Processing and Imaging of Borehole Seismic Data from the Victor Kimberlite, James Bay Lowlands.

Report for the OMET-DSI Project

By

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Summary

Downhole seismic data were acquired at the Victor kimberlite, in the James Bay Lowlands of Ontario, in order to attempt to produce an image of the pipe at 10-300m depths and in doing so, evaluate the applicability of this method in delineating diamond resources. The survey was designed to allow two different imaging strategies, one using shot points located inside the kimberlite pipe and the other using shots within the host sedimentary rocks. In theory, shot points inside the kimberlite have the potential to image directly the kimberlite-sediment contact whereas shots in the nearby ($\leq$250m) sediments should indirectly determine the kimberlite margin by mapping truncations of reflections from the sedimentary layers.

The downhole seismic data were processed to extract a very weak signal from the reflected wavefield and to establish the origin of this signal in spatial coordinates. Data processing was carried out at the Geological Survey of Canada using a conventional processing approach developed for Vertical Seismic Profiling data acquired in sedimentary basins (oil and gas application). Specific processing and imaging strategies were also used to adapt to the survey geometry and geological environment at Victor. The processed data shows many reflections the sedimentary layers (using the shot points in the sediments) or from the kimberlite (using shot points located in the kimberlite). The migration of these reflections shows that the indirect mapping approach has the best potential to define the geometry of the kimberlite at depth. Despite these encouraging results, we identified two physical limitations that likely influence the interpretation of kimberlite margin location from these seismic images.

The first limitation is related to the acquisition geometry. The kimberlite margin is located too close to the edge of the migrated section defined by the recording borehole and, therefore, is in an area where migration results are less reliable. This limitation can easily be resolved in future surveys by selecting a borehole located further inside the kimberlite.

The second limitation is associated with the frequency content of the data. VSP data with higher frequencies will have higher vertical and horizontal resolution and are likely to produce a sharper image of the kimberlite margin. Unfortunately, the thick overburden and shot hole conditions seem to have attenuated significantly the high frequencies of VSPs from shot points located in the sediments. The loss of sharpness associated with lower frequency content may become significant if high precision is required for the position of the kimberlite margin. Spectral balancing and bandpass filtering improved the

sharpness on migrated sections, especially for VSP sites 7 and 8. However, these techniques only work on the part of the spectrum with real signal and cannot compensate for un-recorded frequencies.

Continuous physical rock properties in a vertical borehole located in the country rocks are clearly needed to establish precisely the reflectivity sequence in the sediments. This information is required to assess what sedimentary units or contacts we image on the seismic sections and how well our migration succeeded in positioning them. It should also allow a re-calibration of the velocities which should provide a more accurate positioning of the reflections on the migrated sections and help determine what can really achieved with the indirect imaging approach.

Contents

1 Introduction

The goal of processing Vertical Seismic Profiling (VSP) data is to extract the very weak reflected wavefield from the data recorded and to establish the origin of this signal in spatial coordinates. Data processing was carried out at the Geological Survey of Canada using DSISoft, Promax, and Seismic Unix (SU). DSISoft is a public domain processing software package developed by the Downhole Seismic Imaging consortium for mineral exploration (Beaty et al., 2002) which provides a portable, affordable and simple development environment using Matlab 5 as its foundation. Promax, a commercial seismic processing software was used to migrate the VSP data and produce imaging results. Seismic Unix (Stockwell, 1999) was utilized for some specific analysis and to produce some figures. In general, processing followed a conventional approach developed for VSP data acquired in sedimentary basins (oil and gas application). Specific processing and imaging strategies were also used to adapt to the survey geometry and geological environment at Victor. The main processing steps applied to the Victor datasets are discussed in the following sections, but first, we will introduce the survey design, imaging strategies, and data quality as all dictate the choice of the processing methods and parameters.

1.1 Survey Design vs Processing and Imaging Strategies

The acquisition geometry used at Victor is outlined in figure 1. A true vertical borehole located in the Victor North pyroclastic kimberlite (V-03-303C on figure 1) was used as the recording hole. This borehole exits the kimberlite and intersects the sedimentary rocks at 240m and the Precambrian basement at 323m. The survey was designed to allow two different imaging strategies, one using shot locations inside the kimberlite and the other with shot points placed in the nearby sediments. Shot points located inside the kimberlite can provide direct imaging of the kimberlite wall by analyzing reflected energy recorded on the three component downhole receivers (figure 2). Polarization of reflected seismic waves is key as reflections from the kimberlite wall could originate at many azimuths to the borehole. This approach requires minimum interference between reflections of different origin and should provide optimum results if the kimberlite has a low internal reflectivity. The shot points located in the sediments provide an indirect method of determining the shape of the kimberlite by mapping the truncations of reflections from the sedimentary layers by the pipe wall (figure 2). This second approach requires receivers located inside the kimberlite, which is the case for the top 240m of the recording borehole. The flat sedimentary layers deeper than 240m intersect the borehole and hence, provide no useful information about the geometry of the kimberlite. Both strategies have their advantages and inconveniences but a combination of the two should help produce an accurate image of the kimberlite.

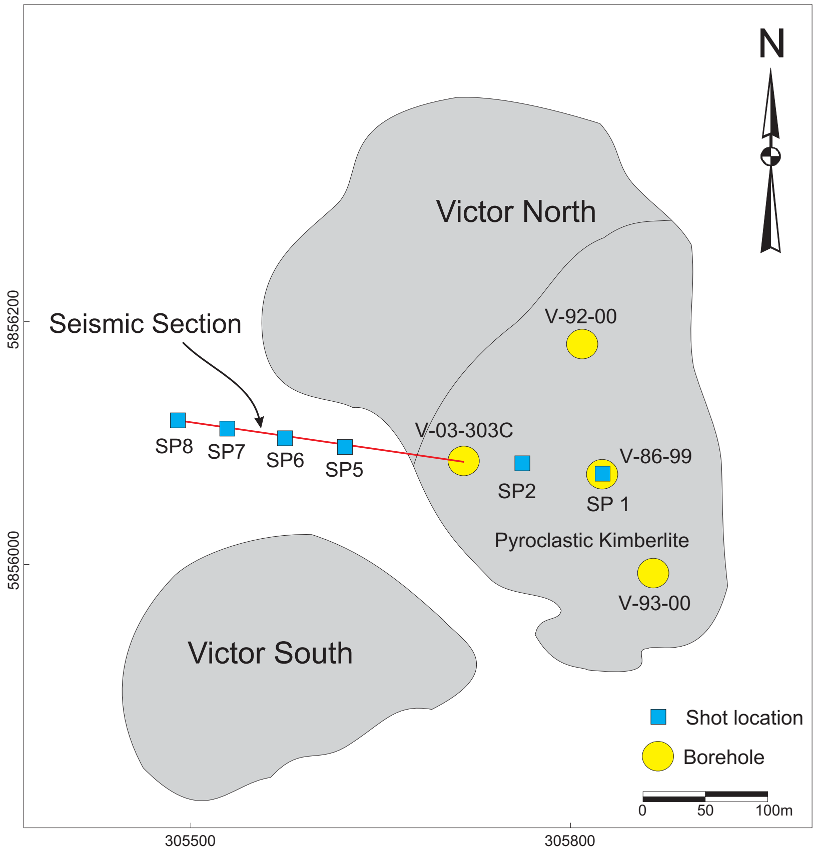


Figure 1: Acquisition geometry used at Victor. The borehole seismic data were acquired to image an approximately E-W vertical section of Victor North pyroclastic kimberlite. Shot points 1 and 2 are located in the kimberlite whereas shots 5 to 8 are in the sedimentary rocks. Receivers were placed in borehole V-03-303C at depths ranging between 10m and 287.5m. The boreholes with logging information (V-86-99, V-92-00 and V-93-00) are also displayed on the figure.

VSP field records are always characterized by strong direct arrivals propagating downward. Reflections from flat sedimentary layers which propagate toward the surface usually have less energy (figure 2). Thus, the processing of VSP data acquired with shot points in the sediments (indirect mapping approach) consisted primarily in extracting the upgoing wavefield from the direct arrivals. The shots located inside the kimberlite were also processed similarly as the upgoing wavefield may provide some useful information about the internal structure of the pipe. However, for the direct imaging approach, reflections from the kimberlite wall will mostly be downgoing waves (figure 2). Separation of these reflections from the direct waves is difficult because delays between these two arrivals are short near the surface and non-existant near where the borehole intersects the sediments. Traveltime modelling was required to identify reflections from the kimberlite wall. Migration of these reflections are shown in the section on direct imaging approach.

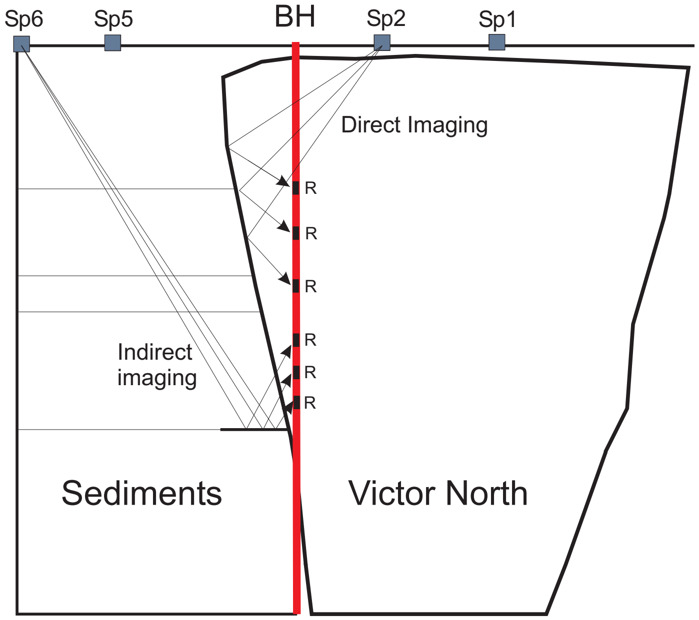


Figure 2: Sketch of the direct and indirect imaging approaches provided by the survey geometry. Shot points located in the sedimentary rocks will provide indirect mapping whereas shot points located inside the kimberlite will allow direct imaging of the kimberlite wall.

1.2 Data Quality

Data quality ranges from fair to very good, depending primarily on shot hole conditions and the level of background noise being created by other activities at the site (mostly drilling and occasional traffic). During acquisition, several shots (5 to 8) were fired at a specific shot location while receivers were kept at the same position. Stacking of shot records improved the signal-to-noise ratio, especially for deeper receiver positions. Stacked vertical components from all shot sites are shown in figure 3. VSP data from sites 1, 2, and 5 have clear and prominent direct arrivals whereas VSP 6, 7, and 8 have weaker first breaks. VSP data acquired with larger source-borehole separation have extremely weak first arrivals at shallow receiver positions (see VSP 8 on figure 3). A closer analysis of these arrivals revealed that they are upgoing waves and probably refracted waves that propagated at the base of the overburden. VSP data from shot points 5 to 8 are also characterized by strong downgoing S-waves, most likely resulting from wave-conversion phenomena at the overburden-kimberlite and/or overburden-sediments interfaces (see figure 3). Both downgoing P- and S-waves will be removed during processing. Upgoing reflections are extremely weak and are only locally observed on VSP 1, 6, 7 and 8.

1.3 Frequency Content

Generally, the frequency content of the seismic data appears to vary as a function of shot hole conditions. VSP data with higher frequency content will produce images with greater vertical and horizontal resolution. In general, shots located inside the kimberlite (SP 1 and 2 on figure 1) produced higher frequencies than those in the sediments. Shot points located close to the kimberlite (SP 5 and 6 on Fig. 2) also provided higher frequencies than shot points 7 and 8. Shot holes 1 and 2 were mostly filled with water whereas the other shot holes were filled with a combination of water and mud which had migrated from the overburden. Figure 4 shows results from a frequency analysis of the vertical component recorded for shot location 2 and 7. The signal is distributed between the 10-40 and 130-160 Hz panels for shot point 2 and between the 10-40 Hz and 70-100 Hz panel for shot point 7. Both datasets have strong amplitudes between 40 and 100 Hz. The frequency spectrum obtained from each VSPs were used to establish the parameters of a bandpass filter (30-40-180-190 Hz) applied early in the processing sequence. For comparison, a frequency bandwidth of 30-450Hz was recorded in the igneous rocks of the Sudbury impact structure (Snyder et al., 2002).

