Geological Survey of Canada

CURRENT RESEARCH
2005-C1

Downhole seismic imaging of the Victor kimberlite, James Bay Lowlands, Ontario: a feasibility study

G. Bellefleur, L. Matthews, B. Roberts, B. McMonnies, M. Salisbury, D. Snyder, G. Perron, and J. McGaughey

2005

Natural Resources Canada | Ressources naturelles Canada

Canada

CURRENT RESEARCH

ISSN 1701-4387
Catalogue No. M44-2005/C1E-PDF
ISBN 0-662-39475-5

A copy of this publication is also available for reference by depository libraries across Canada through access to the Depository Services Program's website at http://dsp-psd.pwgsc.gc.ca

A free digital download of this publication is available from the Geological Survey of Canada Bookstore web site:

http://gsc.nrcan.gc.ca/bookstore/

Click on "Free Download".

Toll-free (Canada and U.S.A.): 1-888-252-4301

Authors' addresses

G. Bellefleur (gbellefl@nrcan.gc.ca)
B. Roberts (broberts@nrcan.gc.ca)
D. Snyder (dsnyder@nrcan.gc.ca)
Geological Survey of Canada
615 Booth St., Ottawa, Ontario K1A 0E9

L. Matthews
Mira Geoscience
800 6th Ave. SW., Calgary, Alberta T2P 3G3

B. McMonnies (Bruce.McMonnies@ca.debeersgroup.com)
De Beers Canada Exploration
1 William Morgan Dr., Toronto, Ontario M4H 1N6

M. Salisbury (msalisbu@nrcan.gc.ca)
Geological Survey of Canada
Box 1006, Dartmouth, Nova Scotia B2Y 4A2

G. Perron (gervais@mirageoscience.com)
J. McGaughey (johnm@mirageoscience.com)
Mira Geoscience
310 Victoria Ave., Westmount, Quebec H3Z 2M9

Publication approved by CGD

Original manuscript submitted: 2004-11-16

Final version approved for publication: 2005-02-01

Downhole seismic imaging of the Victor kimberlite, James Bay Lowlands, Ontario: a feasibility study

G. Bellefleur, L. Matthews, B. Roberts, B. McMonnies,
M. Salisbury, D. Snyder, G. Perron, and J. McGaughey

Bellefleur, G., Matthews, L., Roberts, B., McMonnies, B., Salisbury, M., Snyder, D., Perron, G., and McGaughey, J., 2005: Downhole seismic imaging of the Victor kimberlite, James Bay Lowlands, Ontario: a feasibility study; Geological Survey of Canada, Current Research 2005-C1, 7 p.

Abstract: 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 to 300 m depths and, in doing so, to 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 over the kimberlite pipe and the other using shots over the host sedimentary rocks. It was hoped that shot points over the kimberlite would directly image the kimberlite–sedimentary rock contact, whereas shots over the nearby (<250 m) sedimentary rocks would indirectly determine the kimberlite margin by mapping truncations of reflections from the sedimentary layers. Results demonstrate that the indirect mapping approach has potential to define the geometry of the kimberlite at depth.

Résumé : On a obtenu des données sismiques de puits sur la kimberlite de Victor, dans les basses terres de la baie James (Ontario), afin de tenter de produire une image de la cheminée à entre 10 et 300 m de profondeur et, ainsi, d'évaluer l'applicabilité de cette méthode à la délimitation des ressources en diamants. Le levé était conçu de manière à permettre d'utiliser deux stratégies d'imagerie différentes, l'une utilisant des points de tir au-dessus de la cheminée de kimberlite et l'autre, des points de tir au-dessus des roches sédimentaires encaissantes. On espérait que les points de tir au-dessus de la kimberlite fourniraient directement une image du contact kimberlite-roches sédimentaires alors que les tirs au-dessus des roches sédimentaires à proximité (moins de 250 m) permettraient de déterminer indirectement la marge de la kimberlite par l'imagerie de la troncature des réflexions fournies par les couches sédimentaires. Les résultats démontrent que la stratégie par imagerie indirecte offre des possibilités pour la définition en profondeur de la géométrie de la kimberlite.

