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In The Shadow of a Headframe: Deep Exploration Using Integrated 3-D Seismic and BHEM Aat The Louvicourt Mine, Quebec

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ABSTRACT

A 3-D seismic survey was acquired in 2001 to explore for deep massive sulphide ore deposits in the vicinity of the Louvicourt mine near Val d'Or, Quebec. The seismic data was reprocessed in 2002 and the optimum imaging offsets and azimuth have been determined. The seismic stacked volume shows a detailed image of the existing mine as well as a new deep and steeply dipping reflection. A follow-up drilling program was undertaken to verify the nature of the deep seismic anomaly and BoreHole ElectroMagnetic (BHEM) data was acquired to evaluate the proximity of electrical conductors that could be indicative of a massive sulphide body. BHEM methods, although well suited for the resistive hard rock environment, are constrained by limitations of their sensitivity and resolving power of regional and local geological noise. These limitations are critical for a detailed exploration program in the vicinity of existing orebodies and mines. The interpretation of BHEM data from brown field exploration projects can be improved by both new data acquisition strategies and data processing procedures. In and within the vicinity of an existing mine, a vertical transmitter loop can sometimes provide a unique perspective for the explored volume with higher than expected data quality. The 3-D seismic volume provides geometrical information about deep impedance anomalies and can help in the design of an optimised drilling program. Forward modelling of BHEM data using potential conductor geometries derived from 3-D seismic data can then be used to guide long-term exploration strategies. The joint use of surface 3-D seismic and BHEM data has led to the identification of an extensive zone of disseminated sulphides close to the Louvicourt mine.

INTRODUCTION

The Louvicourt mine is located 25 km East of Val d'Or in Quebec, Canada (Figure 1). The mine, which is now decommissioned, is located within a 1.5 to 5 km wide band of Archean age volcanic rocks that extend over 40 km (Pilote et al., 1998). The host rocks are subvertical and composed of felsic to intermediate volcanoclastics interlayered with andesitic flows and rhyolite domes (Pilote et al., 1998). The 15.5 Mt Louvicourt orebody is a polymetallic (Cu-Zn-Au-Ag) VMS type deposit that extends between depths of 355 and 920 m.

In 2001, a 28 km^2 3-D seismic survey was acquired to accelerate the deep (1-2 km depth range) exploration program around the Louvicourt mine. The survey's objective was to identify other Volcanogenic Massive Sulphide (VMS) deposit similar to the Louvicourt deposit. In the area, most lithological contacts are steeply dipping and a review of petrophysical data has suggested that they should be weakly reflective. On the other hand, strong reflections and diffractions are expected from massive sulphides that are locally rich in pyrite (a high impedance iron sulphide). The exploration approach was to use 3-D seismic in an area where lithologies are transparent to seismic waves and anomalous massive sulphide accumulations are the main source of reflections. Within the 3-D seismic area is the partly mined out Louvicourt deposit, which can be used as a template for the identification of similar bodies and to calibrate the surface seismic survey.

A reprocessing effort was undertaken in 2002 (Adam et al., 2004) and led to a new exploration drilling program from the underground workings of the Louvicourt mine. Whereas the follow up deep drilling based on these seismic results did not identify new ore deposits, measured BHEM data in the exploratory wells confirmed the presence of deep electrical conductors. In this paper we summarise the integrated exploration strategy that made full use of potential conductor geometries derived from 3-D seismic data to understand the electromagnetic responses recorded in the exploration boreholes. This study has led to the identification of a previously unknown zone of disseminated sulphides West of the Louvicourt mine.

