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Geophysical Overview of Lalor VMS Deposit

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ABSTRACT

The Manitoba exploration team of Hudbay Minerals Inc. (Hudbay) identified the Chisel Basin within the Snow Lake belt as having high potential for a large Volcanogenic Massive Sulphide (VMS) discovery. The basin has historically hosted six past producing VMS mines: Chisel Lake, Chisel Open pit, Chisel North, Photo, Ghost, and Lost.

In 2003, with knowledge of favourable stratigraphy down plunge of Chisel North mine, Hudbay's geophysical group designed a surface time-domain electromagnetic survey, targeting deep conductors in this region. The survey consisted of four large loops planned to systematically cover the Chisel Basin. Two anomalies of interest were identified, a north and a south anomaly. The south anomaly was drilled and intersected non-economic stringer chalcopyrite, pyrite and pyrrhotite. The north anomaly remained untested at the time. In 2007, an 800 m by 800 m model was created for the untested north anomaly. Drilling began in March to test the electromagnetic anomaly and the first hole DUB168 intersected appreciable widths of zinc-rich massive sulphides (7.62% Zn and 0.30% Cu between 781.74 m and 826.87 m (45.13 m), including 17.26% Zn and 0.19% Cu over 16.45 m).

Lalor mine was placed into commercial production in 2014 and as of January 1, 2017 (Hudbay Minerals Inc., 2017) has proven and probable mineral reserve of 14.2 million tonnes (5.12% Zn, 0.69% Cu, 2.61 g/t Au and 26.50 g/t Ag). Exclusive of mineral reserves as stated above, Lalor Base Metal Zone contains indicated resources of 2.1 million tonnes (5.34% Zn, 0.49% Cu, 1.69 g/t Au and 28.10 g/t Ag) and inferred resource of 545,300 tonnes (8.15% Zn, 0.32% Cu, 1.45 g/t Au and 22.28 g/t Ag) and Lalor Gold and Copper-Gold contains indicated resource of 1.75 million tonnes (0.40% Zn, 0.34% Cu, 5.18 g/t Au and 30.61 g/t Ag) and inferred resource of 4.1 million tonnes (0.31% Zn, 0.90% Cu, 5.02 g/t Au and 27.61 g/t Ag). Following the Lalor discovery, Hudbay encouraged testing of various geophysical equipment and technology over the Lalor deposit. The goal was to evaluate and determine which geophysical equipment could improve future exploration success in identifying VMS deposits of similar size, geometry and depth. The surveys conducted over the Lalor deposit include airborne (VTEM, ZTEM, HELITEM, HeliSAM), surface (TDEM, AMT/MT, IP, Seismic, ELF) and borehole (BHEM, gravity, physical property logging).

The main geophysical lesson learned from the Lalor discovery process was that favourable areas which appear fully explored by numerous historical drillholes and geophysics grids may be inadequately tested at depth, due to limitations of the available data. Also, that short grid lines may be insufficient to record the full response from deep flat lying anomalies. These lessons will aid in planning future VMS exploration programs for Lalor-type deposits.

INTRODUCTION

Volcanogenic Massive Sulphide (VMS) deposits are associated with minerals that have a strong physical property contrast with their host rocks. Due to this contrast, geophysical techniques have been instrumental in the discovery of VMS deposits, especially buried deposits. In 2007, the Lalor deposit was discovered by drilling a Deep Electromagnetic (DPEM) anomaly from a Time Domain Electromagnetic Survey. Following the discovery, several test surveys were carried out over the Lalor deposit to characterize its geophysical response and develop a future exploration strategy for VMS deposits with characteristics and challenges similar to the Lalor deposit.

In this paper, we discuss the process that led to the discovery of Lalor and highlight the results and interpretation of select geophysical test surveys over the Lalor deposit. We also compare data quality from different sensors within the same geophysical method and draw attention to some lessons learned from the Lalor discovery process.

LALOR VMS DEPOSIT

Location and Geology

The Lalor deposit is a VMS deposit located near Snow Lake, Manitoba, about 700 km north of Winnipeg (Figure 1). It occurs in the Snow Lake arc assemblage found in the Chisel Basin sequence of the Flin Flon Greenstone Belt (Blakley, 2008). The Snow Lake arc assemblage is a 20 km wide by 6 km thick section that consists of three volcanogenic successions which display a geodynamic evolution setting from primitive arc (Anderson sequence to the south) to a mature arc (Chisel sequence) to an arc-rift (Snow Creek sequence to the northeast) (Bailes and Galley, 1999).

In "Proceedings of Exploration 17: Sixth Decennial International Conference on Mineral Exploration" edited by V. Tschirhart and M.D. Thomas, 2017, p. 619–635

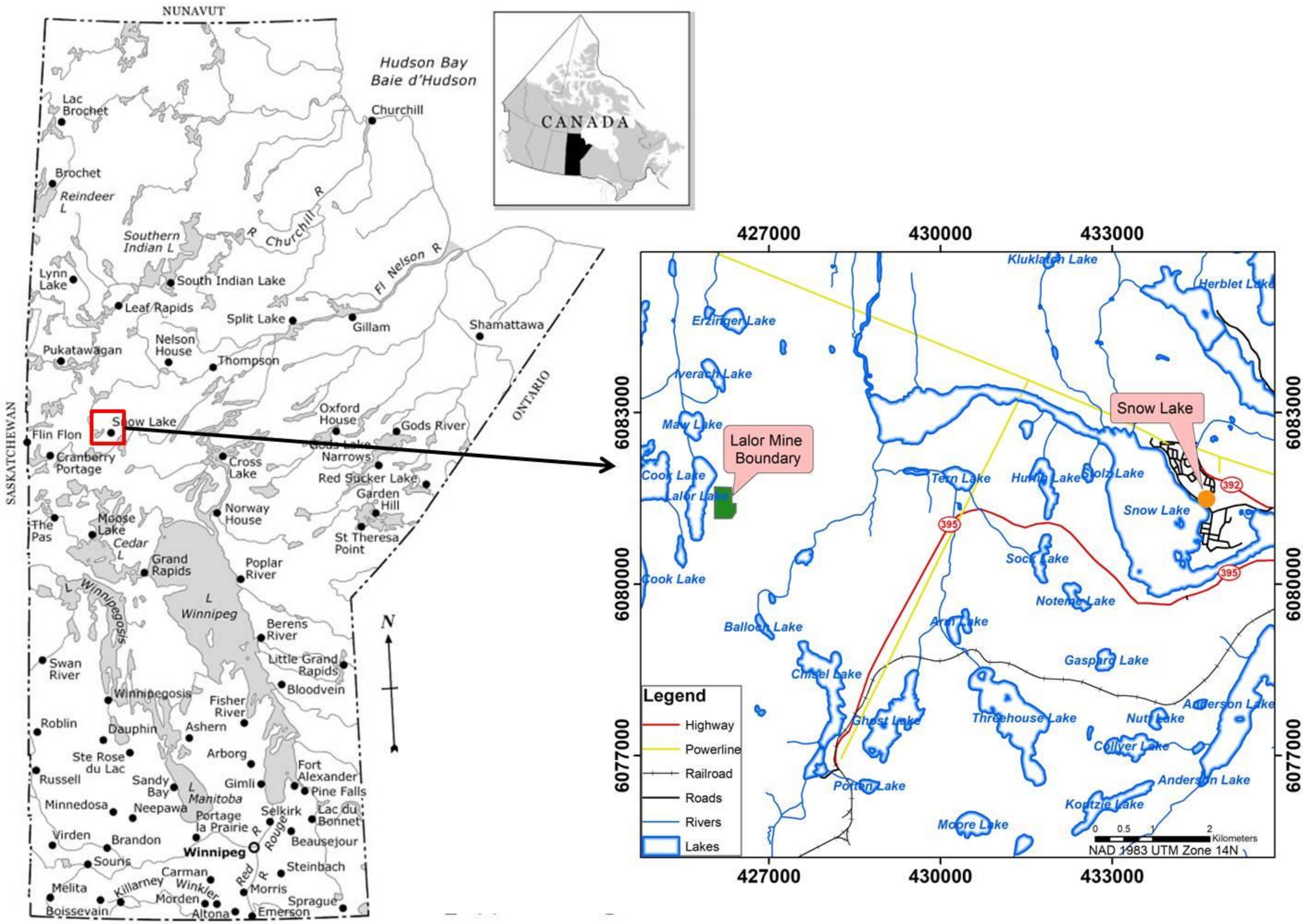


Figure 1: Location map (modified from http://atlas.nrcan.gc.ca).

The Chisel sequence is divided into the Lower and Upper Chisel subsequences with deposits in the area typically located in the Lower Chisel sequence near the contact with the Upper Chisel sequence (Galley et al., 2007; Figure 2). The Lower Chisel sequence has historically hosted the Chisel Lake, Chisel Open pit, Chisel North, Photo, Ghost and Lost past producing VMS mines. The contact between the Lower and Upper Chisel sequences dips gently towards the northeast and has been interpreted as a structural contact (and is retained as such in this paper) although alternate explanations for the distribution of rocks are being explored (A.H. Bailes, Hudbay unpublished internal report, 2010, 2015).

The footwall rocks of the Lalor deposit are extensively hydrothermally altered and dip approximately 30° towards the east-northeast (Caté et al., 2014). In the immediate footwall of the massive sulphide zones, large crystals of aluminosilicate minerals, including kyanite, staurolite, garnet, cordierite, and anthrophyillite are prominent (Bailes et al., 2013). These aluminosilicate minerals are found in gneiss and schist that formed from high-grade metamorphism of hydrothermally altered protoliths of volcanic origin (Caté et al., 2014). The hanging wall rocks are relatively unaltered and dip steeply toward the northeast. Its units reflect diverse variation in the rock types that include mafic and felsic volcanic and volcaniclastic units, mafic wacke, fragmental units of various grain sizes, and crystal tuff units (Blakley, 200; Carter, 2017).

The Lalor VMS deposit is flat lying and consists of 14 mineralized zones with mineralization beginning at approximately 600 m from surface and extending to a depth of approximately 1,480 m. The mineralization trends about 320° to 340° azimuth and dips between 30° and 45° to the north. Lalor deposit has a lateral extent of about 900 m in the north-south direction and 700m in the east-west direction (Blakley, 2008; Carter, 2017). Three groups of ore lenses are observed within the Lalor deposit: the top and southwesternmost group consist of near solid (semi-massive) to solid (massive) zinc-rich sulphide lenses, the bottom and northeasternmost group consist of semi-massive to disseminated copper- and gold-rich sulphide lenses; and the group located in the intermediate levels consist of gold-rich, sulphide-poor lenses (Caté et al., 2014). Disseminated blebs and stringers of pyrrhotite and chalcopyrite occur locally within, adjacent to and generally in the footwall of the zinc-rich massive sulphides (Blakley, 2008; Carter, 2017).

