between 600m and 900m, while the other large conductor is found below 1000m (Figure 4). The small conductor has the same location and dipping angle as the green plate in Figure 3, and thus is interpreted as the zinc zone. The larger conductor, however, is below the purple plate and extends in depth to 2000m. This is likely reflecting the deeper copper/gold mineralization, but more work needs to be done to verify the model.

Is the deep conductor an inversion artifact?

The blind inversion in the previous section reveals two conductors. The small shallow conductor is supported by both the plate modeling and the deposit model from drilling. It is confirmed to represent the zinc zone. Although drilling has confirmed the existence of the second deeper deposit, from our perspective here, we can proceed without that knowledge. As such, a basic question would be: "How confident are we with the existence of the deep conductor?" In other words, is the deep conductor required by the data or just an inversion artifact?

This question is approached from two ways:
(1) Forward modeling: If the deep conductor is erased from the inversion model, how does its removal affect the data? To investigate this we cut off the deep conductor based on a contour of 0.01S/m (Figure 6a), and forward model the resulting model. Figure 5a shows how an example sounding responds. Without the conductor (red curve), the late time channels drops much more quickly than the observed data (blue curve). They differ by a factor of 10 at the late time channel, which is well above the noise level. This indicates that the deep conductor, or at least a conductor below the zinc zone, seems to be required by the data. This is not proof however, since by altering the conductivity distribution around the region where the anomaly has been removed, it may still be possible to fit

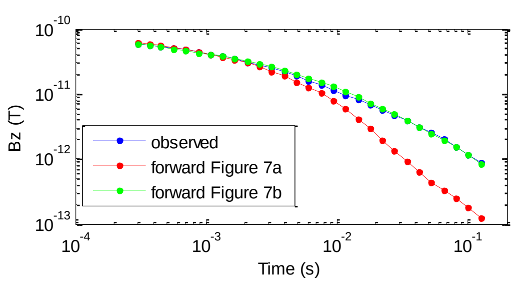

Figure 5. The deep conductor in the data. This sounding is located at 2500E on Line 5350N.

the data. Thus a better approach is through a more formal hypothesis test.
(2) Inversion: We hypothesize that the earth does not have a high conductivity in the region of interest and attempt to construct a candidate. If a model without the deep conductor can be found to fit the data, the existence of the conductor is in doubt. Conversely, if the constructed model still shows a conductor in the same location, we have enhanced confidence that the feature is real. We thus carry out another inversion using the conductor-removed model (Figure 6a) as the initial and reference model. The weight of the smallest component in the model norm is set to be large such that the inversion prefers a model that is as close to the reference model as possible, i.e. any structure creating conductive material at that conductor-removal area is suppressed. While the conductor of the zinc zone remains almost unchanged, the final model of the hypothesis test inversion again builds up a conductor in the area where the deep conductor was removed from (Figure 6b). The new model fits the field data as well as the blind inversion model (green curve in Figure 5) and the deep conductor moves closer to the location of plate model (Figure 6b). Compared to the blind inversion, the conductivity of the deep conductor has been reduced but it is still much greater than the reference model. The conductivity is also smeared out over the area in which structure had been penalized. The overall reduced conductance of the deep conductor is compensated somewhat by the increased conductivity at the zinc zone and other places around the conductor-removal area.

Based on the above analyses we have enhanced confidence

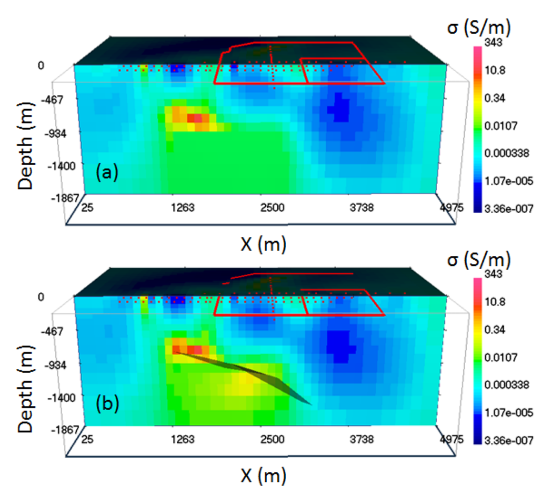

Figure 6. Conductivity models of the hypothesis test. The cross section on 5700N is shown. (a) The model with the deep conductor removed is used as the initial and reference model for the test inversion. (b) The result of the hypothesis test inversion. The plate models are shown as shaded area.