INTRODUCTION

Downhole seismic surveys were undertaken at the Victor kimberlite as part of an Ontario Mineral Exploration Technologies (OMET) project involving the collaboration and support of the Geological Survey of Canada, Mira Geoscience, University of Toronto, University of Alberta, De Beers Canada, Falconbridge Ltd., Cameco Corp., and Anglo American plc. The purpose of the OMET project is to develop and demonstrate the effectiveness of downhole seismic imaging (DSI) in mineral exploration and to help transfer this technology, developed previously by the GSC-led DSI Consortium, to the mining industry. Specific objectives of the present study were to assess the potential of the downhole seismic method to complement information provided by boreholes and to help define the geometry and volume of a kimberlite pipe at depth for resource evaluation purposes. Mapping the margin of a kimberlite is an experimental application of the downhole seismic method that could add significant value to the technology.

The Victor kimberlite is located in the James Bay Lowlands approximately 90 km west of Attawapiskat (Fig. 1); it comprises two separates pipes, Victor South and Victor North (Fig. 2). The pipes were emplaced into flat-lying, mid-Devonian to mid-Silurian sedimentary rocks, which unconformably overlie the Precambrian rocks of the Superior Province (Kong et al., 1999). The thickness of the sedimentary sequence is approximately 300 m in the Victor kimberlite area. The pipes are characterized by two textural types of kimberlite formed at different times. The northwestern part of Victor North resembles hypabyssal kimberlite but comprises numerous lapilli tuff horizons and sedimentary rock breccias and is associated with an early phase of emplacement (Webb et al., 2004). The sedimentary breccias are composed of now-eroded stratigraphic units and are also found along parts of the pipe margin. The southern part of Victor North, and Victor South, which are referred to as the 'pyroclastic kimberlites', are composed mainly of pyroclastic, lapilli-bearing olivine tuff deposited during a later eruption event that excavated a second crater crosscutting the original crater (Webb et al., 2004). The borehole seismic data were acquired to image an approximately east-west vertical section of Victor North pyroclastic kimberlite (Fig. 2).

The Victor pipes are undergoing a feasibility study and their geometry is relatively well defined by drillholes. Thus, the Victor kimberlite is an excellent site to test borehole seismic imaging. If successful, this potentially more economical approach could be directly applied to 15 other diamondiferous kimberlites of the Attawapiskat cluster and potentially to

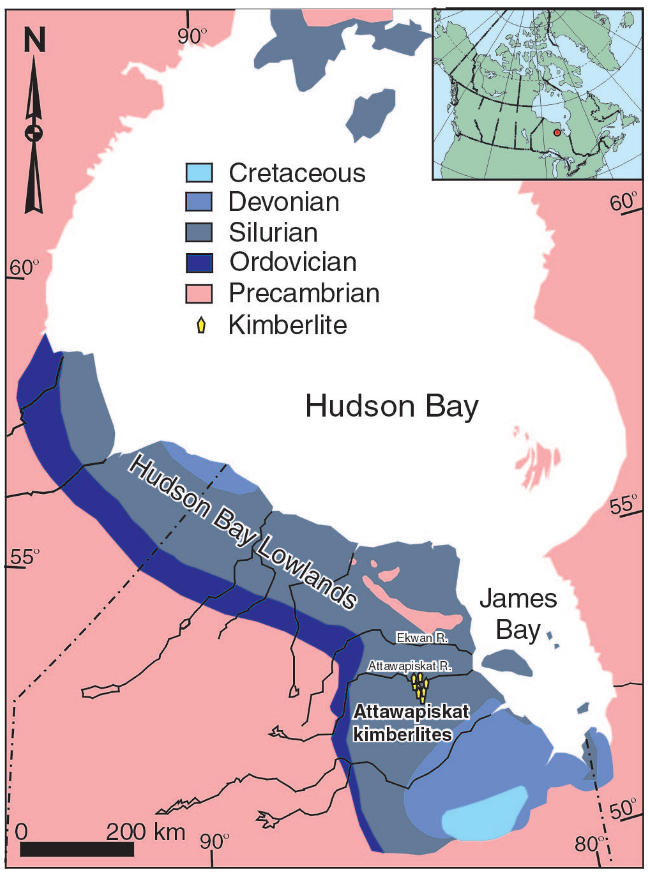

*Figure 1. Location map showing the regional geological setting and the Attawapiskat kimberlite cluster (*modified from *Kong et al., 1999). The Victor kimberlite is part of the Attawapiskat cluster.*