Lalor mine was placed into commercial production in 2014 and as of January 1, 2017 (HudBay Minerals Inc., 2017) has proven and probable mineral reserve of 14.2 million tonnes (5.12% Zn, 0.69% Cu, 2.61 g/t Au and 26.50 g/t Ag). Exclusive of mineral reserves as stated above, Lalor Base Metal Zone contains indicated resources of 2.1 million tonnes (5.34% Zn, 0.49% Cu, 1.69 g/t Au and 28.10 g/t Ag) and inferred resource of 545,300 tonnes (8.15% Zn, 0.32% Cu, 1.45 g/t Au and 22.28 g/t Ag) and Lalor Gold and Copper-Gold contains indicated resource of 1.75 million tonnes (0.40% Zn, 0.34% Cu, 5.18 g/t Au and 30.61 g/t Ag) and inferred resource of 4.1 million tonnes (0.31% Zn, 0.90% Cu, 5.02 g/t Au and 27.61 g/t Ag).

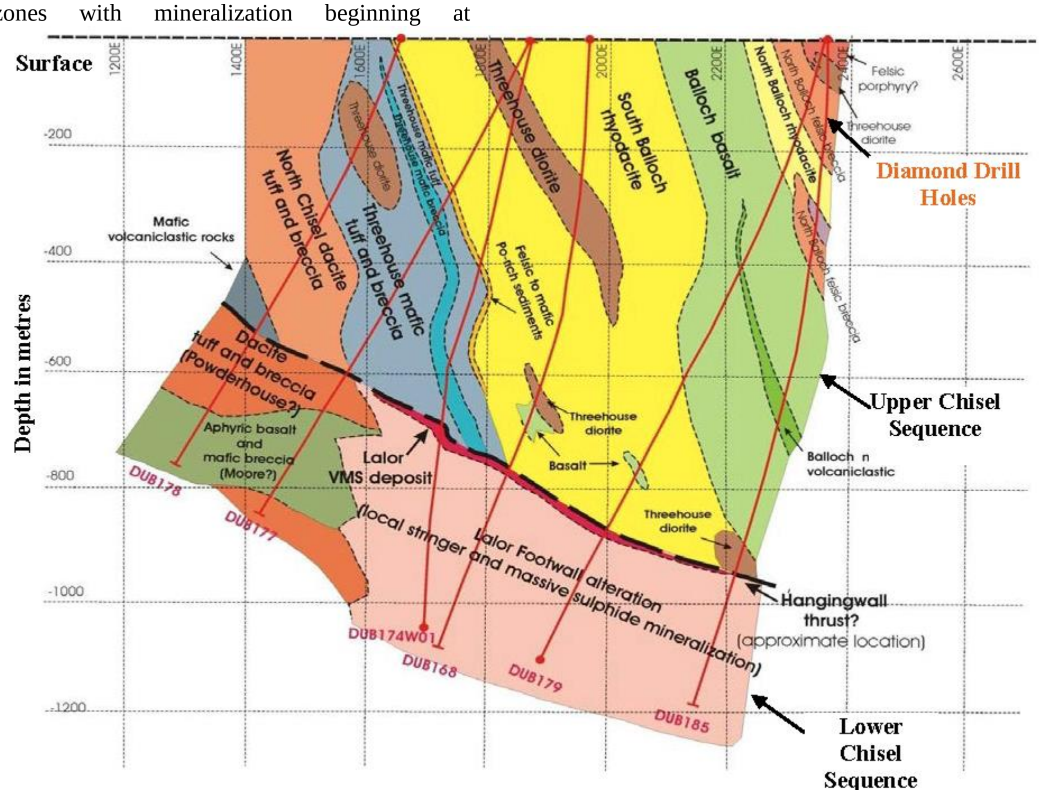


Figure 2: Northeast-southwest vertical section of the Lalor geology based on diamond drillholes DUB178, DUB177, DUB174W01, DUB168, DUB179 and DUB185. Rocks above the Hanging wall contact belong to the Upper Chisel Sequence and rocks below the contact belong to the Lower Chisel sequence (modified from A.H. Bailes, Hudbay unpublished internal report, 2010).

Pre - Lalor Discovery

Electromagnetic (EM) geophysics survey played an important role in the discovery and delineation of various deposits and zones in the Flin Flon-Snow Lake Belt due to the strong conductivity contrast between the VMS deposits and their host rocks. As a result, EM surveys became the go-to geophysical exploration tool for VMS deposits in the belt. Prior to Lalor discovery, most exploration in Snow Lake was focused on shallower depths (< 500 m) and geophysical EM surveys were planned accordingly using shorter line lengths, smaller loops and high transmitting frequency.

In 2002–2003 Hudbay decided to explore down-dip and down-plunge of known mineralization in the favourable Chisel Basin. It was known that the favourable Chisel Basin was getting deeper (> 700 m), so it was expected that a potential EM response from a conductor at that depth would have a low amplitude and broad anomaly profile. The Chisel Basin geology is generally mineralized and moderately conductive, hence, it was anticipated that without collecting high quality data and boosting the amplitude from a potential conductor at depth, its EM response may be indistinguishable from the elevated background response typical of most places in the Chisel Basin. For this reason, it was necessary to survey later in time and to boost the amplitude of the later time channels which highlights areas of higher conductivity which are more representative of massive sulphides.

The high quality data was needed but it was impractical to collect with the receiver Hudbay owned at that time. During this period, Crone Geophysics had released a new DPEM late time channel system, which included a high speed time domain receiver capable of collecting significantly higher quality data in a fraction of the time it would have taken with the receiver Hudbay owned at that time. Prior to deciding to purchase the new receiver, a test survey designed to mimic the response of the new receiver was conducted over the deepest portion of the Chisel North Mine (approximately 600 m vertical depth). The test involved setting the old receiver to 16384 stacks (compared to 1024 stacks typically used with the old receiver for previous surveys). It took almost half an hour per reading to collect and record so many stacks. The test was determined a success as the recorded data showed a clean decay throughout the full range of the time channels. This confirmed there was a strong measureable secondary field present at surface, interpreted to be produced from the highly conductive Chisel North lenses at approximately 600 m depth. Following the success of the test, the new Crone receiver was purchased (Koop et al., 2014).

Several line-kilometres of the DPEM survey using multiple loops was planned to cover the area down-dip of the Chisel Basin (Table 1). Survey and interpretation techniques that collectively may have led to the discovery of the Lalor deposit by boosting the low amplitude response from a conductor at depth and improving the overall data quality to ensure a response from a conductor at depth was distinguishable from the elevated background conductivity include:

1. Laying very large transmitter loops, approximately 2 km x 2 km, compared to historical survey loops of approximately 600 m x 600 m. This improved the dipole moment and amplitude of the EM response.

2. Laying two identical large transmitter loops in parallel (i.e. the two wires on each loop edge were connected at the corners). This cut the resistance in half, thereby doubling the current and the dipole moment, resulting in improved amplitude of the EM response.

3. Using square shaped loops (e.g. 2 km x 2 km) designed for optimum field coupling which resulted in higher dipole moment over rectangular shaped loops with the same total wire length (3 km x 1 km) designed for the purpose of getting a greater number of survey lines to reduce cost by laying fewer loops.

4. Increasing the number of stacks recorded which resulted in cleaner higher quality data than historical surveys.

5. Using long survey lines (greater than 3 km) because it was known that the favorable Chisel Basin (and hence any potential targets) lay at depths greater than 700 m which meant that the wavelength for a complete profile was expected to be about three to four kilometres.

6. Use of lower frequency (5 Hz or lower) to highlight conductors in the later time channels which are more representative of massive sulphides rather than (15 Hz or higher) that was historically used for exploration.

Table 1: 2003–2005 DPEM survey parameters.

Loop #	Sensor Type	Survey Year	Loop Size (km)	Current (A)	Stacking	Frequency (Hz)
1	Induction Coil	2003	2 x 1.8	13	1024	5
2	Induction Coil	2003	2 x 1.4	13	1024	5
3	Induction Coil	2003	2 x 1.7	13	2048	5
4	Induction Coil	2003	2 x 2	13	1024	5
1	Induction Coil	2005	3.2 x 1.7	10	2048	5

Lalor Discovery

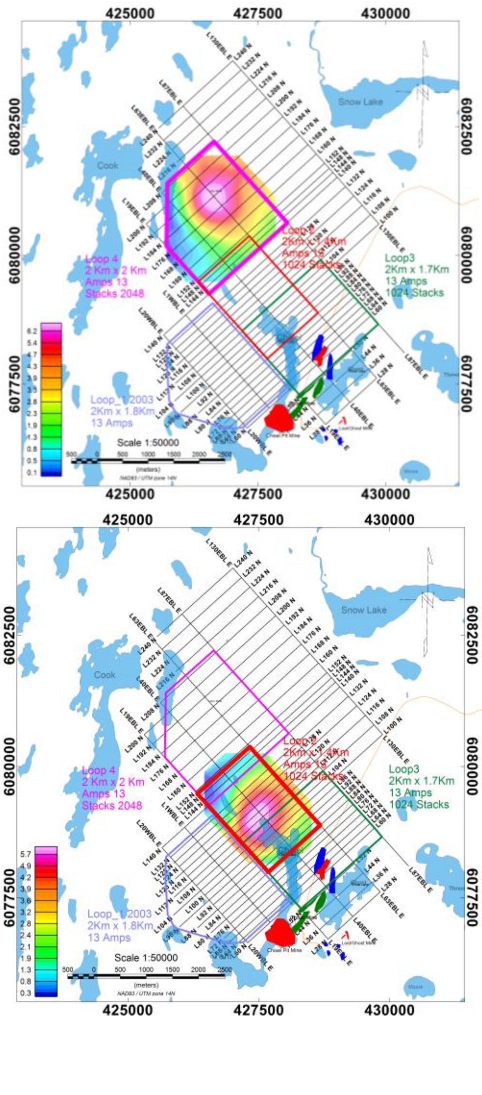
Following the four 2003 DPEM surveys (Loop 1–Loop 4; Table 1), the anomaly from Loop 2 (also known as the South Bull's Eye; Figure 3) and the anomaly from Loop 4 (also known as the North Bull's Eye) were considered interesting and worth following up. In March 2003, CH0305 was drilled to test the South Bull's Eye anomaly (Koop et al., 2014). The hole intersected 15–20% sulphides dominated by pyrrhotite and chalcopyrite stringer. 1–10% stringer pyrrhotite and chalcopyrite was also intersected between 645 m–750 m (including 30–40% chalcopyrite between 743.42 m–743.72 m).