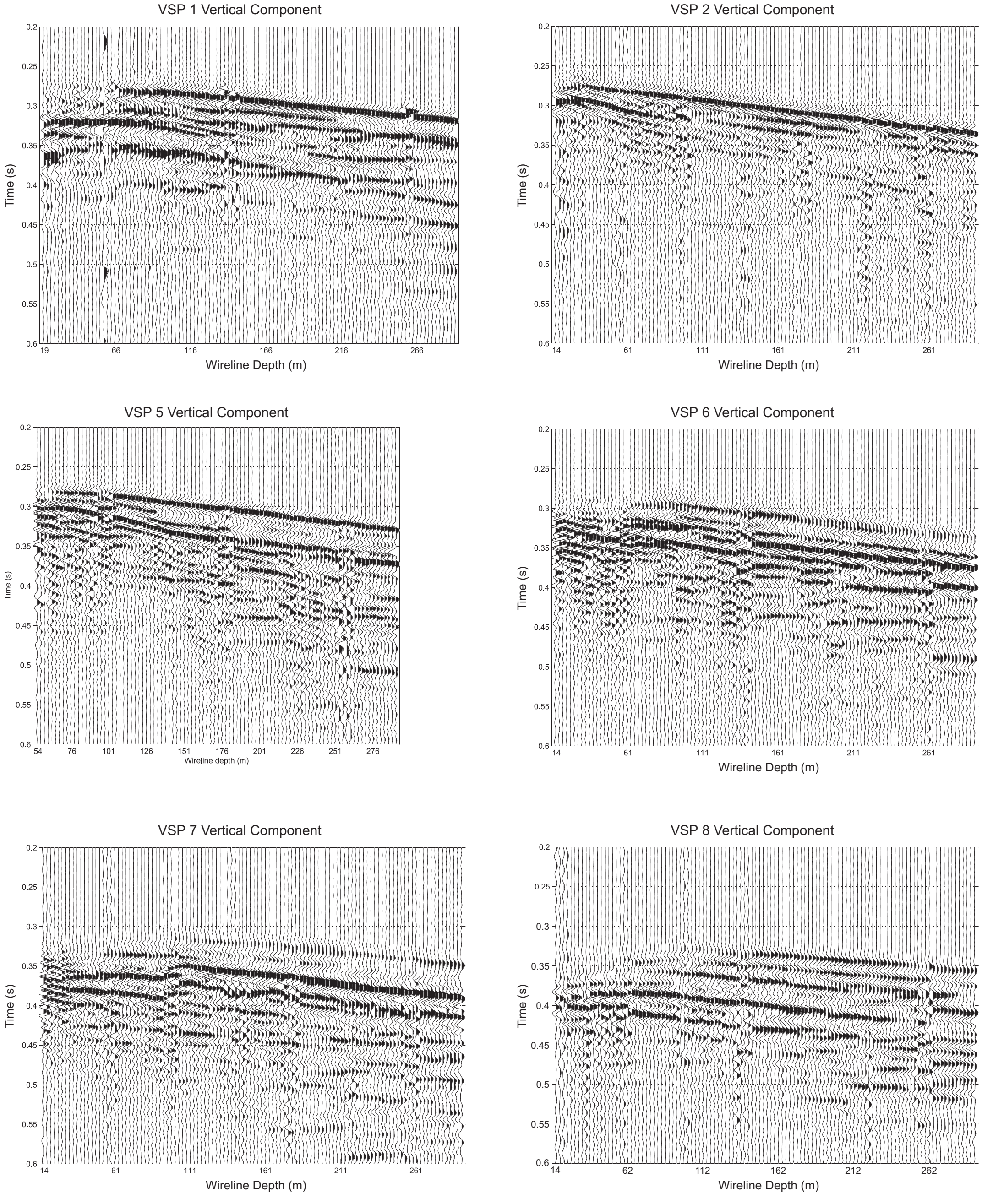


Figure 3: Raw vertical components from all shot sites.

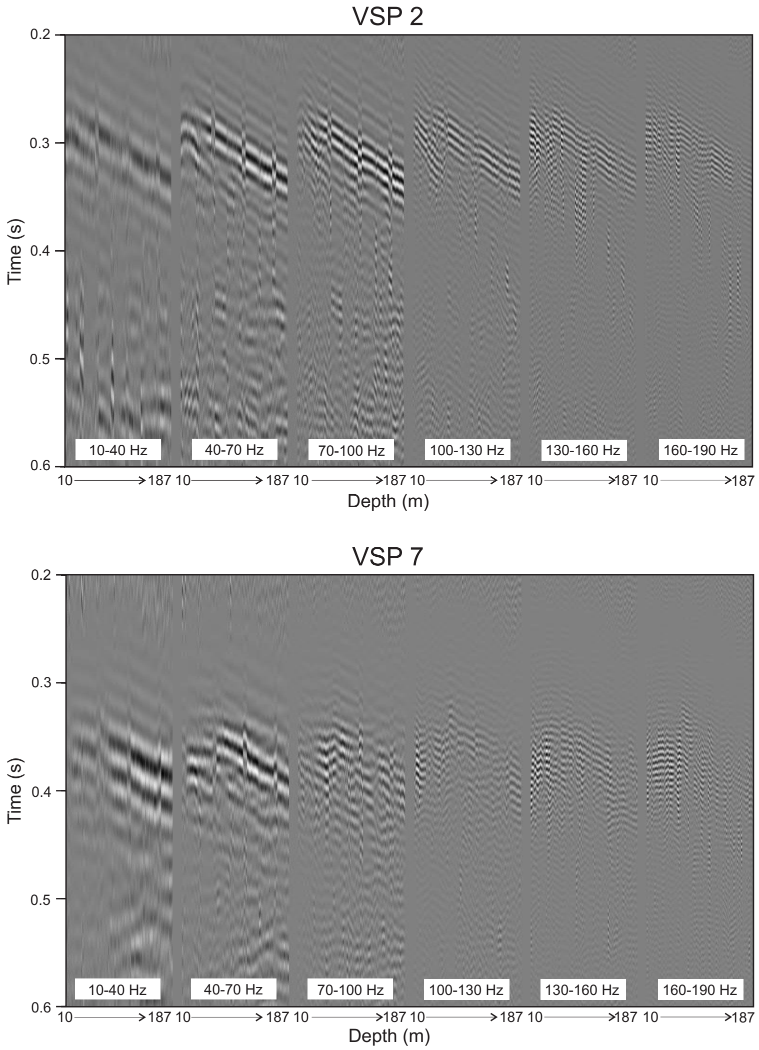


Figure 4: Frequency analysis of the vertical component from shot locations 2 (top) and 7 (bottom). Data acquired with the air gun (VSP 2) have higher frequencies than those acquired with the mud gun. This difference is explained by the different conditions in the shot holes.

2 Indirect Imaging Approach

All VSP data were processed to extract the upgoing wavefield. A summary of the processing flow is listed in table 1. The processing steps applied to the data are described in the following subsections.

2.1 Geometry

The first processing step consisted in converting each SEG2 record to the DSISoft format. The geometry information required for further processing steps were assigned to raw DSI records based on the information contained in the observer notes. The data were then sorted with respect to wireline depth to be ready for stacking.

2.2 Drift Statics and Stacking

During the acquisition, a surface geophone was placed close to the shot holes. The main purpose of the surface geophone was to identify and correct any delays between shots fired at the same location. For most VSPs (VSP 1, 2, 5, and 6) the surface

Geometry	
Sort	Wireline Depth
Bandpass filtering	30Hz-40Hz-180Hz-190Hz
Trace Amplitude Balancing	1s window
Remove ringing from horizontal components	Maximize ringing on 1 component then apply predictive deconvolution: Start of window = 0 s End of window = 1 s Operator lag = 15msec Operator length = 25msec Prewhitening = 1%
Receiver re-orientation	Rotation based on window from 6 msec before to 8 msec after first breaks
Mute	Direct P-wave arrivals
Removal of downgoing P- and S-waves	f-k velocity filter
Spectral Balancing	
Bandpass filtering	70Hz-80Hz-180Hz-190Hz
VSP Kirchhoff Migration	Individual and simultaneous migration of radial and vertical components

Table 1: Summary of processing flow for VSP datasets recorded at the Victor kimberlite.

data was of sufficient quality to estimate the time shifts between each record. In general, the time shifts were short and acceptable (less than 2ms). The time shifts were estimated by cross-correlating the surface traces and subsequently applied to the data to assure optimal stacking. Time shifts could not be established at VSP sites 7 and 8 because of improper geophone planting in the frozen muskeg. Based on the shifts observed at the other sites, this may not have a significant impact on the final results. Traces recorded with the surface geophone during acquisition of VSP 6 and 7 are shown in figure 5.

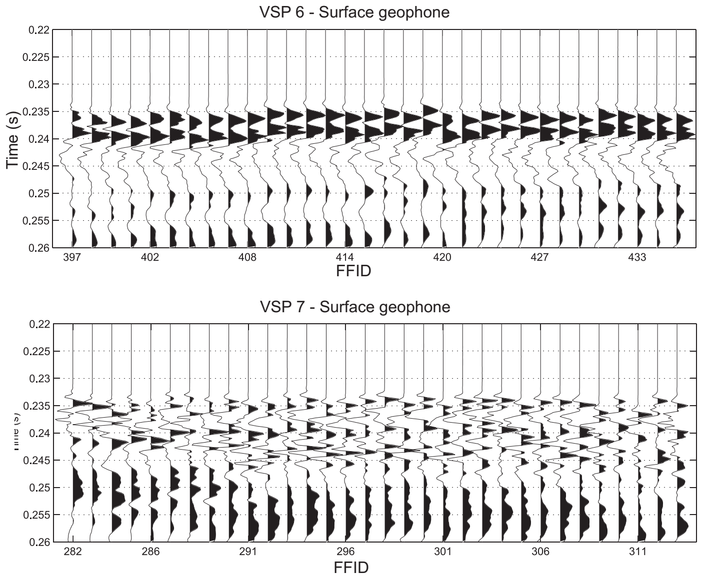


Figure 5: Some seismic traces recorded with the surface geophone close to shot holes 6 (top) and 7 (bottom).The direct arrivals have a shift of approximately ± 2ms on VSP 6. The shift will have to be corrected to improve stacking results. The waveforms of direct arrivals recorded close to shot hole 7 are unusable and are the result of a poorly planted geophone.

2.3 Predictive Deconvolution

The direct P- and S-wave arrivals were followed by reverberations (e.g., ringing) sometimes very strong on the horizontal components and partly masking other seismic arrivals. The reverberations are possibly related to poor coupling between each receiver unit and the borehole wall. The GSC sonde has a three-point support mechanism to stabilize each unit and to reduce angular oscillations about the longitudinal axis of the tool. However, the three-point support system did not provide satisfactory coupling everywhere in the recording borehole. During a previous survey in new Brunswick, reverberations were found to be more problematic in boreholes with irregular walls (Bellefleur et al. 2003). This may locally be the case for the recording borehole at Victor.

