IPP Research Project

PROGRESS REPORT
(Draft copy)

Downhole Seismic Imaging Studies at Normetal, Québec

An Industrial Partners Project Between Falconbridge and the Geological Survey of Canada

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Introduction:

This report summarizes acquisition, preliminary processing and interpretation of downhole seismic imaging (DSI) data from borehole 95-28-05 at Normetal, Québec (Fig. 1). The method used in this type of survey is similar to vertical seismic profiling (VSP) techniques utilized for hydrocarbon exploration (Hardage, 1985) and academic research (Rector, 1988; Luschen et al., 1991; Miao et al., 1995). Since boreholes used in mineral exploration are rarely vertical, and the imaging algorithms generally must operate in three dimensions rather than within a 2-D profile, the term 'DSI' is used here, rather than the more commonly used abbreviation 'VSP'. The DSI method makes use of seismic recordings made with a downhole geophone clamped to the wall of the borehole. For the present survey the seismic source consisted of small explosive charges detonated near the surface, but other types of sources (e.g., airgun or vibroseis) and source locations (e.g., downhole) are also possible. In general, explosives provide the most powerful source, but alternative sources may have other advantages, such as better repeatability, reduced environmental impact and lower cost. The overall objective in DSI profiling is to record reflected and scattered signals (echoes) from geological contacts, and to use these signals to infer local geological structure in the vicinity of the borehole. In principal, reflections are generated where there is a significant and abrupt change in one or more elastic properties, such as velocity, density, or their product, acoustic impedance. Large changes in acoustic impedance occur at contacts between contrasting rock types, and very large changes can occur between massive sulphide ore bodies and their host rocks (Salisbury et al., 1996).

The specific objectives of this project are to: 1) investigate the feasibility of DSI techniques for delineating geological contacts in the Normetal area, with a view toward more extensive application of this method for exploration in the future; 2) characterize the seismic response of an off-hole electromagnetic anomalies observed in borehole 95-28-06.

Data Acquisition:

Acquisition of downhole seismic in borehole 95-28-05 took place between May 24 and May 27, 1996. The original planning for this project called for the excavation of two shooting pits, approximately 400

