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Reflected and scattered seismic wavefields from the Halfmile Lake orebody, New Brunswick, Canada

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ABSTRACT

The Halfmile Lake massive sulfide deposit comprises three lenses of various size and shape. Finite-difference modeling and Vertical Seismic Profiling data acquired at Halfmile Lake show that the lenses produce prominent scattered (P-P and S-S) and mode-converted waves (P-S and S-P). Up to now, seismic exploration for massive sulfide deposits has mostly utilized P-wave energy reflected or scattered at mineralized zones (P-P waves). In Vertical Seismic Profiling data, the most prominent amplitudes are reflected energy originating from the Deep lens. The shape and size of this lens and the contrast in physical properties between sulfide and host rocks explain the strong amplitudes. In comparison, the wavefield scattered at the smaller Upper and Lower sulfide lenses has smaller amplitude. Our results show that mode-converted and S-S waves could potentially help the detection and location of deep massive sulfide deposits and provide additional information on the structure and stratigraphy of the deep geological framework.

INTRODUCTION

Results recently obtained at various mining camps demonstrate that seismic methods are increasingly becoming relevant to the deep exploration of massive sulfide deposits (see Eaton et al., 2003 for a summary). Up to now, seismic exploration for massive sulfide deposits has largely utilized P-wave energy reflected or scattered at mineralized zones. However, elastic wave theory and finite-difference modeling predict that base metal deposits can convert a significant part of the incident seismic energy, producing converted waves potentially useful for mining exploration (Bohlen et al., 2003). In practice, converted waves are not considered in mining exploration because they are rarely recognized or observed in the seismic data. Here, we present prominent scattered (P-P and S-S) and mode-converted waves (P-S and S-P) originating from a deep massive sulfide lens at Halfmile Lake, New Brunswick, Canada. The various wave types were recorded on Vertical Seismic Profiling (VSP) data acquired in a borehole intersecting the deepest sulfide lens (Figure 1). We also show results from finite-difference simulation which provide further insights on the scattering/reflective characteristics of the Halfmile Lake orebody. This model-based assessment of the orebody signature on seismic data can help to determine data processing and imaging strategies useful for mineral exploration.

GEOLOGICAL SETTING

The Halfmile Lake deposit is located in the Bathurst mining district in New Brunswick, Canada. The deposit is part of the Middle Ordovician Tetagouche Group, a bimodal volcanic and sedimentary sequence hosting several Zn-Pb-Cu deposits within a sub-circular area 50 km in diameter (McCutcheon, 1992). The Halfmile Lake volcanogenic massive sulfide deposit, with 25 million tons of total sulfide content, is the largest undeveloped deposit within the mining district. Mineralization consists of pyrrhotite-rich breccia-matrix sulfides and pyrite-pyrrhotite-rich layered sulfides distributed in a laterally continuous sheet. The deposit is hosted by a sequence of felsic volcanic rocks, interbedded sedimentary epiclastic rocks, intrusive subvolcanic porphyries, and mafic volcanic rocks. Folding of the stratigraphic sequence placed the deposit on the south limb of an overturned antiform (Figure 2), where the average dip is 45o to the north-northwest. However, the sulfide sheet is irregular and steepens locally due to multiple periods of fold deformation. Significant concentrations of sulfides occur in three zones (Upper, Lower, and Deep zones on Figure 2) where thicknesses reach 50m.

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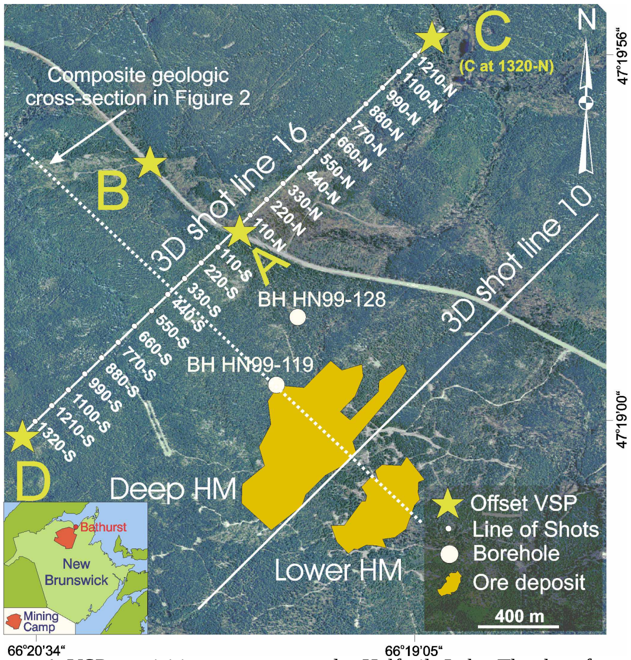

Figure 1: VSP acquisition geometry used at Halfmile Lake. The shots for the offset VSP are indicated by yellow stars. Recording depths in borehole HN99-128 ranged between 265m and 1300m. The location of the composite geological cross-section in Figure 2 is also shown.

