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Introduction

Sustainable management of groundwater resources requires regional knowledge of aquifer systems (Sharpe et al., 2002). In the early 1990s the Geological Survey of Canada (GSC), in collaboration with local partners, including York Region, embarked on a regional study of the Oak Ridges Moraine (ORM) in southern Ontario (Figure 1), designed to improve understanding of the regional geological and hydrogeological framework of a significant Quaternary aquifer complex (see http://gsc.nrcan.gc.ca/hydrogeo/orm/index_e.php). The study used a basin analysis approach which starts with the collation of archival data, including all available borehole data, and integrates that with high-quality geological, geophysical and hydrogeological datasets to develop and test conceptual subsurface geological models. Ultimately, the geological models provide the input to hydrostratigraphic and groundwater flow models (Sharpe et al., 1996; 2002).

High quality data were acquired in the ORM area using a variety of approaches, including sediment mapping, continuous deep drilling, geophysical surveys (surface and borehole), remote sensing, stream baseflow gauging and geochemistry surveys. Geophysical surveys played a prominent role in the multi-disciplinary research program and were particularly important because of the large study area, complex glacial stratigraphy, and thickness of sediments (up to 200 m). Borehole, surface and airborne geophysical surveys provided information on the subsurface at scales of investigation varying from sub-metre to kilometre (Pullan et al., 1994; 2001). To a large extent, shallow seismic reflection surveys were used to delineate subsurface stratigraphy (Pugin et al., 1996, 1999), and to identify regional hydrostratigraphic units (e.g. Sharpe et al., 2003b).

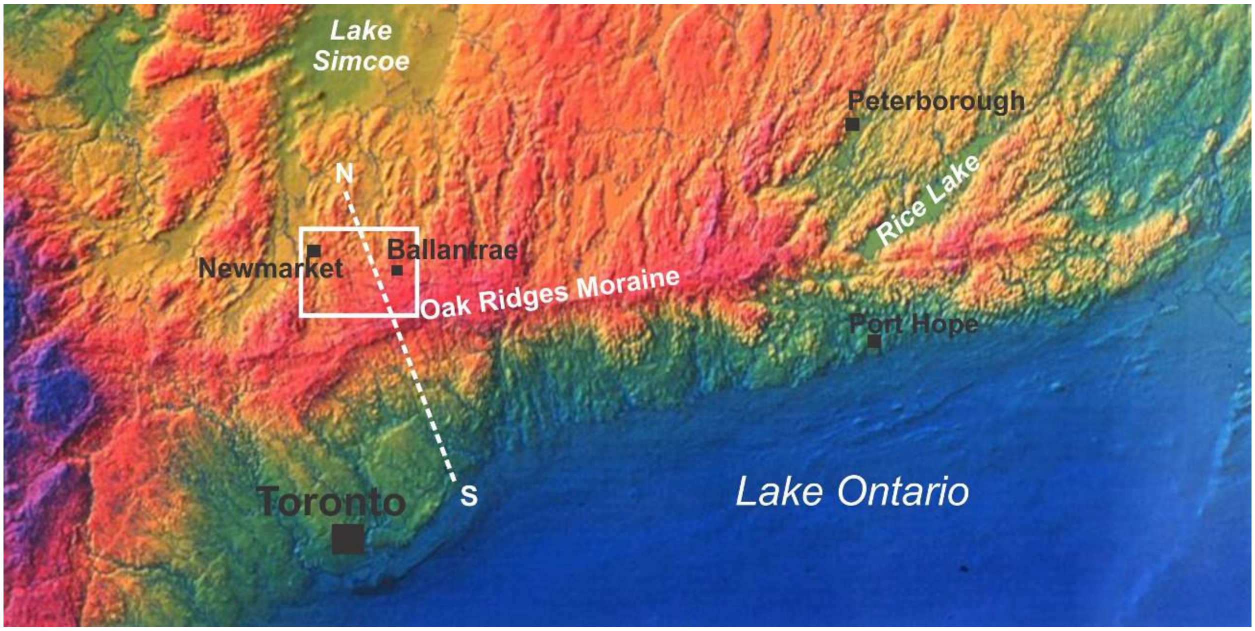

Figure 1: Digital elevation model (DEM) of the Oak Ridges Moraine area in southern Ontario (from Kenny et al., 1999). The dashed white line corresponds to the N-S cross-section in Figure 2. The white box outlines the area shown in Figure 3. To the north of the box, the DEM identifies the surface expression of approximately north-south buried valleys.

This report presents and discusses new data acquired in July 2008, when the GSC carried out a shallow seismic reflection survey along two lines east of Newmarket, Ontario, to investigate an area of thick unconsolidated sediments which had been identified during earlier investigations (Pugin et al., 1999). Assistance was provided by the Regional Municipality of York because of their interest and ongoing search for groundwater resources for the town of Ballantrae (Figure 1). The regional municipality of York has a long term interest in groundwater resources and have carried out, and/or, supported many groundwater investigations across the region in the past several decades. Recent work has focused on aquifer delineation related to community water supply (e.g. CAMC, 2006; KMK Consultants Limited, 2006).

