Downhole Seismic Imaging for Mineral Exploration

Acquisition of downhole seismic data at Halfmile Lake, New Brunswick

Report for the DSI Consortium

By

Gilles Bellefleur and Christof Müller

Geological Survey of Canada
Continental Geoscience Division
Seismology and Electromagnetism Section
615 Booth Street,
Ottawa, Ontario
K1A 0E9

August 23^{rd} 2001

Contents

1 Abstract

Downhole seismic data were acquired at Halfmile Lake, NB, in July 2001. The survey comprised two parts. Part A consisted of 4 offset VSPs with 26 shots fired at each source location. Receivers were placed between 265m and 1300m in the recording borehole. For part B of the survey, shots were distributed at 23 stations spread along a 2.5 km line. Receiver positions ranged between 585m and 815m depth in the borehole. Design for both parts was based on traveltime modeling results calculated from known massive sulphide lenses (Lower and Deep), and the area of sub-vertical stratigraphy connecting these lenses. The acquisition parameters were selected after a test survey done at Halfmile Lake in June 2001.

Part A: Direct P- and S-wave arrivals are observed on the raw offset VSP datasets. After preliminary processing (bandpass filtering, rotation and AGC), several reflections originating from the Deep Halfmile sulphide lens can be identified. P- and S-waves reflected from the Deep lens are observed on data from shot site B. The radial component from shot site C shows a P-to-S converted reflection.

Part B: Data quality is good also for the line of shots. The vertical component from several shot locations contains reflections which are clearly visible on the raw data.

Clear reflections are observed on both offset VSP and the line of shots datasets. We expect the data quality to significantly increase after further processing (future work).

2 Introduction

This report presents the downhole seismic data acquired at the Halfmile Lake property near Bathurst, New Brunswick in July 2001. It also shows results obtained during the different preparation phases of the survey. The Halfmile Lake property comprises three sulphide lenses which compared to the host rocks, have a high acoustic impedance (Salisbury et al., 2000). The objectives of Halfmile Lake VSP survey were three-fold:

1) Get a clear seismic image from known massive sulphide lenses using an offset VSP acquisition geometry.

2) Image an area of sub-vertical stratigraphy between the Lower and Deep Halfmile sulphide lenses. This area of sub-vertical stratigraphy is an exploration target for Noranda.

3) Gather a dataset to test imaging strategies that can be employed at other massive

sulphide exploration sites.

We show un-processed and slightly processed data in this report. These preliminary results show good potential to accomplish the objectives mentioned above. Reflections from the Deep Halfmile sulphide lens can already be observed on the offset VSP. These reflections and others, not visible at this stage, will become more prominent after full processing (future work).

3 Survey Design

The acquisition geometry used at Halfmile Lake is outlined in Figure 1. This design was based on traveltime modeling results calculated from known sulphide lenses (Lower and Deep), and the area of sub-vertical stratigraphy connecting these lenses (see Bellefleur et al. 2001). The survey comprised two parts. Part A used 4 source locations (marked A,B, C and D on Figure 1) at which a total of 104 shots were fired (26 at each site). For part B of the survey, shots were placed along one of the shot lines used during an earlier 3D seismic survey. At each station along this line (marked 1320S to 1210N on Figure 1), three shots were fired for receiver positions ranging between 585m and 815m.

For both parts of the survey, borehole HN99-128 was chosen as the recording hole because it is the only hole that remained open over a long period of time in the Halfmile area. This borehole intersects the Deep Halfmile sulphide lens at a depth of 1336.5m.

4 Test survey

A test survey was conducted on June 22 (2001) at Halfmile Lake. Borehole HN99-124a (Figure 1) was used as the recording borehole. This HQ borehole (hole diameter of 3.75 in) is shallow (145m). Borehole HN99-128 was preserved intact for the real survey. The top part (0-580m) of borehole HN99-128 is of HQ diameter HQ whereas the lower part (580-1340m) is NQ diameter (3 in). Coupling problems in HQ diameter holes were identified in a 3D-VSP survey at Halfmile Lake (Kay and Perron, 1999). Objectives of the test survey were 1) to determine the number of boosters which would provide good signal and 2) to check the response of the tool in the HQ size borehole. The test survey was a good opportunity to test the 4-level receiver array recently purchased from Vibrometrics and received in May 2001. Two shot sites were used for the test survey. Site A (yellow star on Figure 1) is located next to Otter Brook Road while test site B (grey star on Figure 1) is 400m west of that road. Shot holes were drilled at the two shot sites (25 at each site) with a Furukawa drill. The shot holes were 8m deep and had a diameter of 3.5 inch. Some of the shot holes

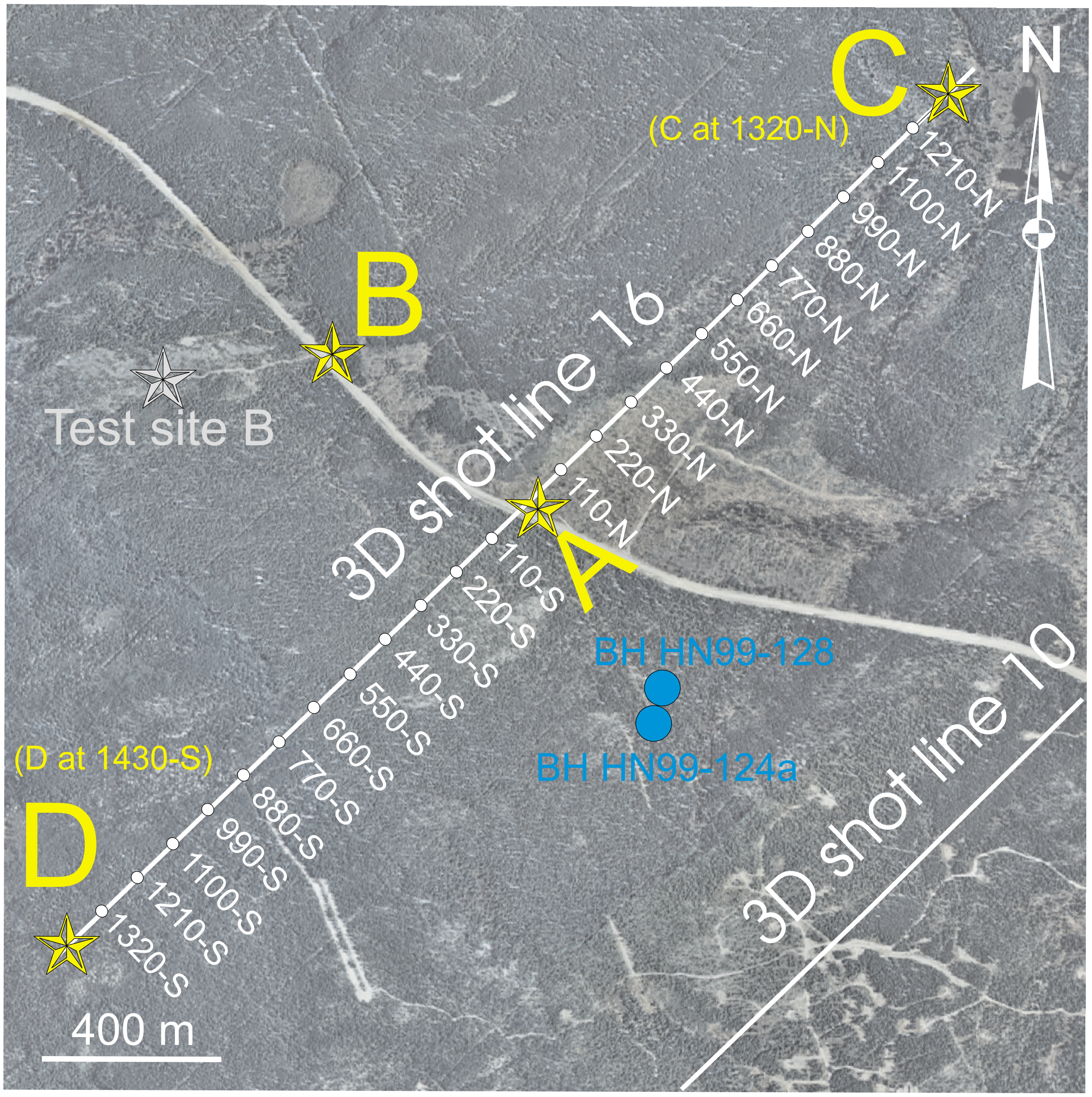

Figure 1: Acquisition geometry used at Halfmile Lake. The survey was divided into 2 parts. The first part consisted of 4 offset VSPs. The shots for this part of the survey are indicated with the yellow stars. Recording depths ranged between 265m and 1300m. For the second part of the survey, shots were distributed along a line (3D shot line 16) between stations 1320S and 1210N. Three shots were fired at each station. Recording depths ranged from 585m to 815m. Also indicated on that figure is the test site B used during the test survey (grey star) and position of the recording boreholes (HN99-124a and HN99-128).

drilled at site A (21) were used in the real survey. Unfortunately, the drill could not access the other shot points proposed in the survey design (sites C and D on figure 1). These sites remained un-tested before the survey.