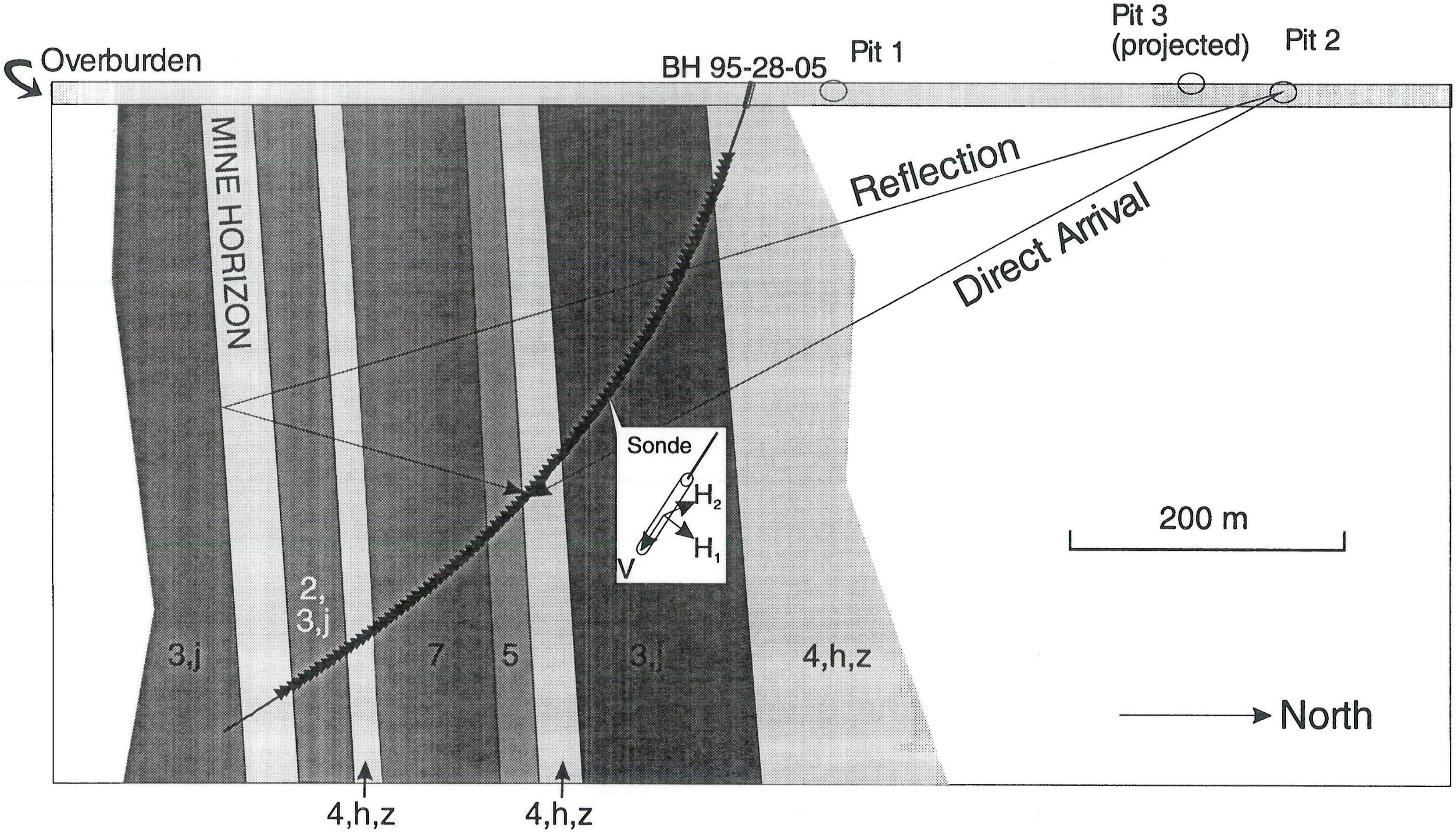


Figure 2. Cross section in the mine north-south direction through the collar of borehole 95-28-05 and shooting pits 1 and 2. Shooting pit 3 has been projected into the section by ca. 510, in the mine west direction. Labelling of lithologies is based on the proprietary cross-section provided by Falconbridge. Generalized lithologies are: 2,3 = mafic-to-intermediate volcanics; 4 = felsic volcanics; 5 = graywacke; 7 = basalt.

87 m, this borehole was abandoned and work shifted to borehole 95-28-05.

For each of the three surveys conducted in borehole 95-28-05, receivers were lowered to a maximum wireline depth of 576 m. Although this was not the bottom of the borehole, this depth was sufficient to intersect the Mine Horizon (Fig. 2). Blasting for these seismic profiles was carried out in pits 1, 2 and 3 (Fig. 1). Pit 4 was not used for DSI profiling. Pit 3 was located in swampy ground, and filled with water naturally. The purpose of shooting in this pit was to attempt to image an offhole conductor between boreholes 95-28-05 and 95-28-06. Pits 1 and 2 did not fill with water naturally, so steps were taken by Falconbridge staff to ensure that the water in the pits was sufficiently deep for seismic blasting. Upon completion of the survey, these pits were backfilled with material that had been excavated earlier.

A Bison 6-channel seismic recorder connected to a PC-AT laptop computer was used to record the seismic signal. Only 4 of the 6 channels were used, for 1 surface channel (a geophone placed in the ground near the recorder) and 3 downhole channels. The downhole seismic tool, or *sonde*, housed three 14-Hz geophones mounted such that one geophone (V, for vertical) records the component of wave particle motion that is directed along the axis of the borehole, and the other two geophones (H_1 and H_2, for hortizontal) record mutually orthogonal components of particle motion in the plane perpendicular to the borehole axis (Fig. 2). The sonde is held fixed to the wall of the borehole using a single clamping arm. The number receiver spacing for pit 1 was 10 m, and for pits 2 and 3 was 5 m. The depth ranges for each pit were 576-62 m (pit 1), 566-52 m (pit 2), and 576-102 m (pit 3).

Raw unfiltered data for the three surveys are shown in Figures 3, 4 and 5. In general, the data quality in this area is excellent, as evidenced by the clean first breaks and lack of noise (in particular, 60 Hz noise, which has been problematic elsewhere).The seismic source consisted of one (or two) 227 g pentolite boosters detonated using seismic (0-msec) blasting caps. In pit 3, the initial 40 shots, corresponding to the deepest receiver levels, were fired using 2 boosters, producing noticeably larger amplitudes in the raw data (Fig. 5). The remaining shots were fired with a single booster. Accurate timing of the shots was achieved using shooting boxes owned by the GSC, which have very accurate internal clocks that trigger on every minute mark. For pit 3, two boxes were used, one at the recorder to trigger the Bison recording system, and one at the shooting location. For the other two pits, a single

