Deep mineral exploration using multi-scale electromagnetic geophysics: the Lalor massive sulphide deposit case study

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Abstract: The Lalor deposit in Snow Lake, central Manitoba, is one of the most significant mineral discoveries in Canada in the past decade. Buried 600 m below the surface, the deposit remained undiscovered until a deep penetrating geophysical electromagnetic (EM) system was employed. Since then, the deposit has been a test site for many modern geophysical systems. This paper presents a comparative study of four EM data sets acquired at Lalor. We image the electrical conductivity structure of the deposit by carrying out independent 3-D inversions of the data. The four data sets are acquired through airborne, surface, and borehole systems, including airborne natural source EM (ZTEM), airborne time-domain EM (HELITEM), surface large loop EM (SQUID), and borehole EM (PULSE-EM). ZTEM has good depth of penetration, but its inversion model may be biased if the background model is not properly chosen. The HELITEM system can complement ZTEM by validating the actual conductivity of the deposit. With the information provided by airborne surveys, surface EM can better define the geometry of the ore body at a local scale and help in defining drilling targets. Once boreholes are drilled, sensors can be sent downhole, possibly probing the ore lenses that are interbedded at a greater depth. Our 3-D imaging experiments demonstrate that modern geophysical technology is capable of making deep exploration and assisting a more informed process throughout the entire workflow from reconnaissance to drilling and development.

Résumé : Le gisement de Lalor à Snow Lake, dans le centre du Manitoba, constitue l’une des plus importantes découvertes de la dernière décennie au Canada. Enfoui 600 m sous la surface, le gisement est demeuré caché jusqu’à ce que soit utilisé un système d’onde électromagnétique (EM) profond. Depuis, le gisement est un site d’essai pour de nombreux systèmes géophysiques modernes. L’article présente une étude comparative de quatre ensembles de données EM acquis à Lalor. Nous produisons une image de la structure de conductivité électrique du sous-sol en réalisant des inversions 3D indépendantes des données. Les quatre ensembles de données ont été acquis avec des systèmes aéroportés, de surface et de puits, dont l’EM de source naturelle aéroportée (ZTEM), l’EM à dimension temporelle aéroportée (HELITEM), l’EM par grande boucle en surface (SQUID) et l’EM de puits (PULSE-EM). La méthode ZTEM offre une bonne profondeur de pénétration, mais son modèle d’inversion pourrait être biaisé si le modèle de fond n’est pas bien sélectionné. Le système HELITEM peut compléter le système ZTEM en validant la conductivité réelle du gisement. Combinée à l’information fournie par des levés aéroportés, l’EM en surface peut permettre de mieux définir la géométrie du corps minéralisé à l’échelle locale et aider à établir des cibles de forage. Une fois que des sondages sont forés, des capteurs peuvent être envoyés dans le trou, pour possiblement sonder les lentilles minéralisées interstratifiées à de plus grandes profondeurs. Nos expériences d’imagerie 3D démontrent que la technologie géophysique moderne peut être utilisée pour l’exploration en profondeur et peut favoriser un processus mieux éclairé à toutes les étapes, de la reconnaissance à la mise en valeur en passant par le forage. [Traduit par la Rédaction]

Introduction

Volcanogenic massive sulphide (VMS) deposits are results of ancient hydrothermal activities in submarine volcanic terranes and are major sources of metals like zinc, copper, gold, silver, and lead (Galley et al. 2007). The Flin Flon – Snow Lake Greenstone Belt is home of many world-class VMS deposits in the central area of Manitoba and east-central Saskatchewan, Canada. In the 1980s, the application of borehole geophysical electromagnetic methods has led to the discovery of Chisel North (Vowles 2000), north of the existing Chisel Mine. In 2007, the exploration team at Hudbay Minerals Inc. discovered a geophysical electromagnetic (EM) target covered by the greenstone belt near Chisel North. Subsequent drilling then identified the target to be a new world-class zinc, gold, and copper–gold-rich VMS deposit; it is now called Lalor (Vowles and Dueck 2014).

The mineralization at Lalor consists of massive (pyrite and sphalerite), stringer (chalcopyrite and pyrrhotite), and disseminated (pyrite) sulphides buried more than 600 m below the surface. The depth of the ore lenses prevented discovery of the deposit by using conventional geological mapping and geochemical sampling. Fortunately, the sulphide minerals, especially at high concentration, can dramatically increase the electrical conductivity of the deposit, making the exploration with geophysical EM methods a viable approach in finding deeply concealed resources. At Lalor, the cover and Precambrian host rock units are
Electrically resistive. The sharp contrast in conductivity between the sulphide-bearing and host rocks is a favored condition for EM geophysics despite the large depth of burial.

