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

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Introduction

Results recently obtained at various mining camps demonstrate that seismic methods are increasingly becoming relevant to the deep exploration of massive sulphide deposits (see Eaton et al., 2003 for a summary). Up to now, seismic exploration for massive sulphide 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 sulphide lens at Halfmile Lake, New Brunswick, Canada (Figure 1). The various wave types were recorded on Vertical Seismic Profiling (VSP) data acquired in a borehole intersecting the deepest sulphide lens (Figure 2). 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.

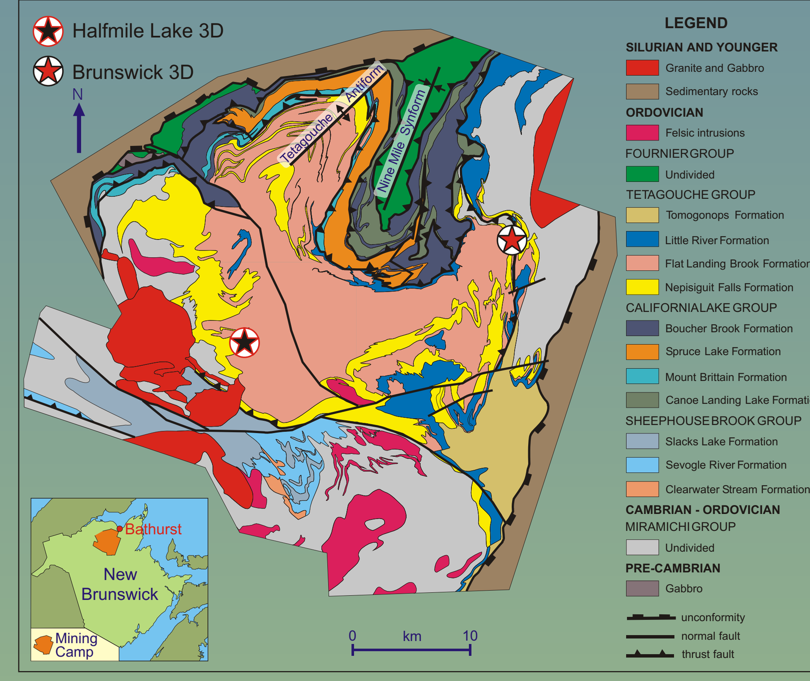

Figure 1 Geology map of Bathurst Mining camp, modified from Thomas et al. (2000). The Halfmile Lake deposit is located in the southwest part of the camp (black star)