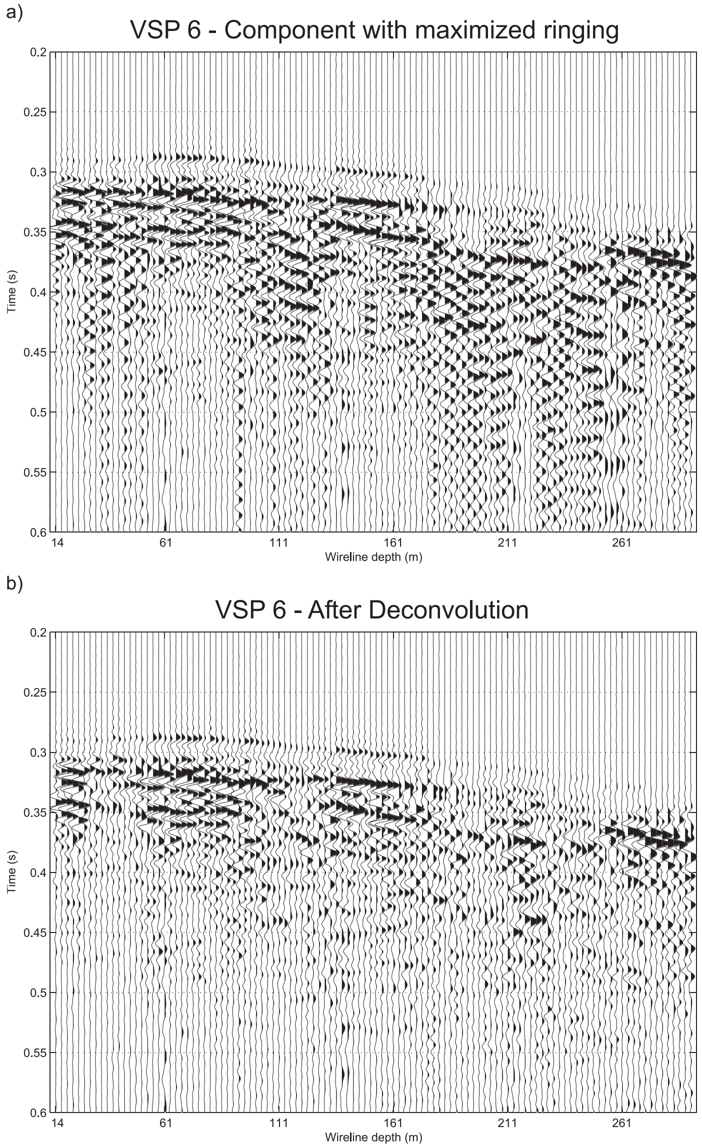


Figure 6: a) Horizontal component with ringing energy maximized. Predictive deconvolution was applied to this component. b) Same component after deconvolution. Ringing is clearly attenuated. This component was rotated back to its original position for the next processing step.

A predictive deconvolution operator was designed to remove the reverberations observed after direct P- and S-waves arrivals. Predictive deconvolution was not applied to individual horizontal components, but to a combined component with maximized reverberation contents (Figure 6a). The reverberations behaved similarly to polarized waves and can be maximized into one horizontal component on which the predictive deconvolution provided improved results. A polarization analysis technique used to orient a triaxial VSP geophone (DiSiena et al., 1984) was applied to maximize reverberations on one component. The polarization analysis window consisted of the entire trace without any gain applied to the data. After deconvolution, the horizontal traces were rotated back to their initial orientation. Figure 6b shows the horizontal component with maximized reverberations after predictive deconvolution.

2.4 Receiver Orientation

The three-component geophone array used by the consortium is not equipped with an external guidance system. As a consequence, the directions of the horizontal components are unknown during acquisition, but have to be established during processing. The direction of the horizontal geophones were deduced from polarization analysis of the direct P-waves arrivals following a procedure described in DiSiena et al. (1984). The two horizontal components are mathematically rotated until the direct P-wave arrival has maximum amplitude on one component. This approach assumes that direct P-waves propagated in the plane defined by the borehole and shot point. The two horizontal components at each receiver location were transformed into radial and transverse components. The radial components point towards the shot location whereas the transverse components are orthogonal to that direction. Figure 7 shows horizontal components from shot sites located in the sedimentary rocks after receiver re-orientation.

2.5 Removal of the Downgoing Wavefield

The downgoing P- and S-waves were suppressed from the data with velocity filters applied in the frequency-wavenumber (f-k) domain (Hardage, 2000). The seismic data were first transformed in the f-k domain using 2-D Fourier transform. The area of the spectrum containing the unwanted downgoing events was then muted and the filtered

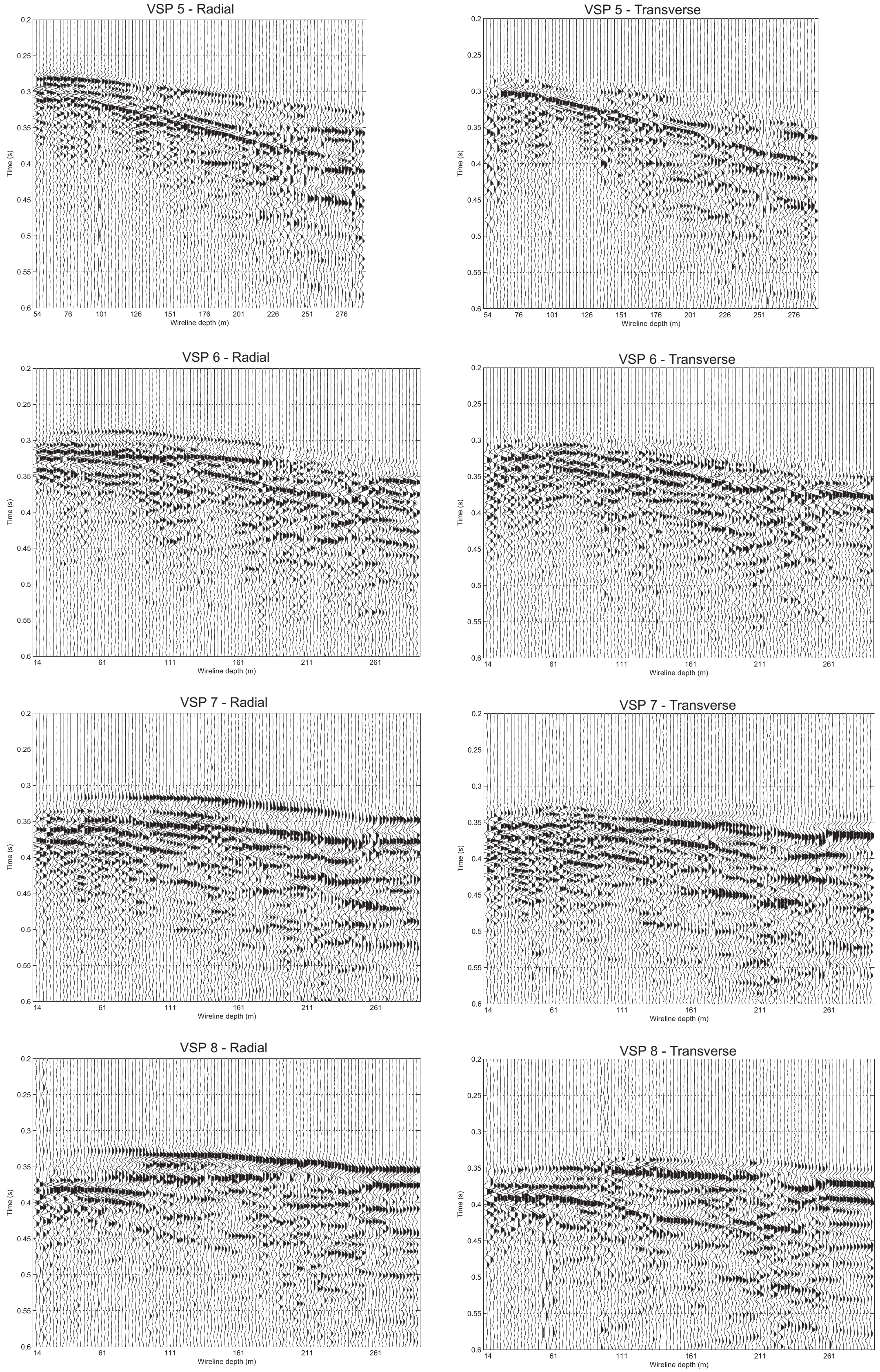


Figure 7: Radial and transverse components from VSP shot sites 5, 6, 7, and 8.

data transformed back into the time-depth domain. Median filters (Hardage, 2000) which are often used to separate the downgoing and upgoing wavefields on VSP data were also tried on the Victor datasets. Median filters are usually applied on a narrow window around the downgoing waves and preserve most of the data from unnecessary filtering. However, median filters did not provide satisfactory results because of the inconsistent waveform of the first arrivals. The first arrivals comprise direct waves at depth but also refracted waves with different waveform for receivers located in or close to the overburden. VSP data after the application of the f-k filter are shown in figures 8, 9, and 10. The upgoing wavefields obtained from this processing step were used for migration.

2.6 Imaging Results

A 3-D VSP Kirchhoff migration algorithm (Dillon, 1988) was used to migrate the Victor Data. To control artifacts due to the limited aperture inherent to the VSP geometry, the dips on migrated images were limited to ± 7.5 degrees from the horizontal. The trace spacing and depth sample rate of the output migrated image are 2m and 2m, respectively. The radial and vertical components were migrated separately and simultaneously. In theory, results from the simultaneous migration should be the most representative of the subsurface along the seismic section. During simultaneous migration, the two components were combined with weights which depend on the energy arrival angle at the receiver. Migration results are shown in a following subsection after a short discussions on migration velocities.

2.6.1 Velocity Estimates

The velocities used for migration were obtained from the average velocity calculated from direct P-wave arrivals. A linear regression through the first break picks provided the velocity (slope) and the near-surface delay time (intercept). These values were used to migrate reflections from the sediments (down to 325m) whereas basement reflections (deeper than 325m) were migrated with a velocity of 6100 m/s obtained from measurements on Precambrian core samples. The average velocities estimated from first arrivals were also used over the small portion of kimberlite between the sediments and the borehole. Figure 11 shows first break picks, velocity, and delay time obtained for all shot locations. Estimated P-wave velocities vary between

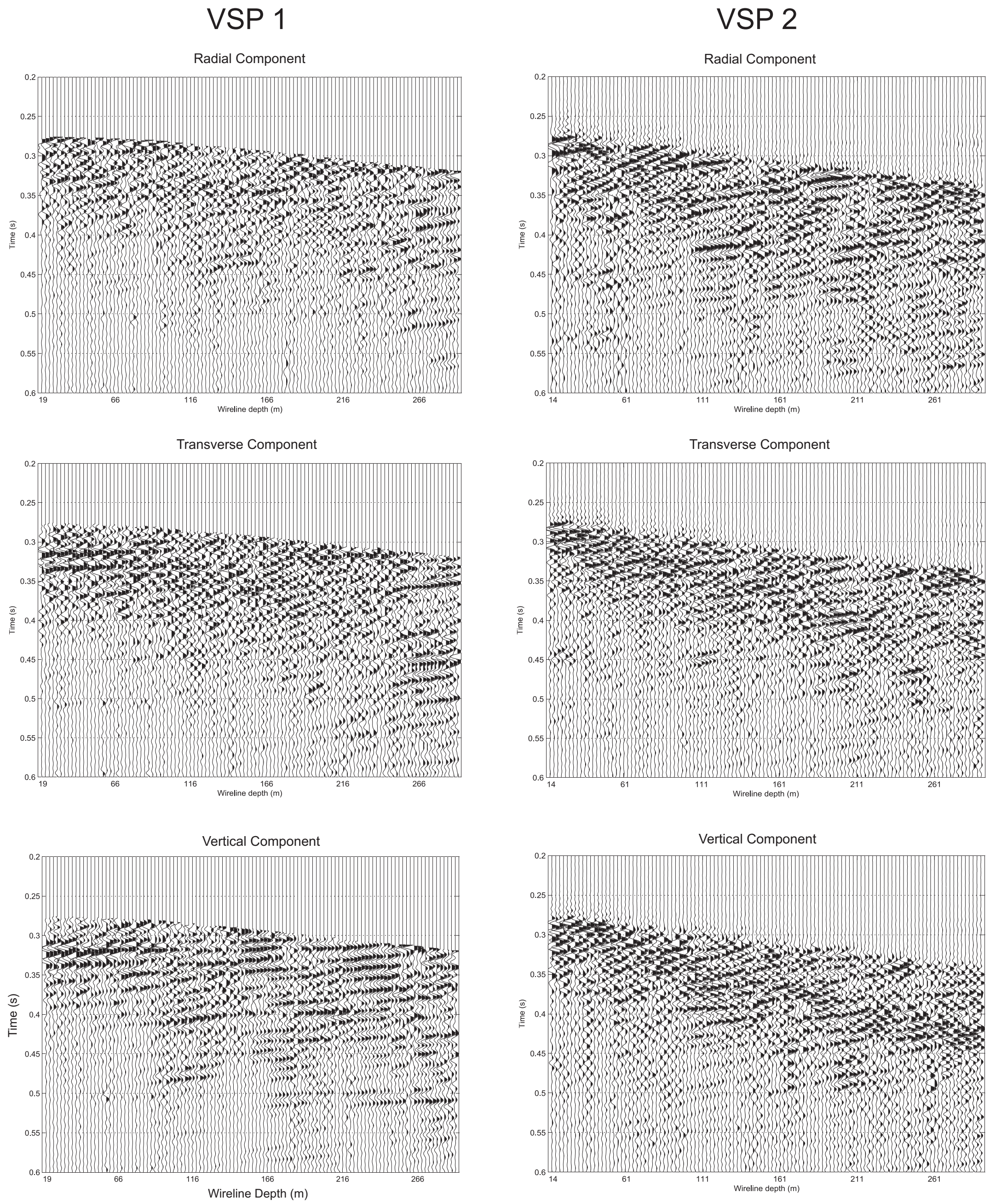


Figure 8: VSP data from VSP site 1 and 2 after fk-filtering.