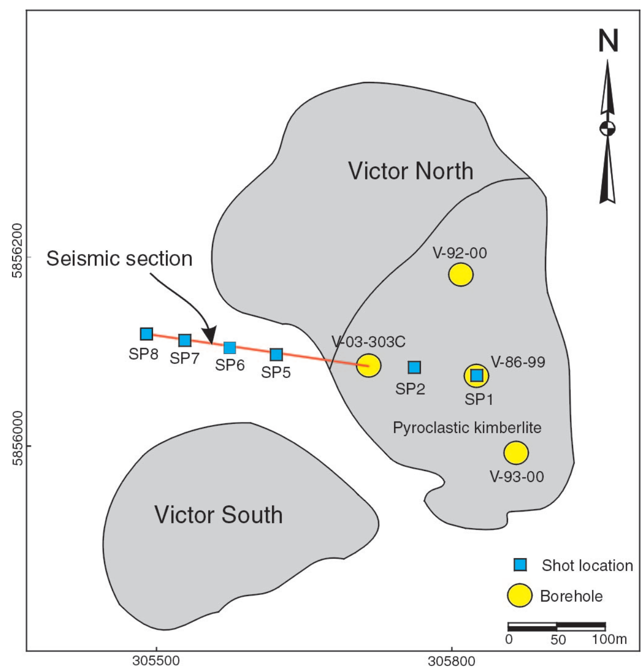

Figure 2. Acquisition geometry used during the Victor kimberlite study. The borehole seismic data were acquired to image an approximately east-west vertical section of Victor North pyroclastic kimberlite. Shot points 1 and 2 are located in the kimberlite whereas shot points 5 to 8 are in the sedimentary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

other types of kimberlite located in different geological settings. Here, we present downhole seismic data from the Victor kimberlite and migration results showing that the approach has the potential to define the geometry of the kimberlite at depth.

SURVEY DESIGN AND IMAGING STRATEGIES

The acquisition geometry used at the Victor kimberlite is outlined in Figure 2. A vertical borehole located in Victor North pyroclastic kimberlite (V-03-303C on Fig. 2) was used as the recording hole. This borehole exits the kimberlite and intersects the sedimentary rocks at 240 m and the Precambrian basement at 323 m. The survey was designed to allow two different imaging strategies, one using shot locations inside the kimberlite and the other using shot points placed in the nearby sedimentary rocks. 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. 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 will provide optimum results if the kimberlite has a low internal reflectivity. The shot points located in the sedimentary rocks 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. This second approach requires receivers located inside the kimberlite, which is the case for the top 240 m of the recording borehole. The flat sedimentary layers deeper than 240 m 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. Only data from shot points located in the sedimentary rocks (SP 5, 6, 7, 8 on Fig. 2) are presented in this paper.

PHYSICAL ROCK PROPERTIES

The direct and indirect mapping approaches provided by the survey design each require an acoustic impedance contrast between specific target rock units. The direct approach will be successful only if the impedance contrast between the kimberlite and the sedimentary rocks is sufficient to produce a detectable reflection. The indirect mapping approach requires sufficient reflectivity between stratigraphic units of the sedimentary rocks.

Physical rock property measurements were made on core samples from kimberlite, granite, and several sedimentary units in order to estimate reflectivities (Table 1). Most kimberlite samples have velocities ranging from 4.6 to 5.3 km/s at 200 MPa, with only one fresher sample with a higher velocity of 6.5 km/s. The sandstone and especially the limestone and dolostone show a wide range of velocities and densities because of variations in porosity. The granite has a much higher impedance (Z = 17) than most of the other samples (12.5<Z<15), implying that the granite–sedimentary rock and the granite–kimberlite contacts will make strong reflectors. The limestone–kimberlite contacts may not always reflect, however, because their impedances often overlap. Reflections are also expected between sedimentary units with different acoustic impedances.

Table 1. Physical rock properties obtained on sedimentary, granite, and kimberlite samples. P-wave velocities were measured at 200 MPa.