In 2005, a DPEM survey was carried out using a loop that encompassed the location of both the North and South Bull's Eye anomalies. This was done to clear up any misgiving that the anomalies could be related to current channeling as each anomaly was coincidentally at the center of its 2003 survey loop (Figure 3). The 2005 survey reproduced both the North and South Bull's Eye anomalies (Figure 3). Comparing both anomalies revealed that the North Bull's Eye anomaly was more conductive than the South Bull's Eye anomaly as it was still present (and becoming more prominent) in the later time channels while the South Bull's Eye anomaly was decaying away in the later time channels (Figure 4). This was interpreted to be indicative of more conductive sulphides associated with the North Bull's Eye anomaly. It also provided support for using lower frequency for future surveys, as a conductor that does not show up until the later time channels may be missed in a high frequency survey.

Using EMIT-Maxwell 3D modelling software the North Bull's Eye anomaly was modelled as an 800 m x 800 m conductive, shallow dipping body at a vertical depth of 800 m (Figure 5; Koop et al., 2014). In March 2007, DUB168 was drilled to test the North Bull's Eye anomaly. The hole intersected a band of conductive mineralization between 781.74 m and 826.87 m (45.13 m). Assay results were 0.30% copper and 7.62% zinc over the 45.13 m, including 0.19% copper and 17.20% zinc over 16.45 m. Drilling at the Lalor Lake was continuous after the discovery of mineralization on the property. A Borehole Electromagnetic (BHEM) survey was performed on DUB168 as well as all other successive holes drilled. The results were used to guide subsequent drilling and delineation of the Lalor deposit. The BHEM surveys were conducted using a one component induction probe (dβ/dt) to measure the Z, X and Y components, looking down the hole.

Post - Lalor Discovery

The marked contrast between the physical properties of minerals formed in association with VMS mineralization and their host rocks makes VMS deposits ideally suited for geophysical exploration (Bishop and Lewis, 1992). With the depletion of VMS sources in surface and near-surface settings changing the current exploration strategy for VMS deposits to include exploration at greater depths than those traditionally mined, there is an increase in demand for geophysical tools that can see deeper. This has encouraged the development of improved geophysical exploration tools (Morgan, 2012).



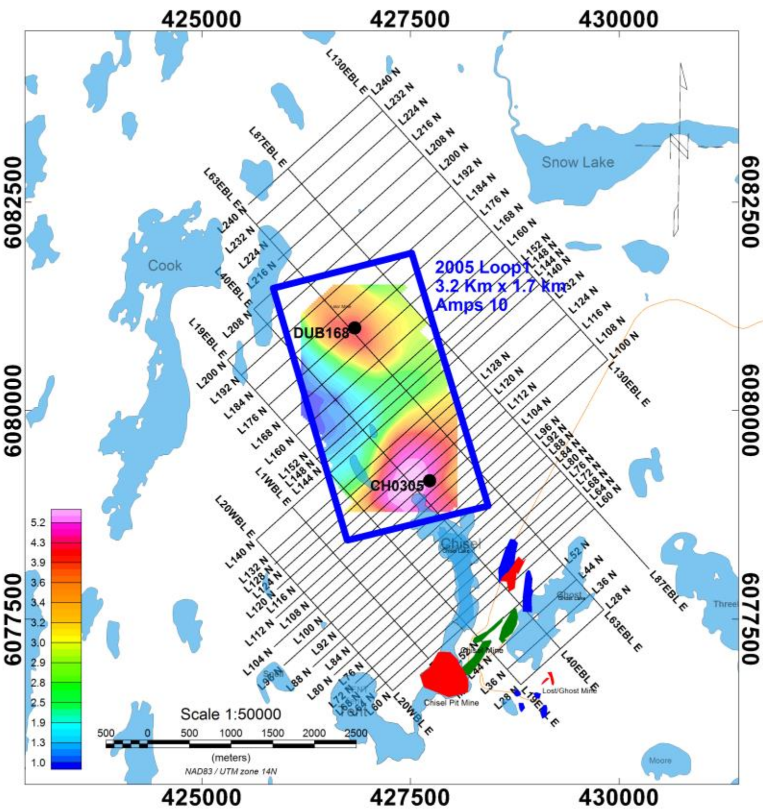


Figure 3: Gridded EM channel 21 data from Loop 4 (top left) and Loop 2 (bottom left) of the 2003 DPEM survey. Gridded EM channel 21 data from Loop 1 of the 2005 DPEM survey (right). Loop 1 from the 2005 survey images both the 2003 DPEM Loop 2 (South Bull's Eye) and Loop 4 (North Bull's Eye) anomaly.

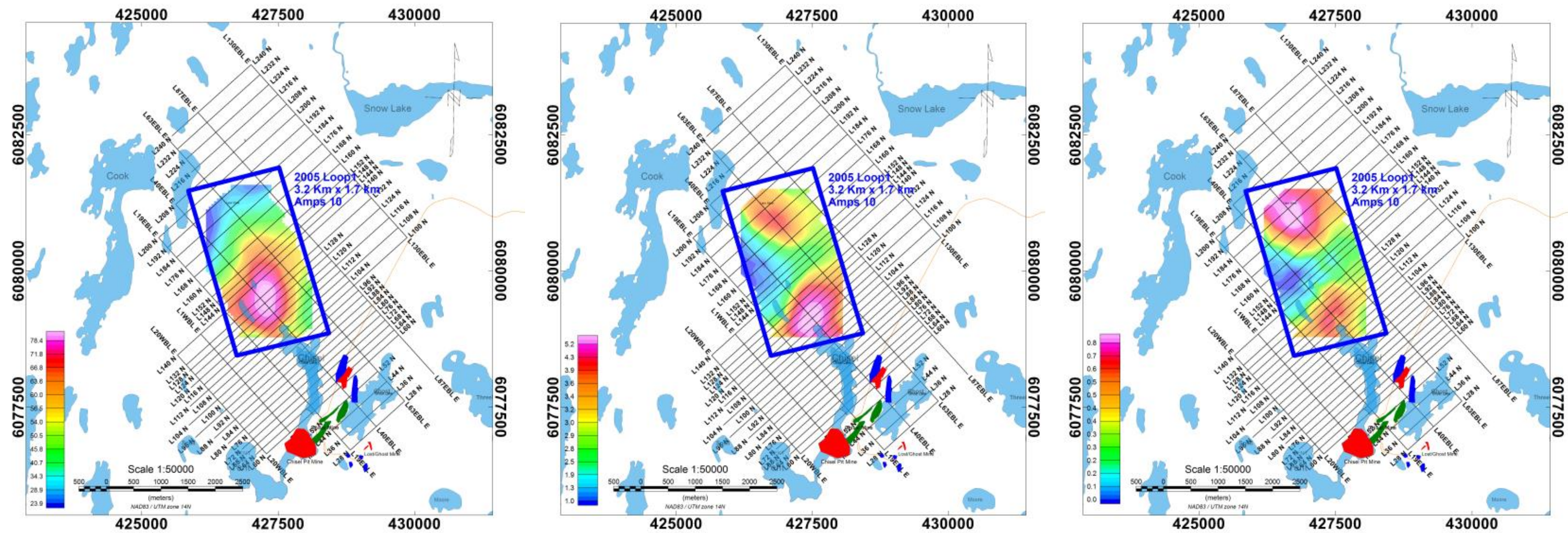


Figure 4: Gridded EM channel 15 (left), 21 (middle) and 24 (right) of the 2005 DPEM survey. In channel 15, the response from the North Bull's Eye anomaly (Lalor EM response) is not seen because it appears later in time. Channel 24 shows the response from the South Bull's Eye anomaly starting to decay away while the response from the North Bull's Eye anomaly is still present (and becoming more prominent).

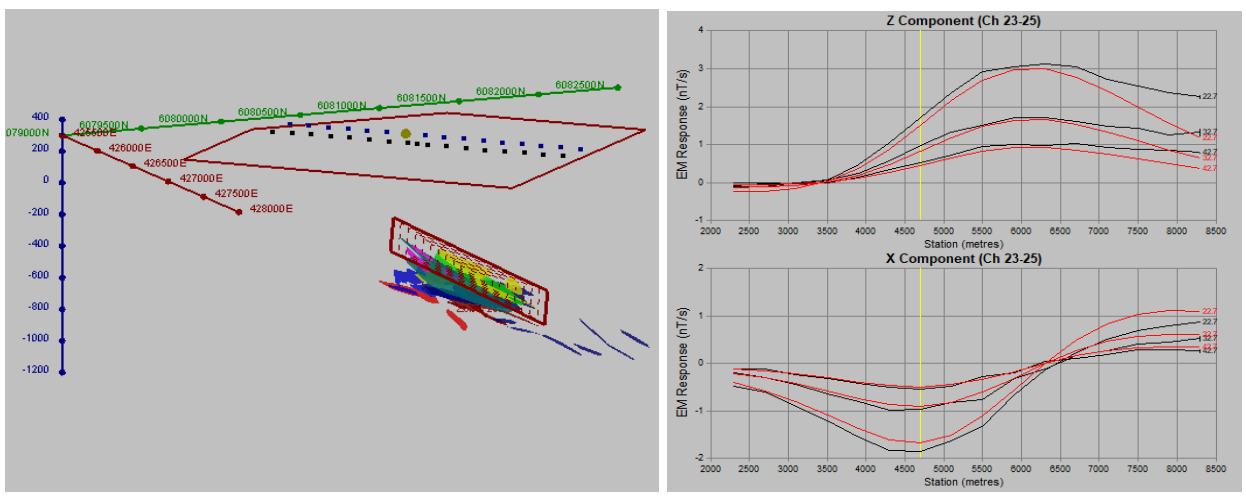


Figure 5: (Left) 800 m x 800 m model plate used to represent the Lalor EM response as seen in the 2003 Loop 4 DPEM data. (Right) Model-profile data fit for channel 23 (17.7 ms) to channel 25 (47.7 ms); model - red, data – black.