Geological Model – Oak Ridges Moraine

A conceptual model of the ORM was developed during the regional study work. It consists of several major sediment packages depicted in a 3-D regional geologic framework and highlights six principal stratigraphic elements. From oldest to youngest these are: i) bedrock; ii) lower sediments (or lower drift sequence); iii) Newmarket Till; iv) channel sediments infilling channels eroded into or through the Newmarket Till; v) Oak Ridges Moraine sediments, and; vi) Halton Till (Sharpe et al., 1996). Figure 2 depicts this sequence in a north-south cross-section across the ORM. The conceptual model identifies lower, channel and ORM sediments as potentially significant aquifers, whereas Newmarket and Halton Till generally form aquitards. Bedrock acts locally as an aquifer or an aquitard.

The four main aquifer targets identified in the conceptual model (Sharpe et al., 1996) include:

1. ORM sediments
2. Channel structures cut into or through the Newmarket Till and filled by ORM sediments
3. Extensive sands within the lower drift sequence, and
4. Lower drift sands infilling valleys on the buried bedrock surface.

Sharpe et al. (1996) recognized that the lower drift is composed of several geological and hydrostratigraphic units, and may in fact be supplying a significant portion of the groundwater used in York Region. However, detailed information on this sediment package is lacking so it is difficult to develop conceptual models of how these deposits were formed and to identify potential groundwater targets within them. The seismic data presented in this report provide new insights and are one way to further an understanding of these deposits.

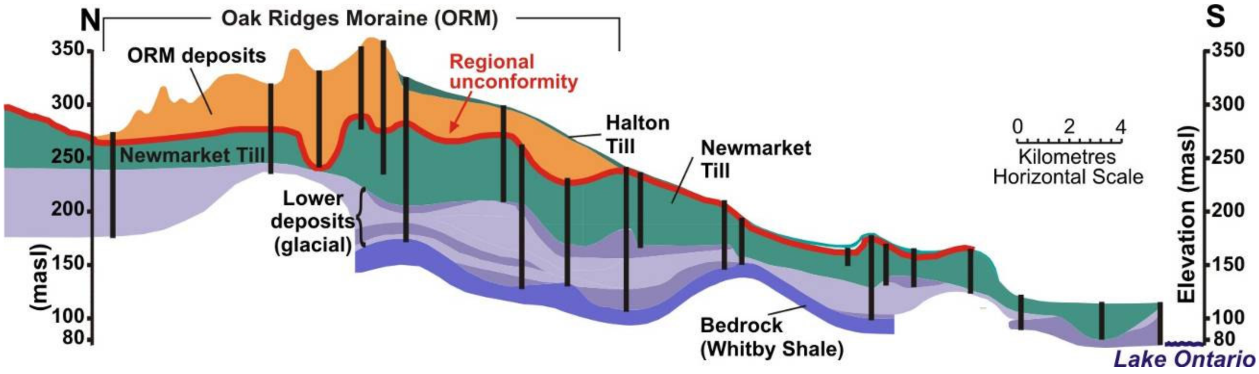

Figure 2: Schematic north-south borehole transect across the Oak Ridges Moraine (see location in Figure 1) showing the six principal stratigraphic elements in the conceptual geological model developed for the area (adapted from Sharpe et al., 1994).

Previous ORM Seismic Reflection Surveys

A summary of the development and implementation of shallow seismic reflection methods is given in the Annex to this report. In the 1990s, the GSC collected ~50 line-km of shallow seismic reflection profiles using 24- or 48-channel engineering seismographs, single 50 Hz vertical geophones as receivers and a 12-gauge in-hole shotgun source. The compressional-wave (P-wave) data were collected with source and geophone spacings of 5 m and with the source positioned 5 m off the end of the array, resulting in source-receiver separations of 5-120 m. A summary of this work, including data processing and interpretation can be found in Pugin et al. (1999).

The locations of the seismic reflection profiles in the Newmarket-Aurora-Ballantrae area are shown in Figure 3. In general, the survey lines were chosen to delineate areas where channel structures cut into or through the Newmarket Till were suspected or indicated by borehole data. The 2008 lines were located ~ 4 km to the east of Ballantrae and were designed to investigate an area where it was known that a thick sediment package existed.