Because of Lalor’s significance in mining geophysics and its future implication on how deep resources should be explored, it has become a superstar property in the geophysics community. Many geophysical EM methods, including most of the mainstream commercial systems, have been tested at the site even after the deposit had been mapped by drillings. A large amount of EM data sets and knowledge from drilling and rock physical properties provide an excellent opportunity for the community to converge to a consensus on how such properties can be more effectively discovered in the future. In 2014, British Columbia Geophysical Society (Vancouver) organized a symposium on the geophysics at Lalor. Thanks to the unprecedented amount of data, the Lalor symposium gained further traction by being hosted again at other major mining conferences, including the Manitoba Mining and Minerals Convention (Winnipeg), the Canadian Exploration Geophysical Society (Toronto), and the South African Geophysical Association (Drakensberg). Our research group at the University of British Columbia – Geophysical Inversion Facility was involved in the Lalor case study as the data modeler. With data contributions from Hudbay and the contractors, we have been actively working on those data from a research point of view (Yang and Oldenburg 2012, 2013, 2017). The extensiveness and complexity of the entire Lalor data can easily warrant another decade of research and a series of publications. In this paper, we present our 3-D imaging results for four select data sets at Lalor with no intention of declaring the end of story. It is indeed our hope that this paper, a summary of four geophysical methods at Lalor at the decennial of the Lalor’s discovery, stirs more convergence on the use of geophysics to solve deep exploration problems and how we can better use the legacy of the Lalor data.

In the following, we first introduce the geological and geophysical setting at Lalor and its implication in exploration geophysics. We then summarize the geophysical work done at Lalor with particular emphasis on the EM methods. Four commonly used systems and their 3-D imaging results are presented. The four surveys are chosen so they represent a multi-scale exploration program. Finally, we discuss the outcome of the EM data inversion and what information prospectors and developers can extract from geophysics.

Geologic background

Lalor is a VMS deposit in the Snow Lake arc assemblage of the Flin Flon domain (Bailes et al. 2016) approximately 8 km west of Snow Lake in central Manitoba, Canada (Fig. 1). The region is...
within the Eastern Flin Flon Domain (EFFD) of the Trans-Hudson Orogen (Pehrsson et al. 2016). The EFFD contains two parts, the older volcanic Flin Flon Domain (1.90–1.88 Ga) and the younger sedimentary Kisseynew Domain (1.85–1.83 Ga). The volcanic subdomains are often separated by sedimentary rock units. The Snow Lake arc assemblage (1.89 Ga) sits at the center of EFFD and is the host of 9 VMS deposits, including Lalor (Bailes 2014). Thehosting Chisel sequence is characterized by discontinuous volcaniclastic horizons. Mineralization at Lalor is located below a shallow-dipping fault and is conformable with the sedimentary succession. The hanging wall rocks overprint the surface, and the footwall rocks are hydrothermally altered and metamorphosed (Legault et al. 2015). Like most VMS deposits, Lalor formed on or right beneath the seafloor following discharge of hydrothermal fluid. The mineralization produces three types of sulphide mineralization:

1. Massive: zinc-rich massive mineralization cap
2. Stringer: copper-gold bearing stringer sulphides within the intrusive pipe
3. Disseminated: an alteration halo of disseminated sulphides around the deposit

When just formed, the mineralization system contains a massive sulphide lens overlaying a discordant stringer sulphide zone within an alteration pipe (Gibson et al. 2007). The 1.8 billion-years-old mineralization system was subsequently buried, metamorphosed, and reshaped into a stack of ore lenses dipping about 30 degrees towards the north (Fig. 1). The zinc-rich upper lenses, from 600 to 1000 m depth have high concentrations of pyrite in the form of massive sulphide. The lower lenses, below 1000 m depth, are mostly stringer sulphides with a high grade of gold and gold-copper concentration (Fig. 2).

Given its world-class reserves, the development of the Lalor was fast-tracked after its discovery in 2007. The construction of infrastructure at Lalor started in 2009, and full-scale development was committed in 2010. Extensive drilling during the development has delineated many details of the ore bodies, but prospectors still have questions regarding the deep extension of the mineralized zone and whether there are other economically interesting targets nearby. As a result, geophysics was considered a viable approach to evaluate the mineral potential of the Lalor deposit.