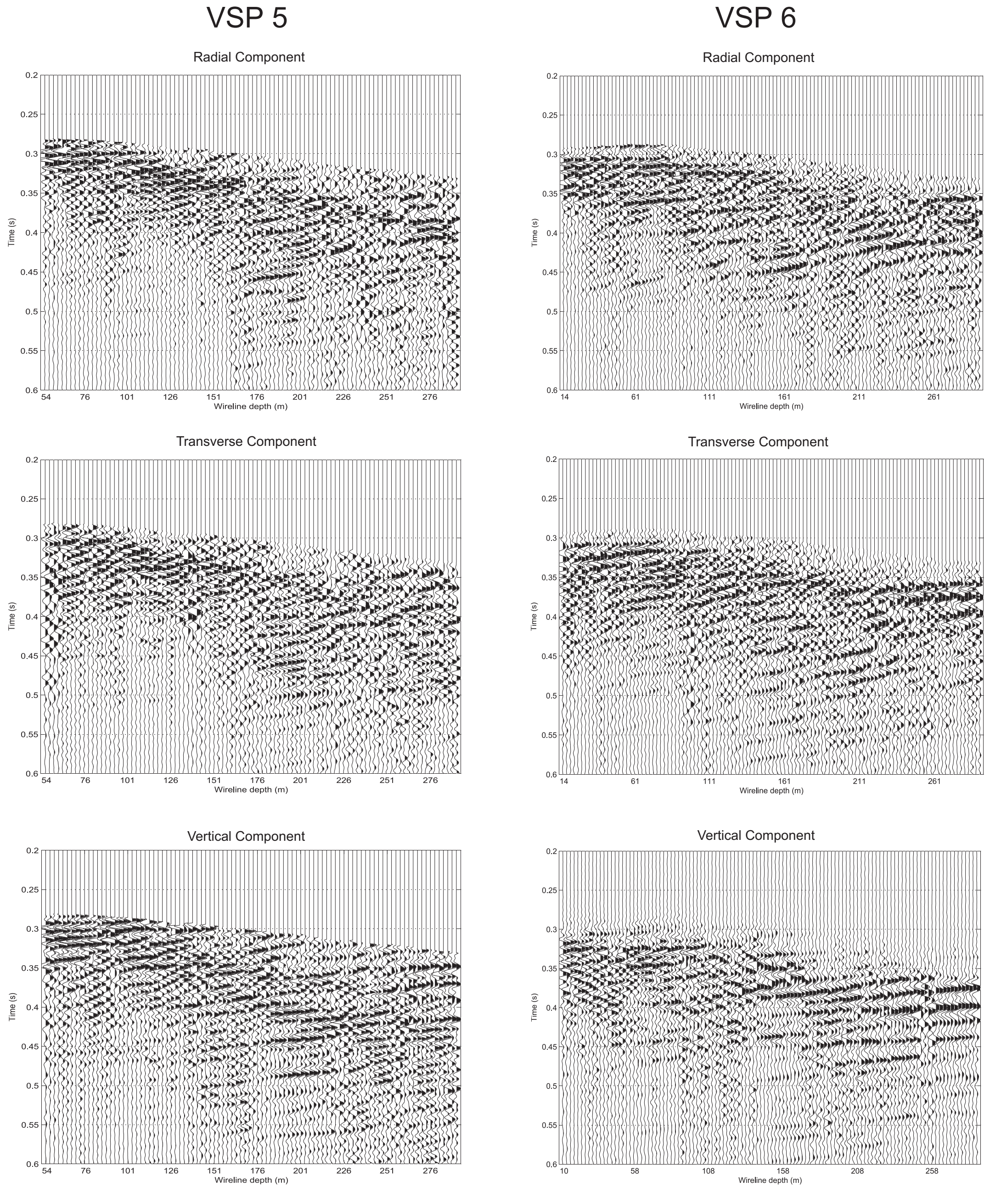


Figure 9: VSP data from VSP site 5 and 6 after fk-filtering.

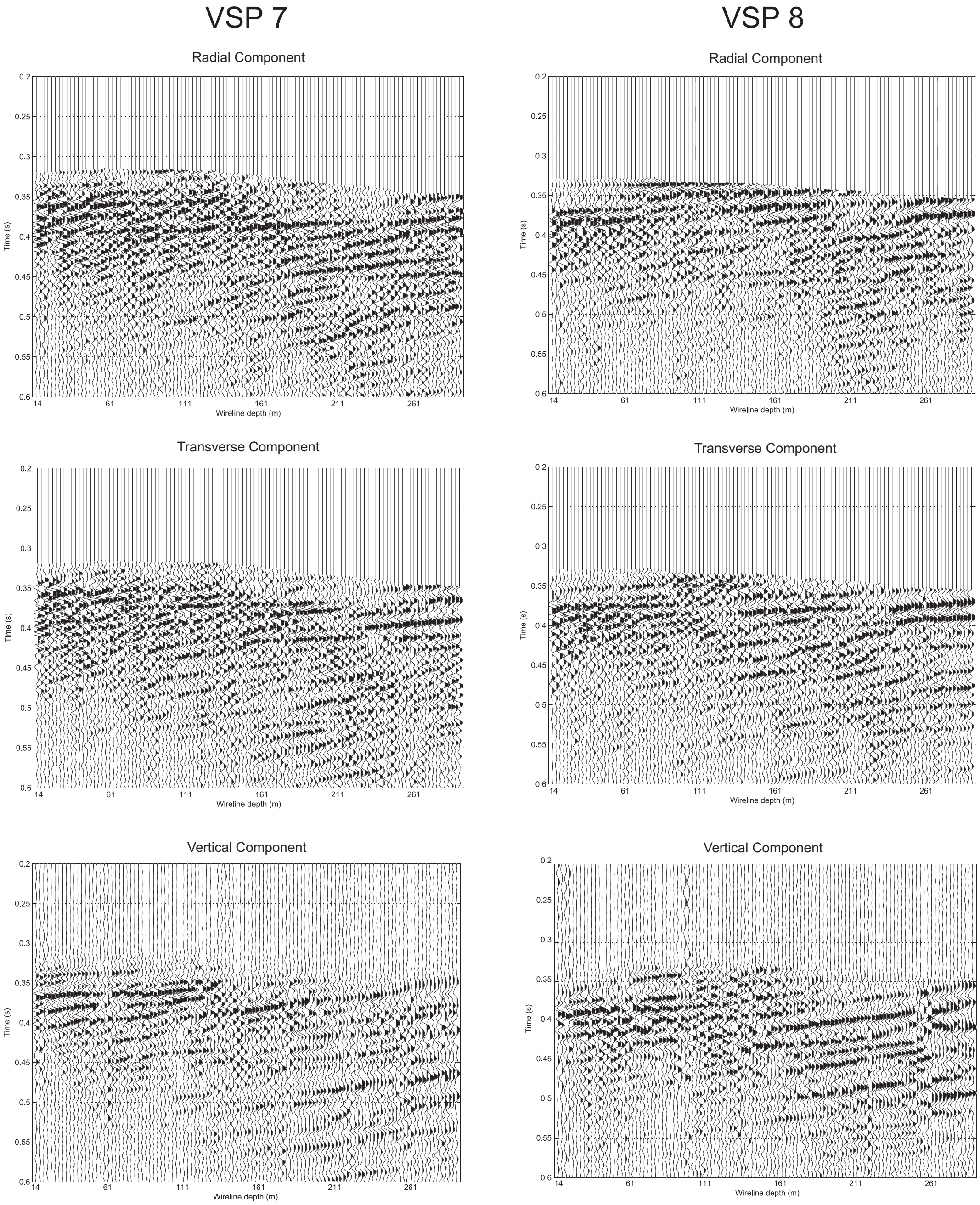


Figure 10: VSP data from VSP site 7 and 8 after fk-filtering.

3766 m/s and 4585m/s. Higher velocities were obtained for the shot sites located in the kimberlite (4585m/s and 4015m/s) whereas first arrival times from VSPs in the sediments defined lower velocities (3766m/s to 3880m/s). VSP 8 provided a significantly higher velocity which did not produced satisfactory migration results. Data from VSP 8 were migrated with a lower velocity (3900m/s).

In general, the velocities estimated from the first arrivals are lower than those measured on rock samples. For the two shot points located in the kimberlite, our estimated velocities are within the range of velocities obtained from borehole logging in hole V-86-99 (Figure 12). This borehole intersects the kimberlite down to approximately 160m and sedimentary rocks between 160 and 180m. Velocities measured in this short intersection of sedimentary rocks are significantly lower (between 2000 and 3000m/s) than velocities estimated from first breaks or from rock samples and may indicate the presence of a low-velocity transition zone near the kimberlite wall. The hypothetical low-velocity zone was not considered during migration.

2.6.2 VSPs in the Sediments

Migration results for VSP sites 5, 6, 7, and 8 and shown in figures 13, 14, 15, and 16, respectively. On these figures, images shown at the top of the page display results obtained from the separate migration of the radial and vertical components. The image at the bottom of the page displays results from the simultaneous migration of the two components. Several observations can be made from these results:

1. It is difficult to correlate reflections across each VSP sections.
2. VSP 5 and 6 have the highest vertical resolution whereas VSP 7 and 8 have the lowest.
3. Correlation of reflections between the radial, vertical and simultaneous radial-vertical migrated sections of a specific VSP is not always trivial.
4. Truncation of reflections does not necessarily match with the kimberlite wall defined from drilling. Best results were obtained for VSP 6, worst results for VSP 8.
5. VSPs with shorter offsets have clearer reflections at shallow depths (compare VSP 5 and 8).