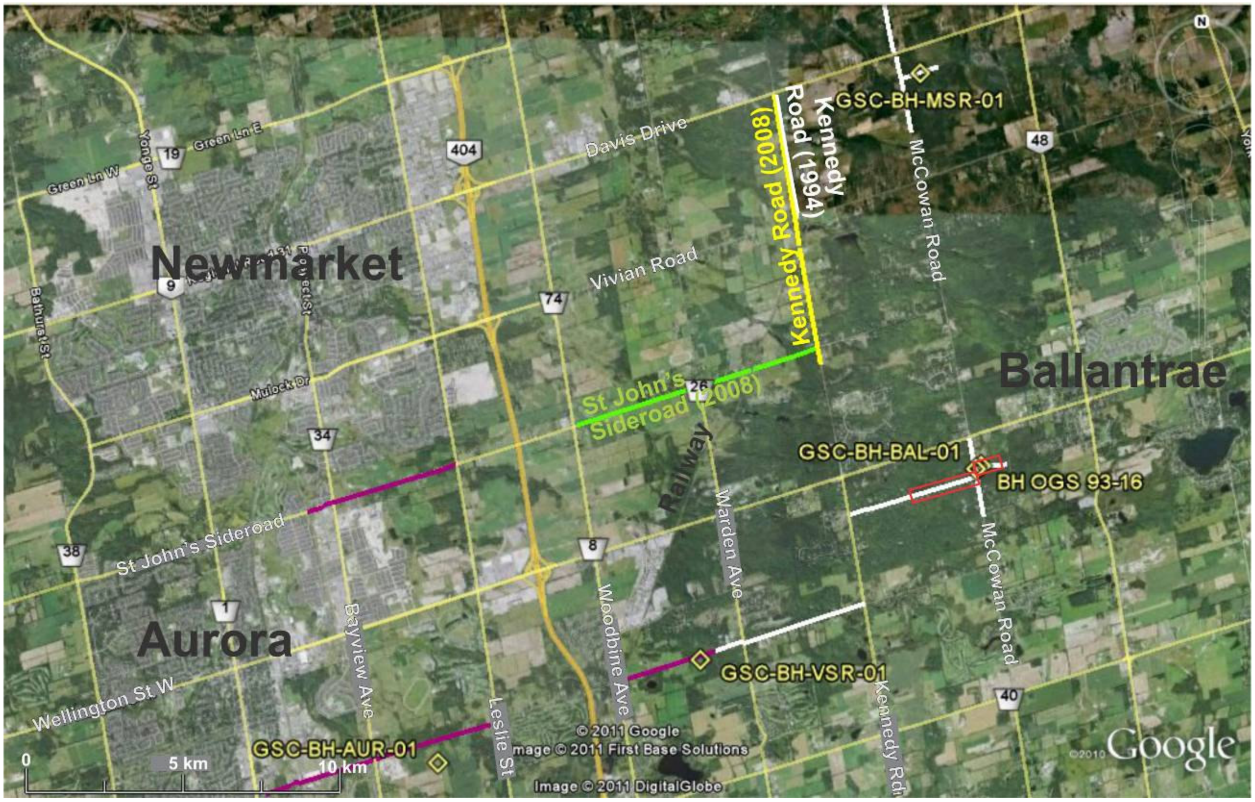

Figure 3: Detail of the Newmarket-Ballantrae area outlined in Figure 1 showing the distribution of shallow seismic reflection profiles acquired by the GSC: 1) profiles near Ballantrae acquired by the GSC in 1993-94 (white lines); 2) data acquired in the Aurora area under contract by Geophysical Applications Processing Services (purple); 3) data acquired by GSC in 2008 along Kennedy Road (yellow) and St John's Sideroad (green). The locations of deep boreholes drilled by the Ontario Geological Survey and the GSC are also shown. The location of the seismic data in Figure 4 is indicated by the red boxes.