**Geophysical methods**

As the focus for mineral exploration is shifting towards deeper deposits, surface-based geologic and geochemical methods are approaching their limits. Geophysical methods, on the other hand, offer the unique ability to penetrate thick covers and make new discoveries. To successfully apply geophysical methods, the sought targets need to possess distinct physical properties. It is important to note that the geophysical signatures vary greatly depending on the type of ore deposit, and geophysical methods should be chosen accordingly (Ford et al. 2007). The Lalor VMS, characterized by high concentrations of minerals like pyrite, chalcopyrite, and pyrrhotite, is potentially detectable by a variety of geophysical methods (Table 1).

The minerals found in VMS deposits usually create density and magnetization contrast with the host rock. However, the anomalous signals in a gravity survey strongly depend on the volume of the target. Because the ore lenses at Lalor are only tens of meters thick and buried more than 600 m deep, the surface gravity data only capture the overall mineralization controlling units at a regional scale; direct discovery using surface gravity is very difficult, although borehole gravity was effective (Schetselaar and Shamsipour 2015). The Lalor mineralization is nonmagnetic, so the magnetic method cannot detect the deposit (Legault et al. 2015).

Seismic is the primary method in petroleum exploration in stratified sedimentary environments, but its use in strongly scattering igneous rock environments is still experimental. At Lalor, the Geological Survey Canada conducted a multi-component 3-D seismic reflection survey (Bellefleur et al. 2015) and a seismic interferometry survey (Cheraghi et al. 2015), which showed that seismic could precisely depict the boundaries of the ore bodies. However, identifying reflectors on seismic images to be mineralization zones is not an easy task if the existence of the deposit is not known beforehand. The high cost of seismic data acquisition is another barrier in its practical application.

Compared with gravity, magnetic, and seismic, electric and electromagnetic methods have many advantages for VMS targets like Lalor. First, the abundance of sulphide minerals can increase the electric conductivity of the ore bodies by several orders of magnitude, generating sufficient EM signals even from thin and deep deposits. The three types of sulphides at Lalor are composed of sulphide minerals with the content varying from 40% to less than 10%, representing a moderately conductive mineralization complex within a resistive volcanic host (Taylor 2014). In addition to the Lalor ore lenses, there are other related conductive features in the region, including the Snow Lake Fault Zone and the Foot Mud Sulphide Horizon (Legault et al. 2015). Second, a wide range of configurations can be designed to probe the earth’s conductivity for different purposes at multiple scales. As a result, electric and EM have always been the primary methods in searching and targeting sulphide mineralization in the mining industry.

Chisel Basin has long been considered as a high potential area for discovery. Historical exploration included drilling and geophysical surveys like Turam, horizontal-fixed-moving loop EM, very low frequency EM, and large-loop TEM in the area around Chisel, Chisel North, and Photo Lake Mines. However, because of the limitation of the equipment and acquisition parameters used at that time, no technology could detect deep ore bodies like Lalor, so most pre-2007 exploration efforts were spent at inappropriate loca-
ponents (Hx or Hy) at multiple frequencies from about 30 to 720 Hz.

...the field continuously along flight lines and measures the horizontal to measure the vertical component (Hz) of the Earth’s magnetic field. This has enabled the discovery of many deep deposits (Legault 2012). Successful application and data interpretation for Lalor have been separately reported by the contractors of airborne time-domain EM (HELITEM) (Hodges et al. 2016) and ZTEM/VTEM (Legault et al. 2015). Second, empirical eyeballing and simple-plate or layered-earth modeling were once the tools used to interpret geophysical data, but new 3-D imaging software (voxel inversion) has advanced so that accurate 3-D conductivity volumes of a region can be obtained, visualized, and interrogated, voxel models can be transferred between different analysis, and geologic or borehole constraints can be imposed to reduce uncertainty.

Airborne natural source EM (ZTEM)

A natural source EM survey uses the naturally occurring electromagnetic waves from lightning and solar interaction with the magnetosphere as the source to energize the Earth. ZTEM, or Z-axis Tipper Electromagnetic (Legault 2012), flies a horizontal coil to measure the vertical component (Hz) of the Earth’s magnetic field continuously along flight lines and measures the horizontal components of magnetic field Hx and Hy at a base station on the ground (Fig. 3). ZTEM data are obtained by calculating the ratio between the vertical component (Hz) and the horizontal components (Hx or Hy) at multiple frequencies from about 30 to 720 Hz.