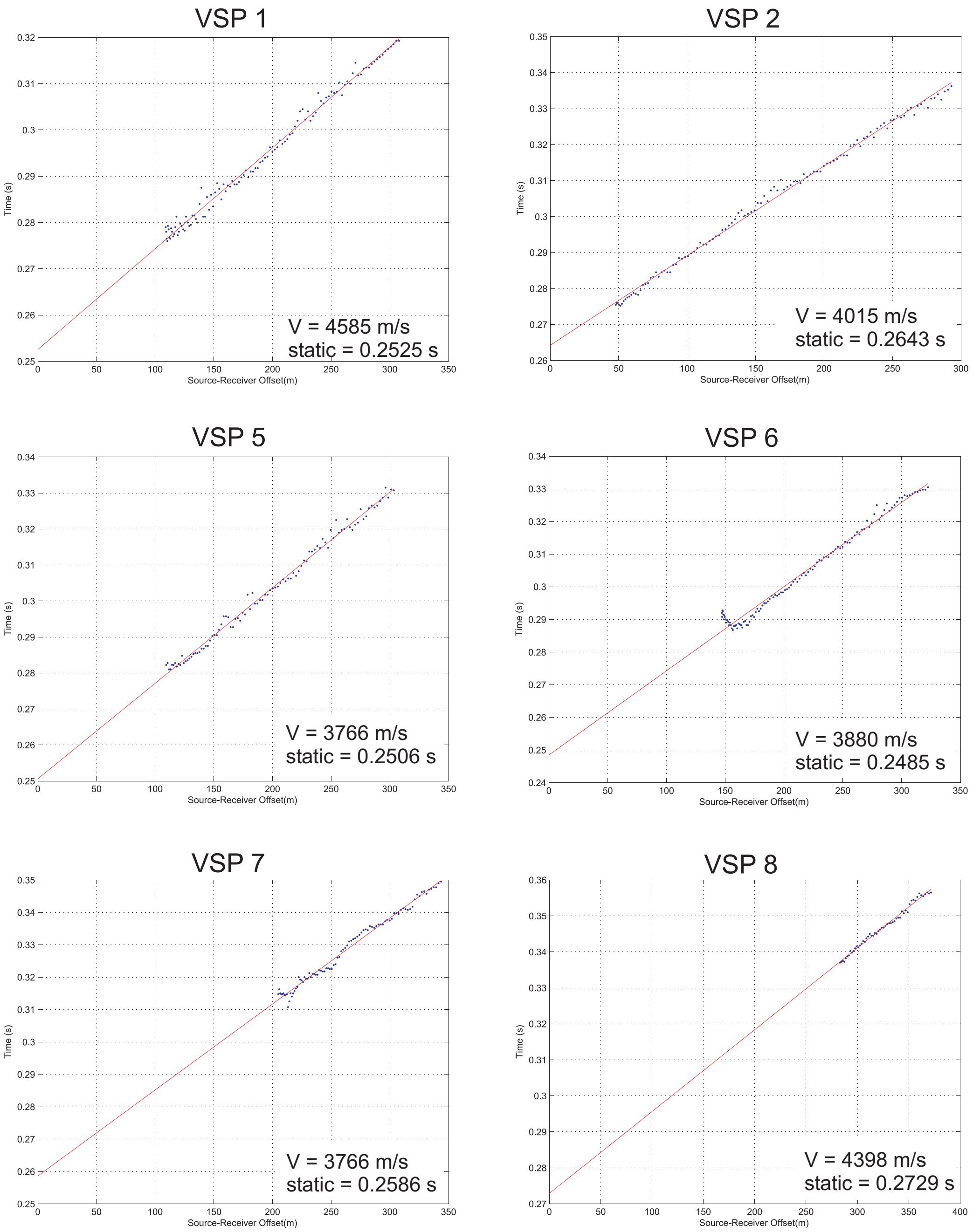


Figure 11: Velocity estimated by fitting a line through the direct P-wave arrivals from all VSP sites. The intercept at the origin gives an estimate of the near-surface delay times.

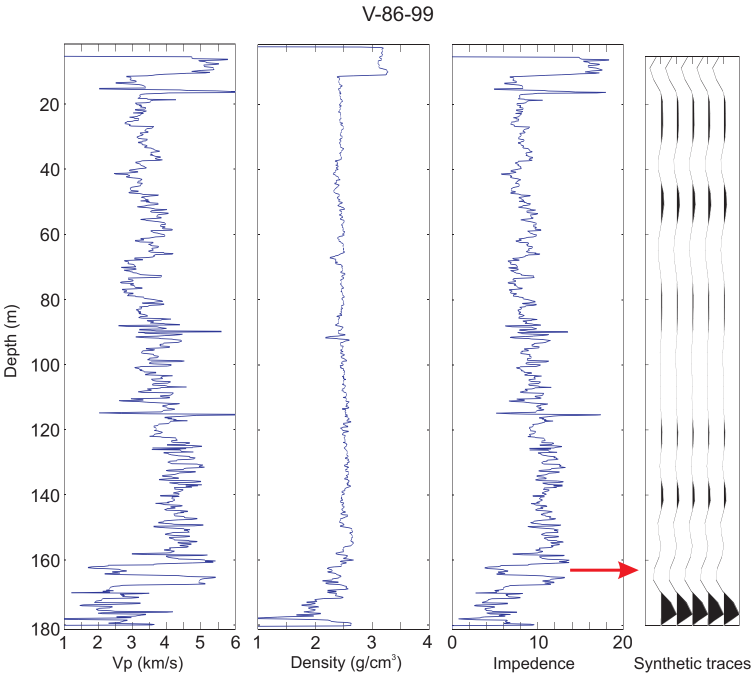


Figure 12: P-wave velocity, density, acoustic impedance and synthetic traces for borehole V-86-99. The synthetic traces were calculated by convolving the reflectivity series with a 60Hz Ricker wavelet. The borehole exits the kimberlite to enter the sedimentary rocks at 160m. The impedance contrast at the kimberlite-sediment contact is sufficient to produce a detectable reflection (arrow). The low velocities in the sediments may be attributable to a transition zone near the kimberlite wall. The synthetic traces also suggest that the kimberlite has a low internal reflectivity.

Observations 1 and 2 can be partly explained by the different bandwidth of each data set. The different velocities used for migration may also complicate the correlation of reflections across each VSP sections. A comparison of the migration sections of the radial and vertical components (separate migration) revealed a difference in bandwidth between these two components. In general, the vertical components are characterized by a higher frequency content. This bandwidth difference confirmed by a spectral analysis (not shown), most likely explains why correlation of reflections between the two migrated components is not always easy. It could also explain why simultaneous migration of the two components did not always provide improved results. Observations 4 and 5 can be explained by the varying location of the kimberlite wall relative to the recording borehole and shot locations. The migration velocity and selected parameters also influenced the locations at which truncation of reflections are observed.

In an attempt to improve the vertical resolution and homogenize the appearance of all migrated sections, we applied spectral balancing and a bandpass filter (70-80-180-190 Hz) to the radial and vertical components. All components were also migrated with a constant velocity of 3765 m/s. Results from the simultaneous migration of balanced radial and vertical components from site 5, 6, 7, and 8 and shown in figures 17, 18, 19, and 20, respectively. All sections have a more uniform appearance. However, sections for VSP 7 and 8 still have a slightly lower frequency content than VSP sections 5 and 6. As a result, correlation are easier to establish between VSP 5 and 6 or between VSP 7 and 8.

The migrated section from VSP 5 displays several reflections, some clearly corresponding to contacts between formations. Others located within formations (e.g., reflections within the Ekwan River Formation) cannot be correlated to specific horizons due to the lack of knowledge of the reflectivity sequence within the sedimentary rocks. Borehole logging (density and velocity) or a zero-offset VSP acquired in a borehole located in the sediments could provide this information. VSP 6 shows similar reflections but they are not as well defined as on the migrated section from VSP 5. The lack of definition on this section partly results from differences between reflections of the radial and vertical components. VSP 7 and 8 display many reflections but not at exactly the same depth locations, indicating that the constant velocity used for migration (3765 m/s) is not appropriate.

The location of the kimberlite wall is best determined from VSP 6 and 7. Reflections on the migrated section from VSP 8 are approximately 20m away from the kimberlite wall (e.g., the two reflections within the Ekwan River Fm.) whereas those from VSP 5 clearly extend within the kimberlite, especially at shallow depths. In addition, the kimberlite wall is poorly imaged at shallow depths for all VSPs, reflecting certain limitation of our survey geometry (see discussions below).

2.6.3 VSPs in the Kimberlite

The two VSPs acquired in the kimberlite are also characterized by upgoing seismic events which probably contain information related to heterogeneities or structures within the pipe. In particular, the vertical component from VSP 1 displays

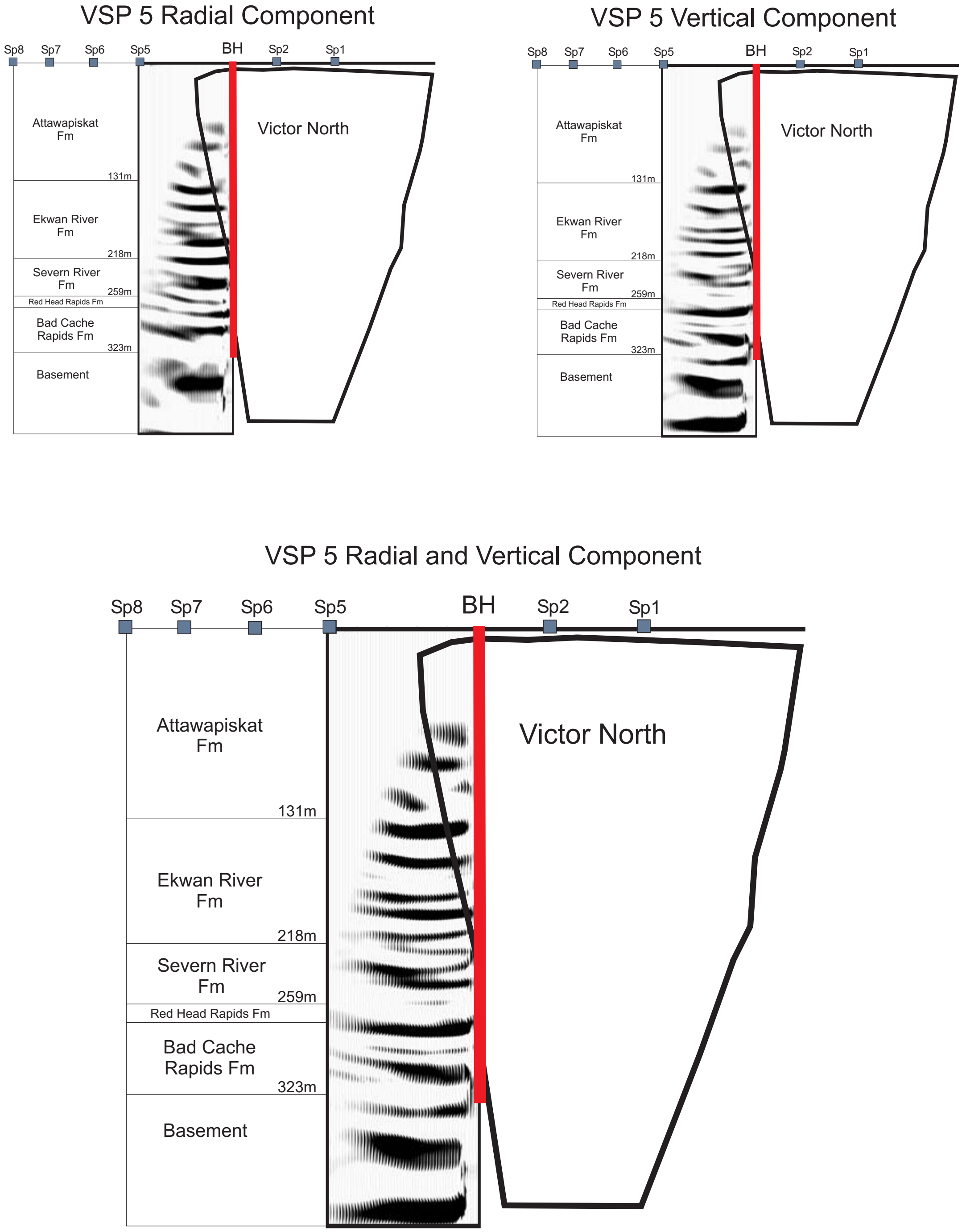


Figure 13: Migration results for VSP 5.