The discovery of the Lalor deposit in 2007 was an important new discovery of its size and depth. Surface drilling continued from the discovery in 2007 through July 2012. A total of 225 surface holes and wedges were drilled for a total of 200,081 m at Lalor (Carter, 2017).

Following the discovery, Hudbay initiated a project to characterize the geophysical response of the Lalor deposit using different geophysical techniques and equipment. The major objectives of the project were to:

- Complete a variety of geophysical survey methods over the Lalor deposit.
- Evaluate the data obtained from the geophysical surveys to available geoscientific information.
- Determine which geophysical tools could improve future exploration for VMS deposits with characteristics and challenges similar to that of the Lalor deposit.

The surveys conducted over the Lalor deposit include airborne (VTEM, ZTEM, HELITEM, HeliSAM), surface (TDEM, AMT/MT, IP, Seismic, ELF) and borehole (BHEM, Gravity, Physical Property Logging). The result of some of the surveys will be highlighted in this paper. These include: HeliSAM survey (EM data), surface TDEM and BHEM (using a $d\beta/dt$ and a β-field sensor), 3D seismic reflection survey, and borehole gravity survey (Figure 6).

EM Surveys

Electromagnetic survey methods are used to map electrical property variation in the subsurface. The main physical property involved is electrical conductivity, which is a measure of how easily electrical currents can pass through a material. Electromagnetic surveys use a transmitter to generate a time-varying EM field in a transmitter loop, called the primary field. The primary field travels through the earth by the process of induction. When it encounters a conductor, it generates eddy currents over the conductor's surface. The eddy currents create a secondary field. This secondary field travels through the earth by induction and is measured by the EM receiver (Balch, 2000).

Airborne EM Survey

In August, 2014, a HeliSAM test survey was conducted over the Lalor VMS deposit. The survey was jointly carried out by Discovery Geophysics and GAP Geophysics Australia, and was one of the earliest production surveys in Canada. HeliSAM uses a multi-parameter technique that simultaneously measures both the magnetic and electrical properties of the earth. It involves the active transmission of an EM signal into the earth with a typical frequency range of 4 to 20 Hz using a ground (inductive) loop. Measurements are recorded using an airborne total field magnetometer receiver.

The HeliSAM test survey at Lalor was carried out using a 1.7 km x 1.7 km loop and 20 A current at a transmitting frequency of 3.75 Hz. The survey consisted of 93 line-km flown at 100 m line spacing. The HeliSAM data were processed to produce 16 channels of EM data along each survey line (Parker et al., 2014). The EM profile data result for line 5600 is shown in Figure 7. The HeliSAM EM data identified the Lalor deposit (Figure 7) and showed a comparable response to the DPEM data (Figure 8). This suggests that for flat-lying conductors, the HeliSAM has depth penetration that is better than conventional airborne surveys and comparable with DPEM surveys.

The HeliSAM has some advantages compared to the DPEM, the main advantage being the helicopter deployment of the system which allows surveys to be completed in virtually any topographic environment, as no line cutting or walking of the survey lines is required. Also data acquisition speed of the HeliSAM is consistent with airborne surveys which are much faster than DPEM surveys.

A drawback for the HeliSAM, in comparison to other airborne systems is that it requires a large ground loop (in what could potentially be rough terrain). In comparison to the DPEM, the cost of HeliSAM for a small grid (few 10's of kilometres) may not be justified when compared to the cost of DPEM surveys. However, for larger grids (100's of kilometres) with contiguous loops, the cost may be more easily justified as the survey time is significantly shortened, depth penetration is comparable to that of DPEM and the overall cost is spread over more kilometres. Another drawback of the HeliSAM in comparison to the DPEM is that it has a minimum flight speed requirement (consistent with other airborne surveys) which limits the number of possible stacks that can be recorded per reading; this could lead to noisier data in some areas. As a result, targets may require high conductivity to be visible at great depths by the HeliSAM. Conversely, DPEM surveys have the flexibility to record longer stacks, if required.

Surface and Borehole EM Survey

Surface TDEM test surveys were carried out over test lines L17600N and L18400N. Borehole EM test surveys were carried out on drillhole DUB178. The surface and borehole EM surveys were carried out using an induction coil ($d\beta/dt$) and a β-field sensor (Table 2). The β-field surface sensor and probe used in this test survey measured and recorded all three components of the EM data, which cut down survey time in comparison to the induction coil and probe used in this test survey (and historical Hudbay surveys) which recorded one component at a time.

Survey Type	Sensor Type	Survey Year	Loop Size (Km)	Current (A)	Stacking	Frequency (Hz)
Surface	Induction Coil	2009	2.7 x 2	20	256	1.67
	β-field	2009	2.7 x 2	20	64	1.67
Borehole	Induction Coil	2010	2.7 x 2	9	512	1.67
	β-field	2010	2.7 x 2	18	256	1

Table 2: 2009–2010 DPEM and BHEM post-discovery test surveys parameters.

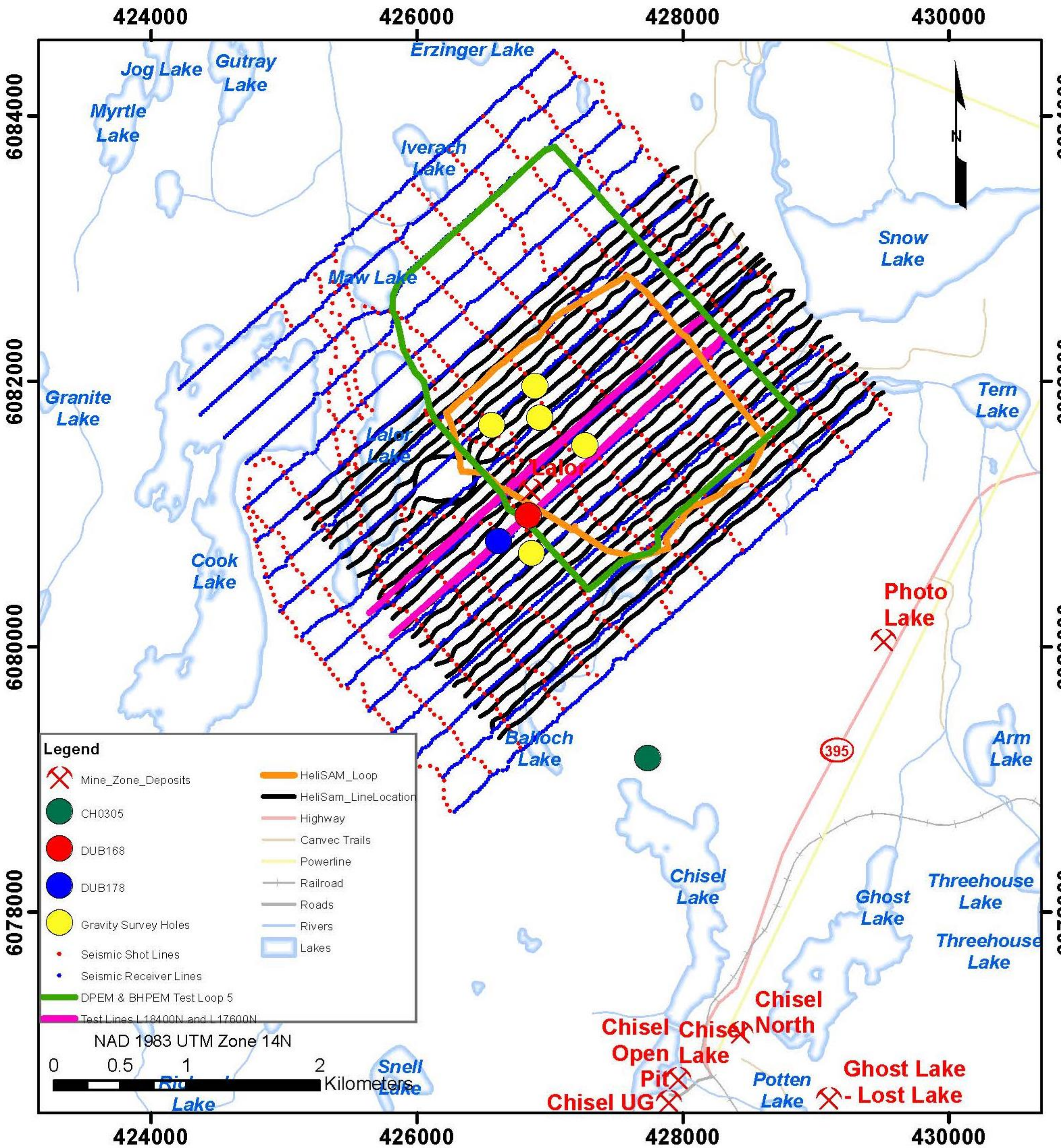


Figure 6: HeliSAM and DPEM test survey grids and loops over the Lalor VMS deposit. Seismic receiver and shot line locations plotted. CH0305 was drilled to test the South Bull's Eye anomaly. DUB168 is the Lalor discovery hole (drilled to test the North Bull's Eye anomaly). DUB178 was the hole used in the BHEM test survey (transmitter loop was same as DPEM). DUB202, DUB279, DUB280, DUB282 and DUB287 were holes used in the borehole gravity test survey.

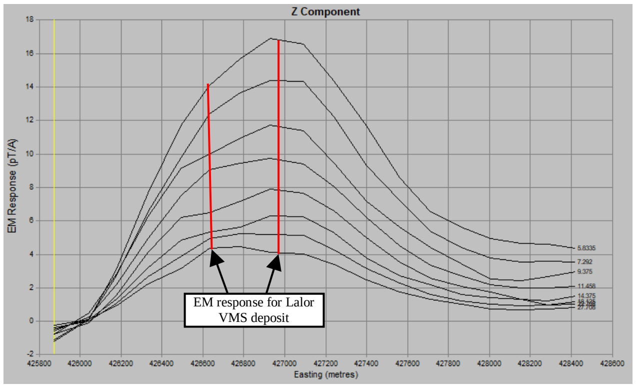


Figure 7: EM profile data, channel 9 (4.792 ms) to channel 16 (32.708 ms), for Line 5600 of the HeliSAM test survey over Lalor. Line 5600 corresponds to the location of Line L18400N used in the DPEM test surveys (line lengths differ) (Figure 8).