OREBODY SIGNATURE ON VSP DATA

The VSP data at Halfmile Lake was acquired after the discovery of the Deep massive sulfide lens using 3D seismic methods (Matthews, 2002). The VSP acquisition geometry (Figure 1) was based on traveltime modeling using known positions of the Lower and Deep sulfide lenses and the assumed area of sub-vertical stratigraphy connecting them. The shot locations were optimized to provide maximum scattered P-wave energy from the deposit for given receiver positions in the borehole. The survey comprised four source locations (sites A, B, C, and D on Figure 1) at which a total of 104 shots were fired (26 at each site). Receiver depths in the recording borehole (HN99-128) ranged between 265m and 1300m, with a 5m interval. At surface, borehole HN99-128 is located approximately 600m north of the deep lens. It deviates from the vertical by 10o at shallow depths and by 18o at 1336.5m where it intersects the Deep lens. The slim downhole receiver unit comprised eight levels with three orthogonal 28 Hz geophones. The source consisted of three 227 g pentolite boosters placed in 8-m deep shot holes, which were filled with drilling dust up to the surface. The sampling interval was 0.5 ms with a total record length of 2.1s. The main objective of the offset VSP survey was to provide images of the vertical extent of the dipping sulfide sheet at specific locations. More details about the Halfmile Lake VSP data can be found in Bellefleur et al. (2004).

The field records are dominated by strong downgoing P- and S-waves on all offset VSPs. The upgoing wavefield is relatively weak and characterized only by a few events originating from the Deep sulfide lens near the bottom of the borehole. Therefore, processing was critical to reveal waves scattered from the orebody. The processing sequence followed a conventional VSP processing approach. After processing, the two horizontal components are transformed into radial and transverse components. The radial component points towards the shot location whereas the transverse component is orthogonal to that direction.

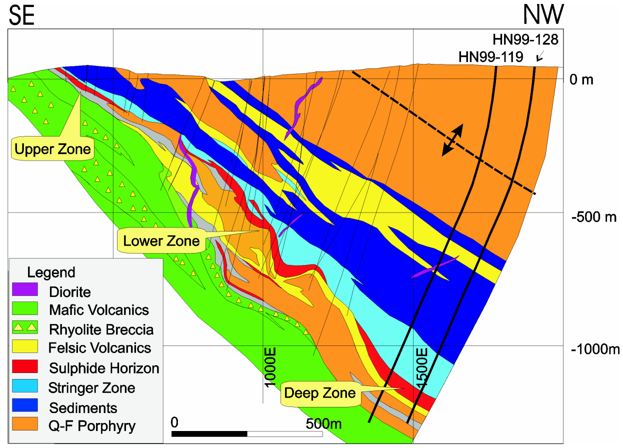

Figure 2 Composite geological cross-section through Halfmile Lake deposit based on projection of drilling results to a southeast-northwest section. Borehole HN99-128 was used for the VSP survey. See Figure 1 for surface location of the cross-section.

Mode-converted waves are frequently observed and analyzed in offset VSP data acquired in sedimentary basins but seldom observed or reported on seismic data recorded over or near known sulfide deposits in crystalline rocks. Elastic wave theory and finite-difference modeling predict strong amplitudes for converted waves originating from a massive sulfide orebody (Bohlen et al., 2003). The processed downhole seismic data from Halfmile Lake show prominent scattered and converted P- and S-waves on all three components (see P-P, P-S, S-S, and S-P events on Figure 3). Such complex scattering from massive sulfide ore has not been observed previously in VSP data. Most of the scattered and converted waves originate from the deep sulfide lens intersected at the bottom of the borehole. Scattered P-waves are particularly continuous on the vertical component from VSP site B (Figure 3). Radial and transverse components are generally characterized by scattered S-waves and P-S and S-P converted waves, but all three wave modes are only observed simultaneously on the radial component from site B (Figure 3). It is important to note that S-wave scattering or S-P converted waves can be expected only if a downgoing S-wave generated at or near the source reaches the orebody.

