3D conductivity models of Lalor Lake VMS deposit from ground loop and airborne EM data sets

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SUMMARY

Lalor Lake is a VMS deposit in central Manitoba, Canada. The deep ore body is buried under the cover rocks up to 1000m. Multiple EM data sets were collected to delineate the compact and conductive alteration zones and two data sets are available to us. The first is HELITEM, an airborne time-domain EM survey that covers the entire exploration area. The second is a ground loop EM data measured by SQUID magnetometers that have high precision at late times. The two data sets map the conductivity structures at Lalor Lake in different ways: the airborne survey covers a broad area but has limited resolving power at depth; the ground survey provides information about the deep targets through very late times but the measurements were made in a smaller area. Individual 3D inversions were carried out for both data sets assuming little a prior information. Both are able to recover the trace of the expected ore body, but the airborne model is smooth and the ground model contains highly conductive anomalies. Then we invert the ground data again with the airborne model as the reference model. The new inversion again confirms the existence of the VMS ore body but also rearranges the conductive material according to the constraints from the reference model. The new model differs significantly from the blind inversion model at the deposit scale. Based on the information from the inversion so far, we conclude both surveys have picked up signals from the ore body in different levels of detail. More analysis and further data are still required to better delineate the target's geometry.

Key words: electromagnetic, 3D inversion, airborne EM, SQUID, volcanogenic massive sulphide

INTRODUCTION

In mineral explorations, nowadays it is common to have multiple geophysical data sets concerning the same geologic targets and the same physical properties. One of the most popular combinations is airborne EM and ground EM for conductivity, based on the idea that the airborne survey provides cost-effective mapping at a regional scale and the ground survey is capable of better imaging the localized structure at the deposit scale. In practice, the airborne data have usually been interpreted from contoured maps of the data or cross sections made from concatenated 1D inversions. The ground EM data, which are often collected along lines, are commonly inverted using plate modelling. The distinct methods of interpreting airborne and ground EM data could leave a gap in comprehensively understanding the geophysical signatures of the exploration targets and potentially create inconsistency in the decision-making process.

As 3D voxel inversion of EM data is becoming more practical, the gap between airborne and ground EM data could be closed by inverting them jointly with the same algorithm. Ideally, we should be able to find a common conductivity model that explains both airborne and ground data. We're pursuing a formal joint inversion but another approach is use a cooperative inversion where the output for one of the inversions is used as constraints or a priori information for the inversion of the other data set. This is our focus here. At Lalor Lake, we have access to two EM data sets, one airborne and one ground loop. We first invert the two data sets individually and compare the inversion models. Then the information in the airborne data is softly incorporated into a new inversion of the ground data through the reference model. This can be a first step toward finding a common conductivity model and importantly, it provides insight about the information provided by the two data sets.

GEOLOGIC SETTINGS OF LALOR LAKE

Lalor Lake is a volcanogenic massive sulphide (VMS) deposit located in the Chisel Basin portion of the Flin Flon Greenstone Belt, and about 8km west to Snow Lake in central Manitoba, Canada. The geophysical EM target at Lalor Lake is compact and highly conductive VMS alteration units deeply buried under about 1000m cover rocks. An extensive drilling program has confirmed mineralization zones at different depths (Figure 1).

EM SURVEYS AT LALOR LAKE

Multiple EM data sets have been collected at Lalor Lake. The data sets we have access are HELITEM for the airborne and SQUID for the ground.

HELITEM is a helicopter-borne time-domain EM system with separated transmitter loop and receiver coils (non-rigid configuration). The transmitter carries a half-sine current waveform at a base frequency of 30Hz. The transmitter dipole moment is about 1.9 million Am2. The time derivatives of the magnetic field in three components at 30 time channels, as late

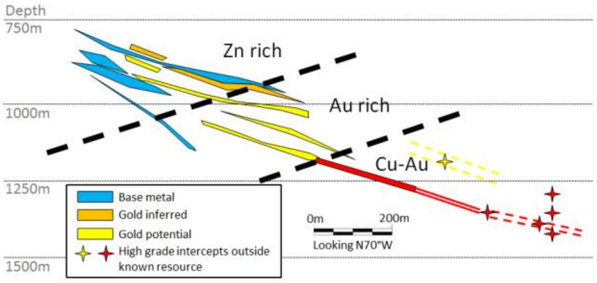

Figure 1. Mineralization zones of Lalor Lake deposit. The zinc-rich zone above the depth of 1000m has been confirmed by extensive drillings; the deeper high-grade copper-gold zone was intercepted by sparse drills, but its geometry and distribution are still largely unknown.

as about 10 ms, were recorded at every sounding location along 18 flight lines 200 m apart to each other. The entire survey covers the Lalor Lake deposit and its neighbouring exploration area (Figure 2).