A total of 12 shots were fired during the test, with 1 to 3 pentholite boosters (227g/booster). Wet vs. dry hole conditions were also tested. The bottom of the shot holes were filled with water for wet conditions. For both conditions, the shot holes were filled to surface with drilling dust and sand. Wet hole conditions provided slightly better results (not shown) but not enough to justify the cost of getting a water tanker and setting water lines to the shot sites for the complete survey. Shot gathers from test site B with 2 and 3 boosters are shown in Figure 2. Clearly, 2 boosters did not provide the data quality required for that survey while 3 boosters were sufficient. This figure also shows that the new 4-level tool is less noisy than the old 4-level receivers. However, the horizontal components of the new 4-level tool show a long coda after the first arrivals, here after referred to as "ringing". Data obtained using 3 boosters at site A (Figure 3) do not show as significant ringing on the horizontal components of the new tool. Part of the strong ringing in Figure 2 is most likely introduced by reverberation within the small hill on top of which test site B was located. Thus, it was decided to move this shot site close to the road for the real survey. Data from that new site (Figure 7) do not show as significant ringing. Other causes for ringing include coupling with the borehole and, most likely, the response of the new receiver tool.

5 Field Acquisition

Because of highly fractured rocks near the surface and the limited supplies of water in the area, it was decided to pre-load the shot holes with 3 boosters (3x227g) and primacord as soon as they were drilled. With this approach, we avoided potential collapse and loss of shot holes prior to or during the survey. The shot holes were drilled and loaded 1 week prior to the survey. Seismic caps, necessary to detonate the primacord, were only attached immediately prior to firing. Pre-loading of the shot holes does not offer the flexibility of re-loading the holes during the survey, especially in case of misfire. However, this approach speeds up the acquisition of data as shooters saved the time otherwise required for loading. Only 3.5 days were required to collect the data.

Table 1 summarizes the recording parameters and acquisition equipment used for both parts of the survey. Equipment and recording parameters were similar to those used in previous DSI surveys. Only minor adjustments were made to take the acquisition geometry into account. Each receiver level was equipped with a stabilization ring (see Perron, 2000) to increase coupling with the borehole. Long clamping arms (80mm) were used in the HQ part of borehole HN99-128 for maximum leverage force.

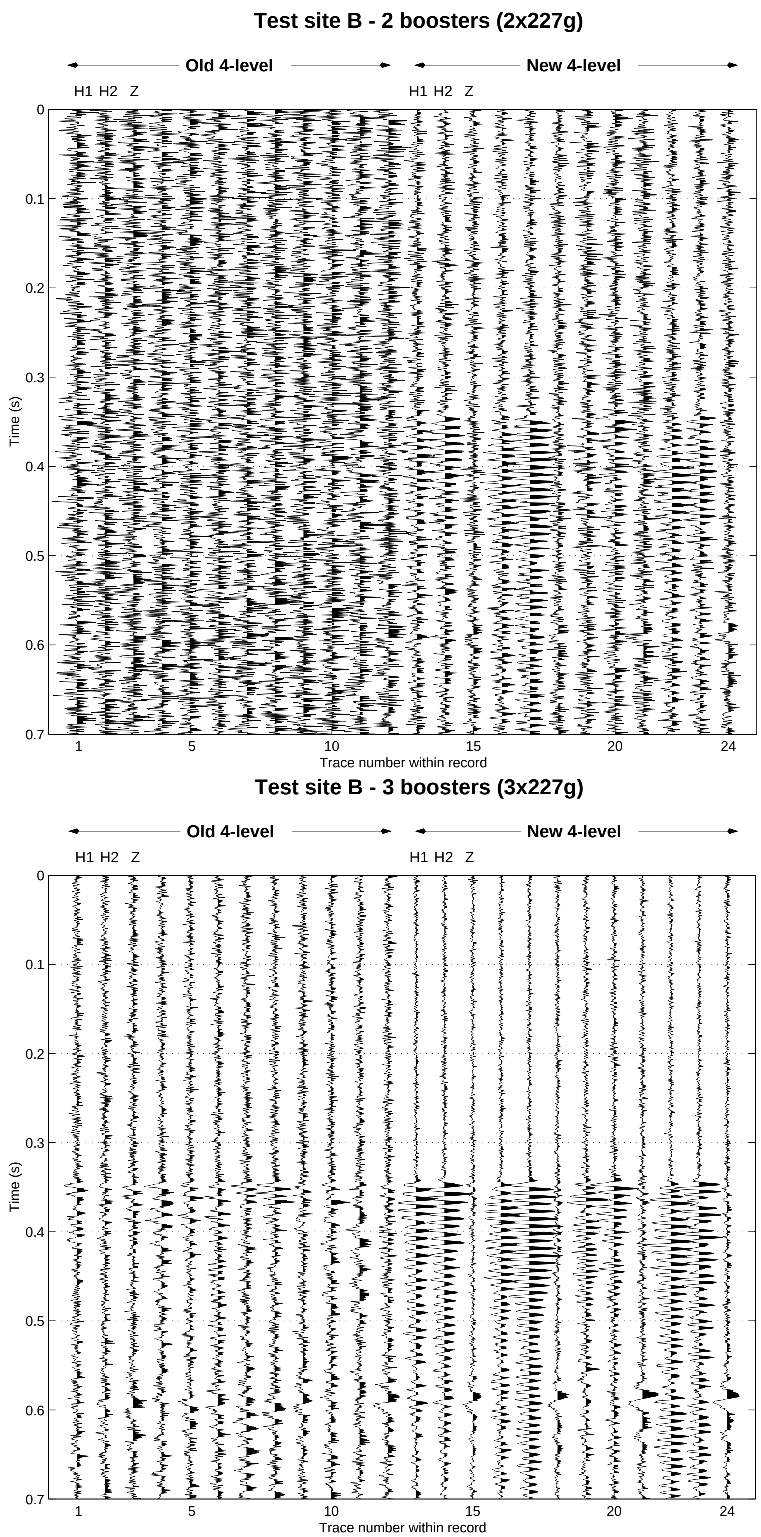

Figure 2: Shot gathers from test site B obtained with 2 boosters (top) and 3 boosters (bottom). The first 12 traces were recorded with the old 4-level tool while the last 12 traces were recorded with the new tool.