FINITE-DIFFERENCE MODELING

Numerical simulations based on the 3D elastic finite-difference method are used to provide further insights on the relationship between seismic wavefield characteristics, physical rock properties, and geology of the subsurface. More specifically, the numerical modeling study allows a realistic model-based

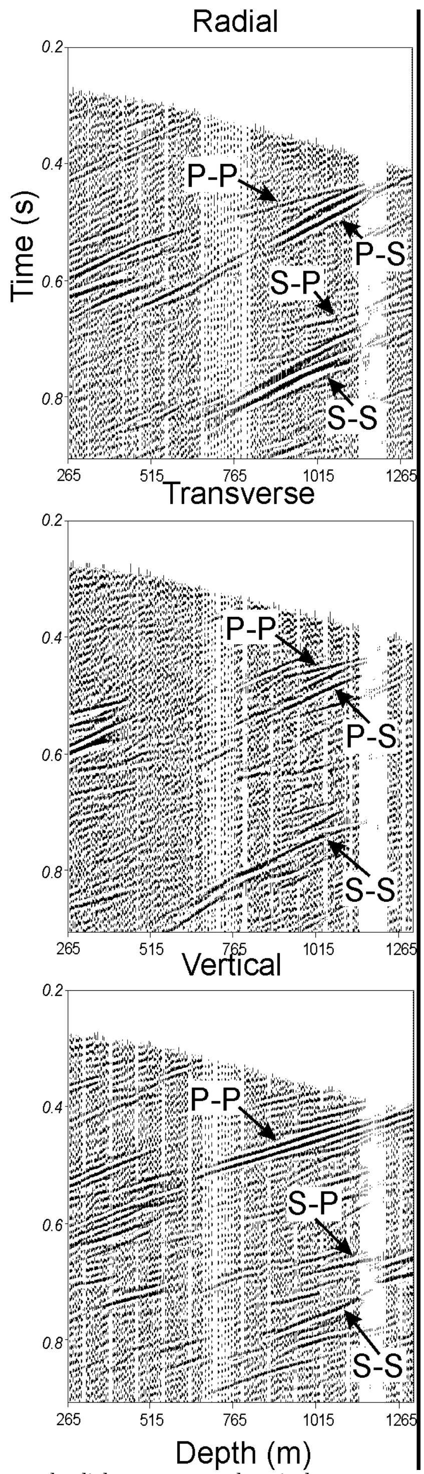

Figure 3: processed radial, transverse and vertical components from shot site B. Several events are annotated: P-P (incident P-wave, scattered P-wave), P-S (incident p-wave, scattered S-wave), S-P (incident S-wave, scattered P-wave), and S-S (incident S-wave, scattered S-wave).

determination of seismic signature of the Halfmile Lake orebody that can be used to improve survey design, data processing and imaging procedures. Here, we show simulation results from a 2D geological cross-section that includes the deposit. The location of this section is shown in Figure 1. The 2D model is constructed from geological information obtained from surface mapping, boreholes and physical rock properties relevant to seismic wave propagation (density, P- and S-wave velocities).

Physical Rock Properties and Model

The first seismic surveys conducted at Halfmile Lake were combined with physical rock property measurements to assess the P-wave reflectivity of the massive sulfides and the surrounding geological units (Salisbury et al., 2000). As part of the TGI-3 initiative, S-wave velocities were measured on rock samples from the Bathurst mining camp. S-wave velocities were measured on many samples previously used for P-wave velocity. Shear-wave velocities are critical to understand mode-converted (P-S or S-P conversion) and shear-wave reflectivity processes between the host rocks and massive sulfide mineralization. S-wave velocities are also essential parameters for FD simulation. Physical rock properties at Halfmile Lake show that host rocks are generally weakly reflective or seismically transparent; whereas, the ore should produce a strong P- and S-wave response (Salisbury et al., 2000). Similar conclusions were obtained from velocity and density logs measured in two boreholes intersecting the Lower and Deep lenses.

The model used for finite-difference modeling is based on the 2D geological composite cross-section shown in Figure 2. This section was slightly extended laterally and vertically, and has a final size of 5km by 2km. Geological information is lacking at depth and could not constrain this part of the model. Therefore, the deeper part of the model assumed continuity of the structures and lithlogical contacts shown in Figure 2. The 2D model was sampled every half meter for a total of 40 millions points. Each point is defined by a P- and S-wave velocity and density. The model does not include attenuation properties. A 3D model would have been more representative of the local geology. Unfortunately, there is no sufficient geological information available in this area to allow a realistic construction of such model.

Modeling Results

Figure 4 shows simulation of shear wave propagation at Halfmile lake for a source located 1km down-dip of the Deep massive sulfide lens. Snapshots of the wavefields at 0.300s and 0.550s are shown on this figure. The snapshot at 0.3s shows the shear wavefront and seismic events occurring ahead of the wavefront. These events result from P-to-S wave-mode conversion occurring at the massive sulfide lenses. The wave-mode conversion occurs ahead of the Shear wavefront because compressional waves travel faster than the S-waves. The snapshot at 0.550s shows strong reflections from the deep zone. These reflections are stronger than the P-to-S converted waves and could be more easily detected at surface, provided that they