The natural EM source is a plane wave propagating downward inside the earth, so the magnetic field on, or near, the earth’s surface is predominantly horizontal unless the field is disturbed by heterogeneity in the earth that creates a nonzero Hz component. Using the transfer function data (Tzx/Hz/Hz and Tzy/Hy/Hy) to find the conductivity contrast is the basis of magnetotelluric tipper method, which requires measuring of Hx, Hy, and Hz fields at every station on the surface. ZTEM can be considered as an inexpensive way of collecting approximate tipper data in the air. Compared with controlled sources, the natural frequencies used by ZTEM are relatively low, allowing a deep penetration up to a couple of kilometers in most mineral exploration sites. The airborne passive acquisition and deep penetration make ZTEM an ideal tool in rapidly mapping a large area at a low cost without losing depth resolution.

At Lalor, ZTEM was flown over a 10 km × 6 km area with a line spacing of 200 m (100 m over the deposit). Figure 5 shows the data maps of 180 Hz that are expected to be sensitive to the target. Because ZTEM data peak at the boundaries of conductivity contrast, red or blue on the map does not necessarily indicate the location of the target. The Lalor ZTEM data are further complicated by a straight-line feature from a power line because the power line acts as a strong near-surface heterogeneity. The power lines are treated as small conductors in our modeling. We converted the data to a conductivity model using a 3-D inversion algorithm (Holtham and Oldenburg 2010). We determined that a 3-D mesh with the smallest cell size of 200 × 200 × 50 m would be sufficient in capturing most of the structure available in ZTEM data without costing too much in computing.

In practice, ZTEM inversion is often complicated by choice of a background model, which is a conductivity model provided to an inversion as the start point of iterations. Because a horizontally layered earth model produces zero ZTEM data, ZTEM is more sensitive to the conductivity difference than to the actual conductivity values. If the background is not properly chosen, the inversion may only recover the relative conductivities. The distribution of relative conductivities still bears the correct structural information but the actual values may be biased, and the data may not be well fit. At Lalor, without knowing the most suitable background, we initiated multiple ZTEM inversions using a number of uniform models. When the background model is too high or too low, the inversion may still fit the data, but the model can become unrealistic or unnecessarily complex. The following criteria were used to help us choose a ZTEM inversion model for interpretation: (i) sufficiently small data misfit, (ii) simplicity of model structure, (iii) agreement with general geologic expectation, and (iv) agreement with other inversion models. Among all the possible ZTEM models, we choose the one obtained with a 3000 Ct uniform background.

Our ZTEM inversion model contains three major conductive features that are similar to previously published ZTEM models (Legault et al. 2015). The reverse S-shaped conductor in the middle of the survey area (Fig. 6, top) is in high agreement with the Lalor deposit and another sub-economic conductor known as “South Bullseye”. The inversion result agrees with the known depth of the Lalor deposit on the cross-section; the dipping geometry is also well resolved by inversion (Fig. 6, bottom). The shallow conductive material above the Lalor deposit is likely artifacts from inversion, and we will further investigate it. The two elongated conductors, one on the left and one on the top-right corner in

Table 1. Applicability of different geophysical methods at Lalor.

<table>
<thead>
<tr>
<th>Method</th>
<th>Physical property</th>
<th>Resolution</th>
<th>Cost</th>
<th>Sensitive to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic</td>
<td>Magnetic susceptibility and (or) remanent magnetization</td>
<td>Low (only horizontal)</td>
<td>Low</td>
<td>Regional structure</td>
</tr>
<tr>
<td>Gravity</td>
<td>Density</td>
<td>Low (only horizontal)</td>
<td>Low</td>
<td>Regional structure</td>
</tr>
<tr>
<td>Electric and Seismic</td>
<td>Electric conductivity</td>
<td>Intermediate (horizontal and depth)</td>
<td>Low to intermediate</td>
<td>Regional structure to local structure</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Elastic moduli and density</td>
<td>High (horizontal and depth)</td>
<td>High</td>
<td>Local interface</td>
</tr>
</tbody>
</table>

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are other regional conductors associated with the complex and worth further investigation (Legault et al. 2015).

In a hypothetical scenario that no deposit is known and ZTEM is used for large-scale green-field reconnaissance, the 3-D model in Fig. 6 provides critical information in showing the location and depth of potential VMS targets. However, the absolute conductivities may be biased if the background is not properly chosen. For an evidence-based exploration program to proceed with the ZTEM anomaly, the conductor needs to be verified as a positive drilling target. We choose an active airborne source time-domain EM survey as an independent validation.

