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Case History

High-resolution seismic reflection imaging of a thin, diamondiferous kimberlite dyke

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ABSTRACT

Seismic reflection techniques are, for the first time, used to image a thin, diamondiferous kimberlite dyke from subcrop to depths greater than 1300 m. Geophysical exploration for kimberlite deposits typically involves airborne potential field surveys that are well suited for detecting vertical outcropping pipes but often fail to reveal thin, subhorizontal dykes and sills. Because seismic techniques are especially well suited for mapping structures that have shallow dips and strong impedance contrasts, a feasibility study and seismic reflection survey were undertaken on the diamondiferous Snap Lake dyke (Northwest Territories, Canada) to evaluate the potential for using seismic techniques on these targets. The dyke (average thickness 2–3 m) provides an excellent test site because a drilling program has defined the gross dyke geometry and provides core samples from the kimberlite and host rocks. The feasibility study involved measuring P-velocity and density of selected cores. Using these data, reflectivity and finite-difference synthetic seismogram techniques were used to explore the resolution limitations and determine the acquisition parameters for a reflection survey. The seismic survey included two 2D lines designed to obtain comparative data sets from different sources (explosives and vibroseis) and ground types (land or lake-ice). The explosive-source land data yielded a superb image of the thin dyke. The vibroseis data, however, detected the dyke only when sources and geophones were on land; the dyke was not imaged beneath the ice due to reverberation and attenuation effects. Correlations are observed between reflection attributes and dyke properties (thickness, structure, and physical properties). The results demonstrate that, in the appropriate situation, seismic methods have great potential for use in kimberlite exploration, subsurface mapping, and detailed imaging for mine development purposes.

INTRODUCTION

Seismic reflection techniques have been infrequently used by the diamond exploration and mining industry. The primary exploration targets are kimberlite pipes, which are effectively detected using airborne magnetic, electromagnetic, and gravity surveys (e.g., Carlson et al., 1999). These potential field techniques succeed because of the strong contrasts in conductivity, susceptibility, and density between the host rocks and the near-vertical weathered pipes that outcrop or subcrop. However, intrusions such as dykes and sills can form thin, subhorizontal sheets that do not yield distinctive potential field anomalies because sharp lateral contrasts in physical properties are absent. As a result, these potentially valuable structures are likely to be overlooked and are not well understood. Since reflection seismic techniques are especially well suited for mapping subhorizontal structures, some dykes and sills have the potential to be excellent seismic targets.

One example of a diamondiferous dyke is the Snap Lake kimberlite in Canada's Northwest Territories (Figure 1). Although the dyke averages only 2–3 m in thickness, the quantity (over 20 million Mt at approximately 2 carats/t) and quality of the diamonds makes the intrusion extremely valuable; De Beers Canada Mining Inc. obtained regulatory approval

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in 2003 to develop Canada's first underground diamond mine. A substantial drilling program has been carried out to define the gross geometry and value of the deposit. The dyke forms a sheet that gently plunges (~15°) to depths greater than 1300 m and extends over approximately 25 km^2 (McBean et al., 2003). Although the general structure has been roughly mapped by drilling, investigations continue in order to obtain more detailed structural data for mine planning. Furthermore, following the dyke downdip may lead to a better understanding of the emplacement process associated with it.

Drilling has obvious limitations in spatial sampling, and the costs are extremely high in this environment. This is partially due to the target depth and properties of the granitic and metavolcanic host rock, but is exacerbated by the remote and logistically challenging location. Shallow drillholes at the updip end of the dyke can be drilled economically, but at greater depths drilling large numbers of holes in order to define the location of the kimberlite is not cost-effective. For example, a single 1000-m hole costs US$200 000 (D. Clarke, personal communication, 2002). The number of future drillholes could

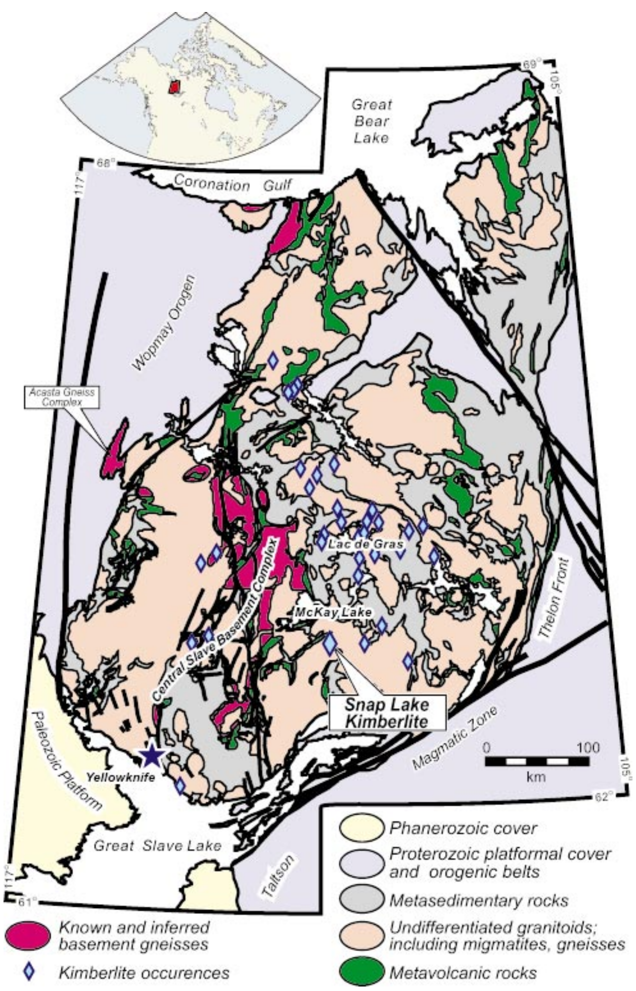


Figure 1. Geologic map of the Slave Province (modified from Bleeker and Davis, 1999). The Archean cratonic core is bounded by fault zones (bold lines), orogenic belts, and platformal cover. Blue diamonds represent known kimberlite pipes, dykes, and sills. The study location at Snap Lake is noted.

be reduced by using seismic reflection techniques to map the intrusion, thereby providing guidance to the drilling program. Therefore, seismic reflection surveying was considered as a potential tool for exploration and for mapping characteristics (e.g., extent, continuity, and thickness) of the dyke.

Imaging thin kimberlite dykes and sills at depths exceeding 1 km is challenging for two reasons. First, resolving or detecting a 1–3-m thick structure requires unusually high frequencies (>200 Hz) for imaging such a deep target. Second, guidance from other seismic reflection surveys of kimberlite dykes is extremely limited; no comparable exploration-scale seismic surveys of thin kimberlite dykes have been reported. Working on a thicker target, Gendzwill and Matieshin (1996) successfully used seismic reflection techniques to identify the top of a 100-m–thick extrusive kimberlite lens (crater facies) buried beneath approximately 100 m of sedimentary cover. The few published engineering-scale seismic surveys carried out on shallow (<100 m) dykes have had only limited success (e.g., Hearst, 1998). Exploration for thin coal seams (e.g., Tselentis and Paraskevopolous, 2002) and thin-bed petroleum reservoirs has developed our understanding of reflection responses from thin layers. However, there are significant differences between detecting these targets in a sedimentary environment and imaging kimberlites in an igneous host-rock setting. To evaluate the potential for success of a seismic reflection survey proposed for the Snap Lake dyke, a feasibility study was carried out. Physical properties measurements of the Snap Lake kimberlite and host rocks were made to estimate acoustic impedance. Then, the theoretical seismic responses of thin kimberlite dykes and the optimal acquisition parameters for a seismic survey were investigated.

The 2D reflection profiles over the Snap Lake dyke were acquired to provide information that was locally useful to the companies involved and to address two questions with broader implications. First, is the seismic reflection method an effective and cost-efficient exploration tool for shallow-dipping kimberlite dykes and sills in a hard-rock environment? Second, can seismic reflection studies image the kimberlite body and related geology at scales that would prove useful for mine planning and development (e.g., faults and detailed dyke topography)? The opportunity to ground-truth seismic results with drillhole data makes the Snap Lake dyke a unique locale for testing seismic reflection techniques on thin kimberlite dykes.