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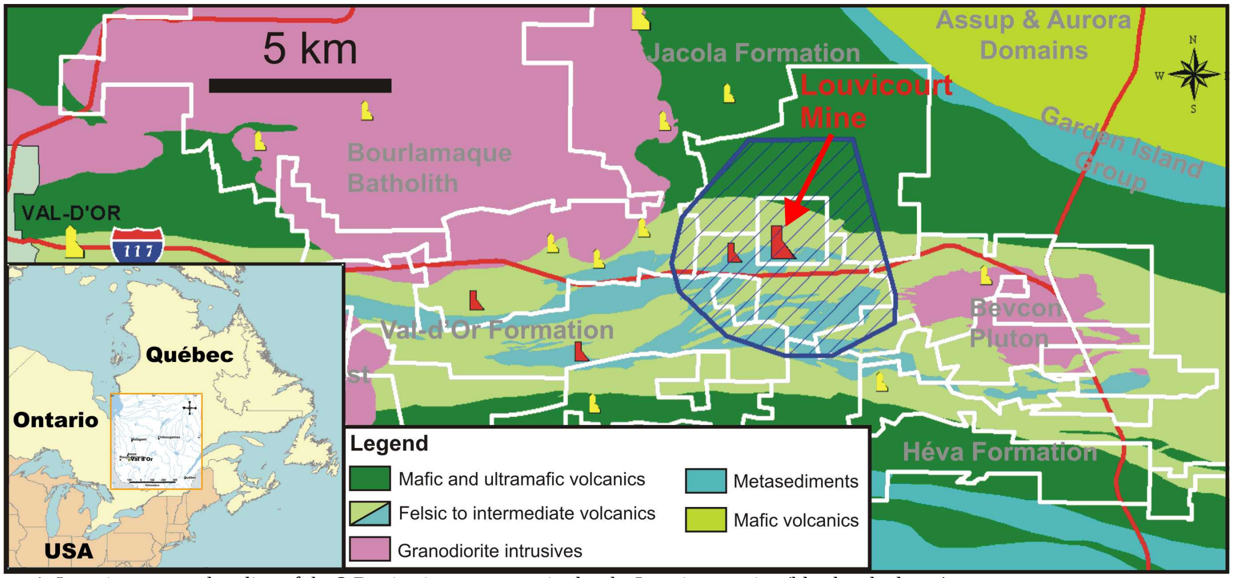

Figure 1: Location map and outline of the 3-D seismic survey acquired at the Louvicourt mine (blue hatched area).

SEISMIC DATA ACQUISITION AND PROCESSING

The Louvicourt 3-D seismic was acquired with explosive sources placed at 60 m interval and were recorded by up to 2370 receivers at 30 m spacing. The source and receiver line separations was 210 m. The recording patch, oriented in the North-South direction, consisted of 12 complete receiver lines in order to record sources at large offsets with a wide range of azimuth. The area covered by the 3-D survey is about 28 km^2 (blue hatch area on Figure 1) using a 20 m square CDP bin. Because the Louvicourt mine is located in the middle of the seismic survey, the data acquisition was scheduled to take place at a time when the mill was shut down for maintenance, hence reducing the cultural noise

The conventional processing of the 3-D seismic data has failed to identify reflections that could be indicative of massive sulphides other than the Louvicourt mine. The reprocessing work summarised here has been focused on optimising specific steps of the processing flow. The key steps of processing the Louvicourt 3-D dataset are refraction static correction, the identification the optimum source-receiver offsets and azimuths. A more complete description of the processing sequence has been reported by Adam et al. (2004).

Refraction static correction

The seismic data acquired in the hardrock environment are strongly affected by time delays caused by low-velocity overburden of variable thickness. At Louvicourt, the shot refraction static and datum corrections (datum being at 400 m above sea level) ranged between -61 and +16 ms and the at the receivers they ranged from -71 to +18 ms. The large refraction correction, up to -132 ms, is in the same range as the target time (e.g. 400 m or ~140 ms). Thus, the refraction static correction is the most important processing step.