Airborne time-domain EM (HELITEM)

A time-domain EM (TEM) system belongs to the category of controlled source EM, in which the EM excitation is artificial and well known. A TEM source loop periodically transmits a current waveform with sudden disruptions, usually a pulse or turn-off. The rapid change of current in the source loop induces EM fields in the subsurface that gradually dissipate with time. The earth’s conductivity can be inferred by measuring how the induced field decays over time; a slower decay indicates a higher conductivity. An airborne TEM system tows a source loop and a receiver coil set in a frame, so TEM soundings quickly take place every few meters along flight lines above the surface (Fig. 3). Compared with ZTEM, airborne TEM requires controlled sources, but its data are the magnetic field strength, a physical quantity directly associated with the amount of conductive material in the earth. Therefore, it is a better tool to constrain the absolute conductivity.

At Lalor, we study the airborne TEM data set from HELITEM system (Hodges et al. 2016). HELITEM transmits a current waveform of a half-sine pulse at a base frequency of 30 Hz and measures the decay rate of the magnetic field from 0.2 to 9.86 ms after the pulse; only the vertical component is investigated here. The response map in Fig. 7a reflects the overall conductivity distribu-

Table 2. List of geophysical electromagnetic surveys at Lalor since 2000 (in chronological order).

<table>
<thead>
<tr>
<th>System</th>
<th>Type</th>
<th>Source</th>
<th>Receiver</th>
<th>Year(s) of survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>PULSE EM</td>
<td>Surface time-domain</td>
<td>Large loops on surface</td>
<td>Small coils roaming on surface</td>
<td>2002, 2003, 2005</td>
</tr>
<tr>
<td>PULSE EM*</td>
<td>Surface-borehole time-domain</td>
<td>Large loops on surface</td>
<td>Small coils in boreholes</td>
<td>2007–2010</td>
</tr>
<tr>
<td>VTEM</td>
<td>Airborne time-domain</td>
<td>Small loop towed by helicopter</td>
<td>Small coil towed by helicopter</td>
<td>2009</td>
</tr>
<tr>
<td>ZTEM</td>
<td>Airborne frequency-domain</td>
<td>Natural source</td>
<td>Small coil towed by helicopter with coils at the base station on surface</td>
<td>2009</td>
</tr>
<tr>
<td>DC resistivity and induced polarization (DCIP)</td>
<td>Surface time-domain</td>
<td>Grounded electrode arrays on surface</td>
<td>Grounded electrode arrays on surface</td>
<td>2009</td>
</tr>
<tr>
<td>Magnetotelluric (MT)</td>
<td>Surface frequency-domain</td>
<td>Natural source</td>
<td>Small coils and electrodes roaming on surface</td>
<td>2009</td>
</tr>
<tr>
<td>JESSY HTS SQUID*</td>
<td>Surface time-domain</td>
<td>Large loops on surface</td>
<td>Small SQUID magnetometers roaming on surface</td>
<td>2009</td>
</tr>
<tr>
<td>DigiAtlantic</td>
<td>Surface-borehole time-domain</td>
<td>Large loops on surface</td>
<td>Small fluxgate magnetometers in boreholes</td>
<td>2010</td>
</tr>
<tr>
<td>EXTREMELY LOW FREQUENCY (ELF) EM</td>
<td>Surface frequency-domain</td>
<td>Natural source</td>
<td>Small coils roaming on surface</td>
<td>2010</td>
</tr>
<tr>
<td>Bolden EM3–2001</td>
<td>Surface frequency-domain</td>
<td>Large loop on surface</td>
<td>Small coils roaming on surface</td>
<td>2010</td>
</tr>
<tr>
<td>UTEM3</td>
<td>Surface time-domain</td>
<td>Large loops on surface</td>
<td>Small coils roaming on surface</td>
<td>2011</td>
</tr>
<tr>
<td>VTEM MAX</td>
<td>Surface time-domain</td>
<td>Small loop towed by helicopter</td>
<td>Small coil towed by helicopter</td>
<td>2012</td>
</tr>
<tr>
<td>HELITEM*</td>
<td>Airborne time-domain</td>
<td>Small loop towed by helicopter</td>
<td>Small coil towed by helicopter</td>
<td>2012</td>
</tr>
<tr>
<td>Audio Magnetotelluric (AMT)</td>
<td>Surface frequency-domain</td>
<td>Natural source</td>
<td>Small coils and electrodes roaming on surface</td>
<td>2014</td>
</tr>
<tr>
<td>UTEM5</td>
<td>Surface time-domain</td>
<td>Large loop on surface</td>
<td>Small coils roaming on surface</td>
<td>2014</td>
</tr>
<tr>
<td>Volterra (EM)</td>
<td>Surface and surface-borehole time-domain</td>
<td>Large loops on surface</td>
<td>Small coils and fluxgate magnetometers roaming on surface in boreholes</td>
<td>2014</td>
</tr>
<tr>
<td>Volterra (IP)</td>
<td>Surface time-domain</td>
<td>Grounded electrode arrays on surface</td>
<td>Grounded electrode arrays on surface</td>
<td>2014</td>
</tr>
<tr>
<td>HeliSAM</td>
<td>Surface-airborne time-domain</td>
<td>Large loop on surface</td>
<td>Total-field magnetometer towed by helicopter</td>
<td>2014</td>
</tr>
</tbody>
</table>