GEOLOGIC SETTING

Tectonic setting

The Slave Province of northwestern Canada is one of the principal Archean components of the North American craton (Figure 1) (Bleeker and Davis, 1999). The Slave Province itself is comprised of interspersed Archean granitoid intrusions, supracrustal sequences, and basement core complexes (Padgham and Fyson, 1992). The voluminous granitoid intrusions dominate the Slave Province and were emplaced pre-, syn-, and post-deformation, with the last magmatic events associated with the formation of the Slave completed by ~2.6 Ga. The Slave Province was incorporated into the North American craton by the Proterozoic, leaving the Slave bounded by fault systems that have been inactive since 1.27 Ga. In addition to large-scale tectonic deformation and modification, a series of Proterozoic diabase dyke swarms sliced through the Slave. These include the Mackay dykes (2.21 Ga), the Lac de Gras dykes (2.03 Ga), the prolific MacKenzie dykes (1.27 Ga), and finally the Franklin dykes (~720 Ma) (LeCheminant et al., 1996). The only recorded magmatic episodes after the Franklin event are the kimberlite intrusions.

The Slave Province is a classic setting for diamondiferous kimberlite pipes, but the discovery of such features is a tale of the 1990s. Pell (1997) provides an excellent review. The Slave Province has a stable and cool mantle root, a necessary characteristic for the development of the diamond stability field (e.g., Haggerty, 1986). The diamonds are entrained in mantle-derived kimberlite; these volatile-enriched, potassic, ultrabasic magmas rise from depths greater than 150 km toward the surface where they are emplaced as small volcanic pipes, dykes, and sills. A fraction of the kimberlites are diamondiferous, and only some of these are economically viable.

Typical pipes have diameters ranging from tens of meters to more than 1000 m and can be envisaged as downward tapering cones with steep sides (80°–85°) and vertical extents of a few kilometers (e.g., Mitchell, 1995). Kimberlite dykes and sills are smaller features that cut across existing structures or layers (dykes) or are emplaced between preexisting layers or along zones of weakness (sills). Most of the kimberlite intrusions in the Slave Province have been identified on the basis of a combined approach of tracing of diamond indicator minerals left by the last glaciation, geophysical techniques (magnetic and electromagnetic), and drilling. These techniques have not been successful at identifying subhorizontal dykes and sills. As a result, in the Slave Province more than 150 pipes were identified by the late 1990s but only two dykes (Snap Lake and Munn Lake) have been discovered using traditional exploration methods.

Within the Slave Province, kimberlite pipes are much more prevalent in the eastern segment, occurring principally in an arcuate zone which trends northwest from Lac de Gras in the central Slave for ~135 km and northeast from the lake for ~100 km (Figure 1). However, isolated pipes exist both north and south of this zone. The central Lac de Gras kimberlites were emplaced during both the Cretaceous and Tertiary, with ages ranging from 97 to 52 Ma. However, other kimberlites in the Slave province erupted as early as the Late Ordovician to Cambrian (450–520 Ma) (Pell, 1997). The Snap Lake dyke falls into the latter age range with samples dated at 535 ± 11 Ma (Agashev et al., 2001) and 523 ± 6.9 Ma (Geospec Consultants, 1999, De Beers Canada Mining Inc. internal report).

The Snap Lake kimberlite dyke: Geologic setting

Snap Lake is located within the Slave craton about 100 km south of the main kimberlite field in the Lac de Gras region (Figure 1). The primary geological units are Archean intrusive rocks, metavolcanic and allied rocks, and supracrustal rocks (Figure 2). The dominant intrusives belong to the Defeat pluton suite (2610–2590 Ma) and comprise granodiorite, tonalite, and monzogranite with locally abundant pegmatite. The intensely flattened mafic metavolcanic rocks are layered amphibolites and are associated with synvolcanic gabbroic intrusions. The supracrustals are primarily high-grade metaturbidites and migmatite. Proterozoic diabase dykes cross the study area. Three main sets are recognized: the east-northeast–striking Mackay dykes, north-northeast–striking Lac de Gras dykes, and the north-northwest–striking Mackenzie dykes (LeCheminant et al., 1996). They range in width from 100 m to a few meters. A detailed summary of the geology hosting the Snap Lake kimberlite can be found in Kirkley et al. (2003).

Kimberlites are hybrid rocks and consist of components derived from four distinct sources: primary mineral phenocrysts and matrix minerals from the kimberlite mantle magma, megacrysts or discrete nodules consisting of large (1–20 cm)

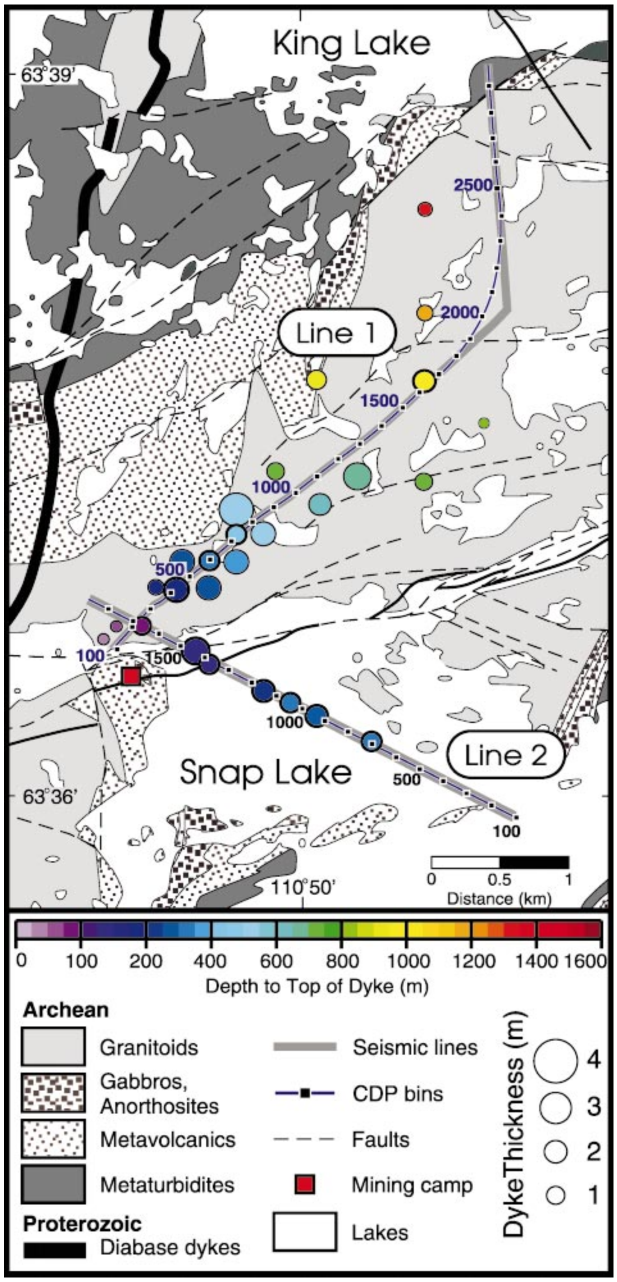


Figure 2. Seismic line locations on simplified geological map (M.P. Stubley, 1998, De Beers Canada Mining Inc. internal report). Drillhole locations closest to the seismic lines are noted. Intersection depth is color-coded, and dyke thickness is given by circle diameter. Common-depth-point (CDP) bin centers are also labeled for comparison with the stacked sections. The mining camp and dyke subcrop location are noted by the red square.

single crystals that could come from the kimberlite or other mantle magma, mantle-derived xenoliths and xenocrysts, and crustal xenoliths and xenocrysts. The latter two rock types represent material entrained in the magma as it moves upward from its mantle source (e.g., Kirkley et al., 1991; Mitchell, 1995). Diamonds themselves are not genetically related to kimberlite but are xenocrysts incorporated into the kimberlite magma in the upper mantle. In general, kimberlites show a range of crystallization and textural properties. The hypabyssal Snap Lake kimberlite dyke is distinctive in the high proportion of coarse-grained macrocrysts (3–10 mm) (Kirkley et al., 2003). This is unusual when compared to kimberlite pipes, but may prove to be typical of thin dykes.