All surveys were done using the same transmitter loop (Figure 6). The Lalor deposit was detected by both sensors (Figures 8 and 9). For both the surface and borehole surveys, the β-field sensor produced cleaner EM profile data than the dβ/dt sensor. The benefits of β-field measurement over dβ/dt measurement have been documented by Le Roux and Macnae (2007) and Asten and Duncan (2012). A number of the benefits include:

- A β-field sensor has a high signal-to-noise ratio which increases its depth penetration capability.
- Direct β-field measurement at low frequency (0.1 Hz to 5 Hz) optimizes sensitivity to strong conductors.
- The preferential attenuation of fast decays in a β-field transient electromagnetic (TEM) survey makes it easier to observe the response of a good conductor in the presence of a not so good conductor, such as a host, overburden or less conductive bedrock feature.
- The response of a good conductor is observed earlier in time in a β-field survey than it is in an equivalent dβ/dt survey which means that it is more likely to be above the noise level.
- Fewer stacks can be used for β-field measurements which improve productivity and saves cost.

Overall, the amplitude of an anomaly and its decay constant are important characteristics in recognizing and interpreting relatively good conductors. As distance from the source increases, the strength of the field falls, as a result deeper conducting bodies generally have smaller amplitudes. The ability to measure small amplitude signals to late time is crucial in the detection of good to excellent conductors (Le Roux and Macnae, 2007). It is important to be able to effectively capture these small amplitude signals, especially as the exploration strategy for VMS deposits changes to include the search for deposits at greater depths than those traditionally mined.

Following these DPEM and BHEM test surveys, Hudbay has made the shift from using dβ/dt sensors to using β-field sensors with the aim of acquiring better quality EM data and improving the chances of detecting small amplitude responses from good conductors at great depths or greater distances from the borehole.

As a geophysical tool in detecting the Lalor VMS deposit, the EM method was highly successful. It proved effective from the air, surface and borehole and can be useful in detecting or delineating deep Lalor-type VMS deposits in brown field or green field environments.

Seismic Reflection Survey

The seismic reflection method maps contrasts in seismic impedance. Seismic impedance is the product of seismic velocity (the speed at which seismic waves are transmitted by rock geology) and density (the mass per unit volume). Seismic reflection surveys gather and record patterns of induced seismic wave reflections from rock layers in the subsurface. These waves are reflected when they reach a boundary between different subsurface layers. The time it takes for the waves to travel back to surface and the velocity of travel can be used to determine the depth of different geological layers (Schuck and Lange, 2007). In 3D seismic surveys, several lines of sensitive receivers and shots are laid out in a grid pattern.

During the winter of 2013, as part of the fourth phase of the Targeted Geoscience Initiative (TGI-4) program, a multi-component 3D seismic survey was conducted over the Lalor VMS deposit by the Geological Survey of Canada. The 3D survey covered an area of approximately 16 km^2 that included 908 shot points and 2685 receiver stations. The 16 receiver lines (inlines) were oriented southwest-northeast parallel to the dip direction of the ore zones and footwall rocks near the deposit. The 15 shot lines (crosslines) were generally located orthogonal to the receiver lines. Prior analysis of the physical rock properties from borehole logging indicated that massive sulphide associated with the zinc-rich zone could produce prominent reflections while impedance of disseminated gold-rich zones did not contrast sufficiently with impedance from host rocks to produce reflections (Bellefleur et al., 2015). Figure 10 shows the inline 1098 seismic reflection profile (southwest-northeast) and a north-south cross-section seismic reflection profile.

A detailed 3D geological model was used to guide the 3D seismic reflection data interpretation. Over 220 exploration and delineation boreholes located near the deposit were used to build this 3D geological model. The model is very accurate in the immediate vicinity of the boreholes but less reliable near the edges or at greater depth (i.e. near 1500 m) where the

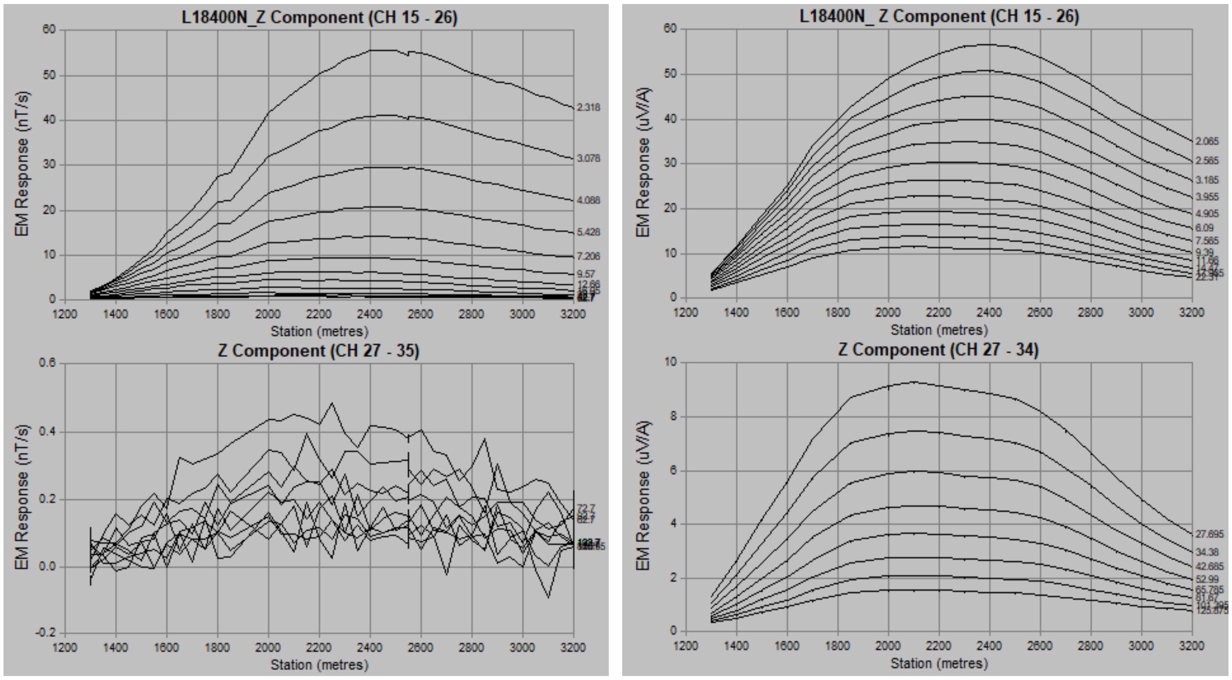


Figure 8: Z-component profile data from line L18400N used in the DPEM test survey. (Left) shows induction (dβ/dt) coil data for channel 15 (1.992 ms) to channel 35 (144.2 ms). (Right) shows SQUID (β-field) sensor data for channel 15 (1.81 ms) to channel 34 (141.61 ms).

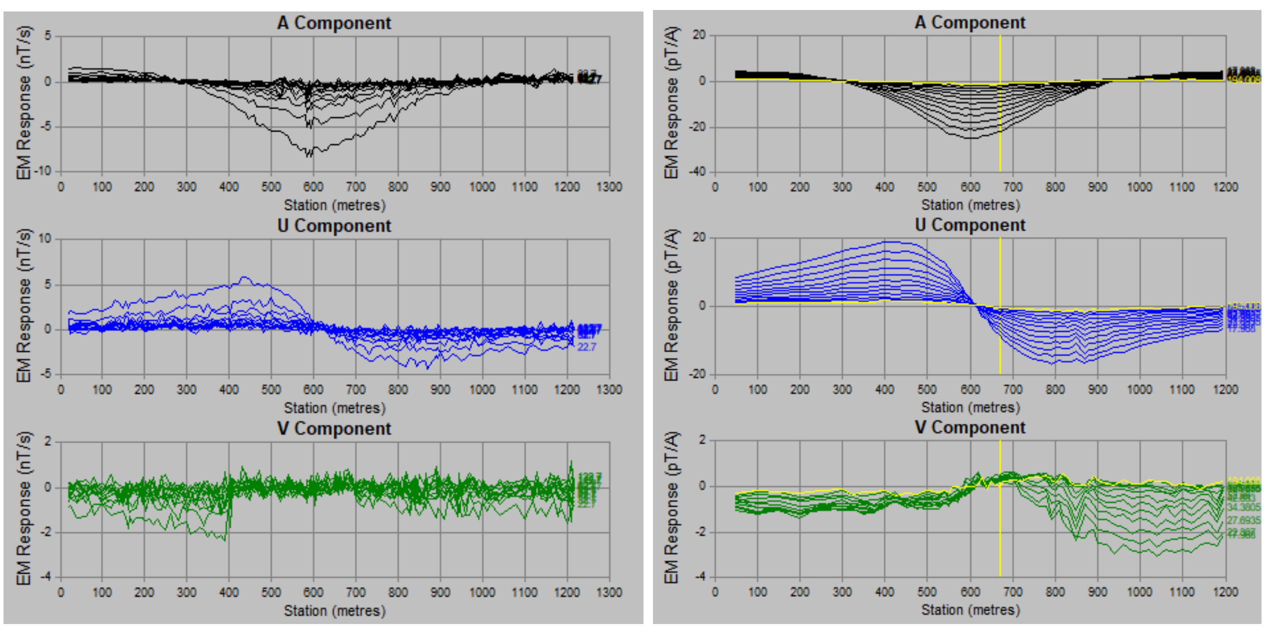


Figure 9: A-, U-, V-component profile data of DUB178 used in the BHEM test survey. (Left) shows induction (dβ/dt) probe data for channel 23 (17.7 ms) to channel 35 (147.7 ms). (Right) shows fluxgate (β-field) probe data for channel 25 (15.7 ms) to channel 36 (218.3 ms).

distribution of boreholes is sparse. Due to the near-vertical orientation of strata in the hanging wall, it is generally devoid of reflections whereas in the footwall, the number and strength of reflections are significantly higher, especially in the intensely altered zone (Figure 10). The most altered footwall rocks are northeast of the deposit (unit shown in pink and purple) and the less altered rocks in the immediate footwall are in general southwest of the main deposit (units in yellow and green) (Bellefleur et al., 2015). Some reflections have been explained with information obtained from the 3D geological model and physical rock properties while some reflections remain unexplained.