Sample	Lithology	Formation	Density (g/cm^3)	Vp (km/s)	Impedance
AT-02'	Limestone	Attawapiskat	2.52	5.83	14.69
AT-03'	Limestone	Attawapiskat	2.13	4.66	9.93
ER-01	Limestone	Ekwan/Severn	2.51	5.12	12.85
ER-02	Sandy limestone	Ekwan/Severn	2.44	4.97	12.13
ER-03	Limestone	Ekwan/Severn	2.52	4.93	12.42
ATT-04	Limestone	Red Head Rapids	2.50	5.63	14.08
ATT-03'	Sandstone	Red Head Rapids	2.42	5.72	13.84
ATT-01'	Mudstone breccia	Red Head Rapids	2.45	4.70	11.51
ATT-02	Limestone	Red Head Rapids	2.50	4.84	12.10
BC-02	Dolostone	Bad Cache Rapids	2.32	4.31	10.00
BC-04	Dolostone	Bad Cache Rapids	2.62	5.69	14.91
BC-05	Dolostone	Bad Cache Rapids	2.58	5.72	14.76
BC-03	Sandstone	Bad Cache Rapids	2.62	5.07	12.28
BC-06	Sandstone	Bad Cache Rapids	2.40	5.16	12.38
GR-02xy	Granite		2.70	6.28	16.96
GR-02z	Granite		2.70	6.14	16.58
GR-01	Granite		2.63	6.33	16.65
K-03	Kimberlite		2.54	4.84	12.29
K-02	Kimberlite		2.44	4.73	11.54
K-01	Kimberlite		2.52	4.61	11.62
K-04	Kimberlite		2.50	4.66	11.65
K-09	Kimberlite		2.68	5.23	14.02
K-10	Kimberlite		2.61	5.33	13.91
K-05	Kimberlite		2.79	6.45	18.00
K-06	Kimberlite		2.55	4.82	12.29
K-07	Kimberlite		2.60	5.30	13.78

Velocity and density logs measured in three boreholes mostly intersecting kimberlite material (V-86-99, V-92-00, and V-93-00 on Fig. 2) were also provided by De Beers Canada to help establish the physical rock property basis of the direct mapping approach. One borehole (V-86-99), which intersects the sedimentary rocks of the Ekwan River Formation at a wireline depth of 160 m, shows that velocities and densities of the sedimentary rocks are significantly lower than those of the kimberlite (Fig. 3). Synthetic seismic traces calculated by convolving the reflection coefficients determined from the borehole logs with a 60 Hz Ricker wavelet (Fig. 3) suggest that the impedance contrast at the

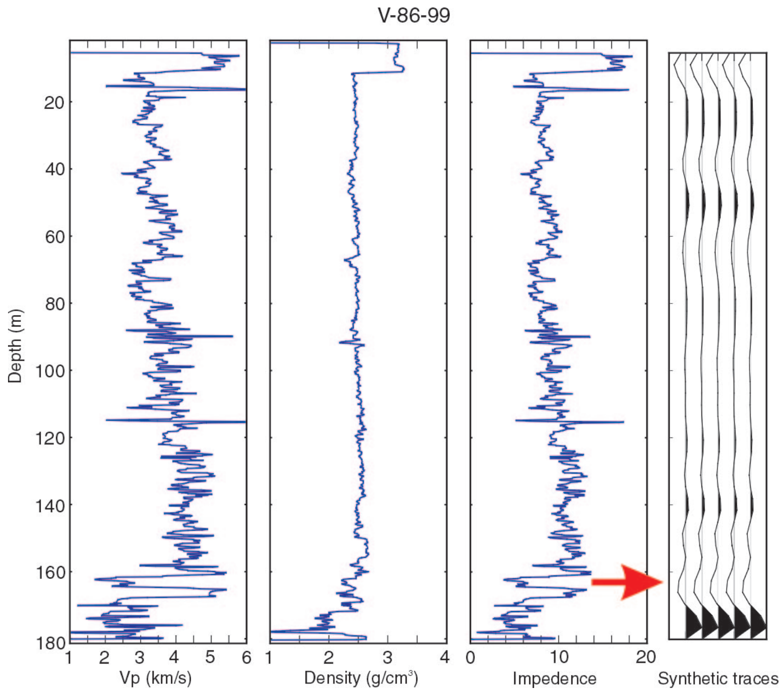

Figure 3.