The geometry and structure of the Snap Lake dyke is defined by drilling and the initial stages of undergound mine development. Based on this spatially limited data, the dyke forms a sheet that dips from subcrop down to the northeast (Figure 2). Dip is approximately 15°, but ranges from 5° to 30°. Dyke thickness is also variable; along the seismic profiles, drillcores document thicknesses from 3.4 to less than 0.5 m (Figure 2). Below 1000 m, the few cores yield intersections of less than 1.6 m. In addition to variability in thickness, the drill intersections indicate that the dyke is complex in form, occasionally feathering into multiple strands or rapidly changing dip (McBean et al., 2003). Although most Slave Province kimberlite pipes are localized along preexisting crustal structures during emplacement (e.g., lithologic contacts, faults), the Snap Lake dyke appears to cut across all major features. The drillcores also show that the dyke is accompanied by some related intrusions, fracturing, and alteration in the adjacent host rock.

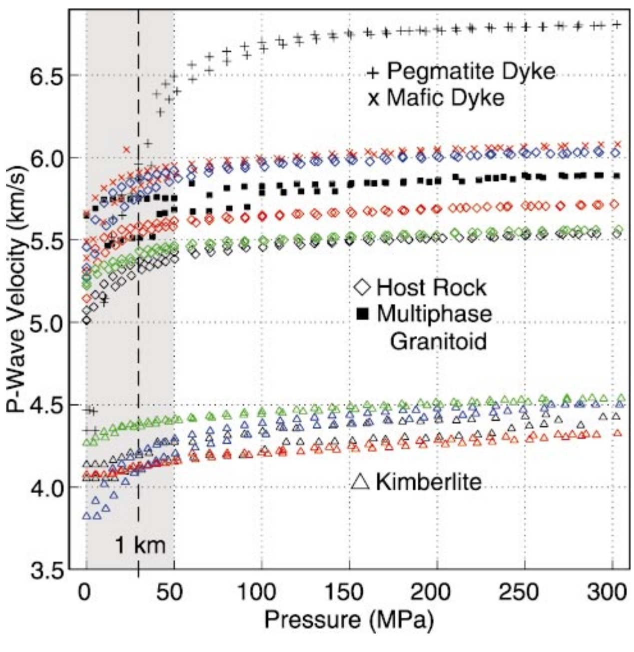


Figure 3. P-wave velocity response of Snap Lake core samples. Velocities were recorded as pressure was increased from 0 to 300 MPa and then reduced back to 0 MPa. Rapid changes in velocity between 0 and 5 MPa represent closure of the larger cracks. Rock types are defined by symbol shapes; individual samples denoted by symbol colors. The dashed line indicates the approximate pressure at 1 km depth; the gray-shaded zone includes the known depth extent of the dyke.

Thin kimberlite dykelets (1–10 cm) are usually encountered within 10 m of the primary dyke. Strong alteration and contact-related carbonate veining usually extend less than 10 cm from the dyke (Kirkley et al., 2003).

PHYSICAL PROPERTIES

The physical properties of the kimberlite dykes and the host rocks determine the impedance contrast to be detected by a seismic experiment. In addition to using published data (e.g., Ji et al., 2002), compressional (P) velocity and density measurements were made on drillcore samples from Snap Lake (D. Schmitt, personal communication, 2001) The P-wave velocities (V_P) were determined from 0 to 300 MPa (3 kbar or

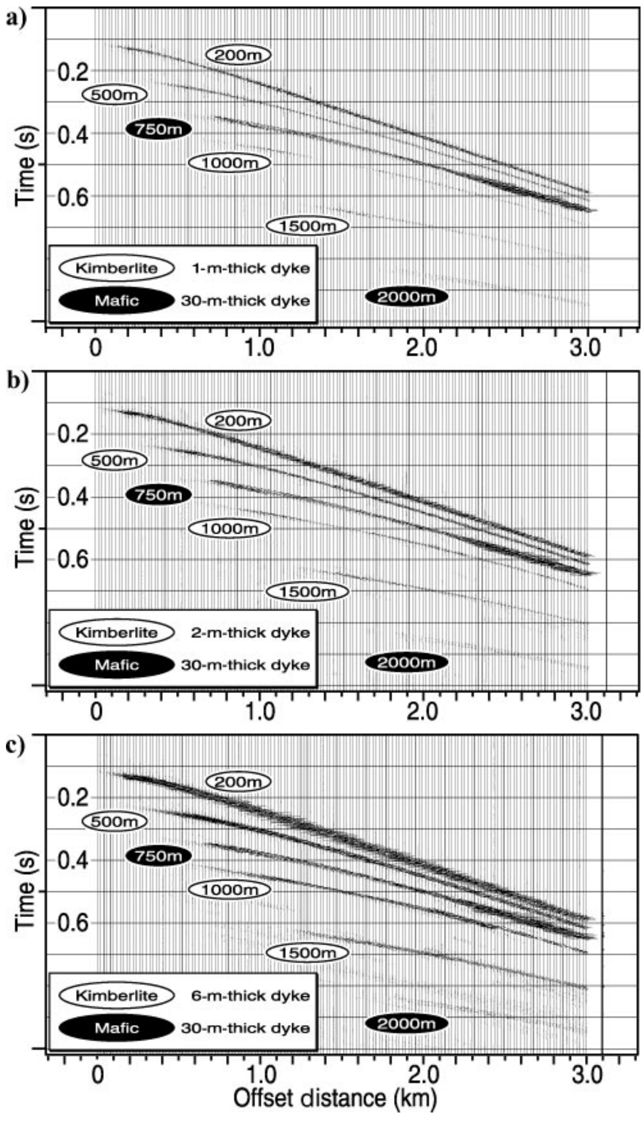


Figure 4. Comparison between different dyke thicknesses. Panels show reflectivity synthetics for a horizontally layered model for kimberlite and 30-m–thick mafic dykes at depths ranging from 200 to 2000 m. True relative amplitude shot gathers are shown for the frequency range 120–500 Hz and for kimberlite dyke thicknesses of (a) 1 m, (b) 2 m, and (c) 6 m. Traces are corrected for spherical divergence to facilitate comparison at greater offsets.