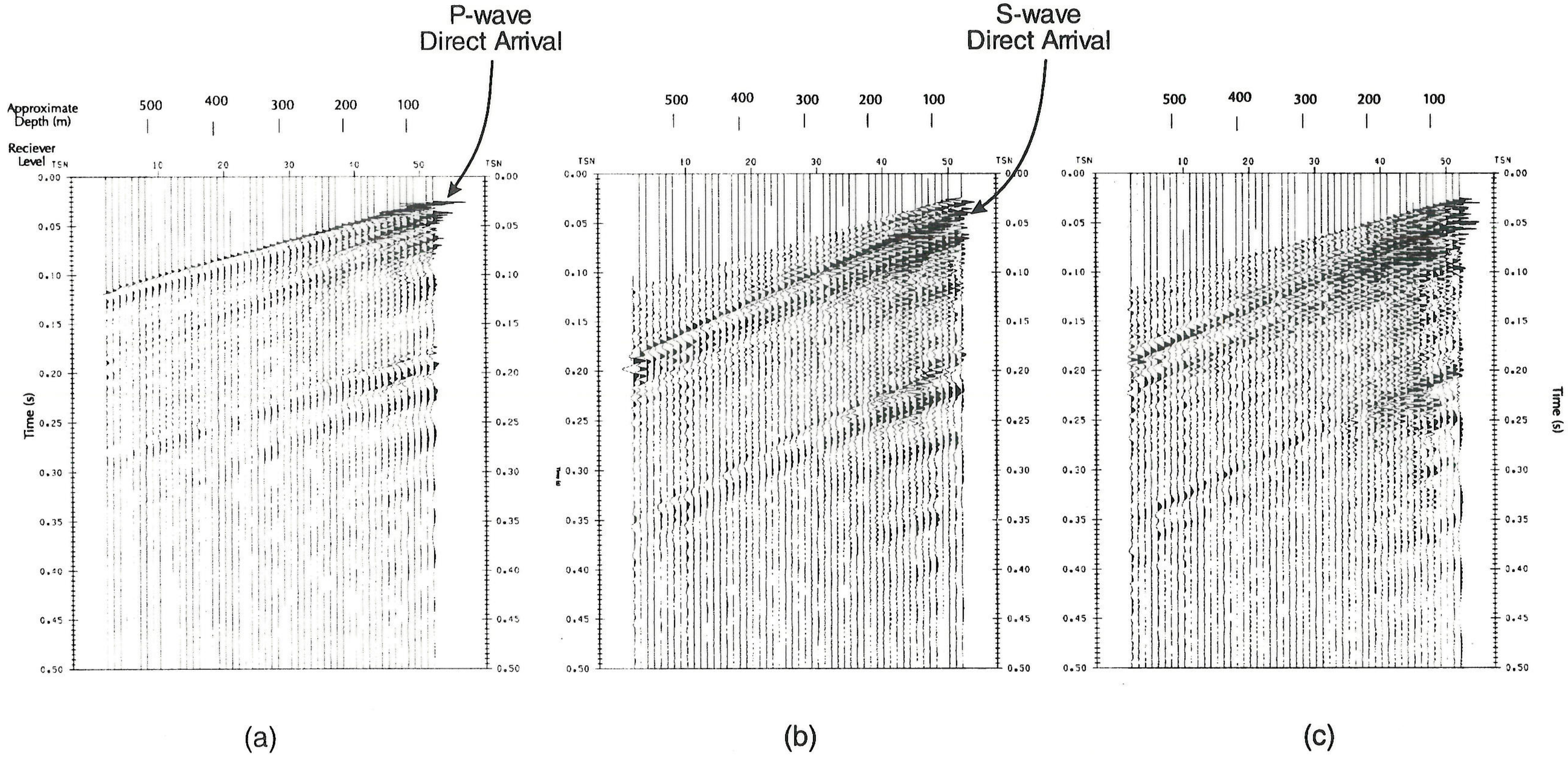


Figure 3. Raw data from pit 1 for the vertical (a), H_1 (b) and H_2 (c) components.