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 60 Hz Ricker wavelet. The borehole exits the kimberlite to enter the sedimentary rocks at 160 m. The impedance contrast at the kimberlite–sedimentary rock contact is sufficient to produce a detectable reflection (arrow). The synthetic traces also suggest that the kimberlite has a low internal reflectivity.

kimberlite–sedimentary rock contact is sufficient to produce a detectable reflection. The synthetic traces also suggest that the kimberlite has a low internal reflectivity. However, velocity and density logs from borehole V-93-00 (not shown) show variations of P-wave velocity sufficient to produce significant reflections, indicating that internal reflectivity may vary locally within the kimberlite. Velocities and impedances determined by logging at in situ pressures (0–10 MPa) will be lower than those determined in the laboratory and reported at a standard pressure of 200 MPa; however, the reflection coefficients will be similar because they are relatively insensitive to pressure.

Table 2. Acquisition equipment and recording parameters used during the Victor kimberlite study.

Acquisition equipment	
Seismograph	OYO Das-1
Receivers	Vibrometric XYZ43CG
Shooting system	I/O firing system
Source	Bolt Model 1900C with 60 in^3 chamber (SP 1 and 2) Bolt Model 1900B TB with 40 in^3 chamber (SP 5, 6, 7, 8)
Recording parameters	
Recording depths	10 m–287.5 m
Receiver spacing	2.5 m
Record length	1 s
Sampling interval	0.25 ms

ACQUISITION

A total of six offset vertical seismic profiles (VSP) were recorded in borehole V-03-303C over a period of five days. An eight-level, three-component receiver unit was deployed in the borehole at depths ranging from 10 to 290 m, with a 2.5 m interval. Recording equipment and parameters were similar to those used in previous downhole seismic surveys done by the DSI Consortium (Snyder et al., 2002). The recording parameters and acquisition equipment are summarized in Table 2.

Air guns were used as the seismic source. They provided a rapid, powerful, and repeatable source signature in the prepared shot holes. The preparation included drilling with a 36-inch auger and insertion of a 24-inch steel casing. The purpose of the casing was to maintain hole stability by keeping out the overburden as the gun fired as well as to provide a consistent source medium. Some water was also required to fill the volume around the casing for better source coupling and to fill up the casing to provide sufficient load on top of the gun for adequate power transmission and source wavelet consistency. Shot holes located in the kimberlite (SP1 and SP2 on Fig. 2) were mostly filled with water whereas the other shot points were filled with a combination of water and mud that had flowed from the swampy overburden into the casing from below. An air gun with a smaller port opening (mud gun) was used in the muddy shot holes. In all cases, gun pressures ranged from 1000 to 2000 PSI depending on gun depth and the type of material in the particular shot hole.

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. Frequency content of the seismic data varies significantly according to the shot locations. In general, shots located inside the kimberlite (SP1 and SP2 on Fig. 2) produced a higher frequency content than those in the sedimentary rocks. Shot points located close to the kimberlite (SP5 and SP6 on Fig. 2) also provided higher frequencies than shot points 7 and 8. A maximum frequency of approximately 100 Hz was measured for direct P-wave arrivals from shot points 7 and 8. Results from a frequency analysis for the vertical component of VSP 2 and 6 are shown in Figure 4. The raw vertical component acquired from shot site 6 is shown in Figure 5a.

DATA PROCESSING

Field records from all shot sites are dominated by strong downgoing waves (Fig. 5a). Reflections from the sedimentary rocks travel upward and are thus recorded in the upgoing wavefield. This upgoing wavefield is weak when compared to the downgoing wavefield and is characterized by only a few events (Fig. 5a). Thus, data processing is required to separate and enhance reflections from the sedimentary rocks. Particularly important processing steps included band-pass filtering (30, 40, 180, 190 Hz) and predictive deconvolution designed to remove a long oscillating coda observed after direct P-wave arrivals on the horizontal components. After deconvolution, the horizontal components of all receiver levels were re-oriented into radial and transverse components. The radial components point toward the shot location whereas the transverse components are orthogonal to that direction. Re-orientation was performed using particle polarization of direct arrivals following a procedure described in DiSiena et al. (1984). The upgoing wavefield on the radial and vertical components holds information necessary to produce seismic images along the section shown in Figure 2. This upgoing wavefield was obtained by applying fk-filters (Hardage, 2000). Spectral balancing and a bandpass filter (70, 80, 180,190 Hz) were also applied to the upgoing wavefield prior to migration. The processed vertical components from VSP shot site 6 are shown in Figure 5b.