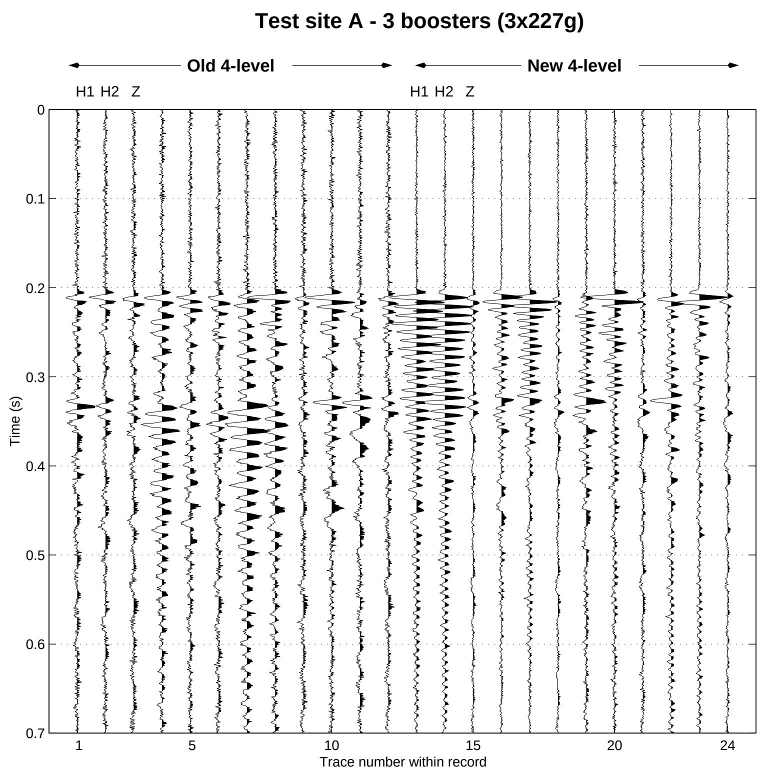

Figure 3: Shot gather from test site A obtained with 3 boosters. Ringing on the horizontal components of the new 4-level tool is less significant than at test site B.

Shorter clamping arms (40mm) were used in the NQ part of the borehole.

Two shooting systems were used during the survey. The GSC clock driven shooting boxes were used at VSP sites C and D (Figure 1). A Macha shooting system with radio communication was used at sites A and B and for the line of shots. Relative drifts between clock driven shooting boxes were corrected using surface geophones located near the recording borehole collar. These drifts were quite significant for some boxes (ranging from 1 to 72 ms/day). Some drifts were also observed with the Macha shooting system, but they were almost always less than 0.5ms (sampling rate) and never higher than 1ms.

Some technical problems occurred during acquisition of the data. The following list summarizes the most important problems encountered during the survey.

- The vertical component of the fifth level (new 4-level tool) showed a high noise level. Traces acquired with that component were muted. This component was working fine during the test survey.

Offset VSP	
Acquisition equipment	
Seismograph	OYO Das-1
Receivers	Vibrometric XYZ43CG (8-level 3-component receiver array)
Shooting System	Macha shooting system (sites A and B) GSC clock driven shooting boxes (sites C and D)
Source	3x227g boosters, primacord and zero-delay seismic caps
Recording parameters	
Recording depths	265m-1300m
Receiver spacing	5m
Record length	2.1s
Sampling interval	0.5ms
Time offset window	-100ms (pre-trigger)
Line of shots	
Acquisition equipment	
Seismograph	OYO Das-1
Receivers	Vibrometric XYZ43CG
Shooting System	Macha shooting system
Source	3x227g boosters, primacord and zero-delay seismic caps
Recording parameters	
Recording depths	585m-815m
Receiver spacing	10m
Record length	2.1s
Sampling interval	0.5ms
Time offset window	-100ms (pre-trigger)

Table 1: Acquisition equipment and recording parameters used at Halfmile Lake.

- Spikes contaminated some shot gathers. Overheating of the seismograph caused some of the spikes. Cross-triggering induced by an electrical storm also produced spikes. Recording was stopped as soon as spikes became clear on the data. Traces with too many spikes are muted.

- The 40mm clamping arms could not be installed on level 6 and 7 (new tool) for recording in the NQ part of the borehole. Several clamping arm screws of the new 4-level were damaged after only 320m of acquisition. Some of these screws could not be used again to attach the 40mm clamping arms. Furthermore, 40mm arms did not fit properly into levels 6 and 7. Some modifications were tried in the field, but results remained unsatisfactory (clamping arms did not close properly). The 40mm clamping arms will have to be modified to fit levels 6 and 7 of the new tool. The 80mm clamping arms were kept on levels 6 and 7.

- The GSC shooting boxes drifted significantly. One box lost time during acquisition and had to be replaced. No data were lost.

- Most of the stabilization rings were not in their original positions at the end of the survey, although they were tightened thoroughly at the beginning of the survey. They were still in place when the clamping arms were changed (e.g., for recording done in the HQ part of the borehole). To be really efficient, such systems should be built in the tool.

6 Data Quality

In the following sections, we present raw data acquired at Halfmile Lake. We also present the same data after a bandpass filter (5-25-105-125Hz), AGC (0.25s) and a first attempt at rotation of the horizontal components. The same parameters were applied to all datasets. Where required, drifts of the clock driven shooting boxes were also corrected (sites C and D). The seismic records are more appropriate for data quality evaluation after application of these basic steps.

6.1 Offset VSP

Figures 4, 6, 8 and 10 show the raw VSP data recorded with shot site A, B, C, and D respectively. On these figures, the vertical and one of the horizontal components are shown. Sites A and B provided the strongest direct P-waves (see Figures 4 and 6). First breaks from site C and D are weaker and, for some shots, closer to noise level (Figures 8 and 10). An extra booster may have been required at those sites. Traces recorded in the HQ part of the borehole (between 265m and 580m) are noisier for sites C and D. Tube waves are present on the data (see Figure 4). Some tube waves are recorded before direct P-wave arrivals. The movement of the receiver chain when changing recording depths most likely generated these waves. Tube waves have higher frequency content than the direct P- and S-waves. No reflections are observed on the raw VSP data.

Figures 5, 7, 9 and 11 show the same VSP data after application of some basic processing steps (bandpass, agc and rotation). Direct P- and S-waves are more prominent and up-going reflections are observed on records from all shooting sites. Several reflections originating from the Deep Halfmile sulphide lens can be identified on some records. P- and S-waves reflected from that lens are observed on data from shot site B (Figure 7). These reflections intersect the borehole (or direct waves) where it intersects the Deep Halfmile sulphide lens. The radial component from shot site C (Figure 9) shows a P-to-S converted reflection. Conversion occurred at the Deep Halfmile lens.

Please note : **Application of only basic processing steps shows reflections from one of the sulphide lens already. We expect the data quality to significantly increase after further processing.**

6.2 Line of Shots

This part of the survey was recorded after completion of the offset VSP surveys. The receivers were placed between 585m and 815m, with a spacing of 10m. The positions of the receivers were based on the following considerations:

- The HQ part of the hole was avoided.
- The 585-815m depth range provided the best quality data on records from the 3 VSP shot sites located on the 3D line 16 (A, C and D).
- Preliminary modeling results (Bellefleur et al., 2001) show that this depth range is appropriate for imaging the area of sub-vertical stratigraphy between the Lower and Deep Halfmile lens.

Figure 12 shows traces recorded from shot station 880S (see Figure 1). The horizontal components (first 48 traces) are not rotated. All components show clear direct P- and S-waves. **The vertical component contains reflections which are clearly visible on the raw data**. The reflections are prominent after bandpass filtering and AGC. Several records from other shot locations also contain clear reflections on the vertical component (Figure 13).

7 Future work

Obviously, more elaborate processing needs to be applied to the downhole seismic data. The next steps will consist of processing of the offset VSPs and line of shot data. Particularly, we will focus on rotation of the horizontal components and removal of the direct P- and S-waves. Some care will have to be taken when removing the S-waves as some reflections observed on the data are located close to or intersect these waves.