In the ground EM survey, two transmitters carrying a ramp-off current were used to couple with the VMS targets in different ways (Figure 2). The large loop has one side approximately over the ore body and measures the magnetic field data along Line 5350N and 5600N. The small loop horizontally offsets the expected target by about 1 km and measures the data along Line 5850N and 2650E. Unlike traditional EM surveys that measure the time derivative of the magnetic field (dB/dt) using coils, this survey directly measures the magnetic field (B) using a SQUID (superconducting quantum interference device) magnetometer. A SQUID has very low internal noise and is able to measure small magnetic signals to very high precision (Chwala et al., 2011; Leslie et al., 2008). This advantage allows the EM survey with a SQUID to record time-domain data at very late times for deep target. The base frequencies used in the large and small loops were 1.667 and 0.5 Hz respectively, corresponding to the latest time channels 126 and 371 ms.

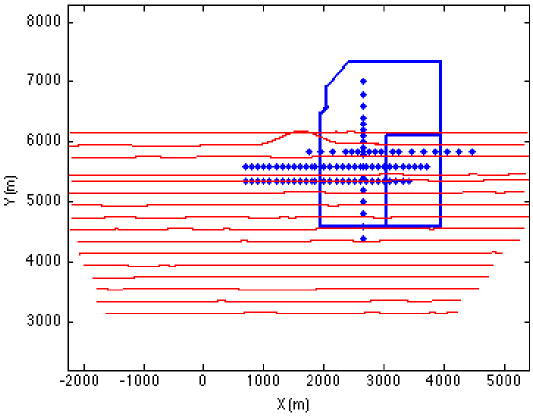

Figure 2. The layout of EM surveys at Lalor Lake area in the local coordinate system. The ground EM survey is shown in blue: solid lines show the two transmitter loops and the dots indicate the receiver locations. The flight lines of the airborne EM are shown in red. The Lalor Lake ore body locates near (2000, 5600).

While both the airborne and the ground data sets are sensitive to the conductivity, they provide different types of information about the same physical property: the airborne data cannot see very deep, but they carry abundant information about the conductivity over a broad spatial range; this can provide crucial information about the near surface and the background conductivity. The ground data have high quality late time information from depth but the receiver locations are spatially limited and this can admit non-uniqueness in inversion.

3D INVERSION ALGORITHM

The 3D EM inversion code used in this study is the one described in Oldenburg et al. (2013). The forward modelling is based on finite volume technique in space and backward Euler finite difference in time. The system of equations is solved by parallel Cholesky factorization. The inverse problem is formulated as an optimization problem

$$\begin{aligned}\min\ \phi = &\frac{1}{2}\left\|W_d\left[F(m)-d\right]\right\|^2+\frac{\beta}{2}\alpha_s\left\|m-m_0\right\|^2\\ &+\frac{\beta}{2}\alpha_x\left\|W_x(m-m_0)\right\|^2+\frac{\beta}{2}\alpha_y\left\|W_y(m-m_0)\right\|^2\\ &+\frac{\beta}{2}\alpha_z\left\|W_z(m-m_0)\right\|^2,\end{aligned}\qquad(1)$$

where the first term measures the weighted data misfit and the rest terms measure the complexity of the model. The coefficients α_s, α_x, α_y and α_z adjust the relative importance of the distance from current model to the reference model m_0 and the smoothness of current model in x, y, z directions. For a given trade-off parameter β, equation (1) is iteratively solved for a model update by the Gauss-Newton method. The inversion usually starts with a large β, and then gradually reduces to allow more structure to be built into the model until the observed data are reasonably fit. The α coefficients, m_0 and the difference matrices W_x, W_y, W_z, along with bounds and weights constraints in the code, are used to incorporate a prior information into the inversion.

3D INVERSION OF AIRBORNE EM DATA

In HELITEM inversion, standard deviation of 10% plus a floor was assigned to the data as uncertainty. The inversion starts with a 0.0005 S/m uniform half-space as a reference model and the data misfit converges to the target misfit after 8 iterations. Figure 3 shows the flight lines and the 3D inversion model at the cross section cutting the known ore body. The recovered model presents a large round-shaped conductive body at the location where the deposit is supposed to be, although the image is quite smooth. The recovered conductivity of the ore body is about 0.01 S/m, which is considered moderate for VMS deposit.