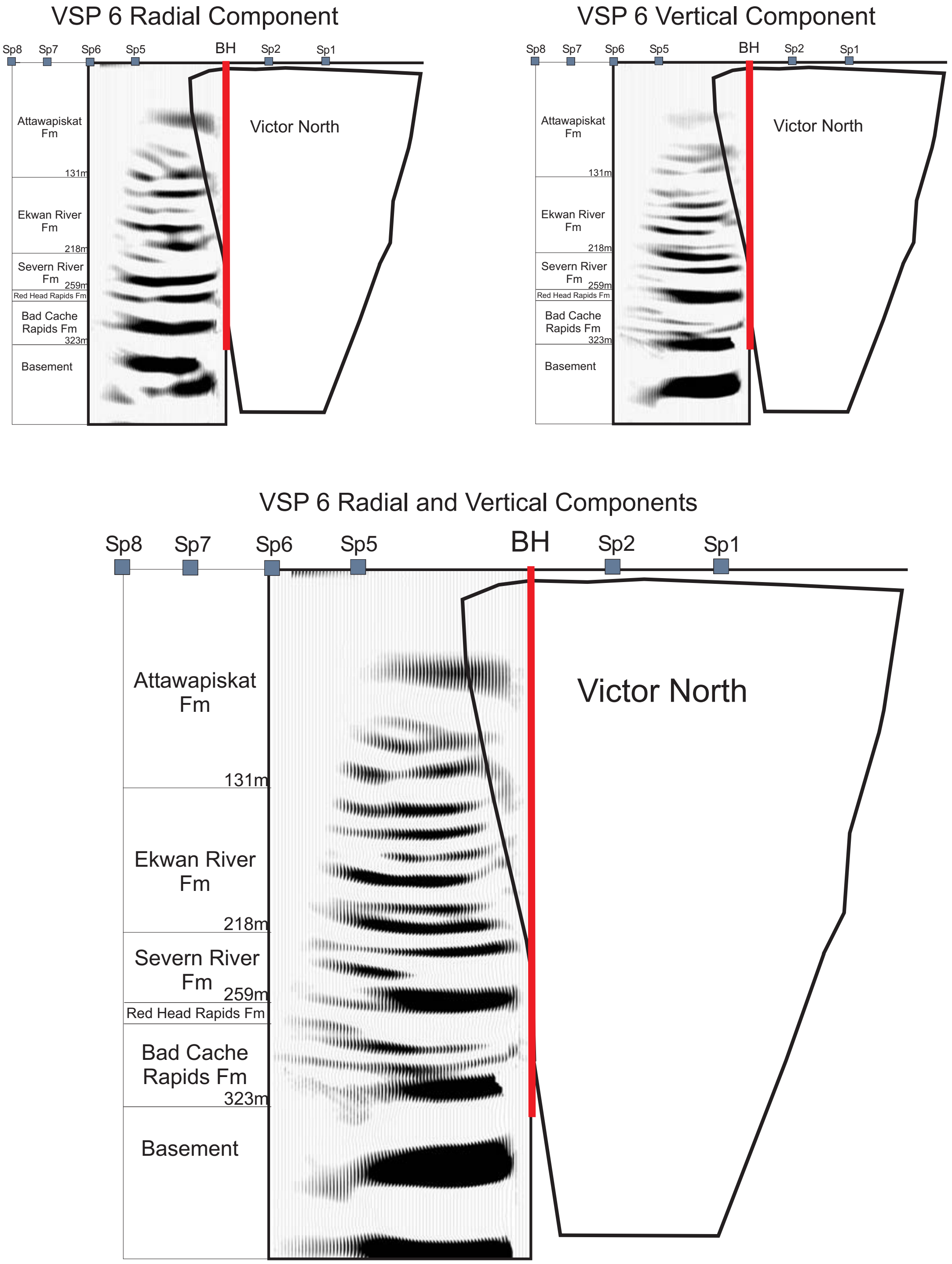


Figure 14: Migration results for VSP 6.

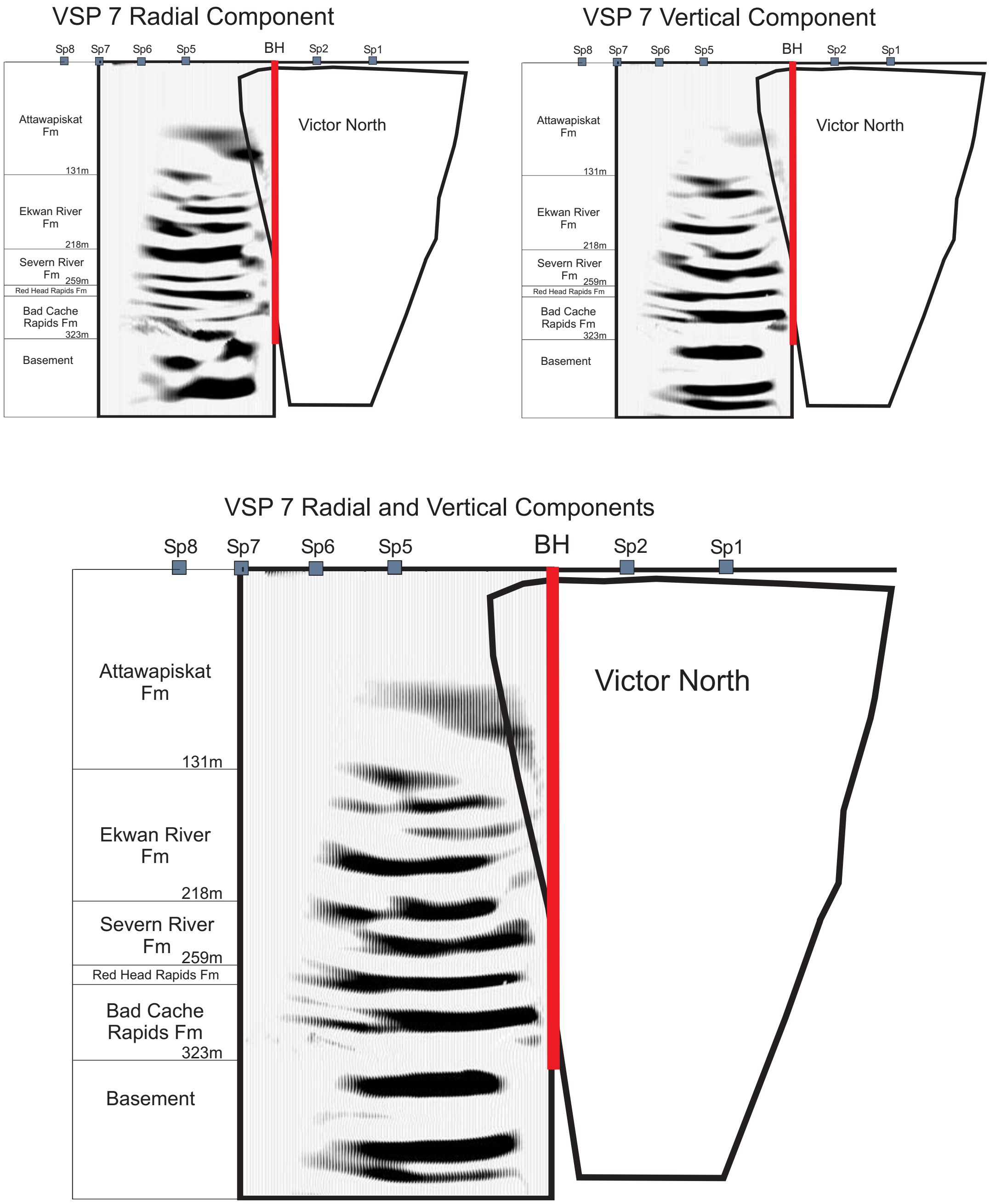


Figure 15: Migration results for VSP 7.

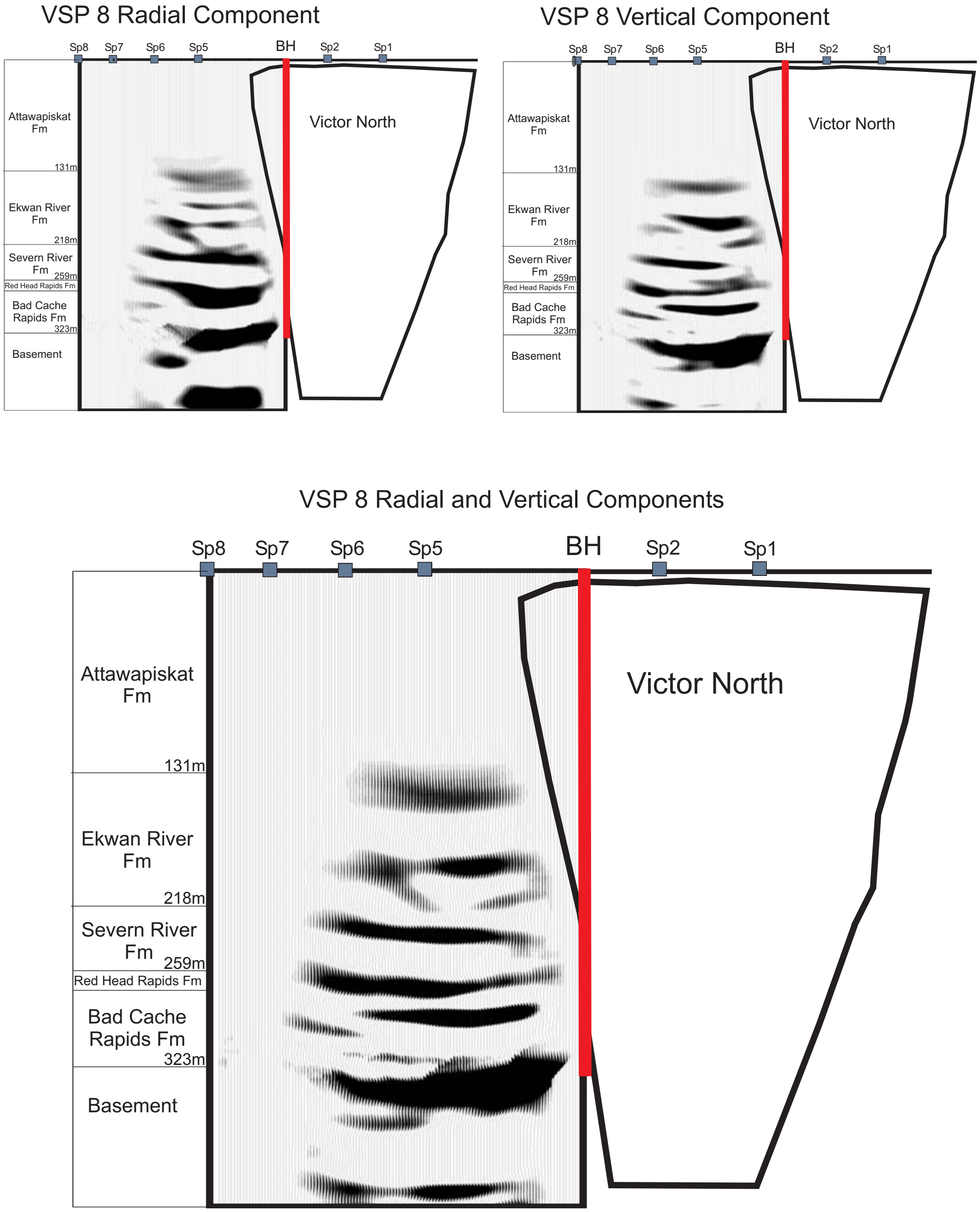


Figure 16: Migration results for VSP 8.

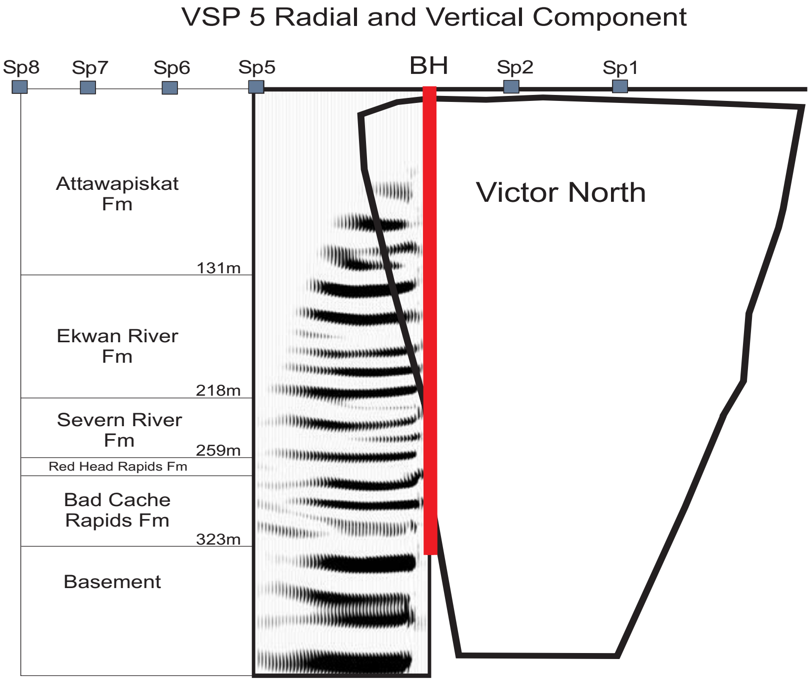


Figure 17: Migration results for VSP 5 data set after spectral balancing.