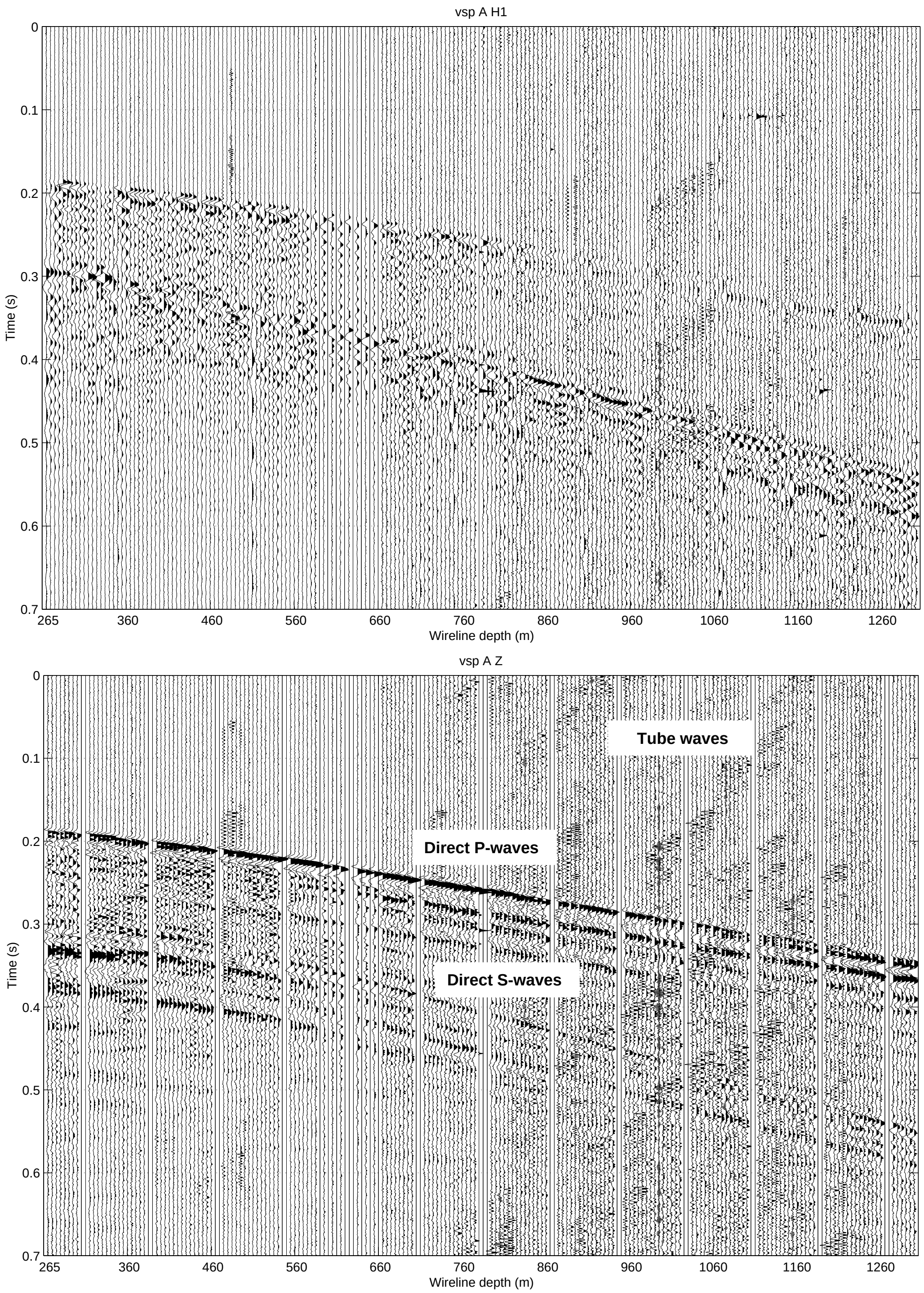

Figure 4: Horizontal and vertical component from site A after preliminary trace editing and energy balancing. Second horizontal component not shown.

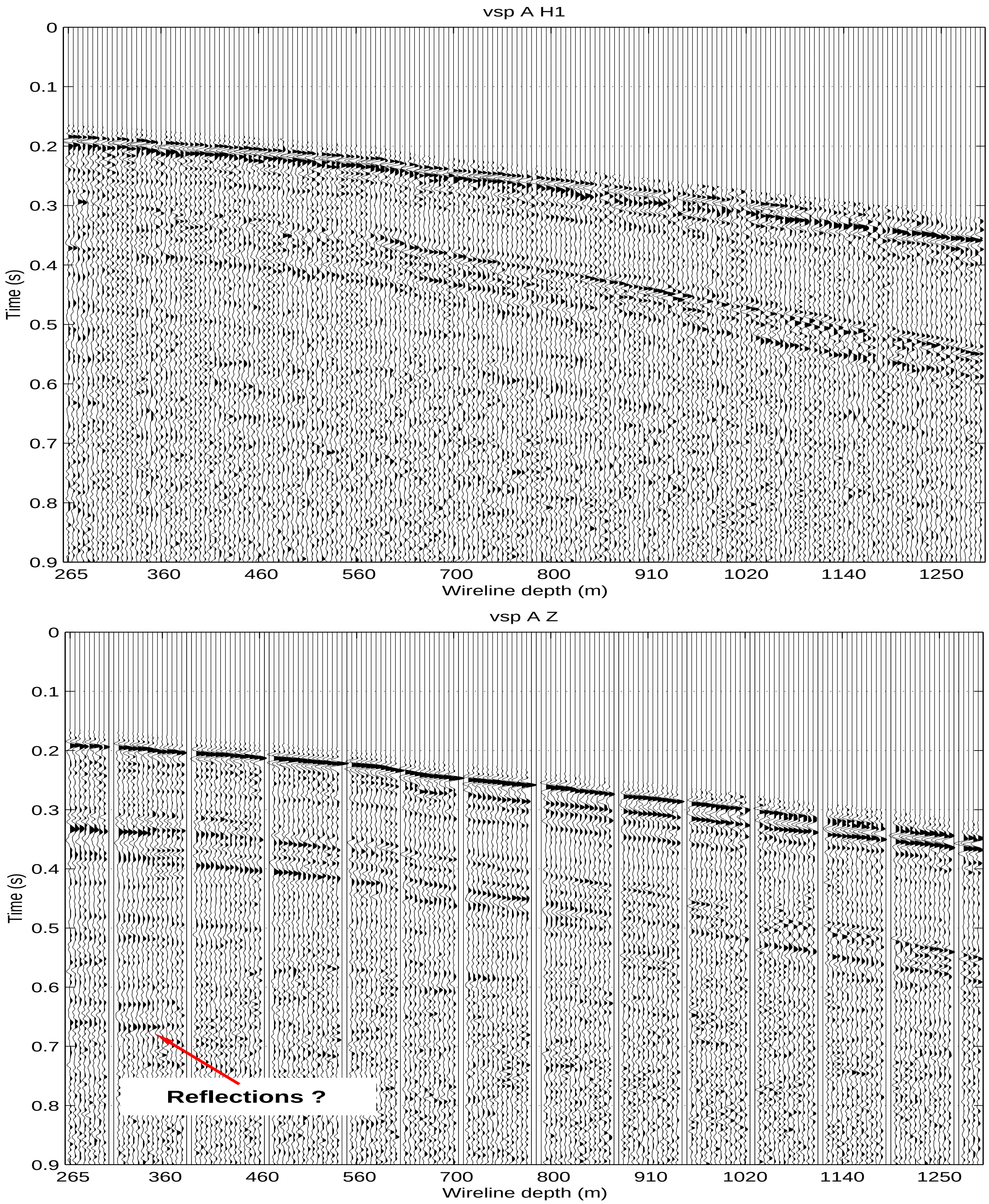

Figure 5: VSP data from site A after trace editing, muting signal above direct P-waves arrivals, bandpass filtering and AGC. The horizontal component (H1, top) is rotated and pointing toward the shot location.