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that a deeper second region of high conductivity exists and this coincides with current knowledge about the deposit. However, further analysis regarding uncertainty can be carried out. This would be expedited by having additional a priori information included into the inversion.

Comparison of B and dB/dt data inversion

Typically dB/dt data from coils are acquired in TEM surveys. A well-known advantage of B-field data over dB/dt data is that the B-field data have high response at high conductivities, but the dB/dt data do not (Smith, et. al. 1998). To illustrate this we forward model the vertical components of B and dB/dt at the center of a 1km-side loop for different conductivities of half-space. The TEM responses at 0.01s as functions of the conductivity are plotted in Figure 7. For this particular time channel, the B field is monotonic until 100 S/m and stays relatively high after the maximum, while the dB/dt rolls back quickly beyond 0.1 S/m. Therefore, it is likely that a target with high conductivity is seen as a weak conductor in off-time dB/dt data.

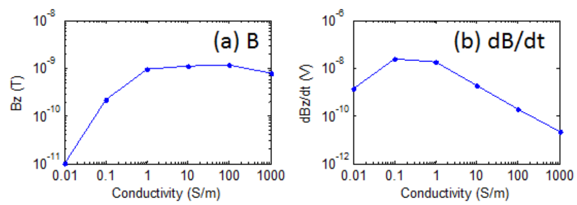

Figure 7. B and dB/dt responses for conductive half-spaces.

In order to compare the detectability of the targets at Lalor Lake using surface B-field and dB/dt data, we design two synthetic inversions. The model in Figure 4, assumed as the true model, is forward modeled to generate a data set of B and a data set of dB/dt at the same stations and time channels using the same 0.5Hz base frequency. No artificial noise is added into the data. The inversion results are shown in Figure 8. The B-field data inversion successfully recovered the two conductors, but the conductors in the dB/dt inversion have distorted geometries and the deep conductor is only seen as a blurred area with greatly reduced conductivity. This example shows the B-field data measurements may be better choice in such TEM surveys.

Conclusions

SQUID TEM data from the Lalor Lake VMS deposit are inverted using our 3D algorithm. The inversion recovers two bodies with very high conductivity. The one between depth of 600m and 900m coincides with the zinc zone in the deposit model and is consistent with the plate modeling. The other is larger in size and is buried below 1000m deep. It is reflective of the copper/gold deposit there. Our confidence in the existence of the deeper zone has been

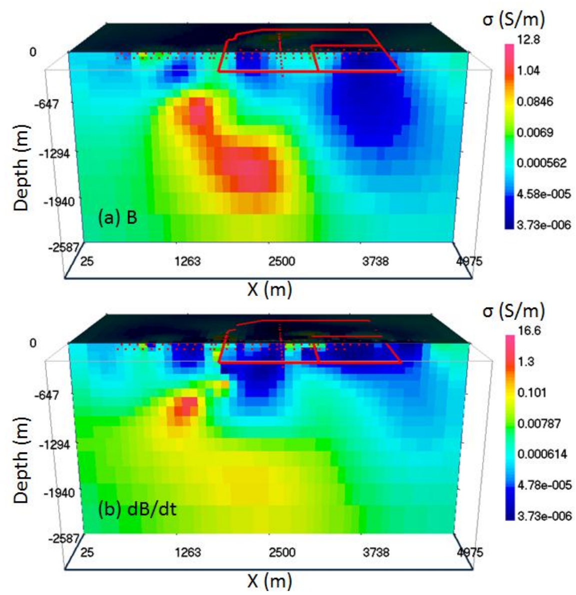

Figure 8. Conductivity models of the synthetic inversions using B-field and dB/dt data. The cross section on 5700N is shown.

enhanced by forward modeling and an inversion employing a hypothesis test where we attempt to find a model that does not have high conductivities at depth. Nevertheless, the inversion generates a model with a conductivity that is a couple of orders of magnitude greater than the reference model. The resulting model, again without a priori knowledge, looks like a reasonable candidate for earth structure. This provides increased confidence in the geologic existence of the second conductive zone.

The relative merits of B-field data over dB/dt data are also investigated. We generate a synthetic B-field and dB/dt data sets based on our inversion model of Lalor Lake deposit using the same specifications and invert them for a fair comparison. The B-field data inversion recovers a model that is very close to the true model, whereas the dB/dt data inversion presents a distorted and blurred image of the targets. This demonstrates that SQUID B-field data, if available, should be the preferred type of data in this type of TEM survey.

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