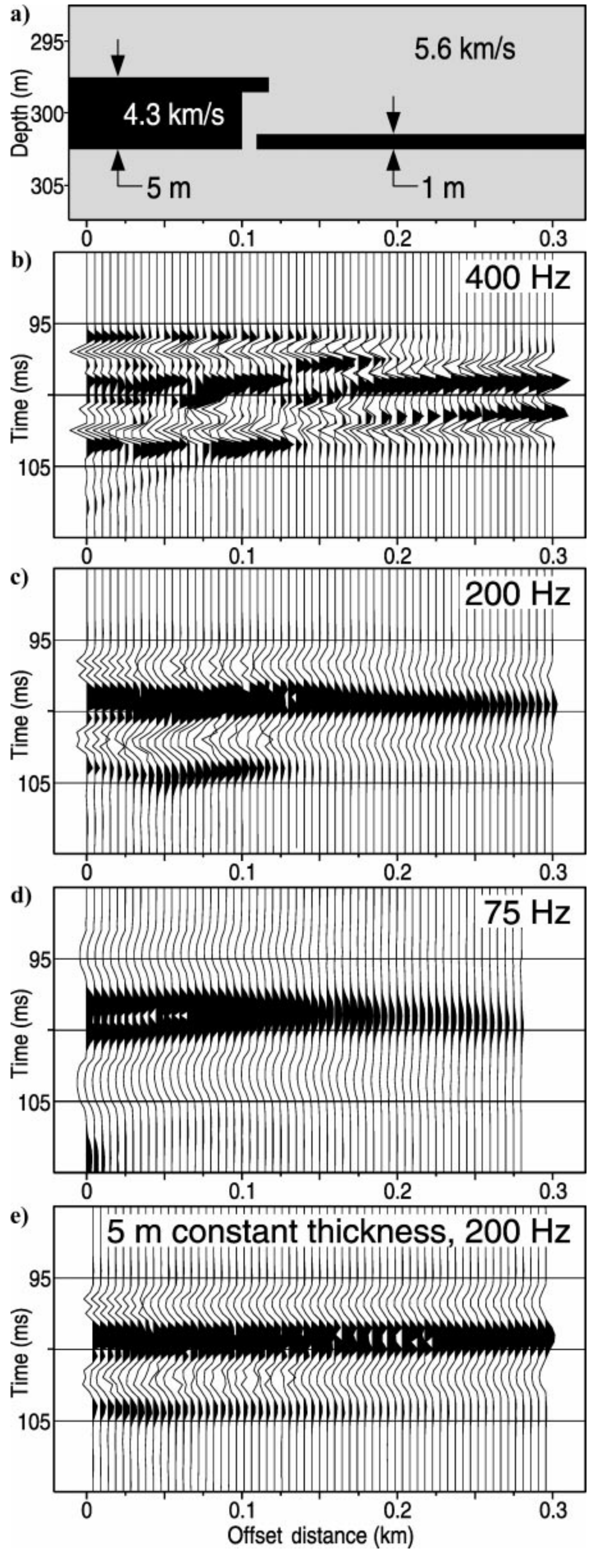


Figure 5. FD modeling of a feathered kimberlite dyke. (a) Portion of model showing the kimberlite thinning from 5 to 1 m thickness. The sequence of shot gathers are all normal-moveout (NMO) corrected and displayed using true relative amplitude and no correction for spherical divergence. Shot depth for all gathers is 0 m. Gathers are generated using a Ricker wavelet source centered at (b) 400 Hz, (c) 200 Hz, and (d) 75 Hz. (e) For comparison with (c), a shot gather acquired from a model with a laterally continuous, 5-m–thick dyke.

~10 km depth) at room temperature; density measurements were made at laboratory pressure and temperature. Figure 3 compares the V_P of all tested samples; they exhibit a number of consistent characteristics. The kimberlite samples exhibit significantly lower V_P (average 4.3 ± 0.1 km/s at 50 MPa) than those measured in the host rock (average 5.6 ± 0.2 km/s at 50 MPa). The kimberlite densities (2.40 to 2.49 ± 0.01 g/cm^3 are consistently lower than those of the host rocks, which ranged from 2.66 to 2.95 ± 0.01 g/cm^3. Thus, the impedance contrast at vertical incidence between the kimberlite and host rocks is large (~0.2); significant reflected energy should be generated. The single mafic dyke sample yielded velocity and density data (5.95 km/s at 50 MPa and 2.775 ± 0.011 g/cm^3) that were surprisingly similar to that of the host rock. If that sample is characteristic, then the mafic dykes should generate

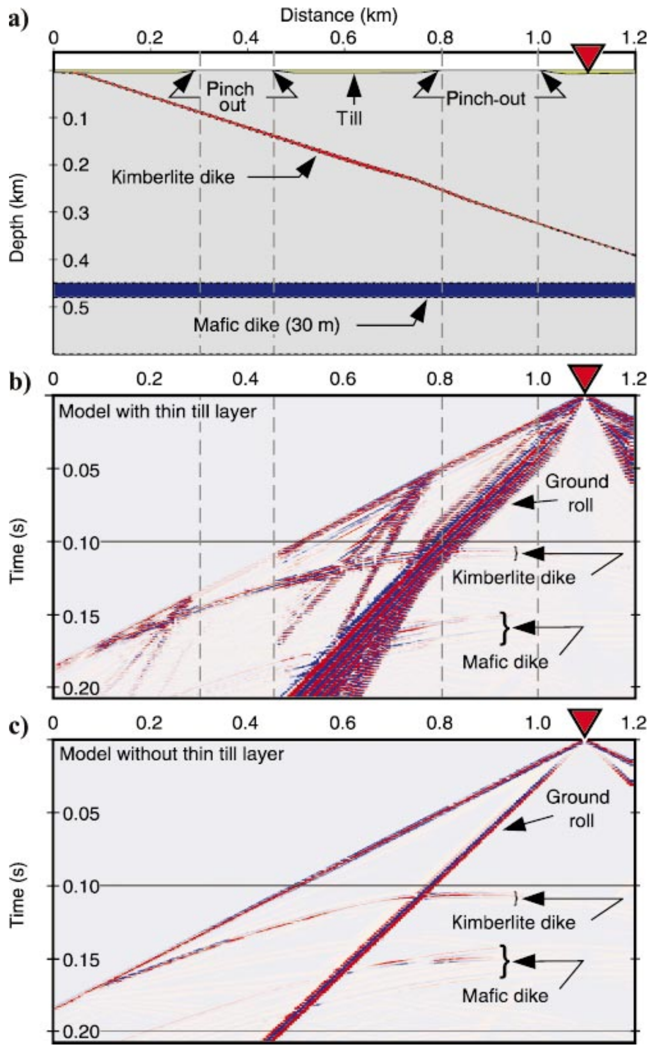


Figure 6. Comparison of ground surface conditions. FD synthetics are modeled from a dipping kimberlite dyke and a horizontal mafic dyke. True relative-amplitude shot gathers are generated using a central Ricker source wavelet of 250 Hz. Traces are corrected for spherical divergence to facilitate comparison at greater offsets. (a) Schematic of the model structure; triangle shows source location. (b) Shot gather for variable thickness till layer at the surface with two pinch-outs to bedrock. (c) Shot gather for full bedrock exposure. Note the correspondence between the surface till and higher amplitude reflections with longer coda.

lower reflection amplitudes than the kimberlites. In contrast, the physical properties of the pegmatite dyke (6.49 km/s at 50 MPa and 2.579 ± 0.010 g/cm^3) indicate that it could generate reflections of similar amplitude to that of the kimberlites, but of opposite polarity.

MODELING AND EXPERIMENT DESIGN

Despite the large impedance contrast, the dyke represents a challenging target for a reflection survey because of the thinness of the sheet and the depth to which it extends. As the dyke thins, higher frequencies are required to resolve or even detect it. For example, in order to resolve the 2-m thickness of a 4.3-km/s kimberlite dyke, wavelengths of less than 8 m or frequencies of approximately 500 Hz are required (e.g., Widess, 1973). Efforts driven by the petroleum industry to detect thin-bed reservoirs show that tuning and thin-bed amplitude-variation-with-offset (AVO) effects can reduce the frequencies required for target detection to as little as $\lambda/20$ (e.g., Gochioco, 1991; Juhlin and Young, 1993; Lin and Phair, 1993, Lin and Schmitt, 2003). Such estimates suggest that even the 1–2-m thick sections of the dyke could be detected if sufficient energy is returned above 200–250 Hz. Although frequencies of this range are commonly used in engineering-scale surveys, there were no comparable surveys to provide a reference for the unique combination of target thickness, depth, and unusual survey environment. Therefore, prior to conducting the experiment, a study was carried out to explore attenuation effects and resolution limitations, and to help determine the acquisition parameters for the survey. The primary questions addressed were (1) could the dyke be detected at all depths of interest? and (2) how much of the structural variability known to exist along the dyke could be documented by reflection data?

Two modeling techniques were used. An elastic reflectivity code (Fuchs and Mueller, 1971) provided fast, accurate calculations of the full waveform response but is restricted to 1D models. A 2D, viscoelastic finite-difference (FD) code (Robertsson et al., 1994), more computationally expensive than reflectivity, was used to model laterally complex structures. For all models, average densities and P-wave velocities based on the drill core measurements were used. Shear (S) wave velocities were calculated assuming $V_S = V_P/(1.73)$. Attenuation (Q) was estimated to be $Q_P = 400$ and $Q_S = 200$ based on crustal refraction experiments in crust dominated by granitic country rock. For the near-surface till layer, a Q_P of 50 was used. Attenuation was considered to be frequency independent, although energy with frequencies greater than 100 Hz may well be subject to higher attenuation (Mavko et al., 1979).