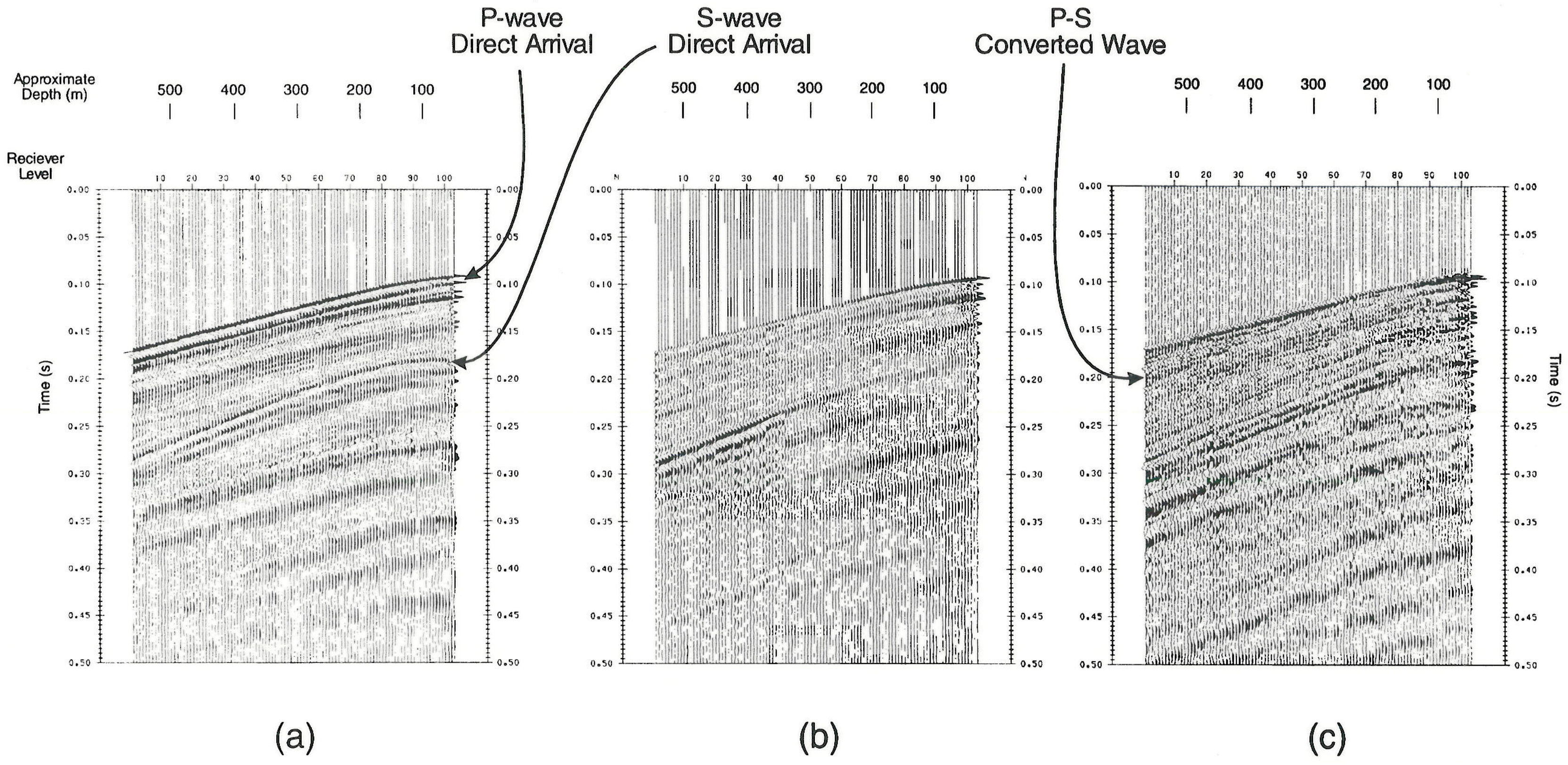
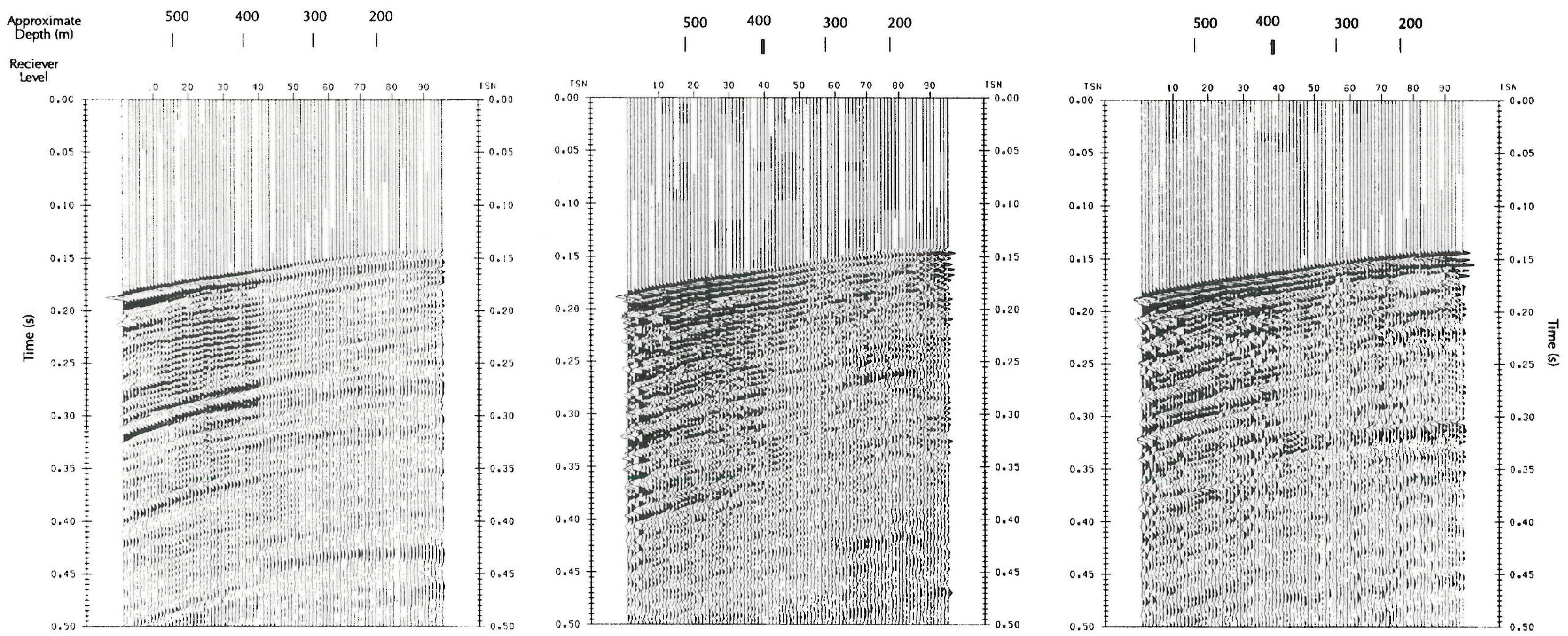


Figure 5. Raw data from pit 2 for the vertical (a), H_1 (b) and H_2 (c) components.



(a)

(b)

(c)

Figure 5. Raw data from pit 3 for the vertical (a), H_1 (b) and H_2 (c) components. Note higher amplitude of the first 40 shots, where 2 boosters were used. All other shots used a single booster.

timing unit was used to trigger both the shooting and recording systems.