IMAGING RESULTS

The VSP data were migrated to produce P-wave reflection images of the kimberlite. The vertical and radial components were migrated simultaneously using a VSP Kirchhoff migration algorithm (Dillon, 1988) to produce a representative

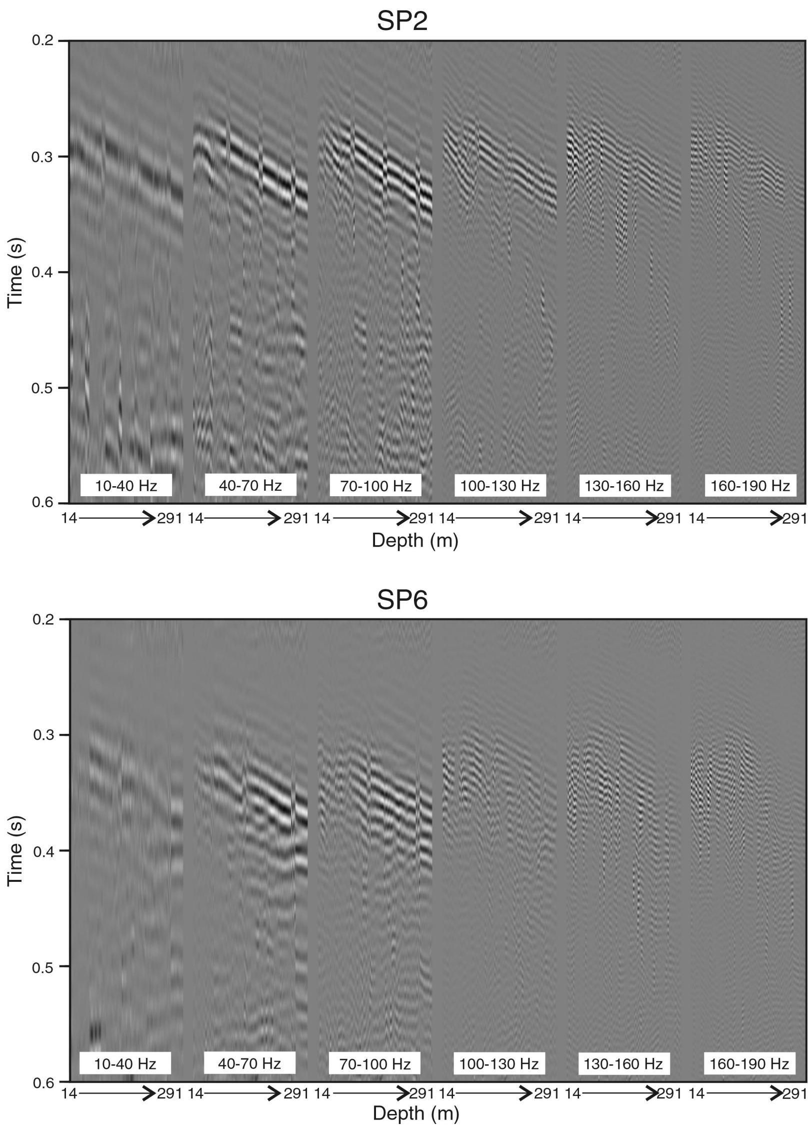

Figure 4.

Filter panels of raw shot gathers acquired in the kimberlite (SP2) and sedimentary rocks (SP6). Most of the signal consists of direct P-wave arrivals. Data acquired within the kimberlite has a larger bandwidth. Most of the signal from the shot point located in the sedimentary rocks is in the 40 to 100 Hz range.