3D INVERSION OF GROUND EM DATA

For SQUID inversion, we assign the same percentage standard deviation. The starting and reference model is a 0.001 S/m uniform half-space. The target data misfit was achieved after 5 iterations. The inversion reveals an image of a conductive complex that consists of one shallower and one deeper concentration of high conductivity (Figure 4). And the conductivity contrast in the ground EM inversion model is high, with some cells having in excess of 10 S/m.

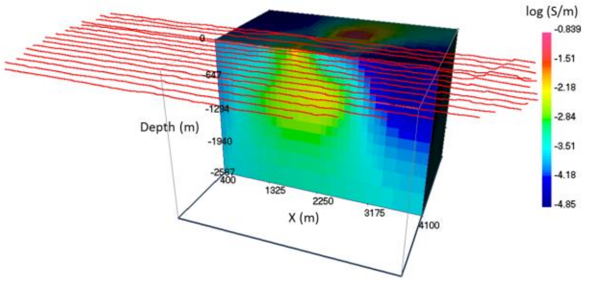

Figure 3. 3D HELITEM inversion model for Lalor Lake VMS deposit. The cross section of 5600N is shown. Red lines indicate the flight lines.

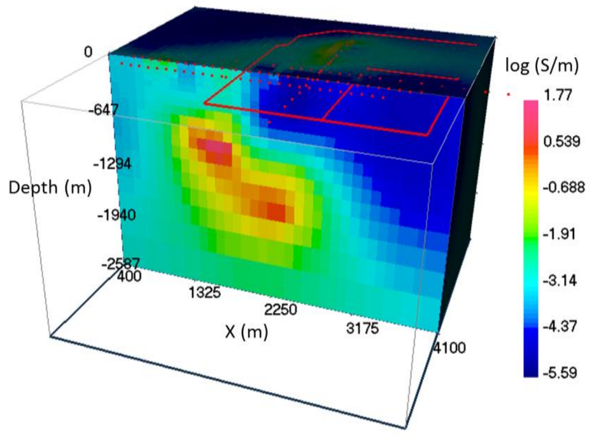

Figure 4. 3D SQUID inversion model for Lalor Lake VMS deposit. The cross section of 5600N is shown. Red lines and dots show the transmitter loops and receiver locations.

We first compare the models from blind inversions of both data sets (the left and middle columns in Figure 5).

On plan view, both models have the same large-scale conductive trend from top right to bottom left leaving the other two corners resistive. However, the airborne model is very smooth and the ground model contains much more structures with localized conductors more than 10 S/m. This can be contributed to that the airborne survey, with higher noise level and higher base frequency, does not have the resolving power the SQUID has at depth.

The cross sections of the two models both show conductive bodies. The conductive feature in the ground model is dipping and seems to be in general accordance with the deposit model in Figure 1, but the volume of the conductor is large, and this raises questions like how large the ore body is and also questions about the resolving power of the data at those depths. We also note that the conductor in the ground model is somewhat deeper than that from the airborne model.

ALTERNATIVE MODEL FOR GROUND DATA

Although the ground data inversion has found a model that seems reasonable, we are still uncertain about the depth of the conductor since the airborne and ground data inversions provide different answers. We are also interested in the credibility of the deep extension of the conductor as revealed by the ground data inversion. Our previous work using inversion with hypothesis testing (Yang and Oldenburg, 2012) indicated that some conductive material at depth is required to fit the ground-based data.

Regarding the airborne data model as a blurred image of the background conductivity, we rerun the ground data inversion with modifications to the model norm so the information from the airborne data is indirectly incorporated:

1. Change the reference model m_0 in equation (1) from uniform half-space to the airborne inversion model;

2. Change α_s from 1E-7 to 1E-5, large enough so that the reference model is honoured and a model as close to the reference model as possible is sought;

3. Set the upper bound of recovered conductivity to be 100 S/m, because the highest conductivity in the blind inversion is about 60 S/m.

The new inversion fits the observed data as well as the blind inversion after 6 iterations. The recovered model is shown in cross section and as a depth slice in Figure 5. On cross section 5600N, the conductor becomes smaller and less conductive and the deeper part of the conductor in the blind inversion model is now recovered as a small tail at shallower depth close the airborne model. The loss of conductive material in the cross section 5600N is compensated by another large conductor to the south of the ground survey lines (bottom right panel in Figure 5). The common features in the individual blind inversion models and those in the alternative model suggest that the ground EM data have enough information for the reconstruction of the large-scale conductivity structures but discrepancies between the results indicate that the ground data, due to data deficiency, may not be able to delineate all of the geometry of the target.