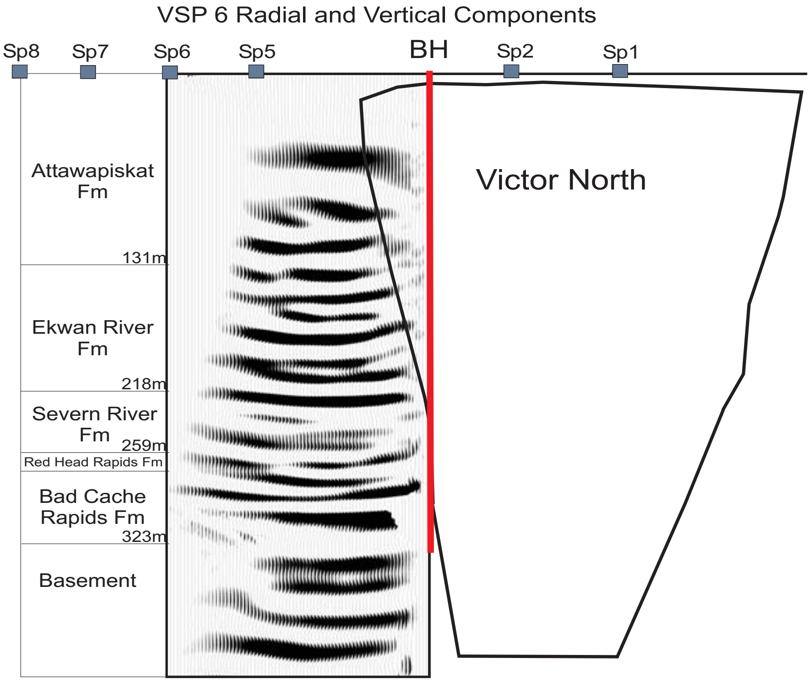


Figure 18: Migration results for VSP 6 data set after spectral balancing.

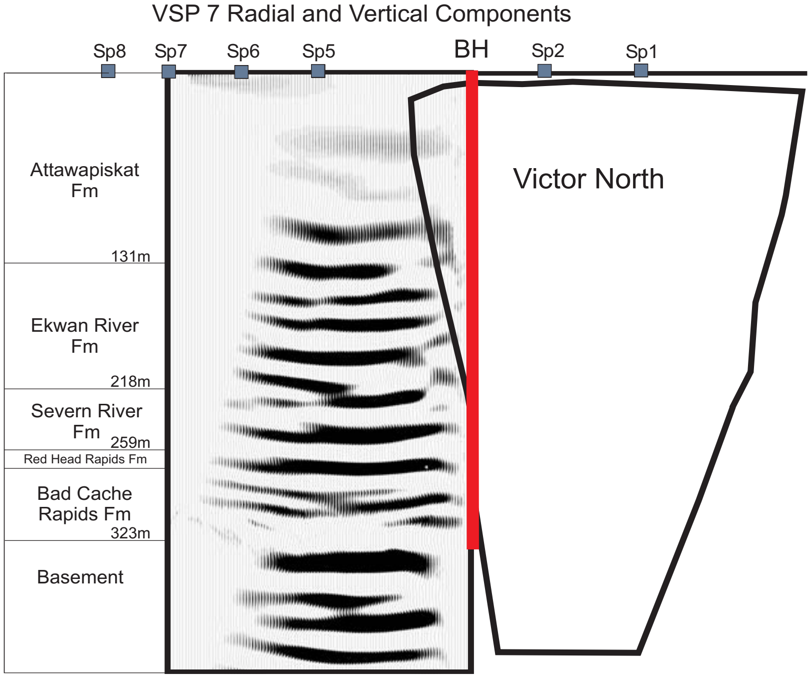


Figure 19: Migration results for VSP 7 data set after spectral balancing.

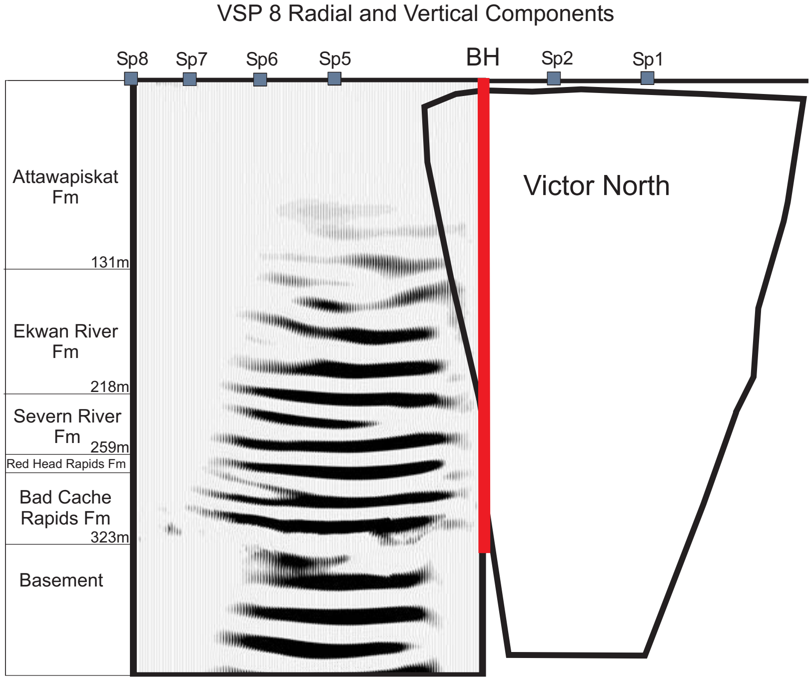


Figure 20: Migration results for VSP 8 data set after spectral balancing.

an unexpected upgoing field with many prominent reflections. The radial and vertical components of VSP 1 and 2 were tentatively migrated to reveal reflectors within the pipes (figure 21). All dips were allowed in the migration as no a priori geological assumptions can be used for the internal heterogeneities and structures of the kimberlite. Both VSPs were also migrated simultaneously to improve the ray coverage. However, migration results in figure 21 are characterized by severe artifacts which indicate that ray coverage is insufficient to produce an adequate image with full aperture migration.

One reflector on figure 21 intersects the borehole at approximately 230m and likely corresponds to the kimberlite-sediments contact. The true position of this reflector cannot be established because it is smeared across the section by migration. At this stage, it is not possible to clearly identify the origin of the other reflectors located in the kimberlite (heterogeneities, wall rock strata truncations, structures or seismic energy bouncing within the kimberlite).

More information about the internal heterogeneities and structures of the kimberlite combined with advanced seismic modelling would be necessary to understand their origin. In addition, the synthetic data could be used to determine if heterogeneities and structures can be imaged with borehole seismic methods. The modelling work would require a detailed geological model of the pipes including all heterogeneities and their associated physical rock properties. This work is beyond the scope of this data processing exercise.

3 Direct Imaging Approach

Downgoing wavefield from VSP 1 and 2 potentially contains reflected arrivals from the kimberlite wall. We calculated traveltime to the kimberlite wall for our survey geometry to establish where these arrivals would be located in the data. Traveltimes were calculated using a simple geometric ray modelling approach assuming that an object can be represented by point scatterers on its surface. In this case, scatterers were located on the kimberlite wall (figure 22). This approach accurately calculates traveltimes but does not account for the dynamics of the reflected amplitudes. We simulated a homogeneous background with P- and S-waves velocities of 4000m/s and 2080m/s, respectively. These velocities were determined from direct P- and S-wave traveltimes from VSP site 2.

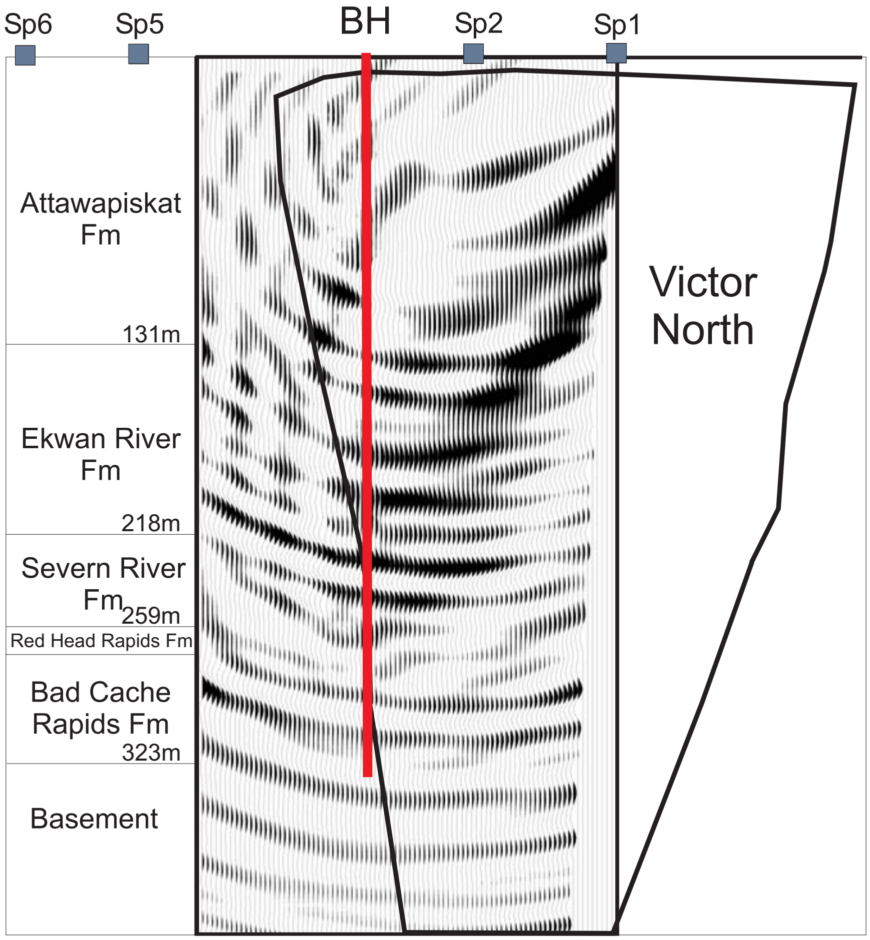


Figure 21: Migration results of the upgoing wavefield from VSP 1 and 2.

Traveltimes for downgoing P- and S-waves and for kimberlite reflections are shown in figure 23a, b and c, respectively. Figure 23d shows the combination of all arrivals. The kimberlite reflections should occur in a limited window between the direct P- and S-wave arrivals. These results also show that delays between the direct P-waves and the downgoing reflections decrease with increasing depths. The vertical component from VSP 1 displays downgoing arrivals in the expected time window which could correspond to reflections from the kimberlite wall. Thus, this component was migrated to test our approach. Instead of migrating all the data on this component, we extracted and migrated a window of data around expected downgoing arrivals obtained by modelling (figure 24). This minimizes the potential interference with other events observed on the vertical component. Migration was performed by allowing vertical dips ±40°and results are shown in figure 25. The results are not really

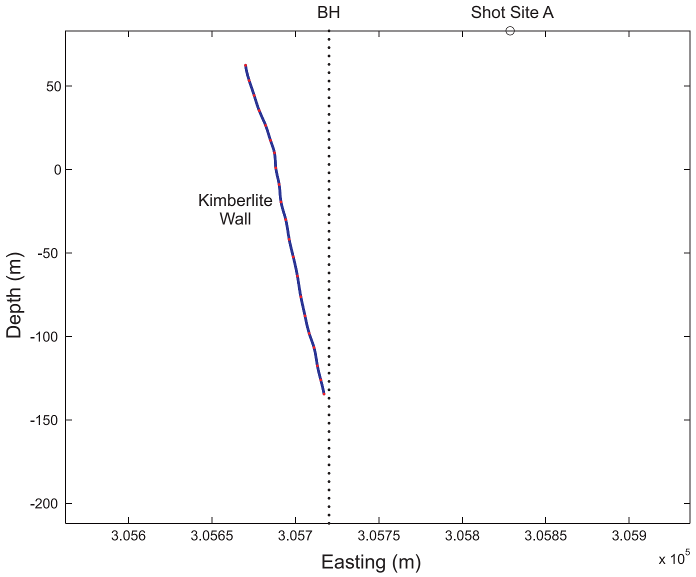


Figure 22: Geometry used for traveltime modeling of the downgoing arrivals reflected on the kimberlite wall.

convincing even if most of the migrated energy is located near the known kimberlite position. The migrated image also shows artifacts suggesting that ray coverage with our survey geometry is insufficient for this imaging approach. There is also a possibility that kimberlite wall reflections interfere with diffraction produced where strata boundaries are truncated by the pipe.