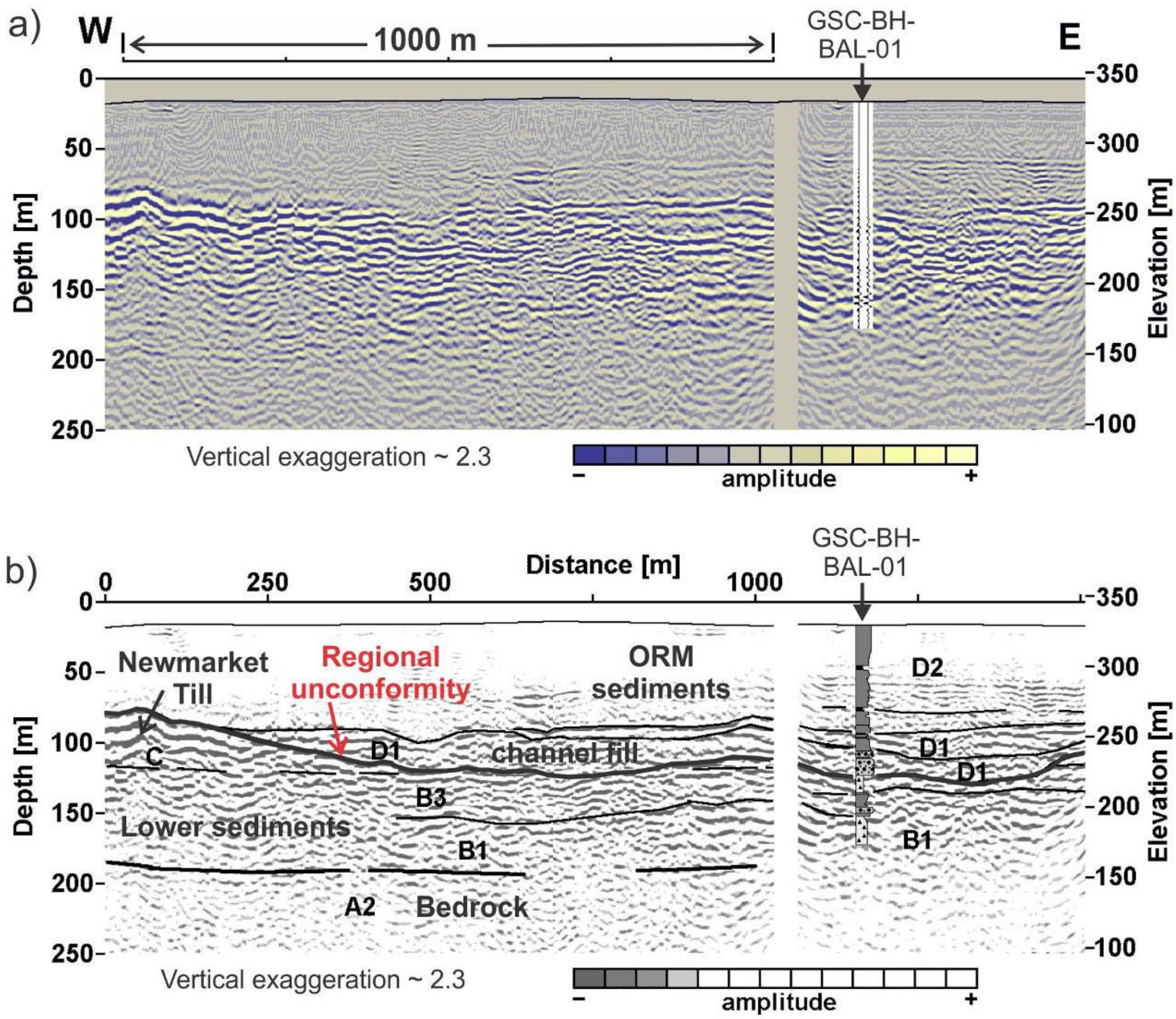

Figure 4: a) Portion of the east-west seismic reflection profile (migrated and converted to a depth/elevation section) acquired southwest of Ballantrae in 1993. Location is shown in Figure 3. The corridor stack (reflection data obtained downhole in GSC-BH-BAL-01 is superimposed on the profile at the borehole location. The break in the profile marks the location of McCowan Road and a north-south offset of 150 m in the seismic line. b) Interpretation of the seismic profile shown with the lithological log from GSC-BH-BAL-01 (see Sharpe et al., 2003a) superimposed at the borehole location. Figure reproduced from Pugin et al. (1999).

Figure 4 presents the interpretation of the 1993 seismic data acquired south of Ballantrae. It shows a broad channel feature defined by the regional unconformity and infilled with a thick sequence of channel fill deposits (D1). These fill deposits are interpreted to extend across most of the channel feature and include a 15 m thick sequence of coarse (bouldery) gravel at a depth of 90 m at the borehole site. Based on these seismic data, the channel extends over an east-west distance of >1 km. The feature is eroded into - and in places through - the Newmarket Till, but does not cut deeply into the lower deposits at this site.

From the early seismic reflection surveys the Newmarket Till was identified as a regional high-velocity marker bed (Pullan et al., 2000), and the regional unconformity at the top of this unit (e.g. Sharpe et al., 2004) was generally seen as a high-amplitude reflection on the seismic profiles. A buried channel configuration was defined and traced beneath the ORM (Figure 5). Multiple buried channels were observed, varying from narrow (<1 km), deep (~100 m) channels with steep and partially failed slopes to broader (2-3 km) channels with low-angle sides and slopes (Pugin et al., 1999). In some cases, the presence of even broader (>5 km wide) channels was suspected (Pullan et al., 2001).