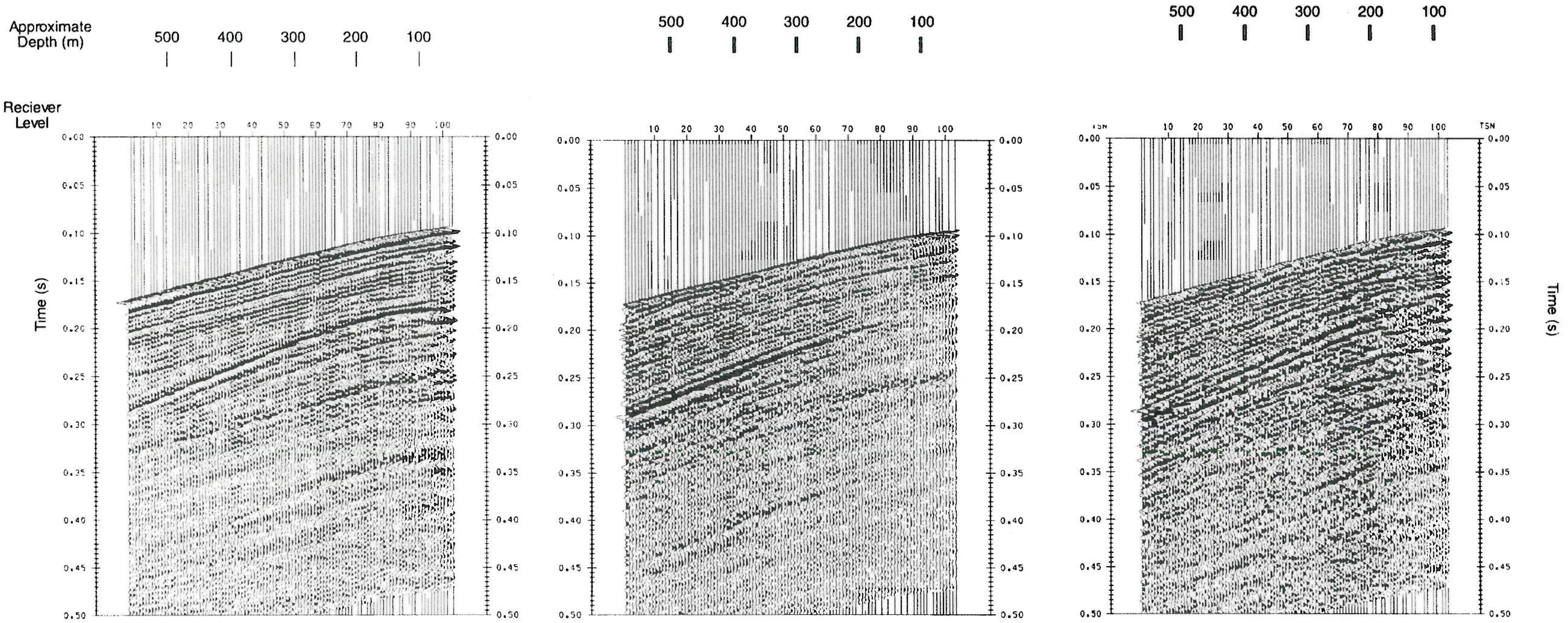
Data Processing

Before processing the data, it was necessary to convert the raw data files, in Bison internal binary format on DOS diskettes, to a standard industry format. This step was accomplished using the software program VISTA. The individual traces were collected together to form composite, or 'gather', files. These were then saved in an industry standard format (32-bit IBM floating point SEGY format) for archival and importing into the ITA Insight seismic processing package on a Sun workstation. The next preprocessing steps involved: 1) updating information contained in the trace headers with positional information; and, 2) correction for slight clock drift and variations in shot time due to changes in water depth. This step was carried out using the surface channel as a benchmark.

The next step in the data processing scheme is spectral balancing, which accomplishes basic filtering of the data. Analysis of frequency spectra of the raw data showed that the signal bandwidth extends up to approximately 180 Hz. Coherent noise in the records tends to be much larger in amplitude, and occurs primarily between 20 and 30 Hz. The spectral balancing algorithm tends to reduce the level of the coherent noise relative to the desired signal.

The following processing step is rotation of the H-component channels. This is required because the absolute orientation of the geophones is not known, since no azimuthal measurement system is used in the downhole aparatus. A statistical procedure is used to achieve this rotation, by computing the rotation angle ϕ that maximizes the energy for one of the components in a short (~ 20-50 ms) window centred on the P-wave direct arrival. Elementary seismology theory tells us that this direction is approximately radial with respect to the shooting location (i.e. the radial direction is coplanar with the shot and receiver). Accordingly, the two rotated channels are labled R (for radial) and T (for transverse). Rotated and spectrally balanced data for pits 2 and 3 are shown in Figs. 6 and 7.

The next steps in the processing sequence are designed to separate the P-wave and S-wave direct arrivals from reflections. The criterion used to achieve this separation is the apparent velocity of the respective arrivals: direct waves are 'downgoing' (arrive first at shallow receiver levels), whereas the reflections are assumed to be 'upgoing', and so will have the opposite sense of dip in the DSI sections.