Evaluation of dyke reflection amplitudes requires a reference but there are no directly analogous surveys of kimberlite dykes. However, a crustal-scale reflection survey carried out across a till-covered, high-grade greenstone belt in northwestern Ontario imaged a series of mafic dykes (Zaleski et al., 1997). The dykes were subvertical and thicker (10–60 m) than the Snap Lake dyke, but the offsets and hardrock environment were roughly analogous. In addition, the survey had acquisition parameters similar to that envisioned for the Snap Lake survey with reasonably high fold (60) and exploration-scale offsets (2.4 km). Explosive charges (0.34 kg) were used and, to reduce high frequency attenuation, the shotholes were drilled through the till into bedrock where possible. Reflected refractions from the dykes were recorded to beyond 1.2 s (~3.6 km offset); frequency content ranged between 40 and 120 Hz. These diabase dykes (V_P of 6.8 km/s) provided a high impedance contrast (~0.1) at vertical incidence relative to the greenstone host rocks (V_P of 6.2 km/s) (Zaleski et al., 1997). The successful detection of dykes with half the impedance contrast and at over twice the range to that expected at Snap Lake provided encouragement. These mafic dykes were used as a baseline in comparative modeling. A link between these field data and our modeling results was made by assuming that if synthetic reflection amplitudes from thin kimberlite dykes were within one order of magnitude of synthetic amplitudes generated by 30-m–thick mafic dykes (e.g., Figure 4), there was a reasonable chance they could be discerned in a survey.

Synthetic reflection gathers were generated using the reflectivity and FD codes to (1) test the AVO response of different dyke thicknesses and source frequencies, and (2) consider the seismic response of laterally varying structures such as discontinuities in the dyke, dyke topography, and variations in the thickness of the till, water, and ice. These tests were undertaken to evaluate the potential for success of a field survey and to determine acquisition parameters, not to comprehensively investigate the reflectivity from thin beds of kimberlite.

The conclusions of the modeling study are based on the results of many different tests run using both modeling codes. Three examples (Figures 4, 5, 6) illustrate some of the results. In Figure 4, the reflectivity code was used to generate shot gathers for a model with horizontal kimberlite dykes (1, 2, and 6 m thick) at 200, 500, 1000, and 1500 m depth and, for comparison

Table 1. Acquisition parameters.

	Line 1 (land)—explosive source	Line 2 (ice/land)—vibroseis and explosive source
Seismic Source		
Pentalite shots	460 shots @ 0.25 kg	23 shots @ 0.25 kg
Shot spacing	8 m (increasing to 12, 16, 24 m along the northern third of the line)	8 m
Shot depth	1–3 m into bedrock	3–6 m into bedrock
Vibroseis	None	222 vibe points
Shot spacing		8 m
Sweep characteristics		Nonlinear 8 × 10 s sweeps from 100 to 500 Hz
Recording		
Sampling rate	0.5 ms	0.5 ms
Record length	2 s	2 s (correlated)
Geophone	28 Hz	28 Hz
Array size	816 phones (1 phone/group)	816 phones (1 phone/group)
Phone/group interval	4 m, 2 m (high-resolution section)	4 m
Maximum offsets	3.264 km, 1.44 km (high-resolution section)	3.264 km maximum offset
Spread geometry	Asymmetric split: 300/516 downdip	Symmetric

with the Zaleski et al. (1997) data set, 30-m–thick mafic dykes at 750 and 2000 m depth. Using a 120–500 Hz source, the figure provides a qualitative comparison of responses from different dyke thicknesses. As anticipated, thinner dykes at greater depths generate weaker responses.

The effectiveness of different source frequencies for revealing laterally variable dyke structure are demonstrated in Figure 5. In this example, the FD code was used to generate the synthetic response from a kimberlite dyke at 300 m depth that feathers from 5 to 1 m thickness (Figure 5a). For this model, shot gathers were computed using a Ricker wavelet source centered at 75, 200, and 400 Hz (Figures 5b, 5c, and 5d, respectively). The 400-Hz source generated data that resolves the thickness of the 5-m dyke and detects the lateral thinning. The 200-Hz gather (Figure 5c) provides some indication of dyke feathering, primarily through a decrease in reflection amplitude when compared with a gather from an unfeathered 5-m–thick dyke (Figure 5e). The 75-Hz source detects the 5-m–thick dyke, but amplitudes fall off significantly from the 1-m–thick dyke.

Figure 6 illustrates the effects of variable conditions in surface properties. This test is particularly relevant to the Snap Lake region, which was subjected to Laurentide glaciation that left areas of polished bedrock interspersed with till-covered areas of varying thickness. The laterally heterogeneous model (Figure 6a) includes a dipping kimberlite dyke of varying thickness (1–5 m, based on drillcore data) and, for reference, a horizontal mafic dyke (30-m thick) at 350-m depth. Two separate shot gathers are shown to compare the effects with (Figure 6b), and without (Figure 6c) a thin layer of glacial till with variable thickness. Note the longer reflection coda associated with the presence of a till layer relative to the model without the till layer.

The modeling demonstrated the feasibility of the proposed survey and provided insight for planning the acquisition geometry. The main conclusions of the study are:

1) At depths shallower than 500 m, sufficient energy in the 200–400 Hz range is returned so that the likelihood of detecting a 1–2-m thick kimberlite dyke is high. As target depths approach 1000 m, weak amplitudes due to attenuation substantially increase the risk of failing to detect the target. Detection is complicated by the laterally heterogeneous dip, thickness, and structure of the dyke. Furthermore, the deformed metamorphosed host rocks and numerous subvertical dykes and faults dissecting the region have the potential of generating a complex reflected wavefield that could conceal the reflections from the thin target.

2) Dyke thickness and detailed structural variation are unlikely to be resolved. Despite this conclusion, detection of the sheet and mapping its surface topography were goals that continued to drive the investigation.

3) Recording to large offsets (>1000 m) can yield useful reflection amplitudes for imaging the dyke at depths greater than 500 m (Figures 4 and 6). Longer offsets yield data uncontaminated by the significant ground roll generated by the till and shallow water/ice along the line. In addition, thin-bed AVO effects may increase reflectivity at greater angles of incidence. This requires further study.

4) With an acquisition layout designed for long offsets, small variations in the topography of the dyke (e.g., 5 m over a 100-m distance at 300-m depth) will be difficult to document. This scale of variation is of interest for mine development, but its imaging is unrealistic for a seismic experiment of this type. Large gaps (>20 m) in the continuity of the dykes should be detectable, but moderate noise levels and 3D effects will likely mask smaller variations in continuity. Feathering of dykes (i.e., rapid changes in dyke thickness over small distances on the order of tens of meters) will only be detected through variations in amplitude.

5) The requirement of high frequencies for detecting the dyke reinforces the need to maximize signal-to-noise ratios (S/Ns) during acquisition (e.g., recording data with high fold and ensuring excellent source and receiver coupling). In addition, the high-frequency reflections require accurate statics corrections, a task made more complex by the large lateral velocity variations in the near-surface resulting from alternating exposed bedrock, glacial till (permafrost), and lakes.