Geological Setting

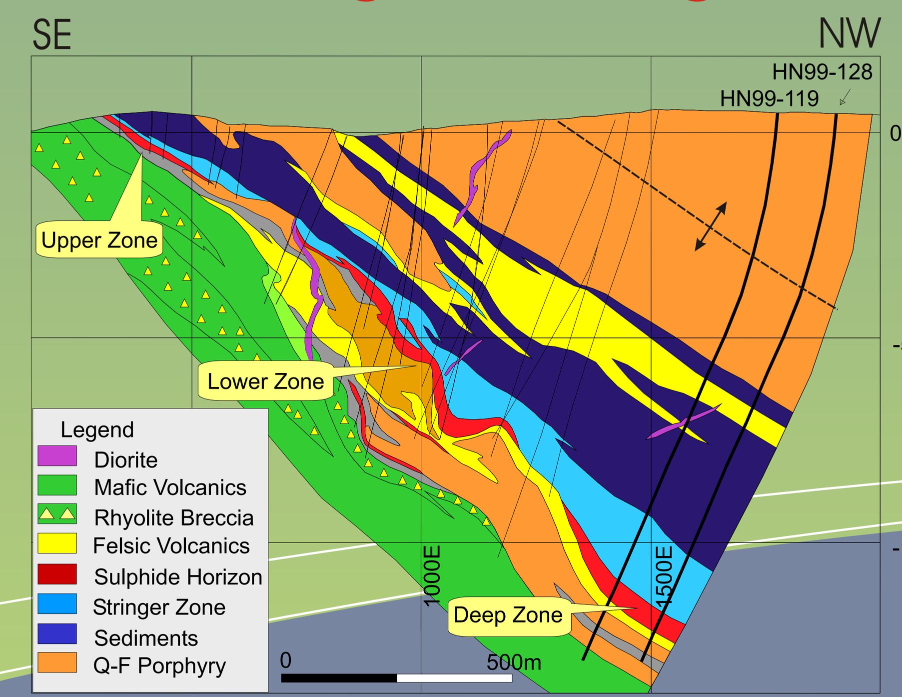

Figure 2 Composite geological cross-section through the Halfmile Lake volcanogenic massive sulphide deposit based on projection of drilling results to a southeast-northwest section. The Halfmile Lake deposit, with 25 million tons of total sulphide content, is the largest undeveloped deposit within the mining district. Mineralization consists of pyrrhotite-rich breccia-matrix sulfides and pyrite-pyrrhotite-rich layered sulphides 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, where the average dip is 45° to the north-northwest. However, the sulphide sheets are irregular and steepen locally due to multiple periods of fold deformation. Significant concentrations of sulphides occur in three zones (upper, lower, and deep zones) where thicknesses reach 50m. P-wave amplitude anomalies on a 3-D seismic survey led to the discovery of the deep zone (Matthews, 2002, see also Figure 7). Borehole HN99-128 was used for the VSP survey. See Figure 6 for surface location of the cross-section.