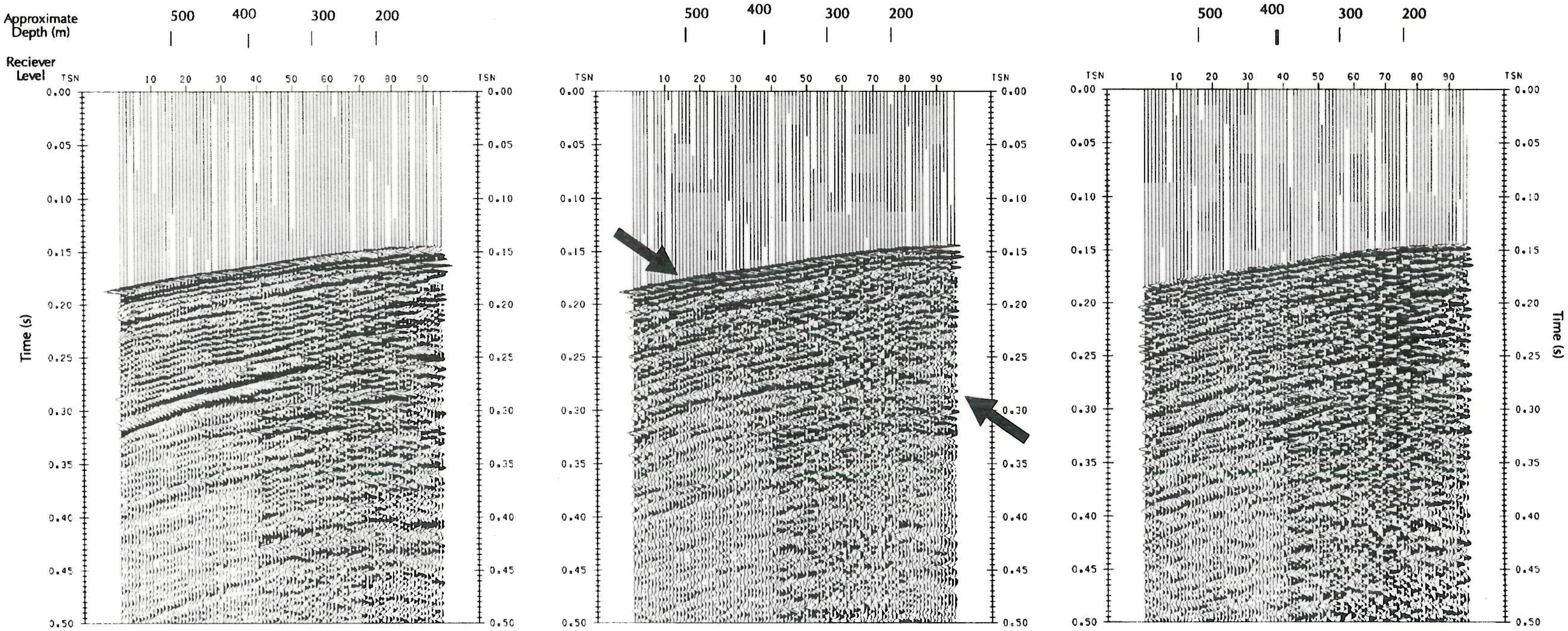


(a)

(b)

(c)

Figure 6. Rotated and spectrally balanced data from pit 2: a) vertical component; b) radial component; c) transverse component.



(a)

(b)

(c)

Figure 7 Rotated and spectrally balanced data from pit 3. Arrows show unusually strong upgoing event (reflection) visible in the radial component record. This reflection originates at ~ 500 m wireline depth.

In general, the reflections are very weak in comparison with the downgoing waves, and are virtually invisible plots of the data thus far. One exception is in Fig. 7, where an unusually prominent reflection is visible. The other important aspect of the processing sequence is deconvolution of the waveform. Unlike surface seismics, DSI can make use of a measured far-field waveform (the downgoing direct arrival). This information is used to deconvolve the reflections in order to achieve the most desirable, short-duration pulse that is possible based on the bandwidth of the data.

The processed data for the vertical, radial and transverse components are shown in Figs. 8-10. Note that the sections have been rotated by 90° with respect to the previous plots, in order to make the depth axis vertical. This orientation of the sections makes the interpretation of the data slightly more intuitive. Due to a fortuitous choice of plotting scales, P-wave reflections are now positioned approximately in the same orientation as the geological units from which they originated. S wave reflections show a shallower apparent dip than their P-wave counterparts. **These sections should be regarded as preliminary processed results, as continued testing is ongoing.** However, these sections do give an excellent indication that numerous reflections were recorded in the survey. Note that the final stage in the processing, that of determining the spatial position of reflections, is yet to be completed.

Preliminary Interpretation

A significant advantage of DSI data over conventional surface seismic data is that it is often possible to determine the geological origin of reflections unambiguously. This determination can be made in cases where upgoing reflections intersect (and terminate at) a downgoing arrival. In that case, the principle of causality ensures that the point of intersection coincides in depth with the reflection point. In figures 8-10, some upgoing reflections have been indicated by arrows. Both P waves and S waves are visible. In principle, use of both wave types permits inferences to be made about different properties of the subsurface.