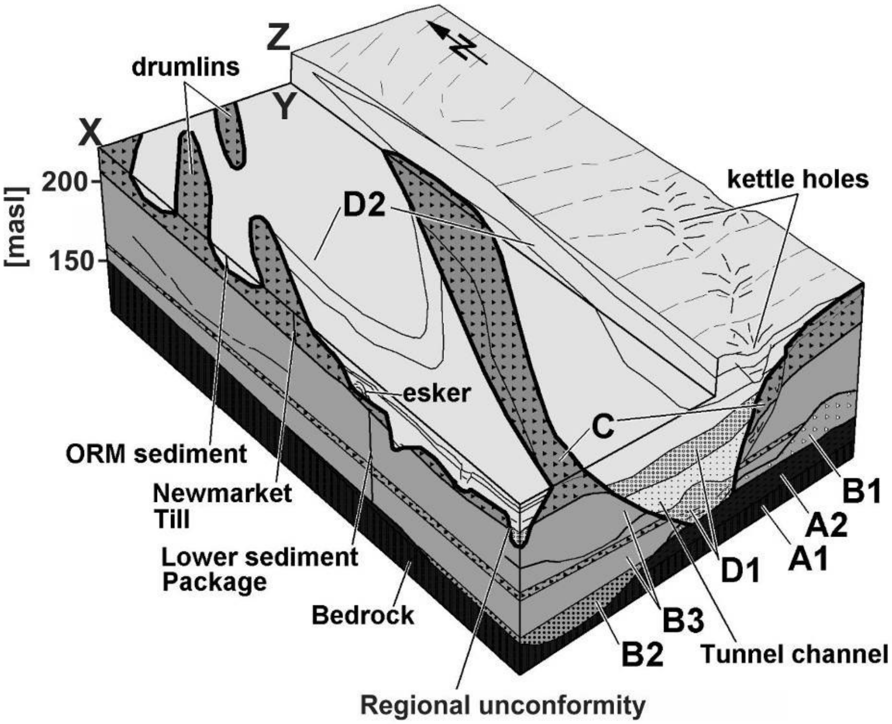

Figure 5: Schematic representation of the seismo-stratigraphic units and their relation to the conceptual geological model. Figure reproduced from Pugin et al. (1999).

Methods and Data Acquisition

The methodology of shallow seismic reflection surveys has evolved considerably since the 1990s. In particular, the GSC has developed a vibratory source/landstreamer data acquisition system (see description in Annex) which has significantly improved the efficiency and cost-effectiveness of seismic reflection surveying (Pugin et al., 2009a). Ongoing developments include the use of multi-component recording (Pugin et al., 2009b).

With the new data acquisition system we are able to efficiently record long regional lines, as well as improve the signal-to-noise ratio of the data, and allow for the processing of variable record lengths. The 2008 data were acquired along Kennedy Road and St John's Sideroad (Figure 6) using the new minivib/landstreamer recording the vertical component of motion. The recording parameters are presented in Table 1. A sample field record is shown in the Annex to this report (Fig. A1-7). In total, 8 line-km of data were acquired in 2 days, in comparison to the 1994 Kennedy Road survey (2 line-km) which took 4 days to acquire.

Table 1: Recording parameters for 2008 seismic reflection survey.

Date of data acquisition	July 9, 2008 (Kennedy Road), July 10, 2008 (St John's Sideroad)
Source	IVI Minivib operated in vertical mode
Source parameters	35-350 Hz linear sweep (0.5 and 0.2 s start and end tapers)
Source spacing	4.5 m
Receivers	28 Hz vertical geophones (1/channel)
#Receivers @ receiver spacing	36 @ 1.5 m plus 12 @ 3 m
Source-nearest receiver offset	3 m
Range of source-receiver offsets	3 – 88.5 m
Recording system	Geometrics 24-channel Geode x 2
Record length	7 s
Sample Rate	0.5 ms
Line Length	4.3 km (Kennedy Road) 3.9 km (St John's SideRoad)

Data were processed using WinSeis™ (Kansas Geological Survey) seismic processing software, in combination with Seismic Unix and in-house seismic processing software. The main processing steps are outlined below in Table 2.

Table 2: Processing flow chart for P-wave seismic reflection data.

Format conversion, SEG2 to KGS SEGY
Spectral whitening
Cross correlation
Editing of the geometry
Refraction analysis for statics calculation
Frequency filter
Scaling (trace normalization)
Bottom mute of remaining surface-wave energy
Static corrections
Velocity analysis
NMO Corrections
Top mute
Stack, nominal fold: 24
Correction for ground surface topography
Conversion to elevation (using velocity analysis results)