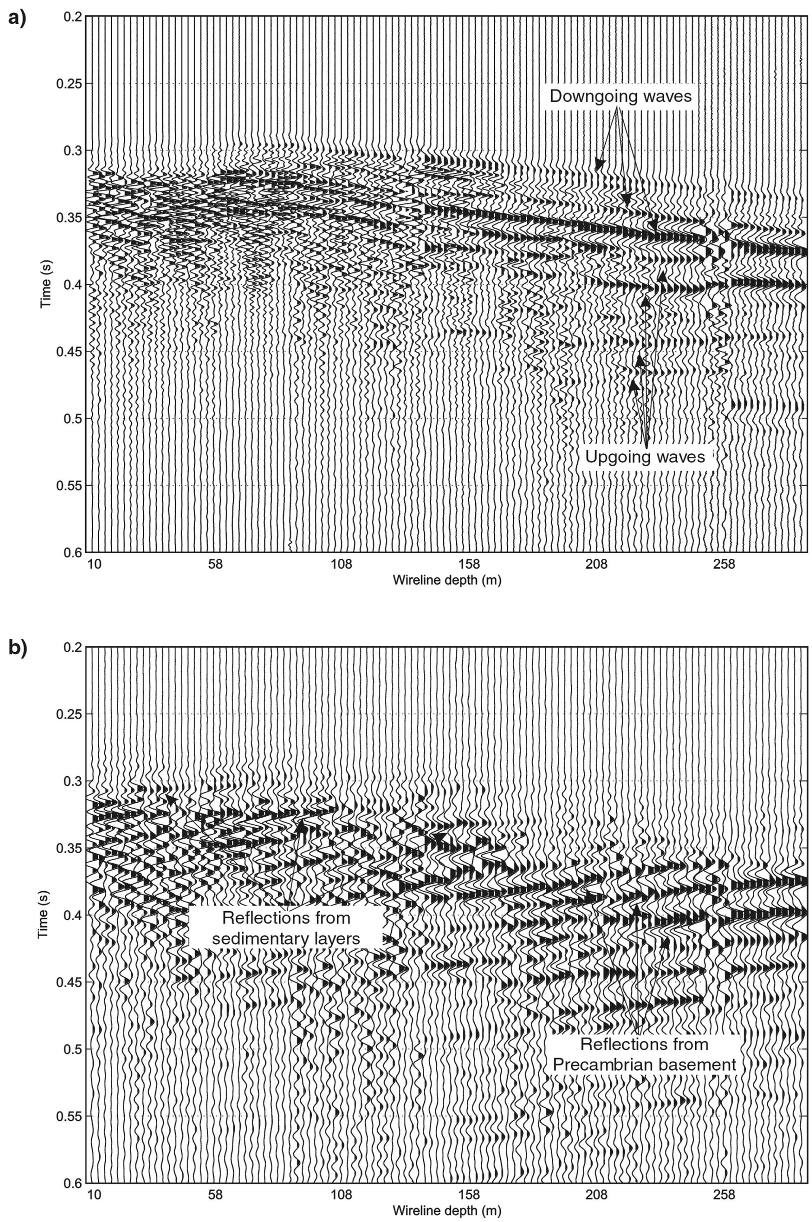

Figure 5.

a) Raw vertical component from shot site 6 (SP6 on Fig. 2) showing mostly direct downgoing waves and weak reflections (upgoing waves) between 60 m and 290 m. Shallower receivers recorded direct arrivals mostly on the horizontal components. ***b)*** *The same data component after processing, showing several reflections. The most useful to the indirect imaging approach are located at depth shallower than 240 m and early travel times.*

seismic section of the subsurface along the profile shown in Figure 2. To control artifacts due to the limited aperture inherent to VSP geometry, the dips on the migrated image were limited to ±7.5° from the horizontal. This allows imaging of the flat sedimentary layers that will indirectly indicate the position of the edge of the kimberlite. Migration results for the vertical component from shot point 6 are shown in Figure 6. The position of the kimberlite wall defined from boreholes is also displayed on Figure 6. A constant velocity of 3765 m/s defined from direct arrivals was used for migration and a source static correction of 253 ms was applied to take into account the low-velocity overburden. The source static correction was also estimated from the first arrivals. The migrated image reveals several reflections from the sedimentary rocks, some most likely corresponding to known stratigraphic horizons (*see* Fig. 6). 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. The location of the kimberlite wall is best determined between 120 m and 220 m. The kimberlite wall is poorly imaged at depths shallower than 120 m, reflecting certain limitations of our survey geometry.