Optimum source-receiver offsets

The steeply dipping reflectors are best imaged with large source-receiver offsets relative to their depth. Consequently, offset-limited seismic stacked sections offer a simple way to enhance reflections that may otherwise stay unnoticed or buried in noise. Figure 2 shows one crossline on which a package of reflections that are from the vicinity of Louvicourt are seen for shot-receiver separation of less than 4000 m (Figures 2a and 2b). A deep (1.4 - 1.8 km) and steeply dipping (~50^o) reflection is clearly identified by shot-receiver separation exceeding 4000 m (Figure 2c). Limiting the shot-receiver offset to less than 4000 m (the conventionally processed data was limited to 3500 m) does not allow the detection of the deep/steeply dipping reflection even if it is stronger than the seismic anomaly associated with the Louvicourt deposit. The offset range used in the commercial processing flow was sufficient to provide a good image of the Louvicourt mine (Figure 3) because it is relatively shallow and does not appear as a dipping reflector.

DRILLING PROGRAM AND BHEM STUDY

Following the identification of the deep reflection West of the Louvicourt mine (Figure 2c), a two well underground exploratory drilling program was designed to verify the origin of the seismic anomaly. BHEM data using both surface loop and underground vertical loops have been acquired to test the presence of electrical conductors that could coincide with the seismic reflection. Practical difficulties with BHEM data interpretations in resistive environment are generally attributed

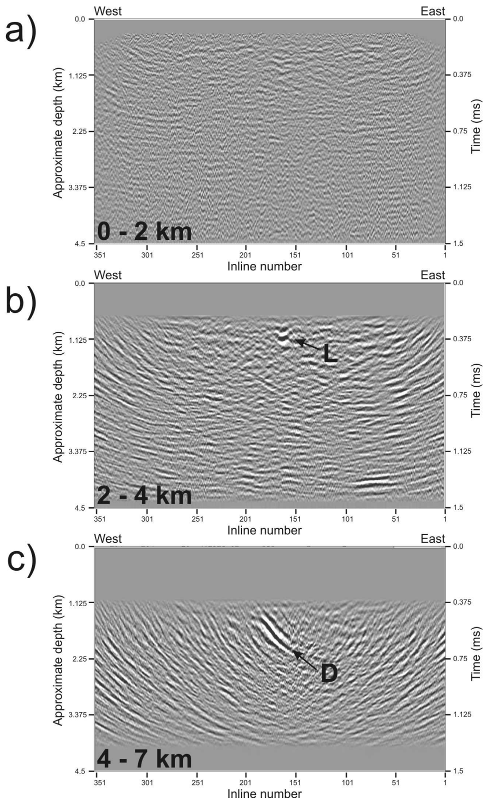

Figure 2: The importance of recording and preserving the data from large source receiver separation is shown on the vertical section extracted from the 3-D stacked volume. The Louvicourt anomaly (marked as L) is best imaged by offsets in the 2-4km range (b). Another, steeper reflection is observed for offset superior to 4 km(c), this reflection was missed by the commercial processing that limited the offsets to 3.5km

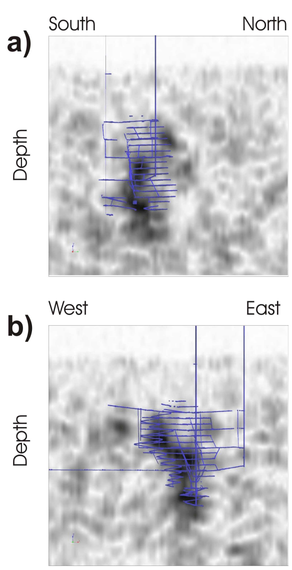

Figure 3: Louvicourt mine viewed by 3-D seismic. What is the cause of the reflection, the mine workings and backfill material or the ore that is still in place?

to geological noise and complex geometries with multiple conductor superposition.