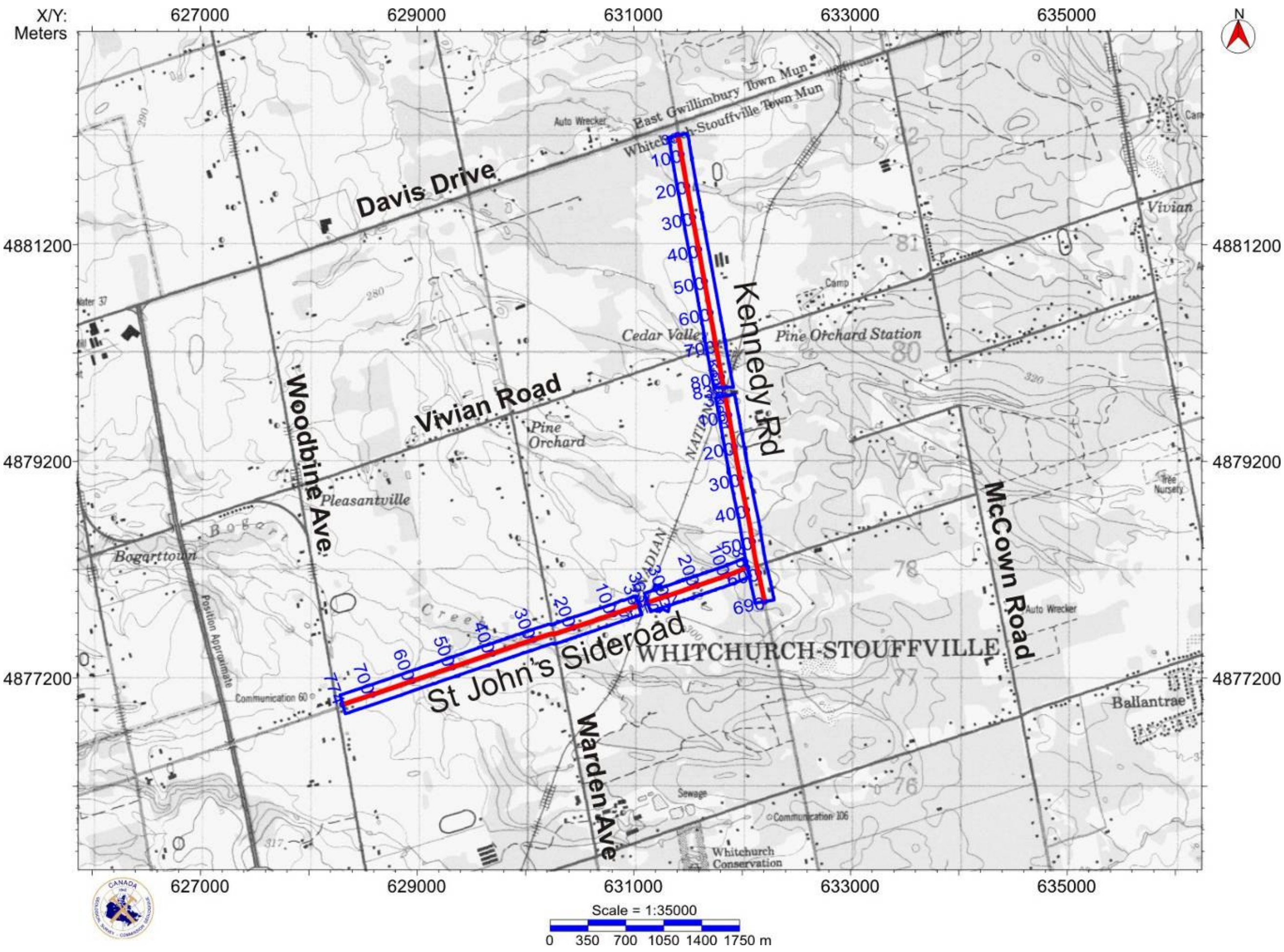

Figure 6: Detailed map of the 2008 survey lines along Kennedy Road and St John's Sideroad showing the exact CMP locations (see seismic sections in Figs. 7, 8).

Results and Discussion

The processed seismic sections for Kennedy Road (KR) and St John's Sideroad (SJSR) are shown in Figures 7 and 8 respectively. Table 3 outlines the correlation between units discussed as part of the ORM conceptual model, and the sequences identified in these figures. The seismic sections show 100-150 m of sediment above bedrock throughout the area. Along SJSR, the bedrock surface (identified in Figs. 7,8 as E.S.1) is interpreted to be relatively flat with an average elevation of ~175 masl, dipping slightly to the east in the 300 m west of the intersection with KR. In contrast, along KR a bedrock valley is observed with bedrock dipping from ~155 masl at Davis Drive and at the railway crossing to 115-120 masl at ~CMP 550 (just north of the intersection with Vivian Road). This was the deep bedrock surface identified, but not entirely delineated, by the Kennedy Road survey in 1994. In comparison, bedrock elevation in GSC-BH-MSR-01 (~2.75 to the NE – see Fig. 3) is ~180 masl, and at GSC-BH-BAL-01 is estimated to be ~170-175 masl (Sharpe et al., 2003a).

Table 3: Correlation table linking sediment components in the ORM area as discussed in Sharpe et al. (1996) and in the seismic interpretations shown in this report (E.S. = erosional surface).

ORM Conceptual Model (Sharpe et al., 1996)	Simplified Lithology	Seismic units (Figure 4)	Seismic units (Figures 7 and 8)
Halton Till	Clay-silt diamicton	Surface layer - rarely identifiable on seismic sections	
Oak Ridges Moraine sediments	Silt, sand, some gravel	D2 D1 (channel fill)	Sequence III and IV (separated by E.S.3)
Regional unconformity			E.S.2
Newmarket Till	Sandy, stony diamicton	C	Upper unit of Sequence II
Lower deposits (Lower drift sequence)	Variable	B (1, 2 etc)	Sequence II
Bedrock surface			E.S.1
Bedrock	Paleozoic (various formations)	A2 (“soft” e.g. shale) A1 (“hard” e.g. limestone)	Sequence I