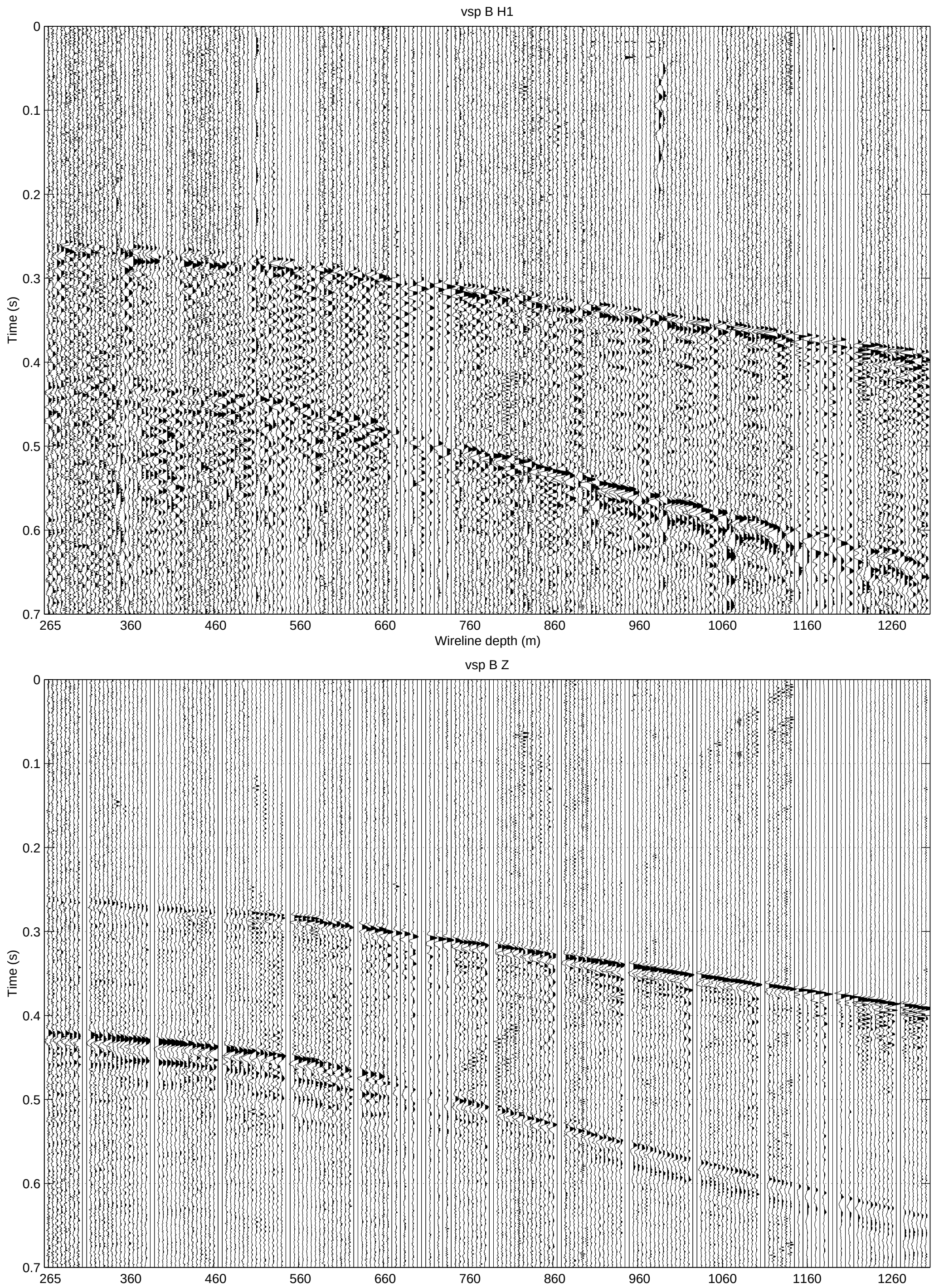

Figure 6: VSP data from site B after preliminary trace editing and energy balancing. The horizontal component (H1, top) is before rotation. Bottom figure shows the vertical component. Data quality is lower in the HQ part of the hole between 265m to 580m.

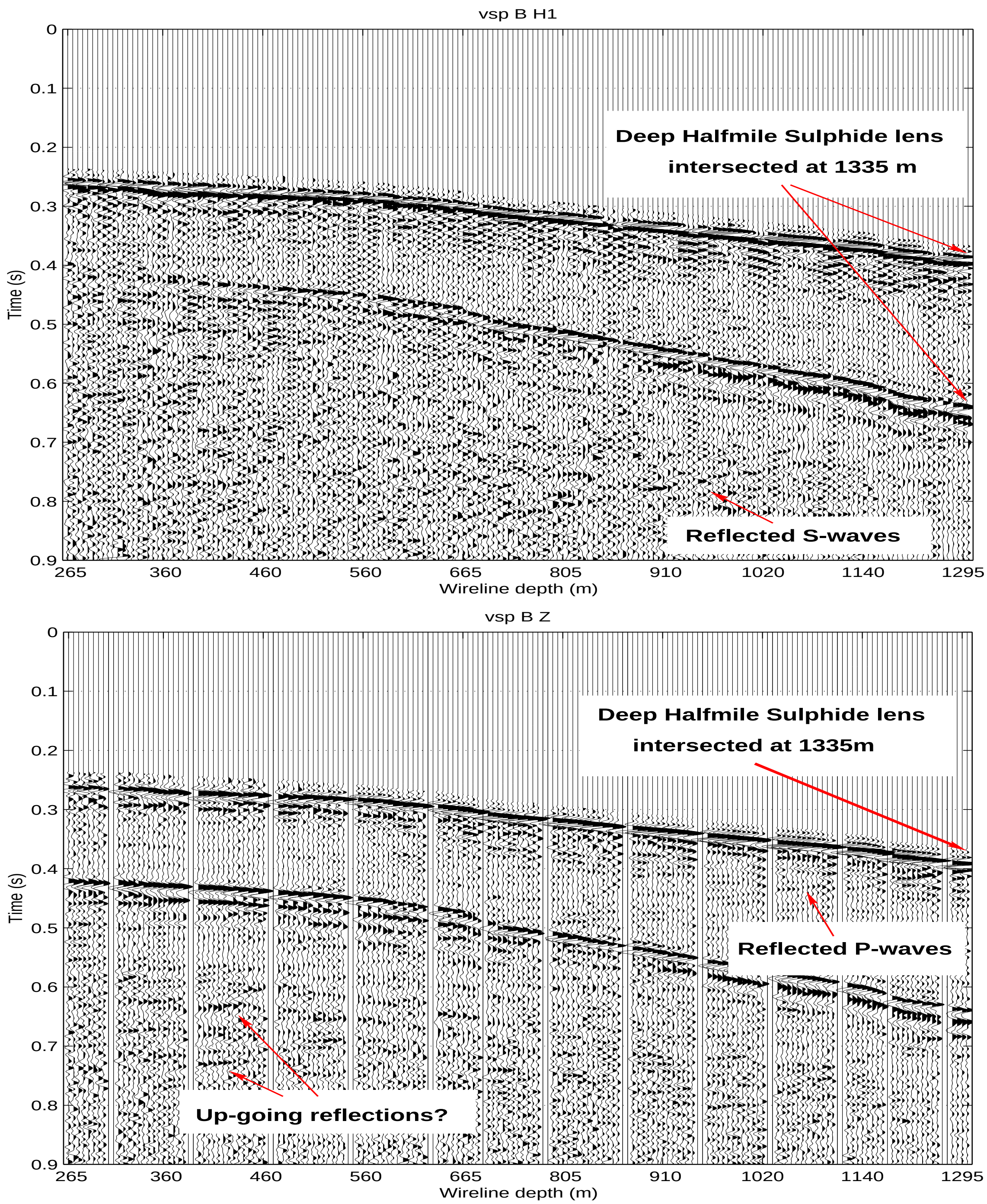

Figure 7: VSP data from site B after trace editing, muting signal above direct P-waves arrivals, bandpass filtering and AGC. The horizontal component (H1, top) is rotated and pointing toward the shot location. Bottom figure shows the vertical component. S-waves (top) and P-waves (bottom) were reflected from the Deep Halfmile sulphide lens intersected at 1336.5m. These events and other up-going reflections will become stronger after removal of down-going P- and S-waves.