4 Discussion

The migrated images show that the indirect mapping approach has some potential to define the geometry of the kimberlite at depth. Despite these encouraging results, we identified two physical limitations that likely influence the interpretation of the pipe wall location from seismic images.

The first limitation is related to the acquisition geometry. The kimberlite margin was located too close to the edge of the migrated section defined by the recording borehole and, therefore, is in an area where migration results are less reliable. This limitation can easily be resolved in future surveys by selecting a borehole located further inside the kimberlite (for example a recording borehole located at shot point 1). Such a borehole location would also help the separation of the direct and re-

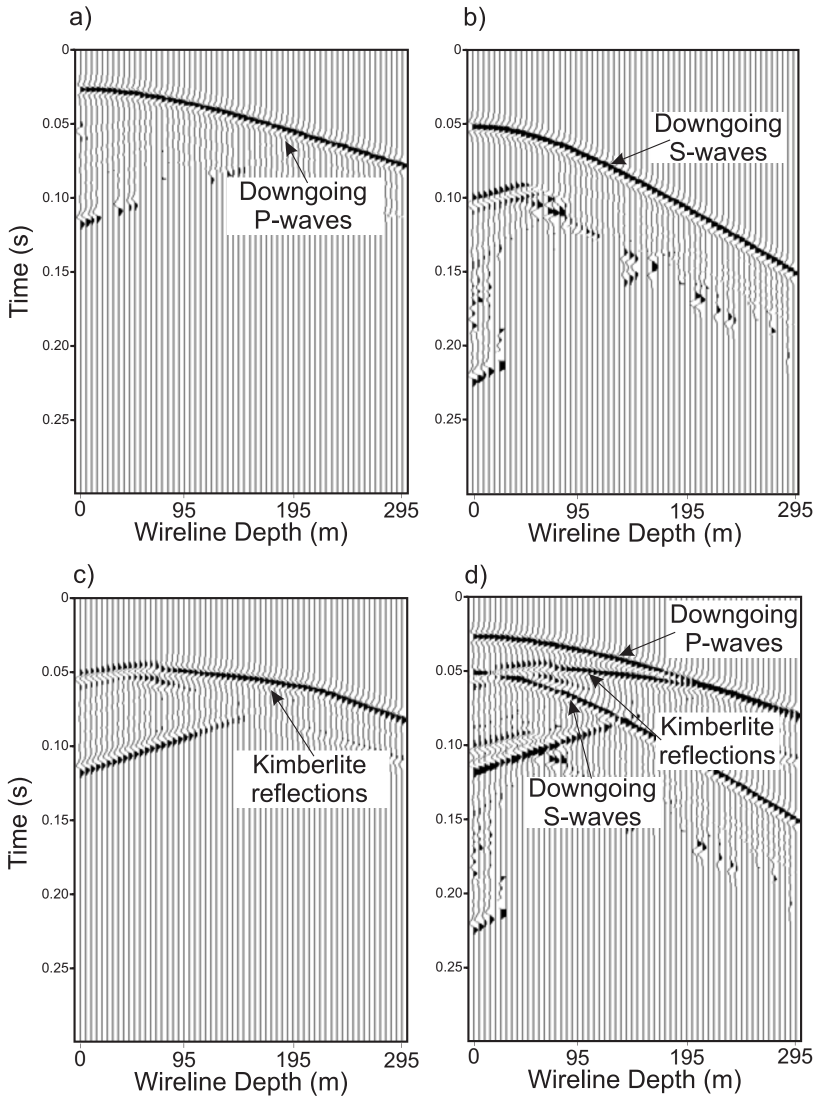
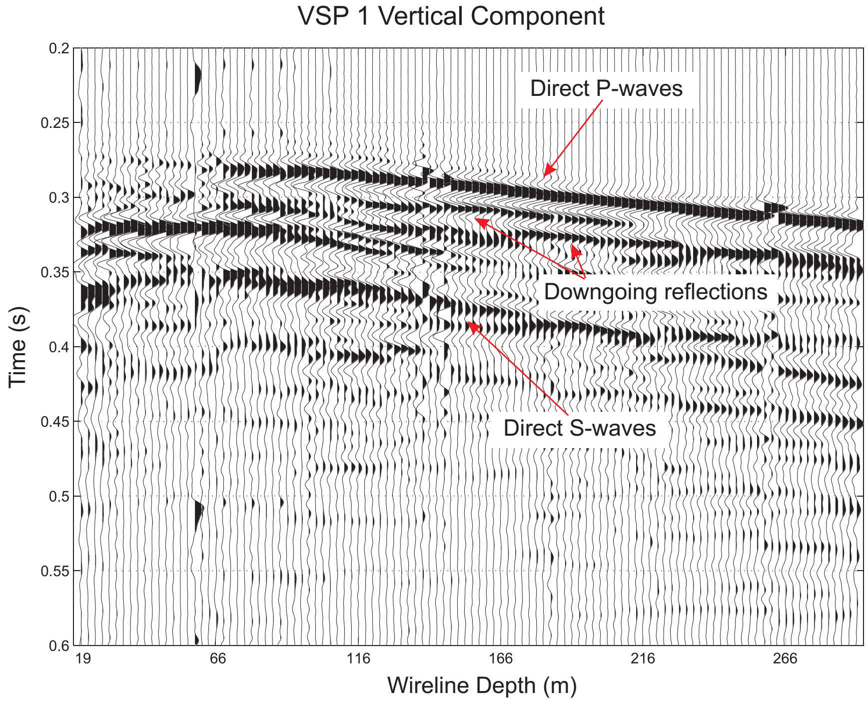


Figure 23: Traveltime modeling of the kimberlite wall for a shot located at VSP site 1. Only the vertical component is shown. a) Direct P-wave arrivals only. b) Reflected arrivals only. c) Combination of the direct and reflected arrivals. The modelling does not take into account the statics due to overburden. Noise on each pannel originates from the application of an AGC gain function.

flected downgoing arrivals from the kimberlite wall for the direct imaging approach by allowing larger delays between the two arrivals.

The second limitation is associated with the frequency content of the data. VSP data with higher frequencies will have higher vertical and horizontal resolution and are likely to produce a sharper image of the kimberlite margin. Unfortunately, the



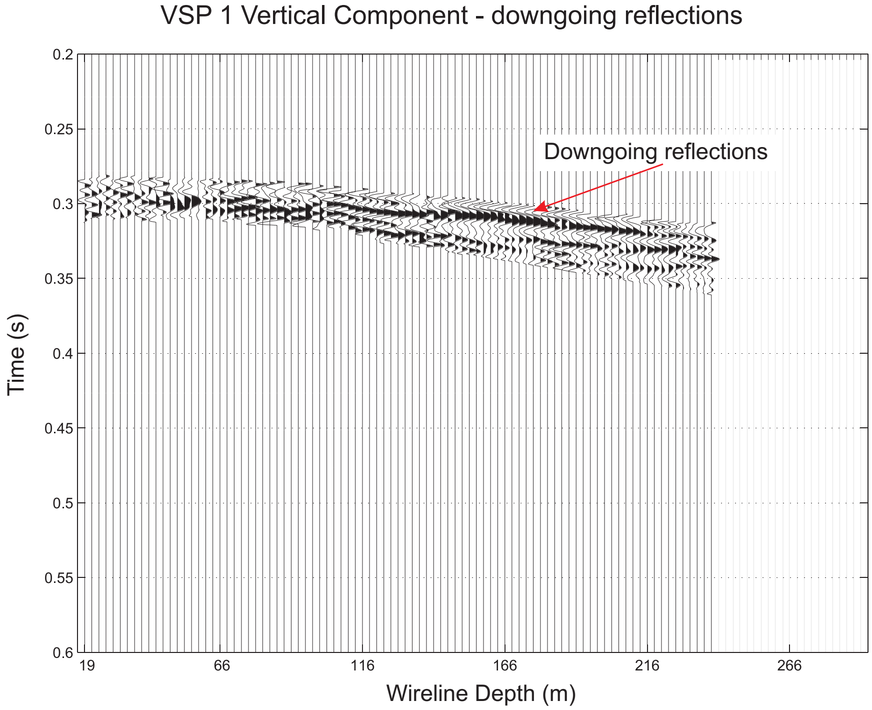


Figure 24: Vertical component of VSP1 showing a downgoing event which could correspond to reflected arrivals on the kimberlite wall (top). These events were isolated before migration but muting data above direct P-waves and below direct S-waves.

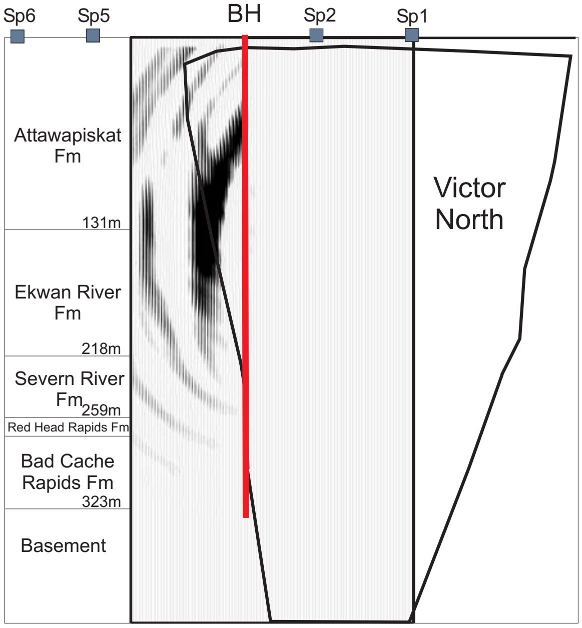


Figure 25: Migration results of the downgoing waves from the vertical component of VSP 1.

thick overburden and shot hole conditions seems to have attenuated significantly the high frequencies of VSPs from shot points located in the sediments. The loss of sharpness associated with lower frequency content may become significant if high precision is required for the position of the kimberlite margin. Spectral balancing and bandpass filtering improved the sharpness on migrated sections, especially for VSP 7 and 8. However, these techniques only work on part of the spectrum with real signal and cannot compensate for un-recorded frequencies. Deeper shot holes reaching the kimberlite or sedimentary rocks are one possibility to improve the frequency content.

Continuous physical rock properties in a vertical borehole located in the country rocks are clearly needed to establish precisely the reflectivity sequence in the sediments. This information is required to assess what sedimentary units or contacts we image on the seismic sections and how well our migration succeeded in positioning them. It should also allow a re-calibration of the velocities which should provide a more accurate positioning of the reflections on the migrated sections and help determine what can really achieved with the indirect imaging approach.

5 Conclusions and Recommendations

VSP data acquired from a borehole in the kimberlite with shot points located in the sediments are characterized by several reflections originating from the sedimentary units and Precambrian basement. This VSP data provide an indirect method of determining the shape of the kimberlite by mapping truncations of the reflections from the sedimentary layers near the pipe. Migration results demonstrate that this indirect approach has potential to define the geometry of the kimberlite at depth. However, the kimberlite margin interpreted from the seismic data would be more reliable for an acquisition borehole located further inside the pipe and higher frequency content data.

Physical rock property measurements were made on core samples from several sedimentary units (see report by M. Salisbury). The sandstone, and especially, the limestone and dolostone show a wide range of velocities and densities because of variations in porosity. Due to the high variations, it is difficult to use the velocity measurements made on local samples to build a continuous velocity function necessary for proper migration of the data. Thus, we strongly encourage De Beers to acquire sonic and gamma-gamma borehole logs in the sedimentary rocks. These measurements will provide continuous physical rocks properties that will allow a better assessment of this technology for indirect location of the kimberlite wall. If borehole logs are acquired in a near future and if GSC management still supports this project at that time, we would be interested to refine migration results of the shot point located in the sedimentary rocks.

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