*Datasets presented in this paper.
The data maps are trimmed to exclude features on both ends of the lines that are known to be irrelevant to the deposit. Because the country rocks are resistive, HELITEM signals are below the noise level \(10^{-12} \text{ V/Am}^2\) for the most part of the survey. The two high data blocks in the middle are believed to be from the mineralization systems associated with Lalor and South Bullseye. The early time channels of HELITEM data contain high-frequency information about small-scale or near-surface features, but they require a very fine mesh, and they do not help resolve the main ore bodies at depth. So, in our inversion, we skipped the first five time channels before 0.37 ms.

Our TEM inversion was based on another 3-D algorithm (Oldenburg et al. 2013). The HELITEM inversion uses a 3-D mesh with the smallest cell size 200 m × 200 m × 50 m. The inversion starts with a uniform resistive background, and iteratively fits the observed data by a conductivity model that contains a deep conductor (Fig. 8). On the plan view, the trending direction of the conductor is consistent with the dipping direction of the drilled ore lenses. The conductivity recovered at the deposit is about 0.03 S/m, which is used to help select a ZTEM inversion model. In a hypothetical exploration scenario, we may use independent information from ZTEM and HELITEM to cross-validate the recovered conductive anomalies in the model.

We note the HELITEM recovered conductor is at an elevation deeper than the drilled ore lenses on the cross-section, and the conductor is longer than the actual deposit (Fig. 8, bottom). The HELITEM model does not resolve the Lalor deposit as well as the ZTEM model concerning the structural information. As many factors can contribute to the poor spatial resolution in the HELITEM model, a further investigation determines that insufficient data coverage in the cross-line direction (Y direction in Fig. 8) limits the inversion’s ability of separating the anomalous signals from Lalor from another shallow sulphide-bearing argillite to the north and from South Bullseye. The long and deep conductor in the HELITEM...
Fig. 5. The observed ZTEM field data (left column) and the 3-D simulated data (right column) at 180 Hz. [Colour online.]

Fig. 6. The 3-D conductivity model from ZTEM data inversion. Plan view at 1000 m below the surface (top) and vertical cross-section through the deposit (bottom). The flight paths and the Lalor ore lenses are shown as white and black lines, respectively. [Colour online.]

Fig. 7. HELITEM data representative of the conductors at depth. Shown are the maps of (a) observed data and (b) predicted data at time channel 9 centered at 0.5 ms after the pulse. The white and black lines indicate the flight paths and approximate location of the Lalor deposit, respectively. [Colour online.]
model is a representation of the three actual conductors combined. The HELITEM resolution would be significantly improved if the data covered the complete anomalies from Lalor and South Bullseye.

The ZTEM data and HELITEM data at Lalor complement each other by providing independent information using different physics. The conductivity recovered by one method is cross-validated by the other one. Nevertheless, the resolution of ZTEM and HELITEM models (200 m) is still too coarse for targeting and drilling purposes. To obtain a more accurate description of the ore bodies, surface geophysical methods have to be applied. For surface methods, we again have the choices of natural source methods (magnetotelluric or audio-magnetotelluric) and controlled source methods. Both of them are capable of providing deep penetration and information about absolute conductivities.

Surface TEM (SQUID)

A surface TEM survey shares the same physical principle with airborne TEM. However, instead of having a pair of small loops and coils moving together with a helicopter, a surface TEM uses a large stationary loop laid on the surface (Fig. 3); this achieves a much greater source moment, quantified by the product of current amplitude and loop area, and hence the survey can see deeper. Larger power and long stacking times at stationary stations of measurement allow a surface survey to collect TEM data at very late time channels; these carry information about deep conductivity structure. At Lalor, the data quality was further improved by using an ultra-sensitive high-temperature (liquid nitrogen) SQUID magnetometer that can detect small signals from a conductor moving with the source loop and all the receivers, which matches the spatial resolution of this surface survey and has better accuracy when modeling the source loop directly sitting on the surface. The SQUID inversion model is compatible with the plate modeling results (Bingham et al. 2014). In addition to the Lalor conductors, it also contains many detailed features that the ZTEM and HELITEM models do not have. The horizontal location of the Lalor deposit is well defined by the conductors in the inversion model (Fig. 11, top). Incorporating surface TEM in a systematic exploration program, this piece of information would be crucial in deciding the drilling locations. The recovered dipping conductors also agree well with the drilled ore lenses on the vertical section (Fig. 11, bottom). Incorporating surface TEM in a systematic exploration program preluded by airborne EM could have saved a lot of time and investment on drilling since the deposit can be quickly located and the depth and geometry can be determined accurately.