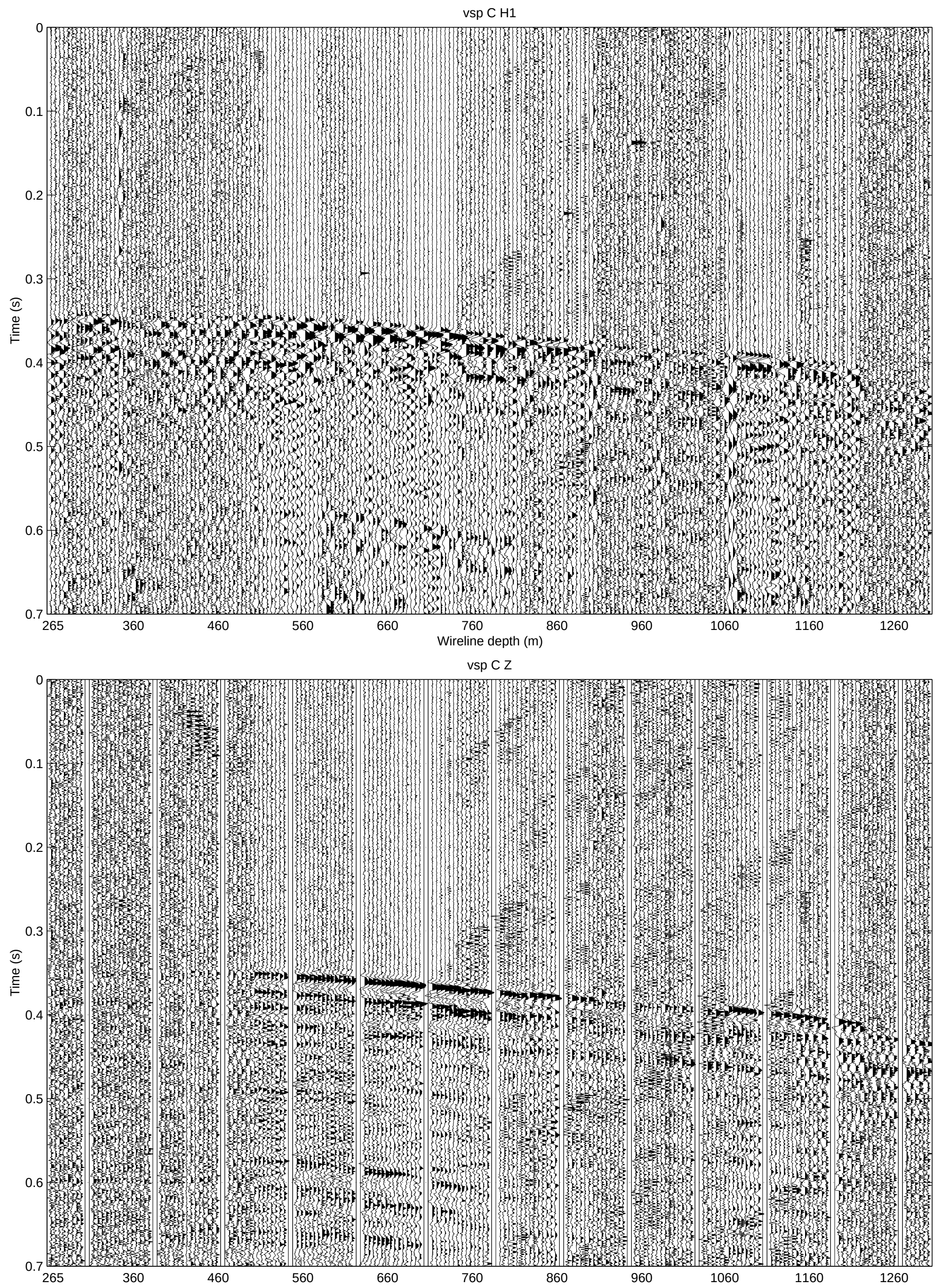

Figure 8: Horizontal (top) and vertical (bottom) components from site C after preliminary trace editing and energy balancing. The second horizontal component is not shown.

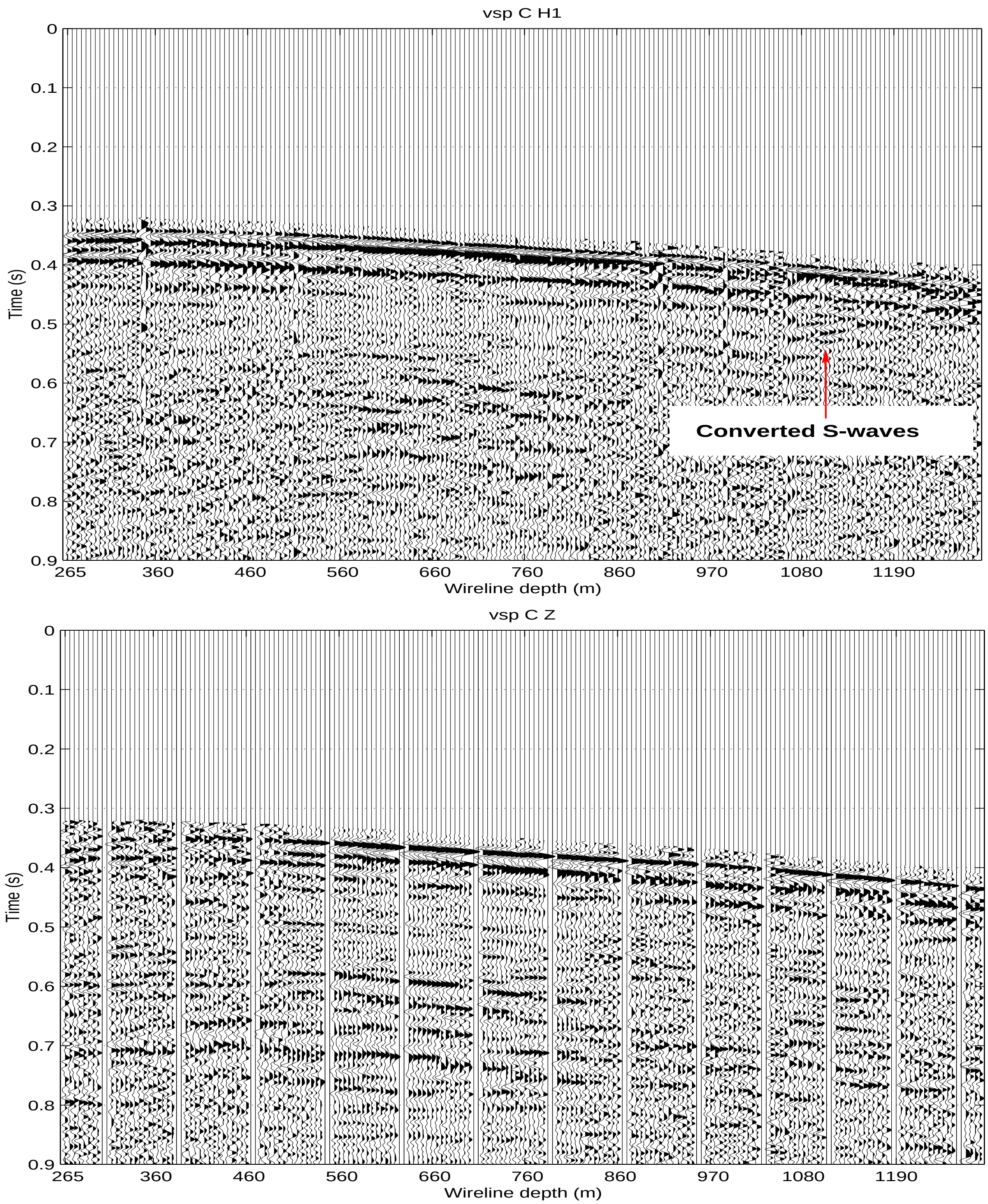

Figure 9: VSP data from site C after trace editing, muting signal above direct P-waves arrivals, bandpass filtering and AGC. The horizontal component (H1, top) is rotated and pointing toward the shot location. Bottom figure shows the vertical component. The up-going reflection (top) indicated by the arrow (top) is a wave converted on the Deep Halfmile sulphide lens (P-to-S conversion, approximate velocity of 3000m/s).