Borehole Logging

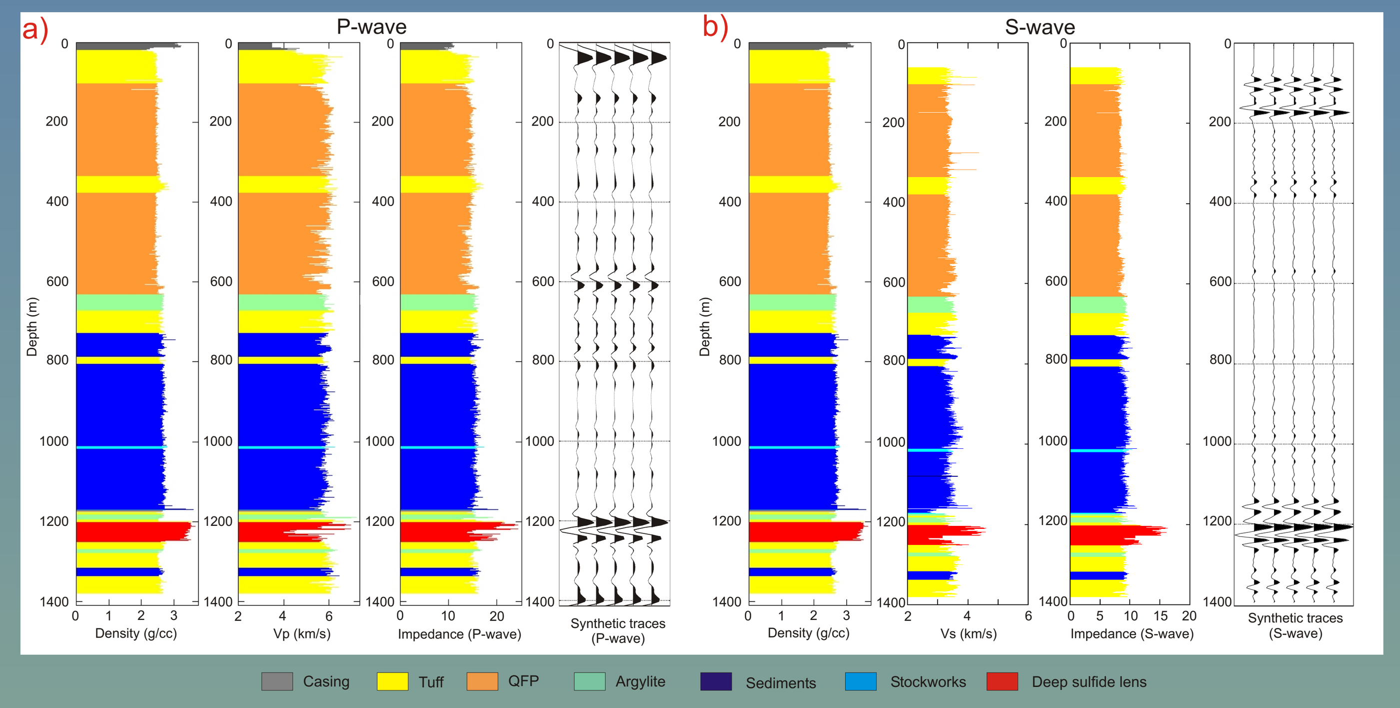

Figure 3 a) Density, P-wave velocity, acoustic impedance and synthetic traces for borehole HN-99-119. The synthetic traces for vertical incidence were calculated by convolving the reflectivity series with a 50Hz Ricker wavelet. A prominent reflection is expected from the deep sulphide lens at1200m whereas host rocks are generally weakly reflective. A weaker reflection at 600m does not correspond directly with a lithological change. b) A strong S-wave reflection is also expected from the deep sulphide lens.