The sediment sequence above bedrock is characterized by two additional erosional surfaces (E.S.) that define the subsurface architecture and stratigraphy. The older surface (E.S.2) can be identified across the two seismic sections as a high-amplitude reflection. On KR it is observed at depth in the section (~170-185 masl), and actually corresponds with the bedrock surface at the south end of the line (Fig. 7). On SJSR this surface rises gently to the west until it is intercepted by the youngest observed ES. This shallower erosional surface (E.S.3) is characterized by a medium-amplitude reflection and some evidence of cut and fill features. It is observed at approximately 50 m depth along KR and on the east end of SJSR. Along KR, this reflector mirrors the surface topography and dips to the north, separating the upper 50 m of sediment from an underlying unit that thins to the north (Fig. 7). Between Warden and Bayview Avenues along SJSR, this E.S. rises to the west, and is within 25 m of the ground surface (~270-275 masl) on the westernmost kilometer of the survey line (Fig. 8).

Based on the high near-surface velocities observed along the west end of the SJSR profile, the erosional surface here (E.S.2 and 3) is interpreted to represent the top of the Newmarket Till (Pullan et al., 2000; Pugin et al., 1999), and therefore is the regional unconformity in the conceptual geological model (Fig. 2) separating Newmarket Till from the overlying Oak Ridges Moraine sediments. Along the rest of the sections, the regional unconformity (E.S.2.) outlines a broad channel feature that has cut through the Newmarket Till and into the underlying lower sediment sequence. At the south end of KR, all material above bedrock appears to have been removed before the channel was infilled. All sediments above this surface are interpreted as Oak Ridges Moraine deposits, and the coherent, low-reflectivity character of these units on the seismic profiles suggests that they consist mostly of fine-grained deposits (sand-mud). Along the entire KR section, ORM deposits are interpreted to be 80-150 m thick.

The large channel outlined by E.S.2 may be related to the broad channel feature mapped south of Ballantrae and intercepted by GSC-BH-BAL-01 (Fig. 4) and the narrower channel delineated beneath Vandorf Sideroad and intercepted by GSC-BH-VSR-01 (see Fig. 8 of Pugin et al., 1999). However, along KR and SJSR the seismic character suggests that the ORM deposits in this channel are predominantly fine-grained. The coarse-grained deposits found in the base of the Ballantrae channel do not appear to exist in this region.

E.S.3. (Figures 7 and 8) thus represents an erosion episode within the ORM sequence. It is assumed that, especially in relation to E.S.2., this was relatively minor erosion episode confined to ORM deposition and not of regional extent. It is highlighted here from the perspective of assessing groundwater targets. It is inferred from the relatively high reflectivity of this surface and the in-filled channel features observed at the contact (see CMPs 300-600 on KR south of the railway tracks and CMPs 80-160 on SJSR east of the railway tracks) that coarser sediments (sand-gravel?) exist on this unconformity. The small channel features in particular may represent a groundwater target, though not likely one that would be useful on a municipality scale.

Based on the above interpretation of the Newmarket Till and ORM sequences along these seismic lines, two occurrences of lower drift sediments are observed in these profiles – the first under the north end of KR (sequence II between E.S.2. and E.S.1.),, and a second more extensive sequence along SJSR (sequence II excluding Newmarket Till). It is possible that these may represent significantly different stratigraphies. The more massive, lower reflectivity sequence along the westernmost 1.5 km of SJSR may represent a channel infilled with Thorncliffe sediments. This type of seismic signature has been observed on the seismic profiles obtained north and south of Aurora (Fig. 3) and interpreted as thick sequences of Thorncliffe formation (Sharpe et al., 2003a, 2011). The Thorncliffe channel fill sediments are analogous to channel fill sediments in the ORM stratigraphic units and this relationship is developed in Sharpe et al., 2011. The lower sediment deposits in the central and eastern portion of SJSR profile are characterized by more coherently-layered, higher-amplitude reflections. Here the lower drift sequence may represent a more complete suite of lower deposits (Thorncliffe plus Sunnybrook, Scarborough Formations etc) as observed in GSC-BH-BAL-01 (Sharpe et al., 2003a). In contrast, the deeper "lower drift" deposits (Sequence II) observed beneath the north end of KR appear to be infilling an incised bedrock depression. The seismic reflection character (high reflectivity, mounded structures) suggest these are coarser-grained deposits, which possibly have a high-yield aquifer potential. These sediments may be as old as early Wisconsinan or possibly interglacial deposits. Thin units of such older deposits have been interpreted above bedrock based in high-quality data in cored boreholes to the west (Sharpe et al., 2003a).

Where Thorncliffe channels occur, they are likely to be oriented northeast-southwest. Recent pumping test results north of Markham have shown that such channels can be significant high-yield aquifers. Groundwater monitoring to assess the effects of a long-term water taking related to construction of a trunk sanitary sewer indicated a NE-SW paleoflow pattern (Inspec-Sol/CRA, 2005-2010).