A substantial amount of BHEM data has been collected in the Louvicourt mining camp since 1996 to identify other VMS deposits similar to Louvicourt. Contributing to the recorded BHEM data in this area, is the partly mined out Louvicourt deposit, which can be used as a template to recognise similar bodies but also can prevent the identification of other conductors. An underground loop transmitter has been deployed at Louvicourt to improve data quality and transmitter-conductor coupling. The BHEM modelling geometry is shown in Figure 4 and the plate modeling was performed using a program described by Qian et al. (2002). This program can handle up to 16 modes of eigen-current distribution and it can produce the secondary field on the surface of the plate, which is the opposite of the primary field as theory indicates. This high precision modeling is important in understanding the secondary field behaviors close to a conductive plate. In this section we propose a methodology to remove the effect of known electrical conductors from the BHEM data recorded in the vicinity of the Louvicourt mine and we discuss the use of an underground loop to enhance the EM response from steeply dipping electrical conductors.

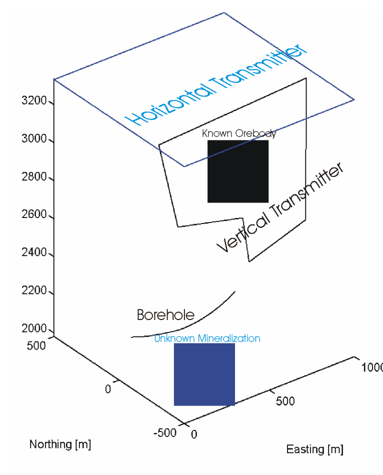

Figure 4: Geometry used for the BHEM modelling study.

BHEM Data Decomposition

Figure 5a shows a typical vertical component BHEM data set collected at the Louvicourt mining camp. There is a dominant long wavelength (> 1 km) background superimposed on a mid-wavelength (~ 100 m) anomaly (arrows on Figure 5). The most likely cause of the long wavelength signal is the Louvicourt orebody, which is located at the borehole collar. The BHEM data shown in Figure 5b has been processed to remove measurements that had anomalous decay values. The long wavelength trend in the data, attributed to the Louvicourt deposit, has been removed using a set of third order polynomials and the filtered BHEM data is shown in Figure 5b. As can be seen, this 100 m wavelength feature displays a fairly clean decay indicating that it is caused by an inductive eddy current system nearby.

This same procedure can be applied to other BHEM data in the study area. All 100 m wavelength features show a rather clean decay. If we mark all 100 m wavelength crossover points in 3D space, they define a clear conductive fairway as shown in Figure 6.

VERTICAL BHEM LOOP

From the 3-D seismic data, we anticipate that potential conductors will have a steep dip toward the East and will be deep, therefore we expect from the modelling results that the BHEM response measured with underground loop excitation will show superior data quality. This geometry was tested in one borehole and the recorded response indicates a large inductive eddy current system. This response can be easily modelled by a plate conductor (marked in red colour in Figure 6). The first eigen-mode time constant for this conductor is 1.5 ms. To match the early time amplitude response, this conductor has to be fairly big (~ 500 X 500 m), moderately conductive (~ 10 S) with a near vertical dip (~ 70^o). This conductor has a strike direction coincident with the red line on Figure 6 and its characteristics and location fit well with the deep seismic reflector identified. This conductivity enhanced fairway appears to be characterised by inhomogeneous conductance distributions; therefore it is impossible to model all the BHEM data using a single homogeneous conductance plate.