Two-dimensional Simulation of Seismic Wave Propagation

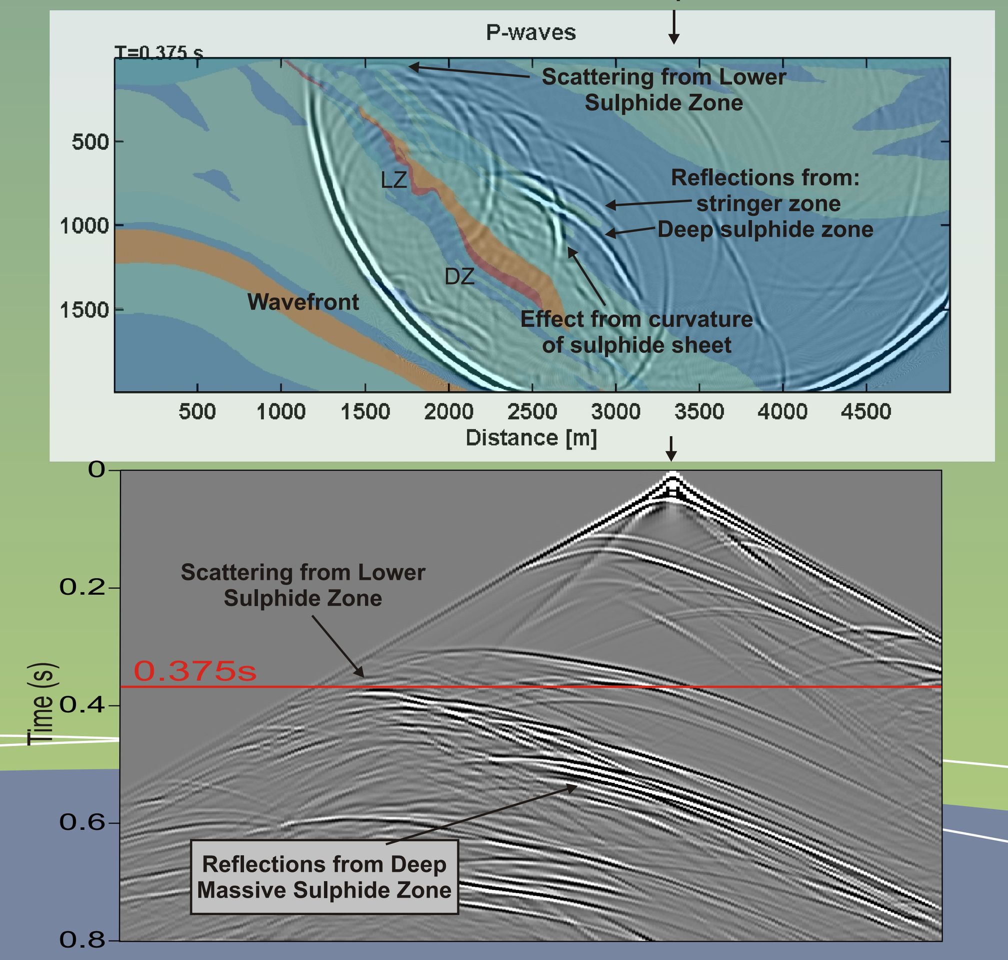

Figure 4 Finite-difference modeling of P-wave propagation from a specific shot location at Halfmile Lake (top). The 2D geological model shown in the background comprises 40 million points with defined physical rock property information (density, P- and S-wave velocity). The massive sulphide lenses are shown in red (LZ and DZ).The Finite-difference modeling required approximately 15 hours on a 40 CPU Linux cluster. The compressional wavefield after 0.375s of propagation (overlay with transparency on top of the geological model) shows strong reflections from the deep sulphide zone (DZ) propagating toward the surface in the downdip direction. This reflection is preceded by a weaker one from the top of the stringer zone (orange in the model). Effects from the curvature of the deep sulphide lens are also observed. At the same time, weaker scattered waves from the lower sulphide zone (LZ) starts to arrive at surface where they would hopefully be recorded with geophones. The corresponding seismogram for this simulation is shown in the lower figure. The red line shows seismic arrivals at surface at 0.375s. Stronger reflections from the deep zone arrive at latter time. This simulation highlights the different response expected from the lower and deep lens (e.g., scattering vs reflection).