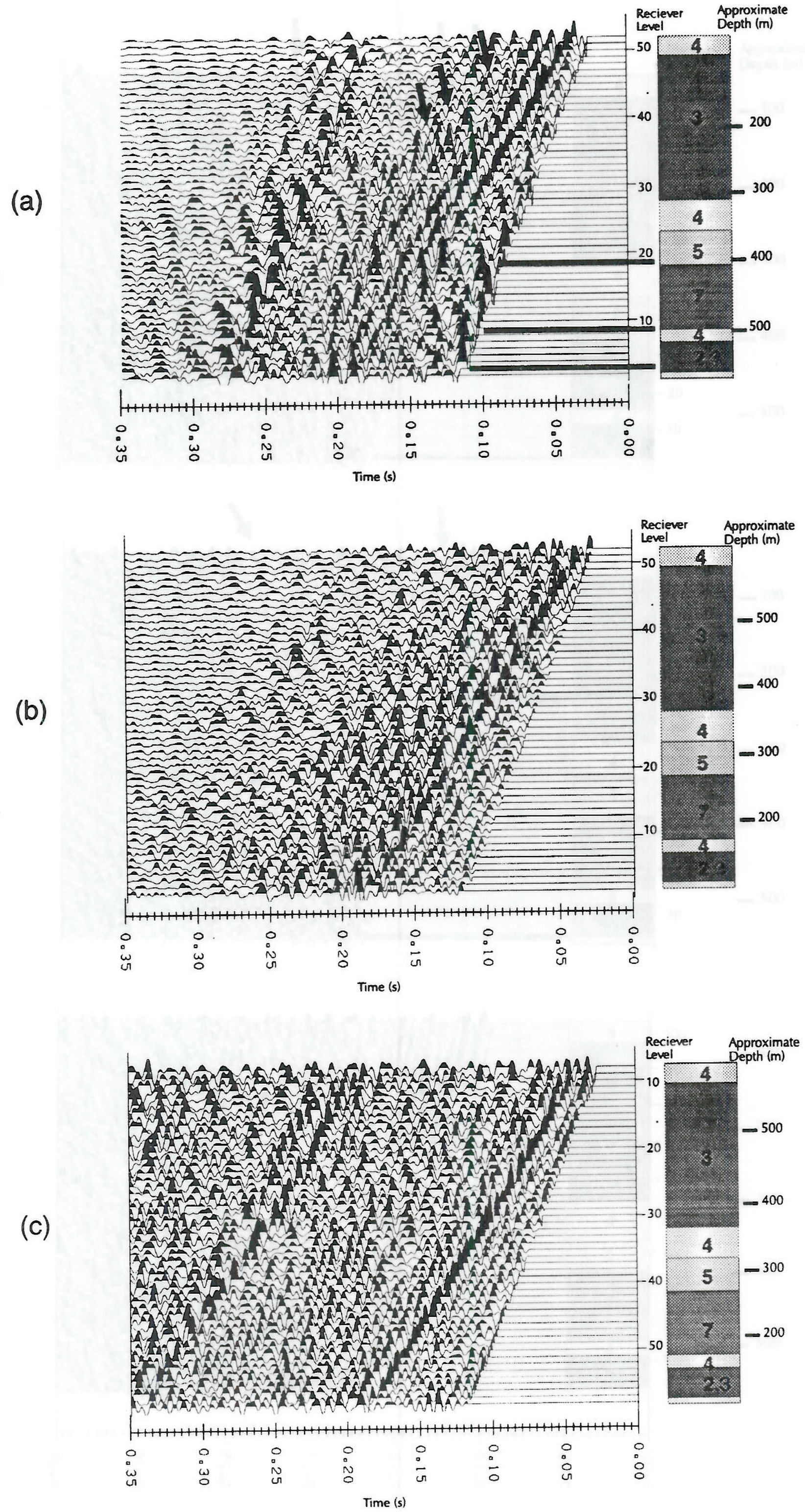


Figure 8. Processed data from pit 1: a) vertical, b) radial and c) transverse components. Arrows in (a) show reflections observed in the vertical component. Downgoing S wave has not been fully removed in (b) and (c).