CONCLUSIONS

Our eventual goal is to invert many different types of ground and airborne EM data at Lalor Lake and attempt to find a common conductivity model. This is a work in progress. Here we have taken our first steps and used 3D inversion to interpret an airborne and a ground loop survey.

Without any prior information, the airborne data inversion recovers the regional trend of conductivity and renders a smooth image of the conductivity model. The inversion of the ground data finds the same large-scale features but with more localized structures at the deposit scale. A large and highly conductive target can be seen extending down to 1800 m deep in the ground data model; this is not seen in the airborne model.

We then carry out another inversion of the ground data but use the airborne model as the input reference model and encourage the inversion to recover a model close to the airborne model. The new inversion recovers the same regional structure but the local features are somewhat different. The supposed deeper ore body in the new model becomes smaller in size, lower conductivity and shallower. We conclude that the ground EM data have more signals from the deep ore body than the airborne data; however, because of the restricted locations of measurements for the ground survey, the amount of information in the ground is not enough to fully reveal the geometry of the target. We are planning to work with additional EM data sets to help us resolve questions about the existence and geometry of the deeper conductor.

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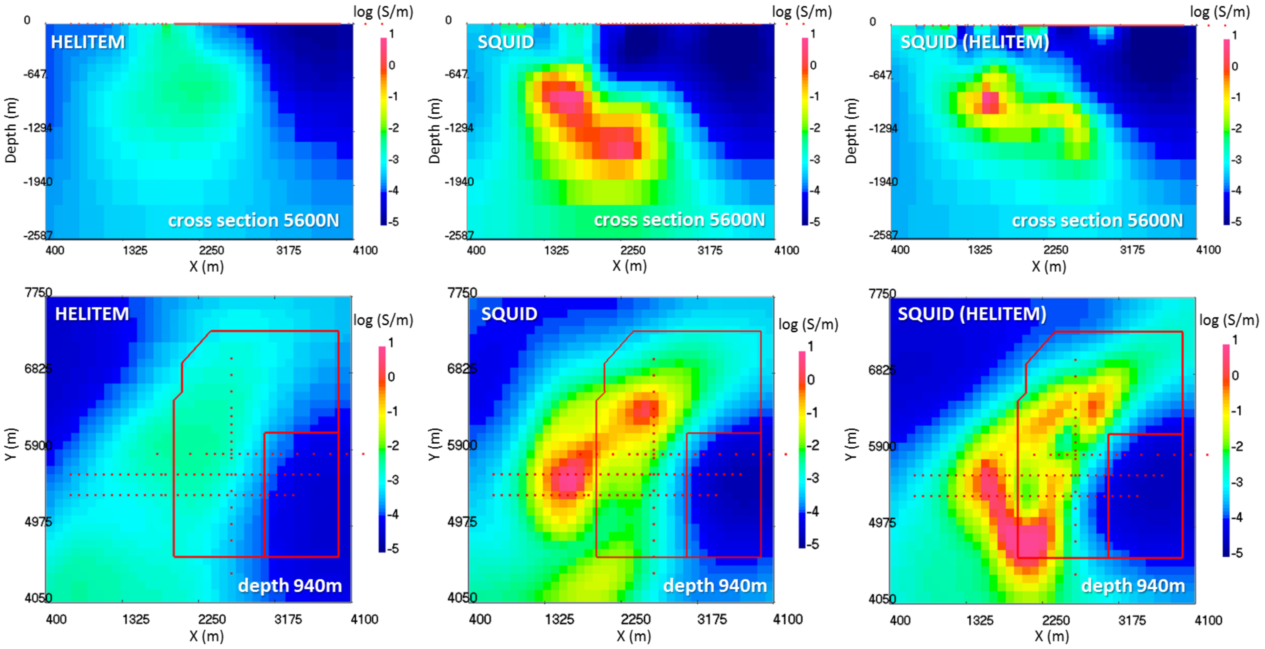

Figure 5. 3D inversion models at Lalor Lake VMS. The left column is from the airborne data inversion; the middle column is from the ground data inversion; the right column is from the ground data inversion using the airborne model as the reference model. The top row shows the cross section 5600N of the three models; the bottom row shows the depth slice at 940m of the models. The colour scale is cropped for a fair comparison and does not suggest the upper and lower limits of conductivity.