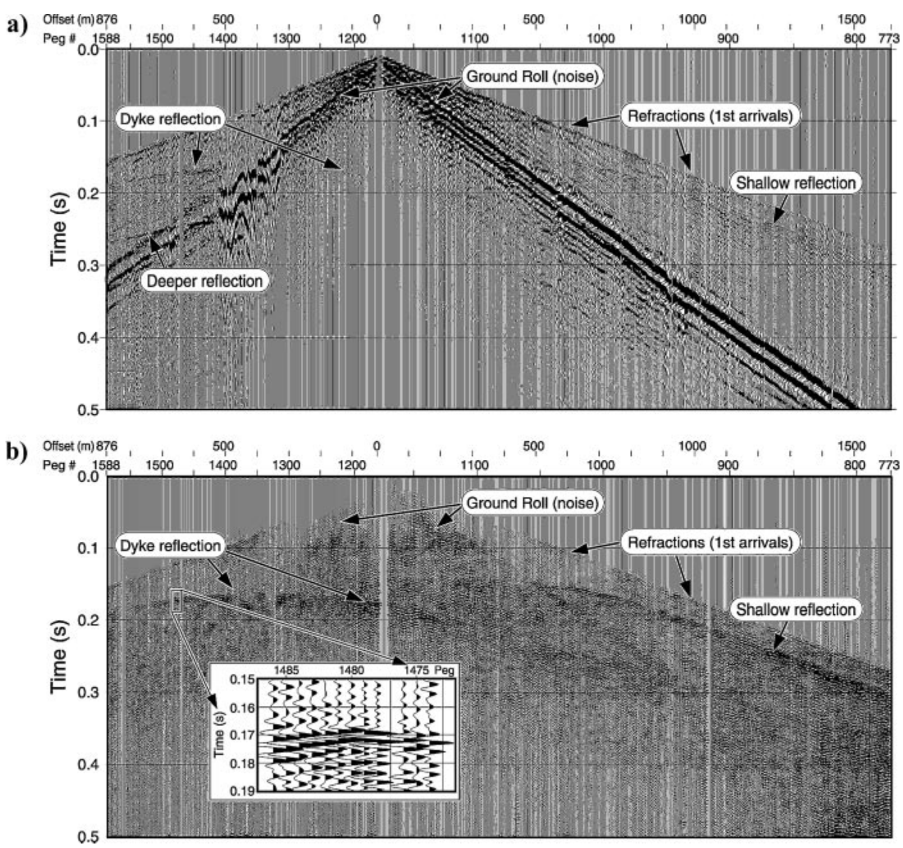


Figure 7. (a) Explosive shot gather (peg 1169, CDP equivalent position is 880; see Figure 2). The low-frequency ground roll dominates the record, obscuring the dyke reflection. The noise between pegs 1410 and 1320 is due to recording on the ice covering a shallow lake. (b) The majority of the noise is removed by bandpass filtering (200–450 Hz). Several reflections including the dyke are visible.

On the basis of these conclusions and other considerations, our industrial partners decided to proceed with a field experiment.

DATA ACQUISITION

The data acquisition layout was designed to achieve multiple goals. In addition to imaging the dyke, the survey was to determine the optimal acquisition parameters for potential future surveys. Therefore, the survey included explosive and vibroseis sources, land and lake-ice coverage, and long offsets. Data were acquired in May 2001 along two lines (Figure 2; Table 1). Line 1 (5.86-km long) was positioned on land to profile downdip (dyke dipping from subcrop to more than 1300-m depth). Line 2 (3.46-km long) was oriented approximately crossdip (dyke depth from 66 to 303 m) with the majority of the profile crossing Snap Lake. Maximum water depth along the seismic line is 15 m, and the ice thickness during acquisition was approximately 1 m.

In order to generate sufficient energy at the high frequencies required, small explosive shots detonated in holes drilled through the glacial till into bedrock were considered the optimal choice. However, drilling numerous shot holes in a granitic environment is costly and, in the sensitive ecology of the north, is accompanied by permitting difficulties. A vibroseis unit is cost-efficient, more easily permitted, and able to operate on both lake ice and land. However, it was unclear if the poorer coupling associated with a minivibe in this environment would limit the high-frequency energy produced. Therefore, both sources were tested (Table 1). The initial intent was to acquire coincident data sets along line 1 using both explosive sources and vibroseis for comparative purposes. Unfortunately, deteriorating surface conditions prevented the late-season use of vibroseis on land for environmental reasons. A direct comparison of sources was achieved, however, along a small portion of line 2, where 23 explosive shots were recorded in addition to the vibroseis data.

The basic acquisition configuration was the same for both explosive and vibroseis lines (Table 1). Data were recorded using an I/O System 2000. The receiver array used single geophones spaced at 4-m intervals. However, to provide improved spatial sampling at the shallow end of the dyke, geophone spacing was decreased to 2-m intervals along the southwestern 1.94 km of line 1 (Figure 2).

DATA PROCESSING

A relatively standard data processing flow was used. However, to enhance the chances of imaging the thin target, considerable effort was applied to statics corrections (refraction and residual) as well as velocity and spectral analyses. The initial processing steps included field geometry, quality control (trace editing and muting), and first-break picking. Refraction statics analyses were accomplished using a 3D inversion algorithm that was applied to the first-break traveltimes to generate a layered velocity model (Hampson and Russell, 1984). The resulting model consisted of a variable weathering layer representing the till and sediments (520 m/s) overlying two granitic layers with velocities smoothly increasing from 5800 to 6100 m/s. Prestack processing included band-pass filtering (120–450 Hz), f-k filtering, spherical divergence, spectral balancing, NMO, deconvolution, and residual statics. Poststack processing included deconvolution, time-variant filtering, and finite-difference time migration.

RESULTS AND DISCUSSION

Reflections from the dyke were detected along both lines. The line 1 land profile acquired using explosive shots was spectacularly successful. The line 2 vibroseis profile had mixed success: dyke reflections were recorded on land, but the ice experiment recorded poor quality data with no visible reflections.

Line 1—Explosive source on land

The quality of the data acquired along line 1 was reasonably high even though the spring thaw had just begun, at times degrading geophone coupling. However, the S/N was sufficient

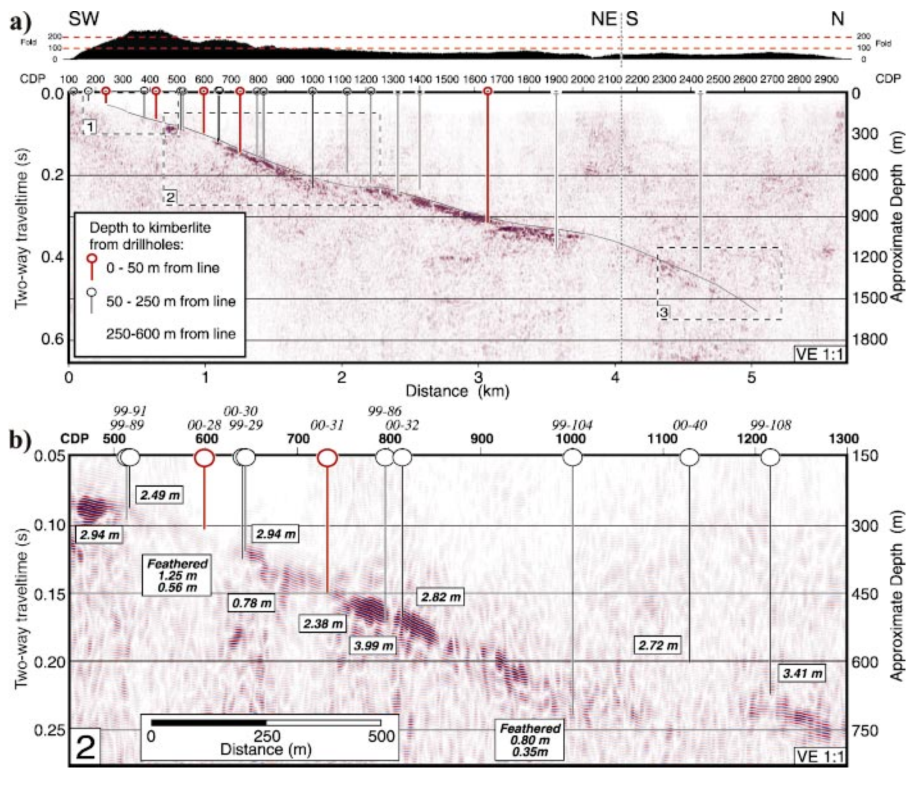


Figure 8. Migrated stacks of line 1: (a) the full profile with a thin black line tracing the top of the dyke reflection package, (b) enlargement of box 2 in (a) showing the dyke reflections through a zone with significant variations in reflector amplitude and dip. Depths to kimberlite from nearby drillholes are indicated. In (b), dyke thickness is labeled for each drillhole. For cores exhibiting significant feathering, the thickest kimberlite intersections are labeled. Note the correspondence between zones of low amplitude with regions that are feathered or have significant crossdip. Approximate depths are calculated assuming 6 km/s and are corrected to a 465-m datum.

that reflections from the dyke can be observed in many of the shot records. Figure 7 shows an example of a shot gather; the dyke reflection below the shot point is at 180 ms (∼550 m). Strong, low-frequency ground roll dominates the unfiltered panel but was easily removed using a bandpass filter (200–450 Hz) (Figure 7b) or f-k filtering. The dominant frequency of the explosive shots was approximately 100 Hz, with good generation of high-frequency energy to well above 400 Hz. The frequency content of the dyke reflections was between 240 and 350 Hz, with a broad range of dominant frequencies that generally decreased with reflector depth due to attenuation. These frequencies are high enough to be well into the predicted range required to detect the dyke.