DISCUSSION

The migrated image shows 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.

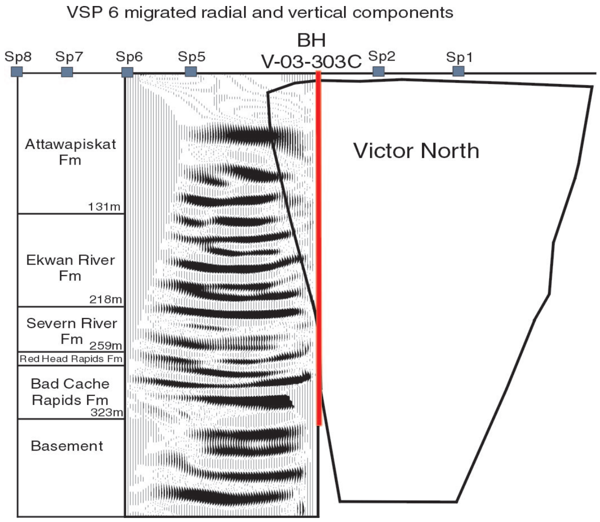

Figure 6. *Results from the migration of the vertical and radial components of shot point 6. The reconstructed image is between SP6 and the recording borehole (V-03-303C). Reflections shallower than 240 m are truncated close to the outline of Victor North as defined from boreholes. The sedimentary rock units surrounding the Victor pipes are also shown. The migrated image was obtained using a constant velocity of 3765 m/s with a trace spacing and depth sample rate of 2 m.*

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 farther 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 reflected 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. The 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 seems to have attenuated significantly the high frequencies of VSPs from shot points located in the sedimentary units. 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 the migrated section. However, these techniques only work on part of the spectrum with real signal and cannot compensate for unrecorded 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 sedimentary units. This information is required to assess what sedimentary units or contacts we image on the seismic sections and how well our migration succeeds in positioning them. It would also allow a recalibration of the velocities that should provide a more accurate positioning of the reflections on the migrated sections and help to determine what can be achieved with the indirect imaging approach.

CONCLUSIONS

The VSP data acquired from a borehole in the kimberlite with shot points located in the sedimentary units are characterized by several reflections originating from the sedimentary units and Precambrian basement. The 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 the potential to define the geometry of the kimberlite pipe at depth. However, the kimberlite margin interpreted from the seismic data would be more reliable for an acquisition borehole located farther inside the pipe and for data with a higher frequency content.

ACKNOWLEDGMENTS

We thank Rob Mayzes (Mayzes Consulting) for the expertise and service provided with the air guns. De Beers Canada kindly provided the borehole logs and core samples.

We also thank Robert Iuliucci for his assistance with the laboratory physical property measurements. This project is part of the Trans-Hudson/Superior Margin Project of the Northern Resources Development program at the Geological Survey of Canada.

REFERENCES

Dillon, P.B.
1988: Vertical seismic profile migration using the Kirchhoff integral; Geophysics, v. 53, p. 786–799.

DiSiena, J.P., Gaiser, J.E., and Corrigan, D.
1984: Horizontal components and shear-wave analysis of three-component VSP data; *in* Vertical Seismic Profiling, Part B: Advanced Concepts, M.N. Tokoz and R.R. Stewart (ed.); Geophysical Press, p. 177–189.

Hardage, B.A.
2000: Vertical seismic profiling: principles (third edition); Pergamon, New York, 552 p.

Kong, J.M., Boucher, D.R, and Scott Smith, B.H.
1999: Exploration and Geology of the Attawapiskat Kimberlites, James Bay Lowlands, Northern Ontario, Canada; *in* Proceedings, VIIth International Kimberlite Conference, Cape Town, South Africa.

Snyder, D., Perron, G., Pflug, K., and Stevens, K.
2002: New insights into the structure of the Sudbury Igneous Complex from downhole seismic studies; Canadian Journal of Earth Sciences, v. 39, p 943–951.

Webb, K.J., Scott Smith, B.H., Paul, J.L., and Hetman, C.H.
2004: Geology of the Victor Kimberlite, Attawapiskat, northern Ontario, Canada: cross-cutting and nested craters; LITHOS, v. 76, no. 1-4, p. 29–50

Geological Survey of Canada Project Y14