Borehole TEM (PULSE-EM)

After the deposit has been drilled following the imaging results from surface EM, geophysics can still play a role by providing even more fine-scale information through borehole measurements. By sending EM receivers down the boreholes, the EM data become very sensitive to the extent, thickness, grade, and position of the ore lenses when the wellbores penetrate or pass the mineralized targets. After the initial drillings that confirmed the discovery of Lalor, a borehole EM data set was acquired using the wellbores. The survey is in time-domain and uses the same large loop on the surface, but all the magnetic coil receivers of the PULSE-EM system are placed in the holes from the surface to the bottom. Data from 70 wells were interpolated in 3-D for quality control and averaged to a 50 m spacing as shown in Fig. 12. We note the rapid changes in field polarity across wells, likely due to the presence of subhorizontal ore lenses. Direct interpretation of borehole EM data can be challenging due to complexities in conductivity struc-
tures resulting in complicated EM data. Three-dimensional inversion techniques are crucial.

Ideally, borehole surveys and drilling should be carried out alternately so geophysical results can guide the next drill; then new wellbores open the path for the next survey. In this study, we inverted the entire borehole data set all at once. The result sets a general expectation for what we can get from borehole data. As we try to resolve structure within the ore bodies, the cells are down-sized to 30 m × 30 m × 30 m. Although the cell size is smaller than the station spacing, the data variability at some locations is much larger than what is allowed by a regularized inversion. So, some high-frequency data are not well fit. We used a 10⁻³ S/m uniform half-space to initiate the inversion. With data close to or even inside the target, the inversion recovers almost the exact position and geometry of the ore lenses (Fig. 13), which only appear as blurred or distorted conductors in the ZTEM and HELITEM model. The borehole data inversion also reveals some scattered conductors trailing the massive part of the sulphide mineralization. Previous drilling has intercepted some stringer sulphides below the main ore lenses at a greater depth. The trailing conductors imaged by borehole EM are in good correspondence with the deeper resources.

Synthesis

Exploration of VMS deposits under thick cover like Lalor is a challenging task because the deposit is small and deep, but the potential area is large. The four EM data sets processed in this paper represent an organized geophysical workflow that goes from regional mapping to delineation of the ore bodies. The conductivity models from the different surveys are not identical since the data were acquired using different survey configurations and measured different types of the fields; other issues like the resolution volume, variable source coupling with the near-planar conductors, and signal to noise ratio were also possible sources of variability. However, the resultant models constitute a solid chain of information about the earth that can aid the discovery at different stages of exploration.

The ZTEM survey, being a low-cost airborne passive method, covers the entire area and has deep penetration. The conductivity model from ZTEM identifies potential conductive targets and provides information about the location, depth, and even dipping angle. Because ZTEM inversion may be biased by incorrect background models, we obtained a number of ZTEM models by using different backgrounds. The uncertainty in those ZTEM models is constrained by another airborne active source method HELITEM, which has a more reliable estimation of the earth’s absolute conductivity. In the specific case of Lalor, our results demonstrated a superiority of ZTEM over HELITEM for imaging the geometry of ore lenses. We think the spatial resolution of HELITEM can be significantly improved if the survey covers the entire Lalor and South Bullseye anomaly. If modeled with a finer mesh, HELITEM could also have the advantages of detecting the weak conductors in the hanging wall and other small-scale feature near the surface that are not clearly imaged by ZTEM (Legault et al. 2015). Nevertheless, as long as we understand the pitfalls in inversion and we interpret the models properly, ZTEM and HELITEM together provide critical information in setting up ground campaigns for pre-drilling imaging.
Surface surveys have more flexibility in choosing the source loop and receivers. By using kilometer-sized source loops on the surface and ultra-sensitive SQUID magnetometer receivers, the surface SQUID data set provided very good estimates for the horizontal location of the ore lenses that is important information for drilling. The SQUID data inversion also images the dipping geometry of the target; this confirmed the deep structure shown in the ZTEM and HELITEM model and added confidence to the targeting.