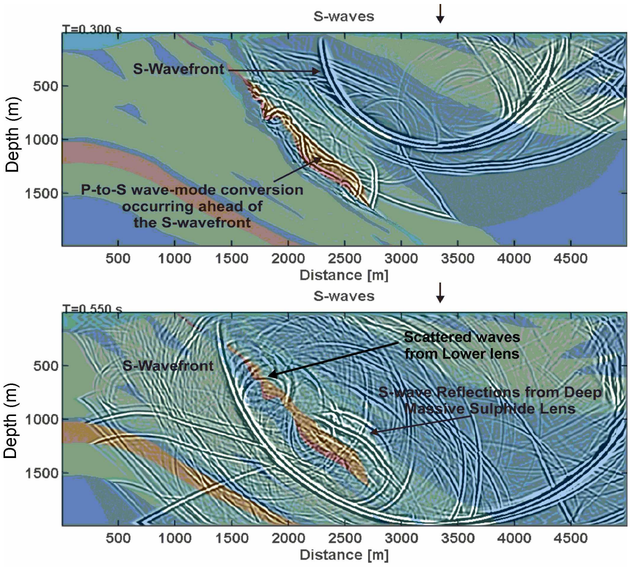

Figure 4: Simulation of shear wave propagation at Halfmile lake. The wavefields at 0.300s (top) and 0.550s (bottom) are shown. The arrow indicates the shot location. The snapshot at at 0.3s shows P-S wave-mode conversion occurring ahead of the S-wavefront whereas the snapshot at 0.550s shows strong reflections from the deep zone. The three sulfide lenses are show in red in the background.

have the right direction of propagation and polarization to be recorded with surface geophones. Both the P-to-S and S-wave reflections are not conventionally utilized in seismic for mineral exploration.

Finite-difference modeling of orebodies of various shapes and compositions demonstrates that scattering directivity is essentially controlled by the shape of the deposit (Bohlen et al., 2003). At Halfmile Lake, this shape factor influences the seismic wavefield recorded in VSP or surface data. The NNW-dipping Deep sulfide lens has a large surface and behaves like a small specular reflector. Downgoing waves traveling from the down-dip direction will likely produce stronger amplitude at receivers also located down-dip. The receiver location with maximum energy varies for each shot location. The VSP borehole, located mostly down-dip of the Deep lens is well positioned to record the four wave modes produced by incident waves from VSP site B. In comparison, the Lower and Upper sulfide lenses are much smaller. They scatter the seismic energy back to the surface. An example of such scattering is shown on the snapshot at 0.55s. According to results obtained for other simulations, the scattering response tends to be relatively independent of the shot location (excluding time shifts). Therefore, different imaging strategies are required to detect the smaller and larger ore deposits.

CONCLUSIONS

The Halfmile Lake deposit includes reflective massive sulfide lenses of known geometry, embedded in a low reflectivity, steeply-dipping hosting stratigraphy. The physical rock and sulfide properties in this environment are favorable to producing prominent scattered/reflected and mode-converted waves (P-P, P-S, S-S, and S-P) in downhole or surface seismic data. In the VSP data, the most prominent amplitudes are reflected energy originating from the Deep lens. The shape and size of this lens and the contrast in physical properties between sulfide and host rocks explain the strong amplitudes. In comparison, the wavefield scattered at the smaller Upper and Lower sulfide lenses has smaller amplitude. The seismic signature of these lenses tends to be less dependent on the source location (excluding time shifts). Our results show that mode-converted and S-S wave could potentially help the detection and location of deep massive sulfide deposits and provide additional information on the structure and stratigraphy of the deep geological framework.

REFERENCES

Bellefleur, G., Müller, C., Snyder, D., and Matthews, L., 2004, Downhole seismic imaging of a massive sulfide orebody with mode-converted waves, Halfmile Lake, New Brunswick, Canada. Geophysics, 69, 318–329,

Bohlen, T., Müller, C., and Milkereit, B., 2003, Elastic wave scattering from massive sulfide orebodies: on the role of composition and shape, in Milkereit, B., Eaton, D., and Salisbury, M., Eds., Hardrock Seismic Exploration, Soc. Expl. Geophys., 70-89.

Eaton, D.W, Milkereit, B., and Salisbury, M., 2003, Seismic methods for deep mineral exploration: Mature technologies adapted to new targets: The Leading Edge, 22, 580-585.

Matthews, L., 2002, Base metal exploration: Looking deeper and adding value with seismic data: CSEG Recorder, 27, 37-43.

McCutcheon, S.R., 1992, Base-metal deposits of the Bathurst Newcastle district: characteristics and depositional models: Exploration and Mining Geology, 1, 105-119.

Salisbury, M., Milkereit, B., Ascough, G., Adair, R., Matthews, L., Schmitt, D.R., Mwenifumbo, J., Eaton, D.W., and Wu, J., 2000, Physical properties and seismic imaging of massive sulfides: Geophysics, 65, 1882-1889.