In general, zinc-rich massive sulphide zones which are associated with pyrite, showed high impedance in contrast to their host rock which was sufficient to produce prominent reflections. The disseminated gold-rich zones, an economically significant part of the deposit, could not be imaged directly with the seismic reflection method. The most common reflection in the Lalor deposit area was seen at contacts between felsic and mafic volcanic rocks regardless of the intensity of hydrothermal alteration and metamorphism. Beyond the immediate vicinity of the 3D seismic model, numerous reflections generally dipping to the northeast on most inlines can be observed (Bellefleur et al., 2015). A few noteworthy reflections are labeled 'A' – 'D' in Figure 10 and are interpreted as follows: 'A' as the continuation of the felsic (yellow) – mafic (green) contact between the geologically mapped Balloch basalts and the north Balloch rhyodacite; 'B' as the contact between mafic volcanic (dark green) and mafic volcaniclastic rocks (light green); 'C' as coinciding primarily with the structural contact between felsic (purple) and mafic (light green) protolith in the most altered part of the footwall; and 'D' as possibly the base of the Lower Chisel sequence near the contact with the Anderson sequence. Reflection 'C' can be used as a proxy for the hanging wall fault contact (Bellefleur et al., 2015). The Lalor deposit and most of the previously mined deposits occurred below this hanging wall contact. The ability to successfully follow this contact in 3D is of great importance to further exploration in the area. Reflection 'D' provides an indication of the general geometry of the volcanic sequence in the area of the 3D seismic survey (Bellefleur et al., 2015). It suggests the volcanic sequence may fold back towards surface. This needs to be verified. If true, it could help identify areas (north of the known Lalor deposit and currently under explored) where the hanging wall – footwall contact and the favorable Chisel horizon is shallower and within mining depth range. This is assuming the favorable Chisel horizon does not pinch out or get truncated further to the north.

As a geophysical tool in detecting the Lalor VMS deposit, the seismic reflection method was questionable. However, it was effective in providing 3D structural information. A detailed database of the physical rock properties and the 3D geology was and will be needed to get the most information from the seismic reflection data. The seismic reflection method appears more suited to brown field exploration, where a lot more information is known as opposed to green field exploration where little information may be known.

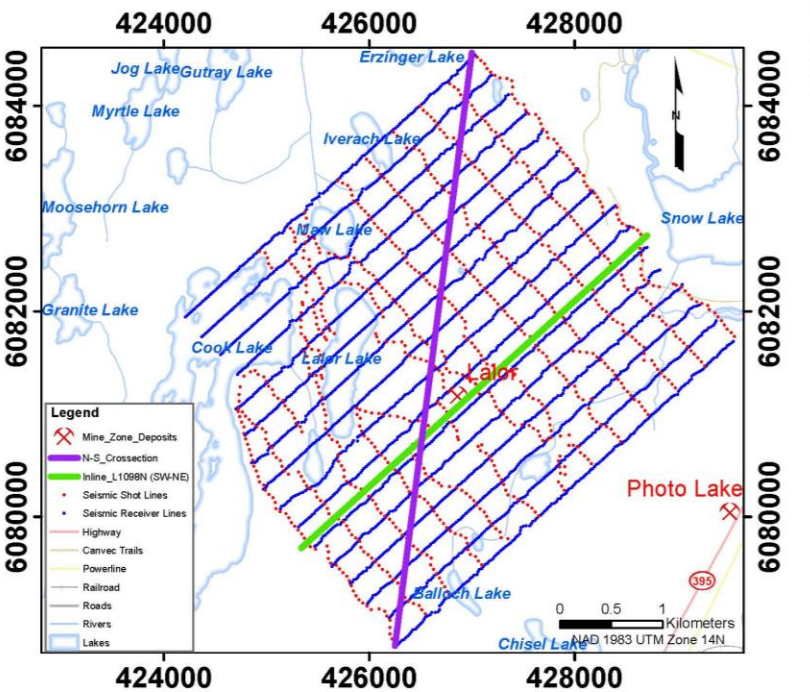
Borehole Gravity Survey

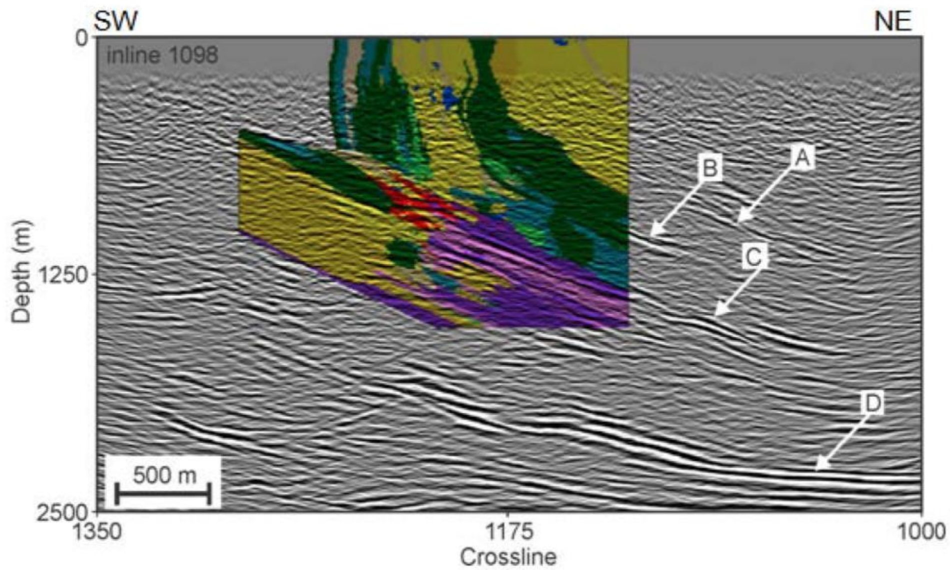
Gravimetric surveys measure differences in the earth's gravity field, which is sensitive to rock density variations. Local excesses or deficiencies in mass produce a corresponding increase or decrease in the gravity field respectively. For borehole gravity, a number of precise gravity measurements are collected by stopping the gravimeter and taking readings at preselected borehole depths. A series of processing steps are applied to the data to allow analysis of the local anomalous gravity response. The processed data reveals information about the distribution of densities in the geological formations both in the immediate vicinity of the hole and remotely from the hole (Nind and MacQueen, 2013).

In February 2014, as part of the TG1-4 program, borehole gravity surveys were conducted on five NQ holes surrounding the Lalor deposit (drillholes DUB202, DUB279, DUB280, DUB282 and DUB287; Figure 11). The survey was completed by Abitibi Geophysics using the Scintrex Gravilog slim-hole gravity sensor. At that time, a borehole gravity meter that could be operated in a NQ (57 mm diameter) drillhole with inclination from -30° to vertical was relatively new to mining exploration. The gravity data for DUB279 is shown in Figure 12.

The borehole gravity data showed crossover anomalies resulting from increased density that generally correspond with the location of mafic rocks. In DUB279 (Figure 12), the highest density of 3.1 g/cm3 observed at approximately 840 m corresponds with intersection of pyrrhotite in mafic tuff and metasediments with no significant assay values. At approximately 920 m down DUB279, a BHEM anomaly is noted which corresponds to the intersection of elevated zinc, silver, pyrite and pyrrhotite related to the zinc-rich zone of the Lalor deposit. There was no distinct gravity anomaly associated with this mineralization.

The wavelength of gravity signals from a given source increases with distance from the source. DUB279, which is one of the closer holes surveyed, is still approximately 250 m away from the Lalor lenses (Figure 11). From Figure 12, could there be a "potential" long wavelength crossover response between 600 m and 1000 m related to the Lalor deposit? Whereas shorter wavelength responses from increases in density occurring closer to the hole (e.g. from mafic rocks) are superimposed on this "potential" long wavelength response. Or was the Lalor deposit too far away from the surveyed holes to have produced a significant response? All five holes surveyed were greater than 250 m away from the Lalor lenses. Holes closer to the Lalor lenses (<150 m) would likely have been more adequate for the test, as the response from Lalor may have been more obvious. According to Nind and MacQueen (2013), the borehole gravity method can aid in reducing exploration cost and time by delivering quantifiable information on the general mass of the mineralization from a few boreholes early in the exploration cycle; a general 3D representation of a massive body can be obtained by inversion of borehole gravity measurements acquired from three or more boreholes bracketing the massive body. The borehole data can also help prioritize BHEM conductors by estimation of mass associated with the conductors. This could be useful in VMS exploration for deposits in areas where graphite is known to be present and problematic. Most VMS deposits as well as graphite are





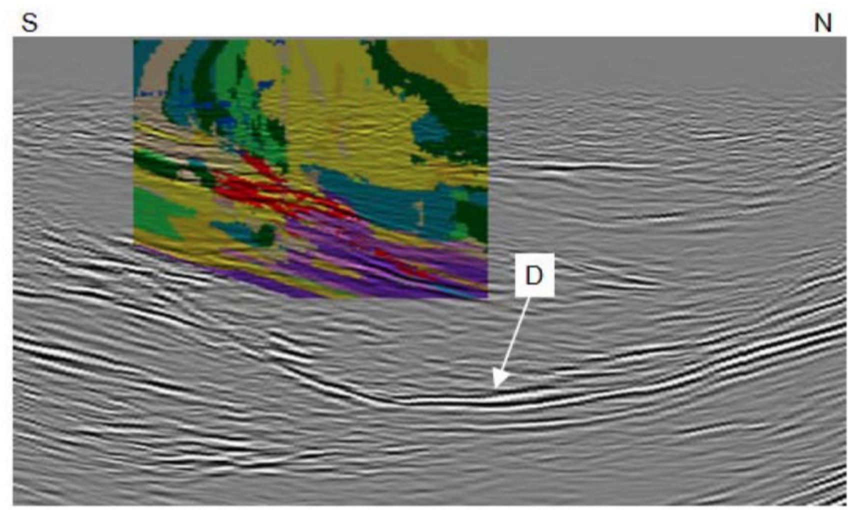


Figure 10: (Left) Plan map showing seismic shot and receiver locations and location of southwest-northeast and north-south sections. (Top right) southwest-northeast section (inline 1098) from the final seismic volume with information from the 3D geological model. (Bottom right) north-south cross-section from the final seismic volume with information from the 3D geological model. See text for interpretation of highlighted reflections 'A' – 'D' (modified from Bellefleur and Schetselaar, 2014).