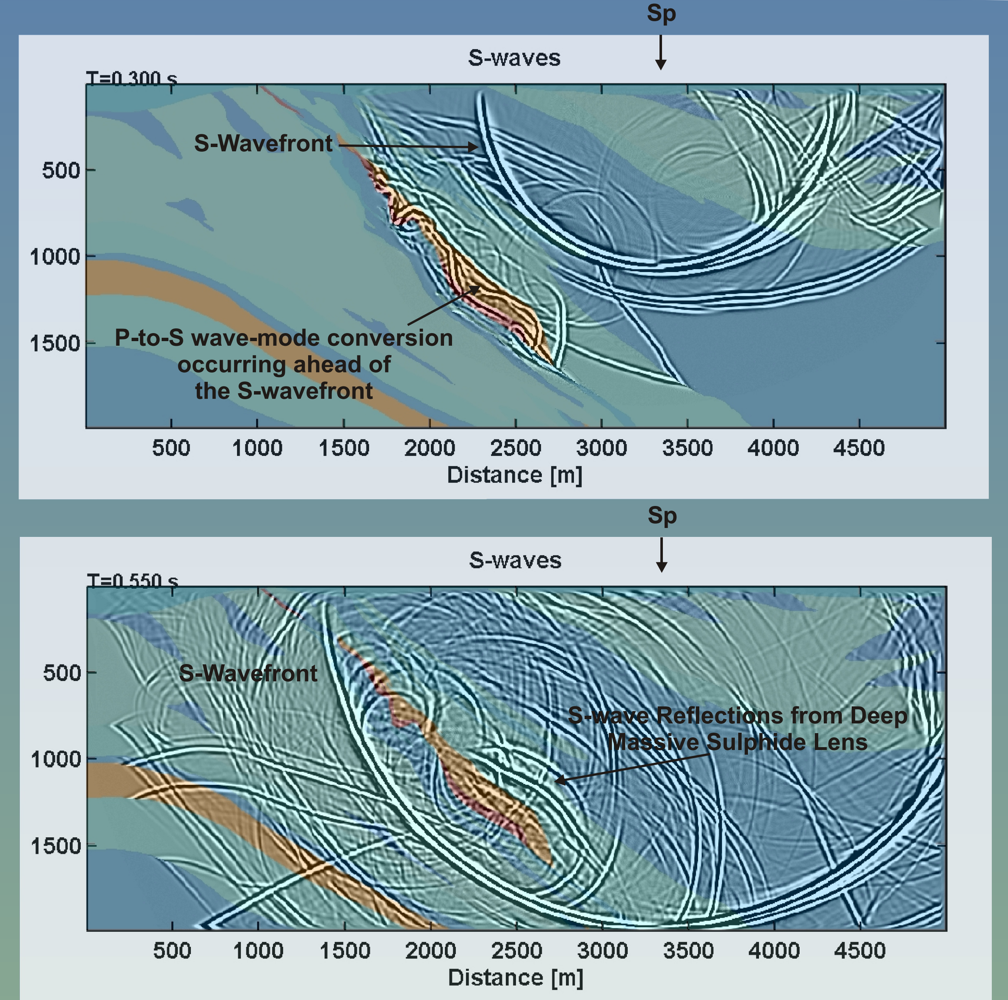

Figure 5 Simulation of shear wave propagation from a specific shot location at Halfmile lake. The wavefields at 0.300s (top) and 0.550s (bottom) are shown. The gain on these two figures was set to highlight the complexity of the wavefield. The arrow indicates the shot location. The three sulphide lenses are show in red in the background image. The snapshot at 0.3s shows P-S wave-mode conversion occurring ahead of the S-wavefront at the deep massive sulphide lens (the downgoing P-wave gets converted to an S-wave at that interface). The compressional waves travel faster than the shear waves and get converted before the shear wavefront reaches the massive sulphide lenses. The snapshot at 0.550s shows strong S-wave reflectivity from the deep zone and weaker scattering from the lower zone. The stringer zone also produced a strong S-wave reflection before the massive sulphide reflection. The strength of this reflection may not be totally representative of the reality as only a limited number of samples with physical rock property measurements was available for the stringer zone (same for P-wave simulation shown in Figure 4). These samples were characterized by velocity and density values close to those measured on massive sulphide samples. In general, the S-wave reflections are stronger than the P-to-S converted waves and could be possibly easier to detected at surface. It is important to note that all wave modes shown in P-wave and S-wave simulations can potentially be recorded at surface.