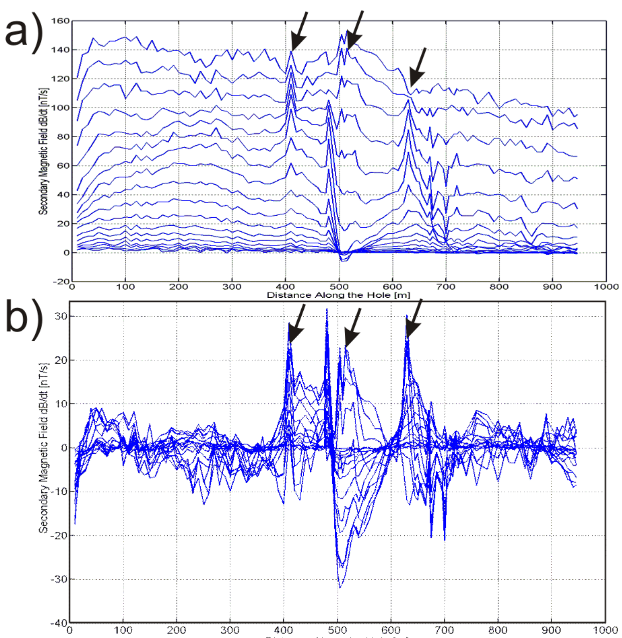

Figure 5: a) Typical vertical component BHEM from the Louvicourt mine area from which anomalous decay have been removed, b) same data as shown in a) after the removal of the long wavelength trend caused by the Louvicourt deposit.

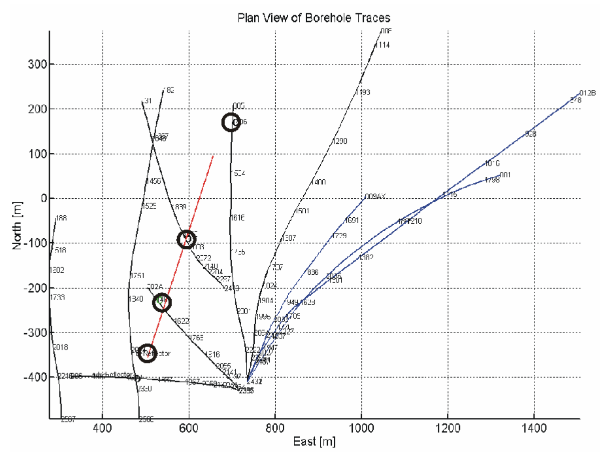

Figure 6: Plan view of the cross-overs identified on the 100 m wavelength responses. The cross-overs, denoted by the red circles, define a clear conductive fairway that corresponds with the orientation of the deep seismic anomaly.

DISCUSSION

On the prestack migrated seismic data volume (Figure 3), the geometry of the Louvicourt deposit is clearly identified. Figure 3 shows that there is a good match between the underground development (indicated in blue on Figure 3), the sulphide in place, and the 3-D seismic data. The origin of the deep reflection that has been identified on the 3-D seismic survey at Louvicourt is not yet completely resolved because key petrophysical measurements that could confirm the acoustic impedance contrast and the electrical conductivity have not been acquired. Given that the location and depth of the seismic anomaly fits with the current geological understanding of the region and the confirmation from the BHEM study that suggest the presence of an extensive conductor with a geometry that is comparable with the seismic reflection, the favoured interpretation is that the electromagnetic and seismic anomaly is caused by an extensive and discontinuous zone of hydrothermal alteration with disseminated sulphides. However the nature and origin of the prominent deep seismic reflection remain unresolved due to the lack of acoustic petrophysical measurements that would confirm the source of the anomaly.

CONCLUSIONS

This study shows that it is possible to enhance the reflections from steeply dipping contacts in 3-D seismic data. In order to obtain a seismic image from steeply dipping reflectors, recordings with large sources-receiver separations are necessary and must be preserved during data processing. By limiting the migration aperture or the offsets during prestack migration the processing time is reduced but target reflections can effectively be destroyed. BHEM measurements acquired in all exploration wells should be filtered to remove contribution from known conductors. Furthermore, the BHEM transmitter loop position must be optimised by using modelling software that can simulate all possible deployment scenarios including the underground development. In cases where the geometry of potential conductors is known by seismic methods, the forward modelling of BHEM can be use to effectively test the possibility of a conductor also being a seismic reflector. This key information can be crucial in the decision to focus exploration in an area where large targets are indicated from the surface seismic data. By measuring the electrical and acoustical properties the approach could become quantitative and even more useful.

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