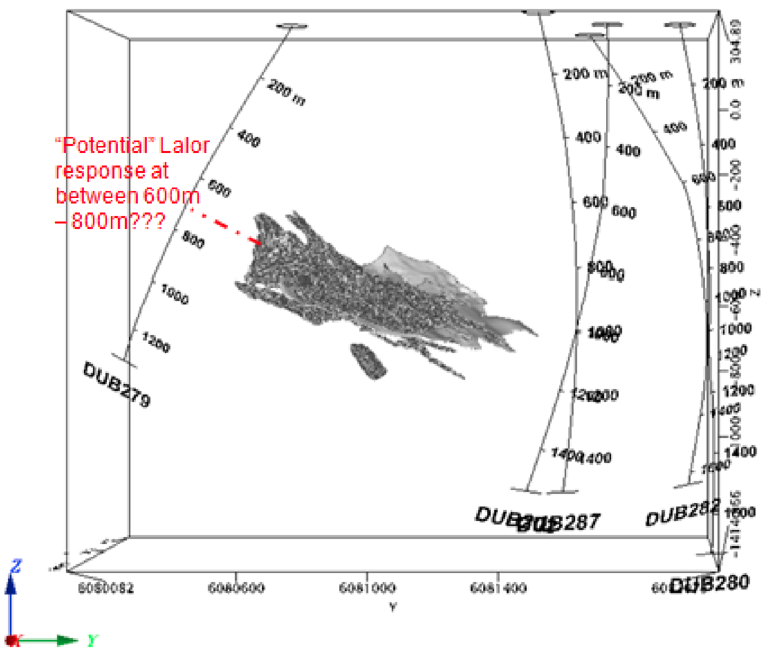


Figure 11: NQ drillholes (DUB202, DUB279, DUB280, DUB282 and DUB287) surveyed during the borehole gravity test survey. Holes are located greater than 250 m away from Lalor deposit.

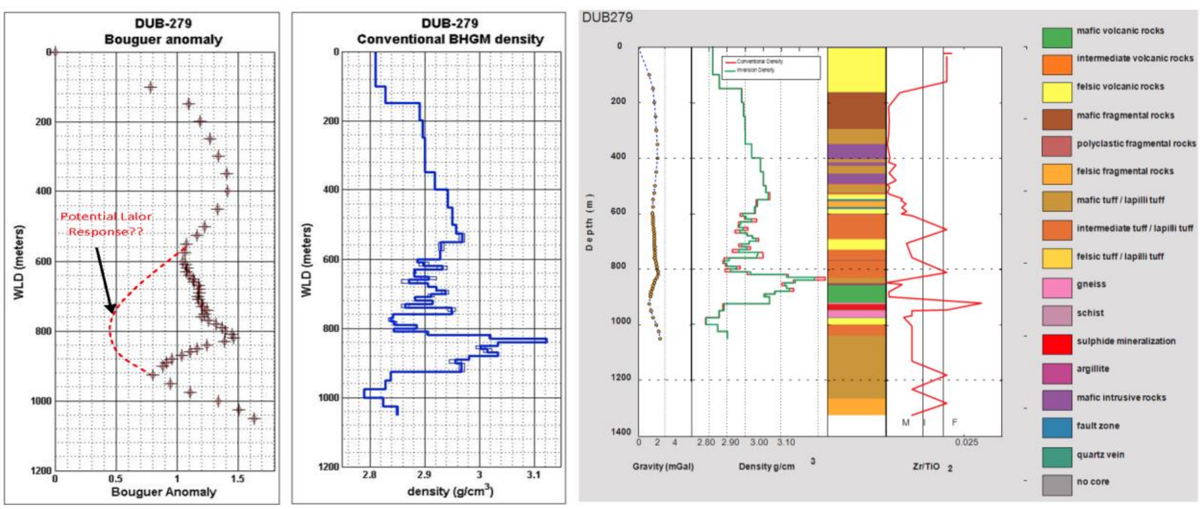


Figure 12: Gravity and BHEM data from DUB279. "Potential" long wavelength crossover response that could be related to the Lalor deposit at between 600 m –800 m (modified from Wasylechko, 2014). In general, the borehole gravity showed anomalies resulting from increased density that corresponded with the location of mafic rocks.

conductive but graphite has a much lower density in comparison to the density of sulphides associated with VMS deposits. The drawback to this is that graphite could sometimes be mineralized with sulphides (e.g. pyrrhotite) which could potentially produce a gravity anomaly.

Whether the test borehole gravity survey detected the Lalor VMS deposit is questionable. The location of the surveyed holes in relation to the Lalor deposit (greater than 250 m away) may have played a role in this as the gravity survey was successful at identifying the increased density associated with mafic rocks and a pyrrhotite intersection unrelated to the Lalor mineralization. The gravity method could potentially be useful in conjunction with the EM method to discriminate or prioritize EM conductors during brown field or green field exploration for a Lalor-type VMS deposits

Lessons Learned

Knowledge of Geology

Good knowledge of the geology of the area of interest is very important. Without knowledge of the geology at a property or deposit scale, exploration programs involving geophysical and geochemical surveys may prove unsuccessful or produce misleading results.

Knowledge that the Chisel Basin was favourable, flat-lying and increased in depth to the north were important information that guided the survey planning and interpretation techniques employed in the DPEM survey that led to the discovery of Lalor. Without this information, historical survey parameters (used by Hudbay at that time) would likely have been used and Lalor may not have been found at that time.

Critical Examination of Available Data

Figure 13a shows the Lalor and surrounding deposits or past producing mines located in the Chisel basin. This area has long been considered favourable, and judging by the number of pre-2007 (Pre-Lalor discovery) geophysical grids and drillholes in Figures 13b, 13c and 13d, would appear relatively well explored. The geophysical survey grids shown in Figures 13b and 13c include grids for surveys such as Turam, Horizontal Loop Electromagnetic (HLEM), Fixed Loop electromagnetic (FLEM), Very Low Frequency (VLF), Moving Loop Electromagentics (MLEM) and UTEM surveys. These surveys have a depth penetration of less than 200 m, with the exception of MLEM and FLEM which have the ability to see to greater depths. However, due to acquisition parameters (e.g. 30 Hz frequency) and limitation of equipment (e.g. 2.4 kw transmitter) used at that time, the full potential of the MLEM and FLEM surveys were not maximized. As a result, although the favourable Chisel Basin area appears relatively well covered by geophysics, none of these surveys had the ability to see a significant body at depths greater than 400 m (Vowles and Dueck, 2014).

Figure 13c shows all the pre-2007 drilling. Green circles indicate drillholes with end-of-hole (EOH) shallower than 500 m. Yellow circles indicate drillholes with EOH deeper than 500 m. Figure 13d shows only the drillholes deeper than 500 m. This reveals that majority of the deep drilling was concentrated on the known deposits with little drilling completed outside the known deposits (Vowles and Dueck, 2014).

When looking at a plan map of geophysical grids and drill collars in an area, it is easy to incorrectly assume that an area has been adequately explored and tested. It is important to be cognizant of what the objective of a historical geophysical survey was (as current objectives could differ from past objectives) and the limits of the available data (e.g. depth of penetration), as areas that appear adequately explored and tested at surface may be inadequately explored and tested at depth.

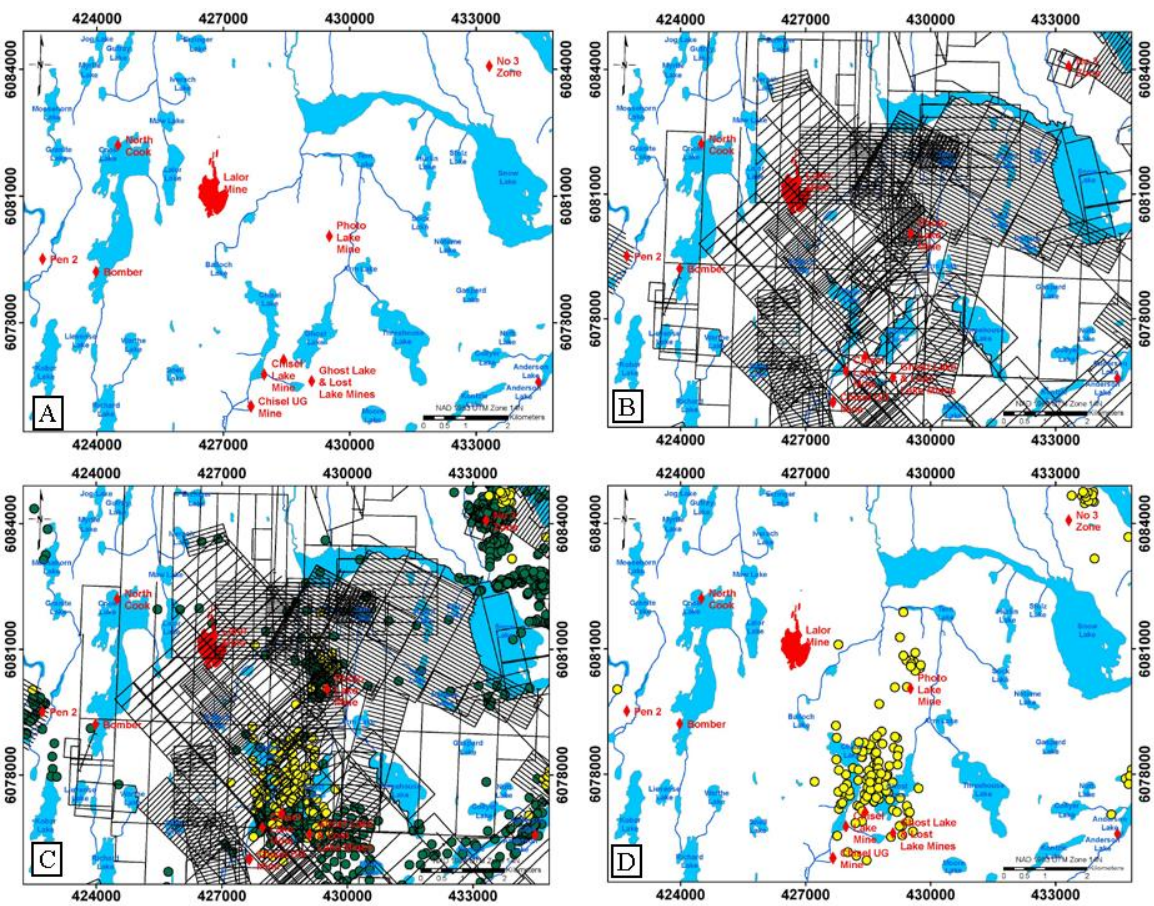


Figure 13: A - Location of Lalor and surrounding deposits or past producing mines. B - All pre-2007 geophysical grids. C - All pre-2007 drillholes (Green – EOH shallower than 500 m; yellow – EOH deeper than 500 m). D - Only pre-2007 holes deeper than 500 m.