3D & VSP Survey Geometry

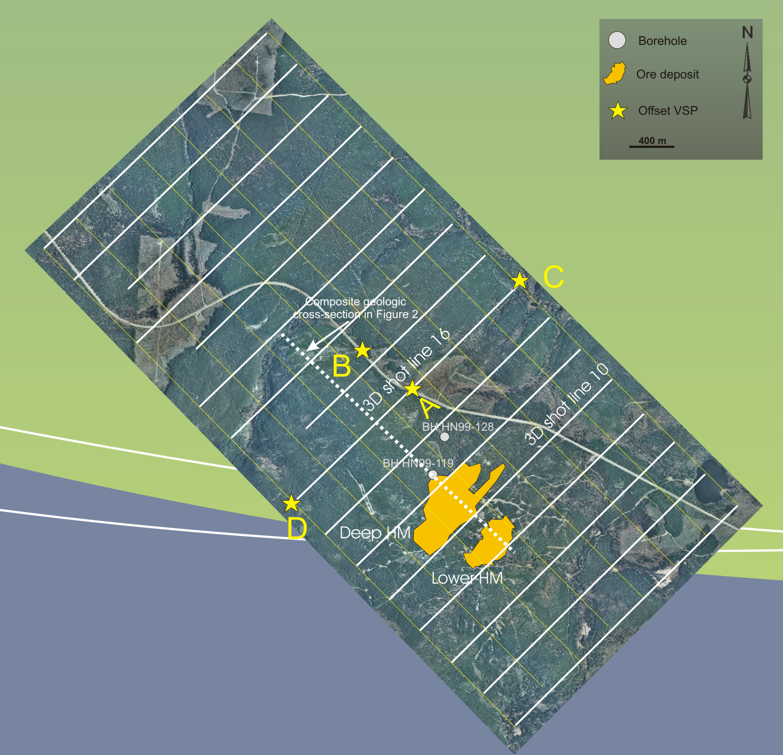

Figure 6 3D and VSP acquisition geometry at Halfmile Lake. The shots for the offset VSP are indicated by yellow stars. Recording depths in borehole HN99-128 ranged between 265m and 1300m. The location of the composite geological cross-section in Figure 2 is also shown. Inline from the 3D seismic volume shown in Figure 7 is at the same location as this cross-section but extends all the way across the 3D grid.

P-wave Amplitude Anomaly on the 3D Data

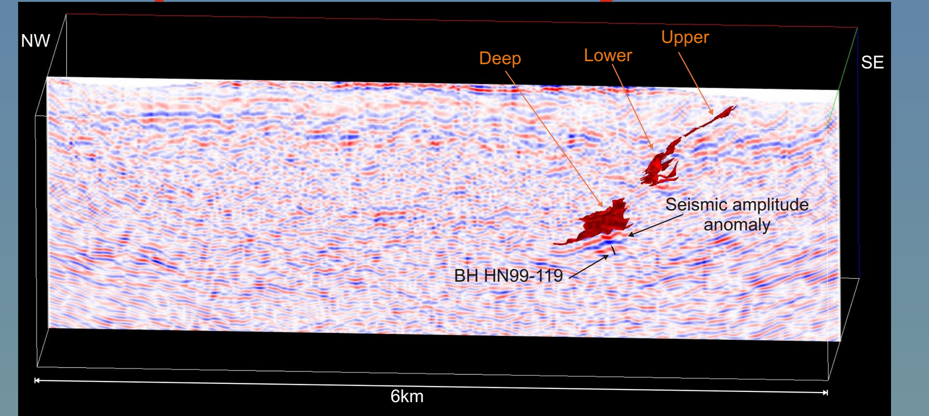

Figure 7 Inline from the 3D prestack migrated volume showing the P-wave amplitude anomaly that led to the discovery of the deep sulphide zone. The migration algorithm used to generate the 3D volume assumed P-wave reflectivity only (e.g. P-P). The position of the upper, lower and deep zones (from geological modeling) are shown in red.