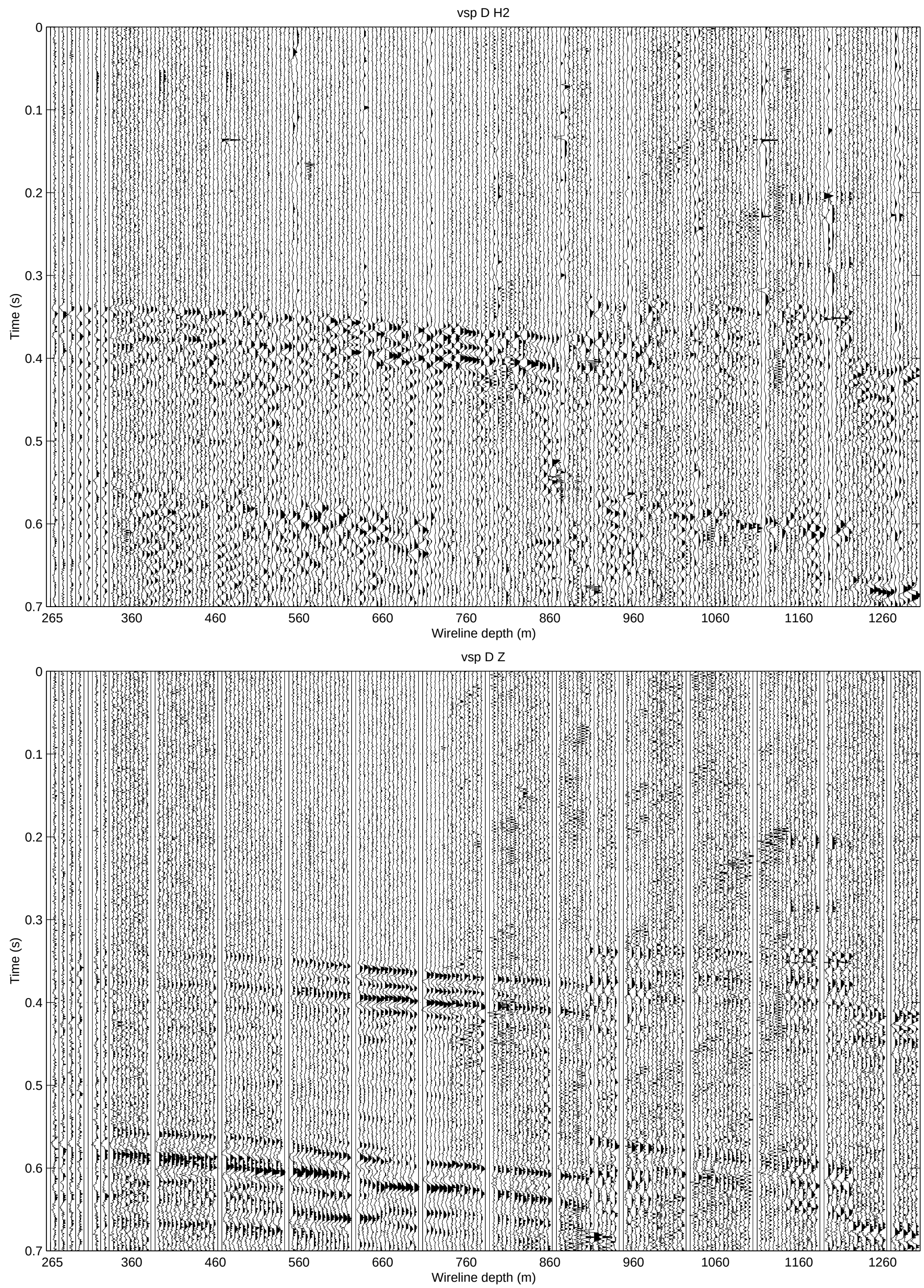

Figure 10: Horizontal (top) and vertical (bottom) components from site D after preliminary trace editing and energy balancing. The first horizontal component is not shown.

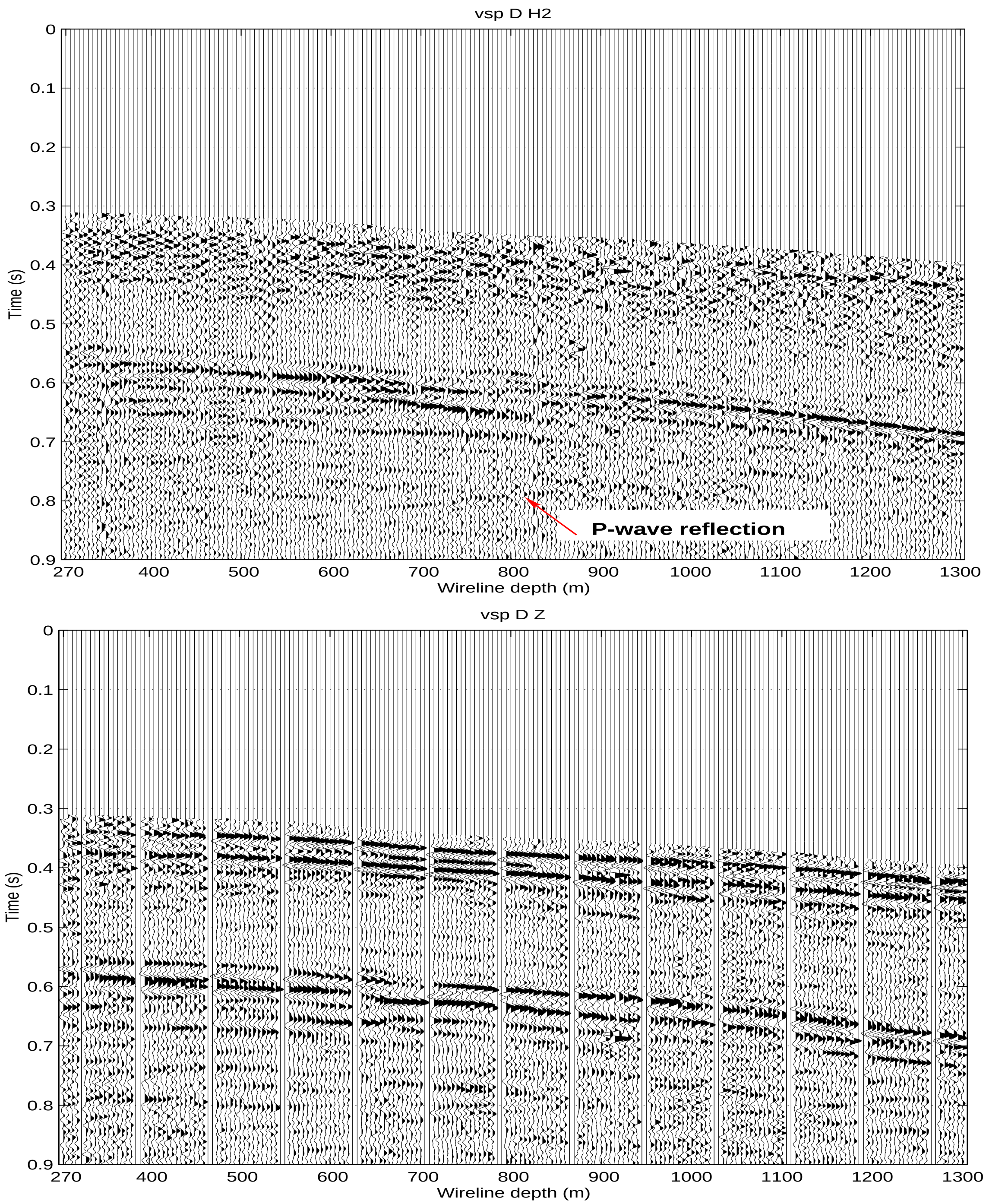

Figure 11: VSP data from site D after trace editing, muting signal above direct P-waves arrivals, bandpass filtering and AGC. The horizontal component (H2, top) is rotated and orthogonal to the borehole-shot direction. Bottom figure shows the vertical component. A P-wave reflection is observed on H2.