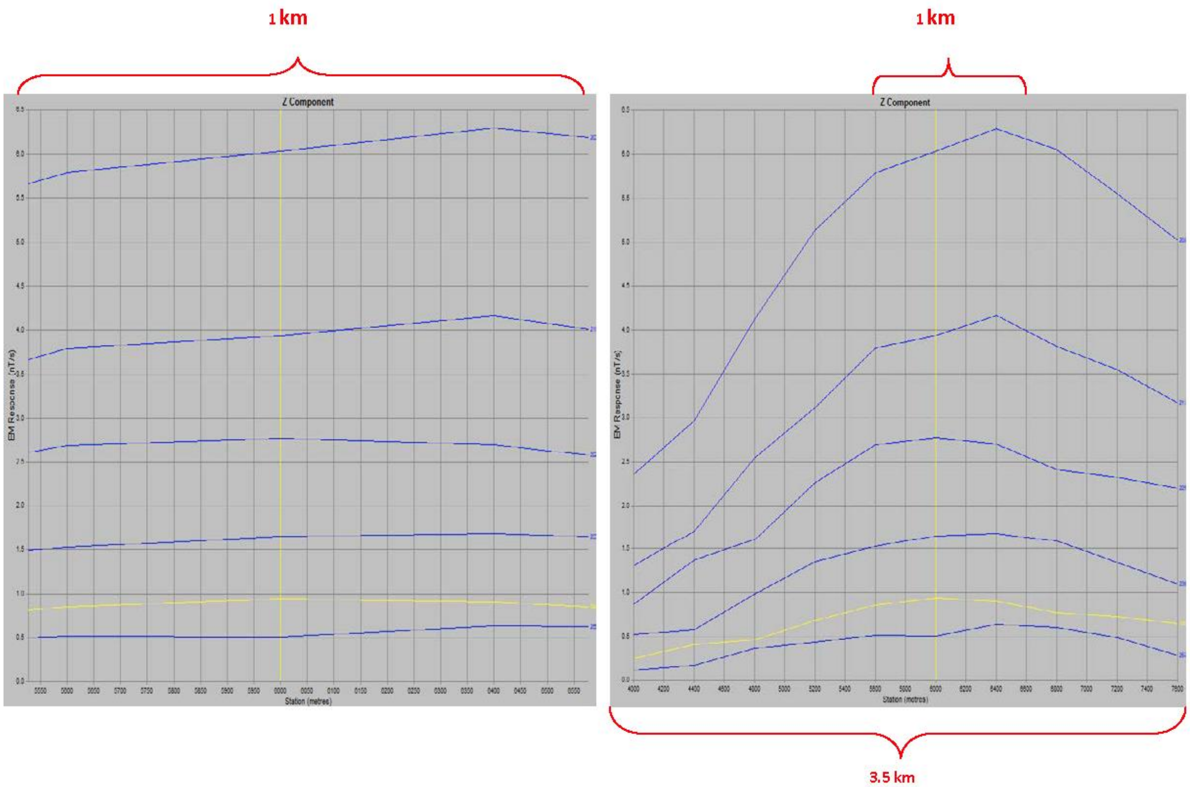


Figure 14: Z-component profile of a DPEM line over the Lalor deposit. (Left) 1km line; (Right) 3.5km line (modified from Vowles (2014)).

Importance of EM Survey Length

Figure 14 shows the DPEM profile of a line over the Lalor deposit. In the profile for the 1 km line it is impossible to make out the anomalous response from the Lalor deposit, as the entire line of measured data is within the anomaly. In the 3.5 km line, the anomalous response from the Lalor deposit is much more obvious because sections of the line of measured data are out of the anomaly and descending towards background conductivity on either side of the anomalous response. This emphasizes that short lines (less than 1.5 km) could miss the full EM profile of a long wavelength response which could be related to a large flat-lying conductor at depth (similar to the Lalor deposit) (Vowles, 2014). This does not insinuate that all grids need to be completed at 3.5 km but for areas with known flat lying geology it would be judicious to strategically extend a few lines of a grid (e.g. centre and ends lines) to see if they show indications of a possible long wavelength response from a large conductor at depth.

Test Conceptual Ideas

The EM geophysical anomaly corresponding to the Lalor deposit may never have been identified (or perhaps identified much later than 2003), if the initial 2003 test survey was not carried out. It is important to periodically review the current geophysical survey practices to ensure they still serve the current and future exploration needs. As exploration strategy changes, consideration should be given to new logical geophysical ideas that could aid exploration. This could involve new or improved geophysical tools, the combination of old geophysical tools or a change in the current survey parameters and configuration. Regardless, if the idea is logical, it is worth testing. It could emerge to be an invaluable tool in the search for new deep deposits.

Explore Early

It took seven years after the Lalor discovery hole was drilled to get Lalor mine into full production. Excluding the time spent in historical work (such as organizing or digitizing data) and conducting geophysical survey(s), the different stages from the period after drilling a discovery hole to full mine production could take on average 5 to 10 years, for a Lalor-sized deposit. This should be taken into account when developing an exploration strategy, especially if the intent is to replace an existing anchor mine with a new anchor mine. The time to start exploring should be sooner, not later.

Blind Post-Discovery Test Surveys

It is great to have so many different test surveys over the same deposit post-discovery, however, hindsight is 20/20. It is easy to pick out the anomaly response from a deposit that is known. In order to aid with future exploration, post-discovery test surveys should not just be carried out with parameters tailored to successfully detect the deposit. These test surveys should also be carried out using the standard survey parameters and practices in order to determine if there would be a response from the deposit, and if there would be enough confidence in that response to drill at those depths (e.g. in the Lalor case at depths >700 m). From the results of the test surveys it could be determined that the standard survey parameters are adequate or they may need to be updated. When possible, part of post-discovery test surveys should be carried out somewhat 'blind'—without knowledge of the exact location and shape of the deposit.

CONCLUSIONS

Geophysical surveys have played an important role in the discovery of VMS deposits in the Flin Flon Greenstone Belt. Following the Lalor deposit discovery, several geophysical test surveys were carried out over the deposit to characterize the geophysical response of the deposit and determine which geophysical techniques and equipment could improve future exploration success in identifying VMS deposits of similar size, geometry and depth.

The EM surveys showed the most prominent response in direct correlation with the Lalor deposit due to the high conductivity contrast between the Lalor deposit and the host rocks. In comparison to DPEM surveys, conventional airborne surveys have a lower depth of investigation. However, the HeliSAM survey had a depth of investigation comparable to the DPEM surveys. For the surface and borehole EM surveys, the β-field sensors provided cleaner data than the dβ/dt sensors due to the β-field sensors high signal-to-noise ratio and sensitivity to strong conductors at low frequency. Less signal stacking was also required for the β-field sensor measurements which improved productivity and saved cost. The EM method was highly successful in detecting the Lalor deposit. It would be an effective tool in detecting or delineating deep Lalor-type VMS deposits in brown field or green field environments.

The 3C-3D seismic interpretation model utilized physical rock properties, and a 3D geological model obtained from exploration and delineation boreholes. Some reflections have been explained whereas some reflections remain unexplained. The Lalor zinc-rich massive sulphide zones, which are associated with pyrite, showed high impedance in contrast to their host rocks and hence produced prominent reflections, The Lalor disseminated gold-rich zones could not be imaged directly with seismic reflection. The most common reflection was seen between the felsic and mafic volcanic rocks (Bellefleur et al., 2015). As a direct tool in detecting the Lalor deposit, the seismic reflection method was questionable. However, it was successful in providing structural information. Most important is the mapping of the hanging wall fault contact; a contact along which the Lalor deposit and most previously mined deposits occurred. The ability to follow this contact in 3D is of great importance. Other interesting reflections exist but more information is needed to further explain them. Detailed information on the physical rock properties and geology was and will be needed to get the most information from the seismic data. As a result, the seismic reflection method appears better suited to brown field exploration, where a lot more information is known as opposed to green field exploration where little information may be known. It could provide great structural information to aid VMS exploration at depth.

The borehole gravity survey identified anomalies resulting from increased density. These anomalies generally corresponded with the location of mafic rocks. The highest density in one of the holes corresponded to the intersection of pyrrhotite in mafic tuff and metasediments with no significant assay values. Further down that same hole, intersection of elevated zinc, silver, pyrite and some pyrrhotite, related to the zinc-rich zone of the Lalor deposit, showed no distinct gravity anomaly associated with this mineralization. Whether the gravity survey identified a response from the overall Lalor deposit is questionable. The location of the surveyed holes in relation to the Lalor deposit (greater than 250 m away) may have played a role in this as the borehole gravity survey was successful at identifying the increased density associated with mafic rocks much closer to the hole. The gravity method could potentially be useful in conjunction with the EM method to discriminate or prioritize EM conductors during brown field or green field exploration for a Lalor-type VMS deposits

The main geophysical lessons learned from the Lalor discovery process are that:

- It is important to be cognizant of what the objectives of a historical geophysical survey was (as current objectives could differ from past objectives) and the limits of the available data, as areas that appear adequately tested at surface may be inadequately explained at depth.
- In areas of flat lying geology, short lines could miss the full EM profile of a long wavelength response which could be related to a large conductor at depth.
- As exploration strategy changes, new logical geophysical ideas involving new techniques, new technology or old technologies with revised survey parameters are worth testing. They could emerge to be an invaluable tool in the search for new deep deposits.

The depletion of VMS sources in surface and near-surface settings is changing the exploration strategy of VMS deposits to include greater depths than those traditionally mined. To improve the odds of success at exploring for deep deposits, 3D integration of geological, geophysical and geochemical data in a single model that is consistent with all the available data would be vital.

ACKNOWLEDGEMENT

The authors would like to thank British Columbia Geophysical Society for initiating and collaborating with Hudbay to organize the 2014 Lalor symposium to present the results from the geophysical test surveys over the Lalor deposit. The authors would like to thank everyone who contributed to carrying out the test surveys and everyone who presented the test survey results at the 2014 Lalor Symposium. The authors would like to thank all Hudbay employees who contributed to make the Lalor project and this paper possible.

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