Orebody Response on the VSP data

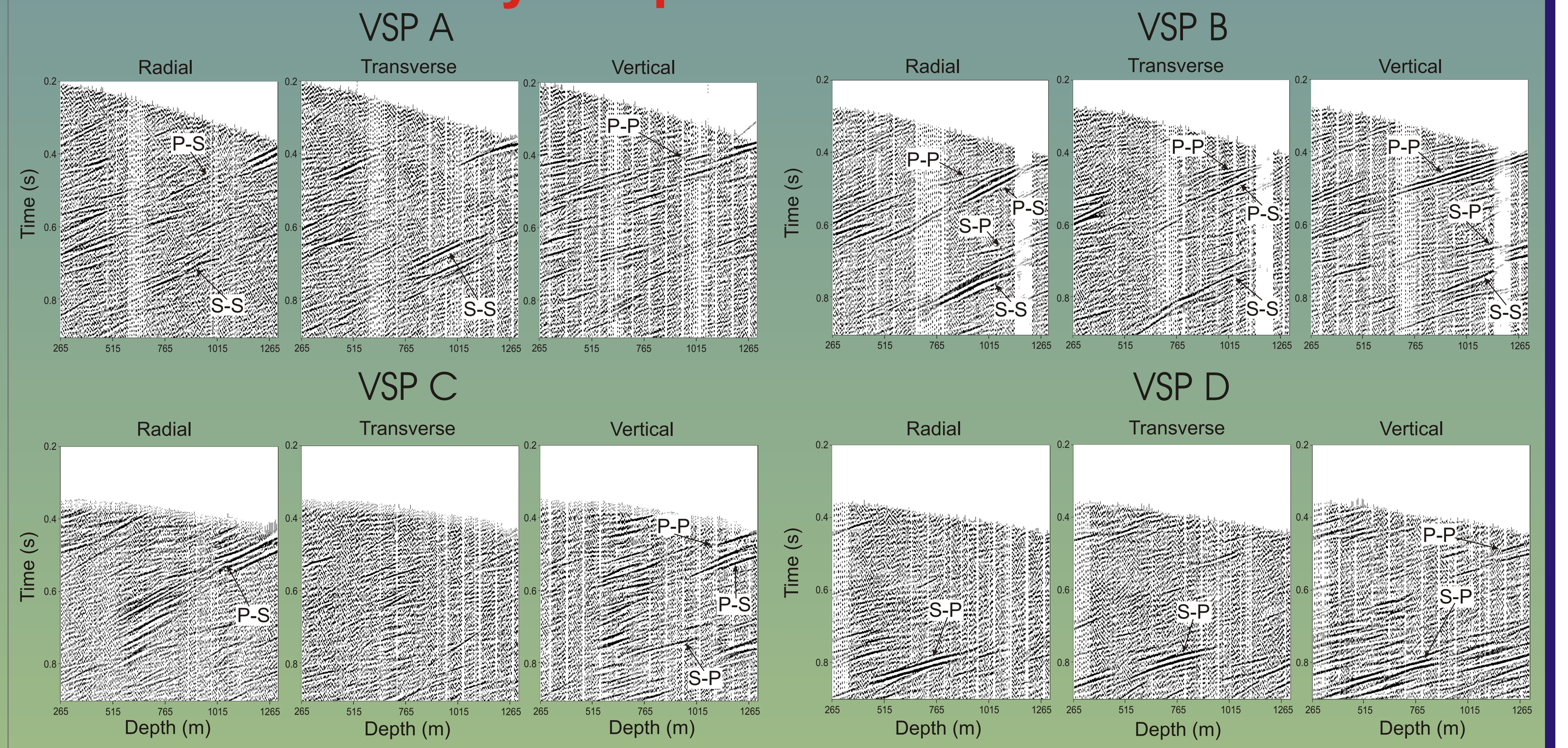

Figure 8 Processed radial, transverse and vertical components from VSP shot sites A, B, C, and D. Important processing steps included removal of the downgoing waves and rotation of the 3-component data. The radial components point horizontally towards the shot location whereas the transverse components are orthogonal to that direction (also in the horizontal plane). An AGC was applied for display purposes. The processed VSP data show prominent scattered and converted P- and S-waves on all three components from all VSP sites. 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). Most of the scattered and converted waves originate from the deep sulphide lens intersected at the bottom of the borehole. Scattered P-waves are particularly continuous on the vertical component from VSP site B. 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. 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. Only VSP site C showed weak downgoing S-waves which were likely insufficient to produce strong S-S or S-P orebody scattering.

Summary

The Halfmile Lake deposit includes reflective massive sulphide lenses of known geometry, embedded in a low reflectivity, steeply-dipping hosting stratigraphy. The physical rock and sulphide 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 sulphide and host rocks explain the strong amplitudes. In comparison, the wavefield scattered at the smaller upper and lower sulphide lenses is characterized by smaller amplitude. Our results show that mode-converted and S-S wave could potentially help the detection and location of deep massive sulphide deposits and provide additional information on the structure and stratigraphy of the deep geological framework.

References

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, pp. 580-585.

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

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

Thomas, M.D., Walker, J.A., Keating, P., Shives, R., Kiss, F., And Goodfellow, W.D. 2000, Geophysical Atlas of Massive SulphideSignatures, Bathurst Mining Camp, New Brunswick: Geological Survey of Canada Open File 3887.