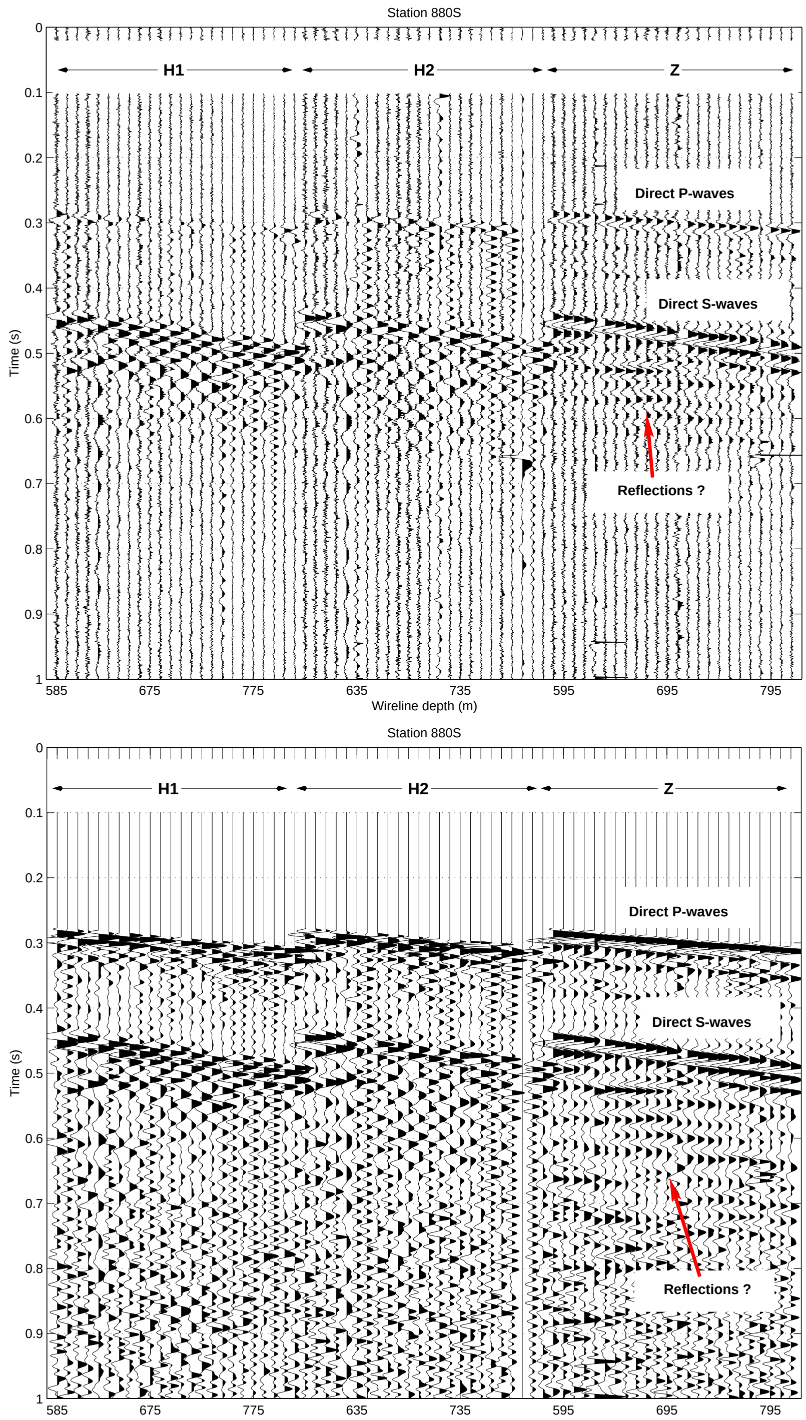

Figure 12: Data collected from station 880S for depth ranging between 585m and 815m. The raw data (top) on the vertical component shows direct P- and S-waves and reflections. The reflections become more obvious after bandpass filtering (5,25,105,125Hz), muting signal above the first breaks and application of AGC (bottom). The horizontal components are not rotated.

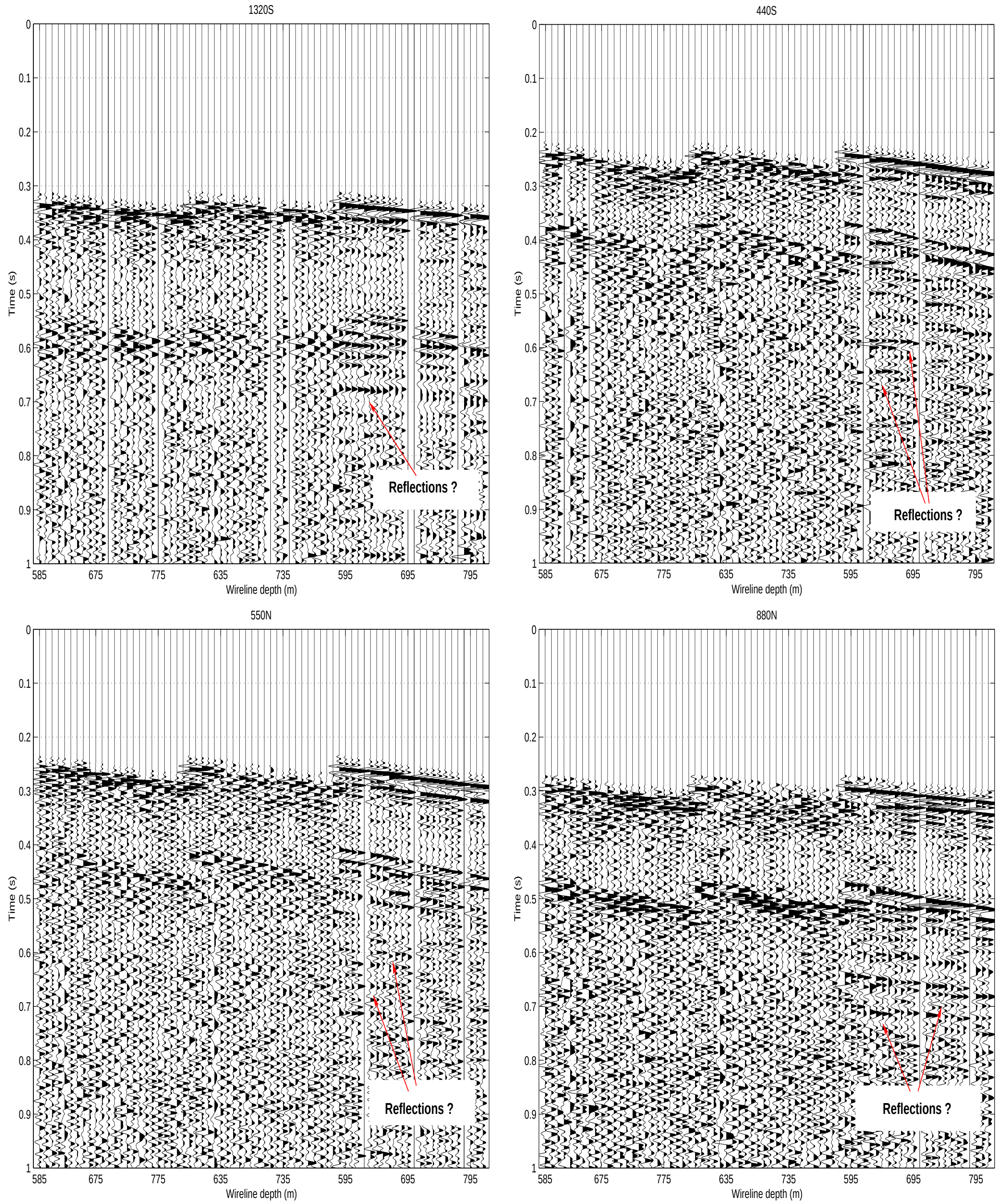

Figure 13: Data collected with sources at stations 1320S, 440S, 550N and 880N. The vertical components (last 24 traces of the records) show some reflections. The horizontal components (first 48 traces) are not rotated.

Three imaging methods will be tested with the processed data (see Mueller et al., 2000). These methods will be applied to the offset VSPs, the line of shots and a combined data set. The reflected S-waves and P-to-S converted waves will also be tested for imaging purposes.

8 Conclusions

The downhole seismic data acquired at Halfmile Lake is of good quality. Reflected P- and S-waves as well as converted waves (P-to-S) from the Deep Halfmile lens are observed on several VSP. These different phases will generate new imaging opportunities. Other up-going reflections are also observed on the offset VSP. The data acquired with the line of shots geometry also show several reflections. At this stage, it is not possible to identify their origin.

9 References

Bellefleur, G., Adam, E. and Müller, C., 2001. The Bathurst DSI Survey Phase I : Modeling of Halfmile Lake Sulphide Lenses. Report for the DSI Consortium, 11p.

Kay, I. and Perron, G., 1999. 3D VSP experiment at Halfmile Lake, Bathurst, New Brunswick. Report for the DSI Consortium, 23p.

Müller, C., Duveneck, E. and Perron, G., 2000. Coherency and polarization weigthed diffraction stack migration for imaging of crustal seismic scatterers. *In* Downhole Seismic Imaging for Mineral Exploration 1999-2000 Annual Report, pp. 41-63.

Perron, G. 2000. Recording Instruments Update. *In* Downhole Seismic Imaging for Mineral Exploration 1999-2000 Annual Report, pp. 11-16.

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, pp.1882-1889.