The dyke is superbly imaged from 30 ms (∼60 m) to 425 ms (∼1300 m) with faint reflections continuing to at least 520 ms (1650 m) (Figure 8). The coincident and near-coincident drillhole data correlate well with the reflection image, but the seismic profile adds considerable detail to the known topography of the dyke (Figures 8–10). Contrasting rather dramatically with reflection profiles in sedimentary environments, the target is the only reflector present that has substantial lateral continuity within the generally transparent granitic host rock. Although this enhances the dyke reflections, the lack of other reflectors limits interpretations of fault locations and regional geological structure. In addition, techniques that benefit from comparisons between reflectors (e.g., semblance and wavelet analyses) are ineffective.

Throughout most of the profile, the reflective package comprises 3–5 cycles (∼20 ms or ∼90 m) in both shot gathers and stacked sections (Figures 7 and 8). Clearly, the dyke thickness is not resolved. The frequency content of the stacked reflections is somewhat lower than those in the gathers. Several factors likely contribute to the exaggerated thickness and reduced frequencies of the reflection package along the profile. Multiples from internal reflections within the dyke as well as those trapped within the thin, intermittent till layer could add cycles to the dyke reflections. This phenomenon is clearly visible in the synthetic models (Figure 6). Large offline variations in topography and thickness of the kimberlite sheet will add complexity to the reflection package imaged beneath the 2D profile. Imperfect statics corrections also could attenuate the high frequencies in the stacked data and increase the effective seismic thickness of the dyke. Finally, the drillcores indicate considerable variability in the degree of feathering, small intrusions (dykelets), alteration, and fracturing adjacent to the dyke. In some regions, reverberations from small-scale layering could add to the reflective coda. The nature and extent of the coda are the subject of ongoing research.

Amplitudes of the dyke reflections vary considerably along the profile. Attributing these variations to specific dyke structure is difficult because all of the factors that influence the thickness of the reflection package can also influence amplitudes. In addition, amplitude variations also may be influenced by compositional variation within the dyke; the unusually high proportion of brecciated material within the dyke itself is heterogeneous, and this may influence reflectivity and tuning characteristics. However, two important observations can be made.

1) Several zones where reflection amplitudes drop and continuity decrease correspond to places where drillcores indicate the dyke changes from a relatively simple planar sheet to a region with considerable 3D variation in topography and thickness (e.g., CDP ranges 500–700 and 850–1250 in Figure 8). Several drillcores in these regions indicate the dyke becomes locally feathered, with many thin splays being intersected. These correlations have important implications for using the seismic data for mine development. The observations suggest that the amplitude data may be useful for illuminating fine-scale structure and thus guiding further drilling to efficiently investigate complex zones that may present difficulties for mining.
2) Amplitudes decrease significantly below 0.35 s (∼1150 m). The few drillcores from these depths indicate the dyke thins to less than 1.6–1.0 m (Figures 8 and 10). Similarly, reduced amplitudes are observed in other regions associated with dyke thicknesses of less than 1.3 m (Figure 8 and 9). This may correspond with attenuation or poor quality acquisition and processing of the high frequencies required to detect the dyke at sub-1.5-m thicknesses. In addition, if tuning effects are playing a role, their influence may be reduced as dyke thickness decreases below 1.5 m.

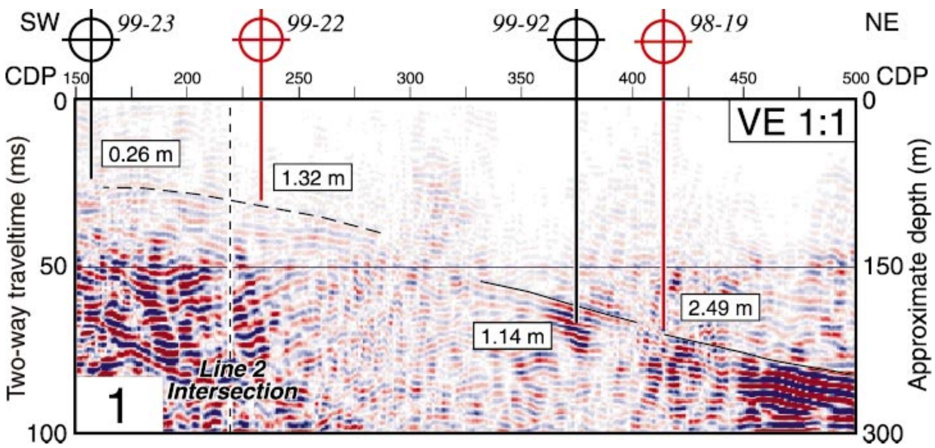


Figure 9. Enlargement of box 1 in Figure 8. Unmigrated stack images the dyke as it approaches the surface at the southwest end of line 1. Black lines delineate interpreted top of the kimberlite dyke. Depths at which near-coincident drillholes intersect the top of the dyke are shown and kimberlite thicknesses are noted. Approximate depths are calculated assuming 6 km/s and are corrected to a 465-m datum.

In order to understand the observed amplitude variations, additional work is required to model thin-layer tuning effects in conjunction with the drillcore and seismic data.

The long offset data were important for imaging the dyke at depth. Tests using selected offset ranges indicate that, for exploration purposes, thin dyke detection below 400 m improved significantly as offsets were increased to 1000 m. When the target depth exceeded 1000 m, slight improvements were observed using offsets exceeding 1000 m.

Line 2—Vibroseis source on lake ice and land

In contrast with the superb reflection data acquired along line 1, the line 2 data set was decidedly inferior (Figure 11). Recording conditions were ideal during acquisition, with no wind and excellent geophone coupling due to cold temperatures freezing the geophones in place. However, the reverberations and flexural wave energy generated by the Snap Lake ice, water, and till layers contaminated the data with noise that proved difficult to remove. The same reverberations also affected the energy returned from the dyke below. Furthermore, high frequencies were attenuated, thereby decreasing the resolving and detection potential of the data set. In the shot gathers acquired when the minivibe was operated on the lake ice, no reflections were observed from the dyke. Reverberations and ambient noise masked any signal, including first breaks, beyond 1000-m offset. Efforts to enhance the dyke reflections were made more difficult because the dyke lies between 20 and 100 ms (60–300 m) depth along the profile. Therefore, at near offsets, the signal was buried in reverberatory noise; at more distant offsets, not enough energy was returned to detect the signal.

Although the majority of line 2 crossed Snap Lake, the northwest 600 m of the line were on land. Along this section, the vibroseis unit successfully detected the dyke with reflections apparent in the shot gathers (Figure 12a). Operation of the vibroseis unit on the frozen ground effectively propagated high-frequency energy; the dominant frequencies of the shallow dyke reflections are approximately 330 Hz.