In addition to the predrilling exploration, geophysics can still be part of the mine development after the drilling starts. Boreholes provide an expressway for geophysical sensors to reach the targets, so borehole EM “de-blurs” the low-resolution images from surface geophysics. At Lalor, being able to pass through the deposit allows borehole data to ascertain the vertical position of the target at the pierce locations as well as the existence of off-well objects. The downhole EM will more specifically show the proximity to, or crossing of, a significant volume of rock with enhanced conductivity and thus the more significant regions of mineralization. Drilling also offers the opportunity of assessing the rock physical properties either through core samples or in situ. Core sample measurements of physical properties at Lalor are available but have not been incorporated into quantitative inversions. Adding physical property information, in conjunction with advanced analysis and constrained inversion, helps reduce uncertainty in the recovered models. From a broader point of view, the EM data, if interpreted using consistent and quantitative approaches like 3-D inversion, can be more easily incorporated into the geologic modeling and the overall exploration program along with geochemical and other non-EM geophysical information (Gibson et al. 2007). We plan to work on the data integration in the future.

Another critical aspect of an exploration program is the exclusion of negative anomalies. The reconnaissance model from ZTEM contains many interesting conductors. Using other methods, for example HELITEM or surface EM, can first help verify the existence of the anomaly and second constrain the conductivity and structure of the targets, so false or noneconomic anomalies can be excluded from the exploration program. This process may also be open to other tools of verification like geologic mapping and drilling if stronger evidence is required.

In this paper, we made a hypothetical discovery of Lalor using existing data sets, which shows that geophysics has the potential to aid mineral exploration problems at multiple levels and different stages of development: reconnaissance, targeting, predrilling
planning, and deposit model updating. We selected four electromagnetic geophysical surveys that contribute to these elements. The sequence of airborne, surface, and borehole progressively goes from lower to higher resolution and thus helps answer geologic questions at different scales (Fig. 14). The general idea of multi-scale exploration is not entirely new and has been studied and applied in practice (Gibson et al. 2007). Our work presented here emphasizes the use of advanced regional mapping tools like ZTEM in the initial phases of exploration and the potential benefit of using 3-D voxel inversions in the decision-making process.

Conclusions

Exploration of deep mineral resources is a challenge for surface-based geologic mapping and geochemical sampling, but this is where geophysics can play a role. Lalor is a tens of meters thick, massive sulphide deposit buried more than 600 m below the surface, an ideal example that showcases how geophysics can be applied to make discoveries. We chose four geophysical EM data sets from Lalor to build a hypothetical exploration program that demonstrated the information geophysics can provide at different stages. The data were all inverted to 3-D subsurface images using state-of-the-art inversion software.

First, we inverted an airborne natural source EM (ZTEM) data set. ZTEM does not require artificial sources, so it is an ideal tool for large-scale mapping. The recovered model indicates the existence of a potential mineralization anomaly, but the result may change with the background model. We used another airborne TEM (HELITEM) to reduce the possible bias in the ZTEM models. The two airborne EM surveys together narrowed down the scale of search from tens or hundreds of kilometers to hundreds of meters with evidence in 3-D subsurface images.

Although the airborne surveys are highly efficient, their images are relatively blurry as a result of the airborne acquisition. Using the guide from airborne surveys, a surface EM survey was carried out. It achieved the maximum depth of penetration by using kilometer-sized source loops and ultra-sensitive SQUID magnetometer receivers. The inversion of SQUID data imaged the exact horizontal location of the Lalor ore lenses, the most important

Fig. 14. Vertical sections of the 3-D conductivity models obtained from four different electromagnetic (EM) surveys: (a) Airborne natural source EM with a 200 m cell size, (b) airborne controlled source EM with a 200 m cell size, (c) surface EM with a 100 m cell size, and (d) borehole EM with a 30 m cell size. The Lalor deposit is indicated by the black lines. The sequence from top to bottom represents a progressive multi-scale exploration workflow. [Colour online.]
information for drilling; the vertical position and the dipping geometry of the deposit at depth were also well resolved, which is a big step from the blurred blobs in the airborne models. Finally, a postdrilling survey took place by sending receivers down the drilled holes; the 3-D model from the borehole data had the exact information about the depth and thickness of the ore lenses, as well as some showing of off-hole targets for further investigation.

Our study was a hypothetical exercise built on the existing data sets, known drilling results, and 3-D inversions at the Lalor VMS deposit. We demonstrated that the modern geophysical EM systems if used with the advanced 3-D imaging technology can provide critical information about the deposit throughout the entire exploration and development program. The EM systems used in this paper can have alternative choices, but we present them as a template that the industry can reference and build on for their specific exploration projects.

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References