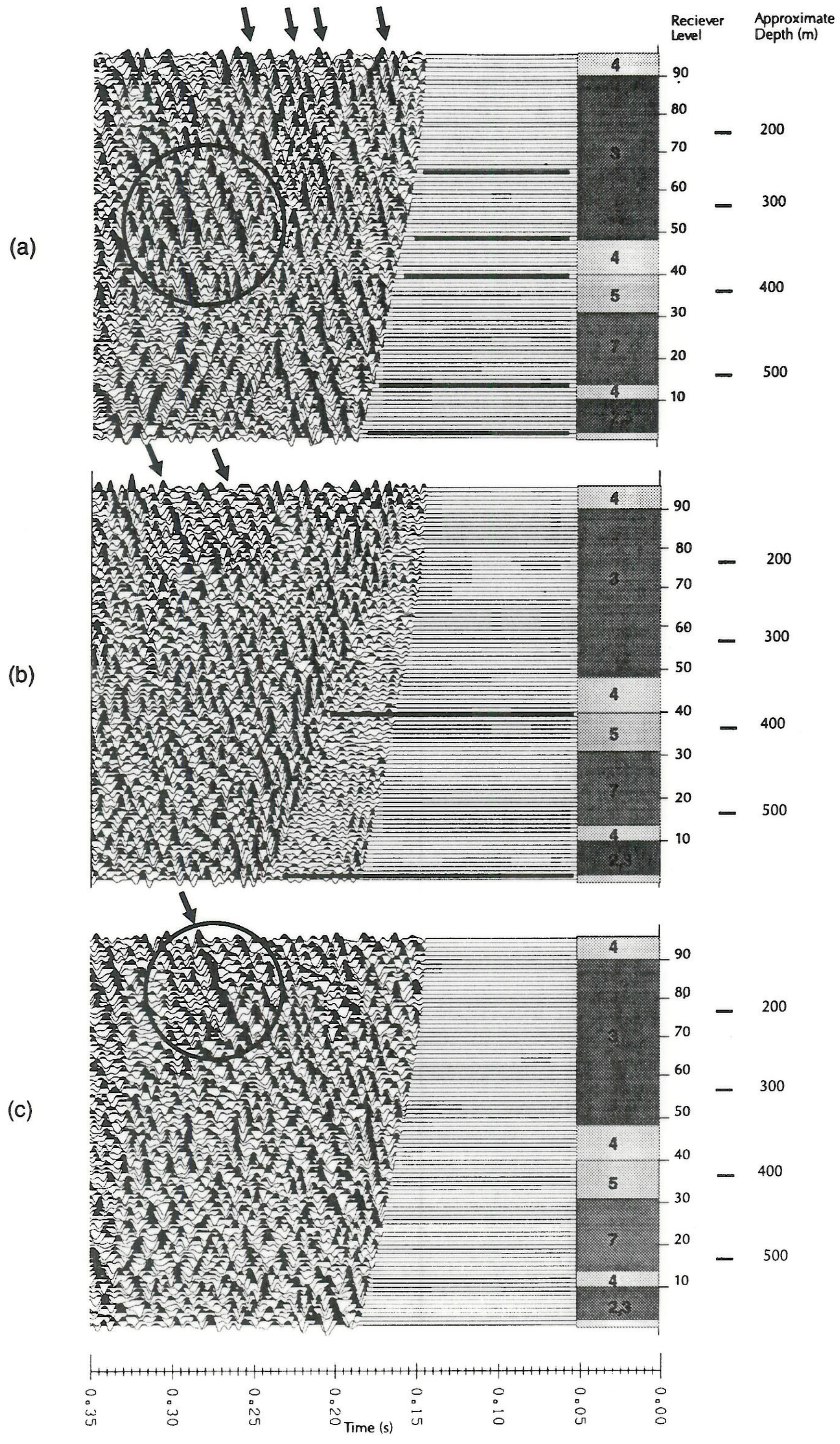


Figure 10. Processed data from pit 3: a) vertical component, b) radial component and c) transverse component. Arrows show locations of most prominent reflectors, which are visible in all three components. In (b), reflections are most likely of the type S-S. Circled areas show anomalously high amplitudes.

Reflection events can be correlated with lithologic changes in the borehole by correlating horizontally (at the same depth) from the point of intersection of the reflection event with the downgoing arrival. Downgoing P waves, for example, coincide in general with the onset of data. The downgoing S wave is visible directly in Fig. 8b, and indirectly in Fig. 10 b where there is a marked change in the level of reflectivity in the radial-component record that corresponds with the S-wave direct arrival. Reflected upgoing arrivals are now clearly visible, especially in the data from pit 3. The best reflections appear to correlate with the Mine Horizon, an overlying felsic unit at ~ 500 m depth in borehole 95-28-05 (unit 4), the graywacke (unit 5) and internal markers within an intermediate volcanic unit (3). The most prominent reflections are circled in Fig. 10a (vertical component) and 10c (transverse component). The polarization implied by these two components is to the side and is consistent with the anomaly being situated between boreholes 95-28-05 and 95-28-06 where a conductor is known to exist based on borehole EM surveys. Projection of this anomalously high-amplitude event up to its intersection with the P-wave direct arrival suggests that it is located close to the Mine Horizon in the stratigraphy. Its generally conformable nature with respect to the other reflections suggests that it is stratabound. Further processing is being applied to obtain an estimate of the spatial location of this feature.

Conclusions

We have reported here on the acquisition and preliminary processing and interpretation of downhole seismic imaging (DSI) data from borehole 95-28-05 at Normetal, Québec. The preliminary results indicate that the data quality is excellent, and numerous reflections have been recorded that appear to correlate, at least in general, with lithologic changes in the volcanic stratigraphy. These results indicate that Normetal is a favourable setting for future DSI surveys. In particular, these results show that: 1) the geology is favourable, since suitable reflectors appear to exist; 2) ambient noise levels are low; 3) overburden conditions are such that excellent coupling of the shots can be achieved. Accessibility and logistical considerations favour winter deployments in the future, however, and future DSI work should be preceeded by dummy probes of the boreholes. One anomalous feature in the DSI data was noted that may be related to a previously observed offhole EM anomaly. Ongoing studies will help to establish the location and geological context of the recorded events.

Acknowledgements

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