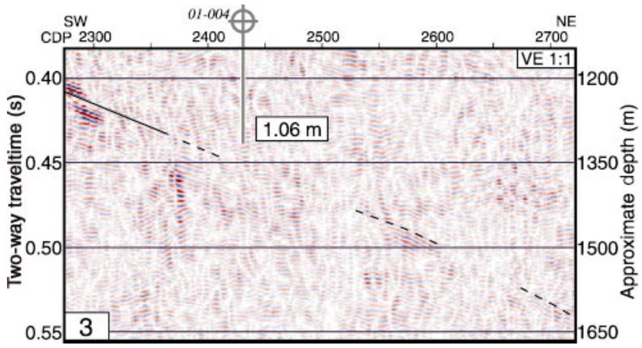


Figure 10. Enlargement of box 3 in Figure 8. Unmigrated stack shows the low-amplitude reflector at the north end of the profile. Although it may be a diffraction, the dyke may be imaged to 1650-m depth; dip appears to increase below 1500 m. Drillcore intersection with kimberlite was 600-m offline. Approximate depths are calculated assuming 6 km/s and are corrected to a 465-m datum.

The stacked section shown in Figure 13 includes only the on-land vibroseis shots recorded into the array. If the on-ice vibroseis shots are included, the image quality degrades significantly. The dyke is imaged beneath the 600 m of the line on land but not beneath the lake ice.

Vibroseis and explosive source comparison

Although a minivibe was the primary seismic source along line 2, 23 shots were detonated along the northwestern portion of the line. This provided an opportunity to directly compare coincident vibroseis and explosive sources on land (Figure 12). The dyke reflection is present in both shot gathers. The frequency content of the shot data is only slightly higher than that of the vibroseis data. However, significantly more energy was output by the 0.25-kg charges. The fact that the minivibe gathers did successfully record dyke reflections is an important observation considering the cost-efficiency and low environmental impact of vibroseis compared to bedrock-coupled explosive shots.

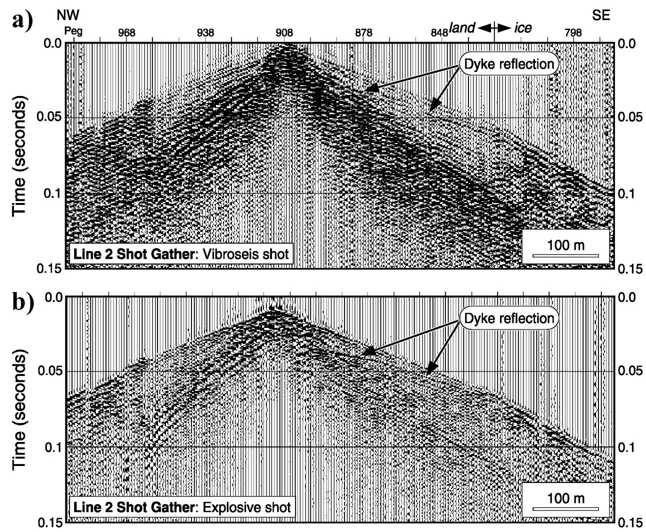
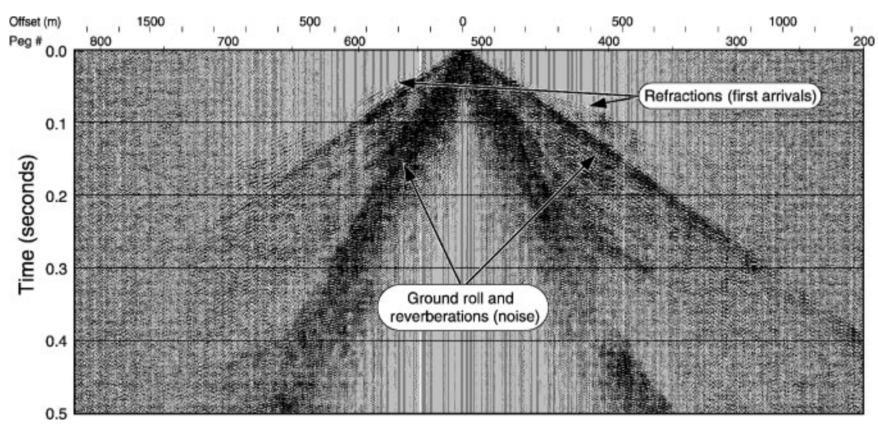


Figure 12. Comparison between nearly coincident vibroseis (a) and explosive (b) shotpoints. These shotpoints are located on land where lines 1 and 2 intersect (Figure 2). The gathers are filtered with a 160-Hz low-cut. S/N is better with the 0.25-kg shot than the vibroseis source. However, both sources detect the shallow dyke, which lies 66 m below the shotpoints.

Figure 11. Vibroseis ice shot gather (peg and CDP 515; see Figure 2). In this portion of the shot gather, the source and all geophones are on the ice surface. Ground roll and reverberations dominate, and the signal attenuates much more quickly than when the geophones are on land (e.g., Figure 7). The 140-Hz low-cut filter does little to improve the S/N.



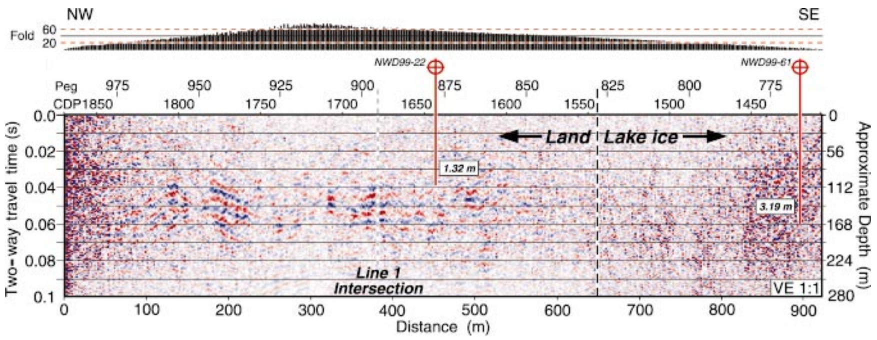


Figure 13. Migrated stack of the northwest quarter of line 2. Only vibroseis shots on land are included in the stack. CDP number denotes centers of 2-m bins. Near-coincident drillhole depths are approximated using 6 km/s and are corrected to a 500-m datum.

SUMMARY

The Snap Lake experiment demonstrated that seismic reflection surveying can be an extremely useful tool for exploration and deposit mapping of thin kimberlite dykes or sills. With an appropriate target, drilling programs that are limited by high costs and poor spatial sampling could be significantly enhanced by the addition of seismic reflection profiles. As an exploration-scale tool for thin dyke detection, the bedrock-coupled dynamite data excelled. The limited success of the land-based vibroseis data indicates that a vibroseis source could also produce acceptable results. Indeed, a subsequent survey clearly imaged the dyke to more than 1300-m depth using a vibroseis source (Diamondex Resources Ltd., personal communication, 2002).

Unfortunately, the failure of the lake-ice vibroseis line is a significant, if not unexpected, outcome because 30–40% of the Slave kimberlite zone is covered by water. Winter surveys have many advantages in this region. Environmental permitting is easier because the fragile terrain and sensitive lake ecosystems limit activities during nonfrozen periods. Mobility is easy when the terrain is covered by snow and ice, but very limited otherwise. The negative results from the minivibe survey on lake ice indicate that alternative techniques for acquiring reflection data over lakes must be used. High-resolution marine surveys may be the solution, but these would present their own technical and permitting challenges.

The survey acquisition parameters and dyke thickness limited the usefulness of the data for detailed mine planning. Dyke thickness was not directly resolved, and 3D structure makes interpretation of fine-scale structure and continuity difficult. However, this initial application of seismic techniques has raised a number of issues that, if addressed, suggest that reflection data may be even more useful for deposit characterization and more detailed mine-development applications. In particular, the variability in reflection attributes appears to be correlated with dyke thickness and structure. In order to understand these observations, ongoing studies are directed towards investigations of thin-layer reflectivity in conjunction with the drillcore and seismic data.

Although subhorizontal kimberlite intrusions are not common, the success of the reflection method at Snap Lake may encourage use of vertical seismic profiling, crosshole tomography, and other seismic techniques to image the more prevalent near-vertical kimberlite pipes. In principle, seismic methods could be used to map the kimberlite pipe–host rock contact, providing an important new tool for characterizing kimberlite deposits.

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