Summary

The seismic reflection profiles obtained in 2008 have delineated a bedrock depression beneath KR between Davis Drive and Vivian Road, and a thick sequence of ORM deposits above the regional unconformity which appears to have cut a channel down to the bedrock surface (to an elevation of ~170 masl) near the intersection of KR and SJSR. This appears to be a broad channel, as the west side of this feature extends ~2.5 km along SJSR. Small channel features within the ORM sediments may be relatively low-yield groundwater targets. These features are along an erosional surface observed within the ORM sediments. Two units within ORM deposits have been observed in other areas (e.g. Vaughan borehole and along the 15th Ave seismic profile, Russell et al., 2003; 2005).

On the west end of SJSR, beyond the ORM channel, thick (>50 m) lower sediments and some indication of broad channel features may be related to the large channel infilled with Thorncliffe sediments that has been recognized south of Aurora and intercepted and cored by GSC-BH-AUR-01 (Sharpe et al., 2003a, 2011).

Acknowledgments

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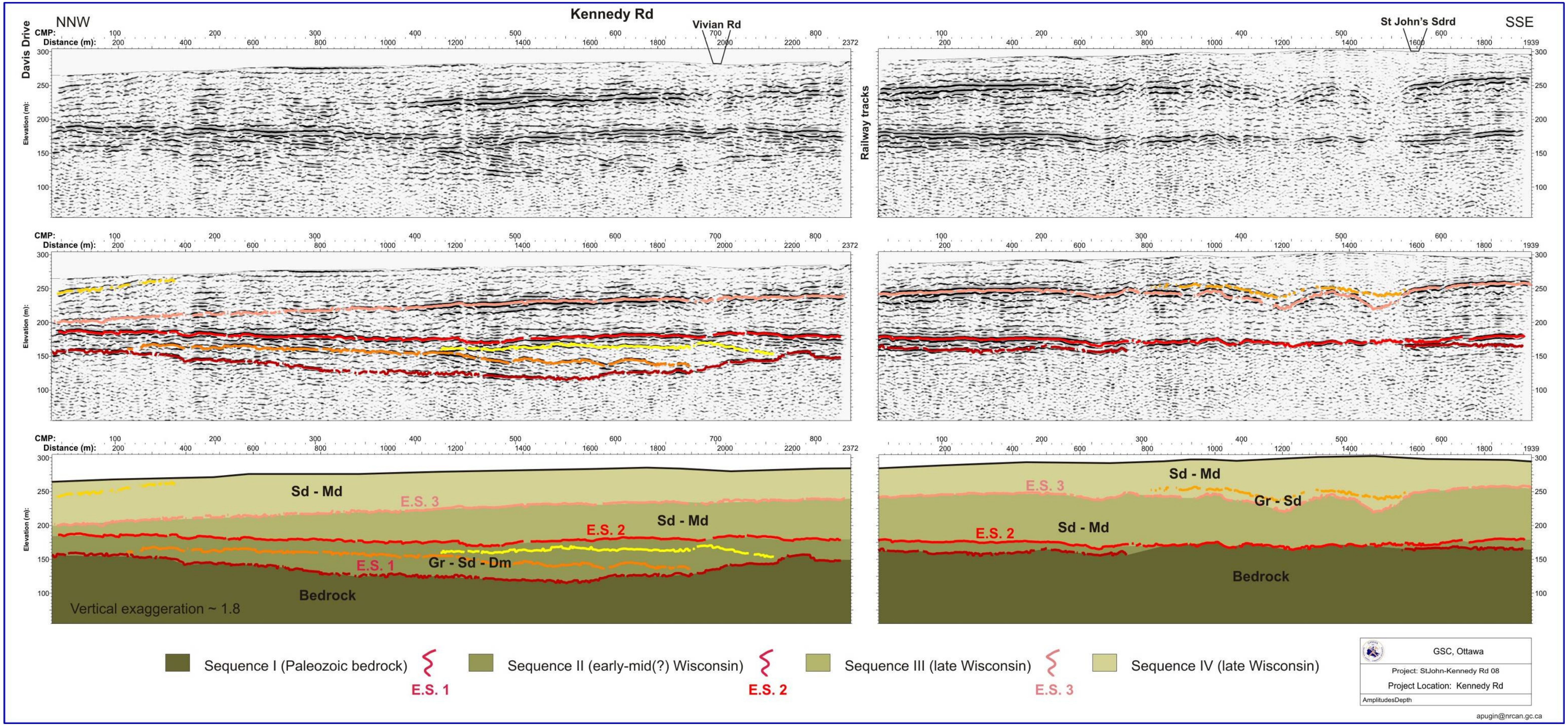

Figure 7: Seismic profile obtained along Kennedy Road in 2008. The break in the section corresponds to the railway crossing where the array had to be picked up and redeployed. The CMP numbers shown as the upper horizontal scale correspond to the numbers shown on Figure 6. The upper panel shows the processed section after topographic corrections and conversion from two-way travel time to depth/elevation (Table 2). The middle panel shows the profile with major reflection events highlighted. The bottom panel details the interpreted subsurface stratigraphy. E.S. = erosional surface. Md = mud. Sd = sand. Gr = gravel.

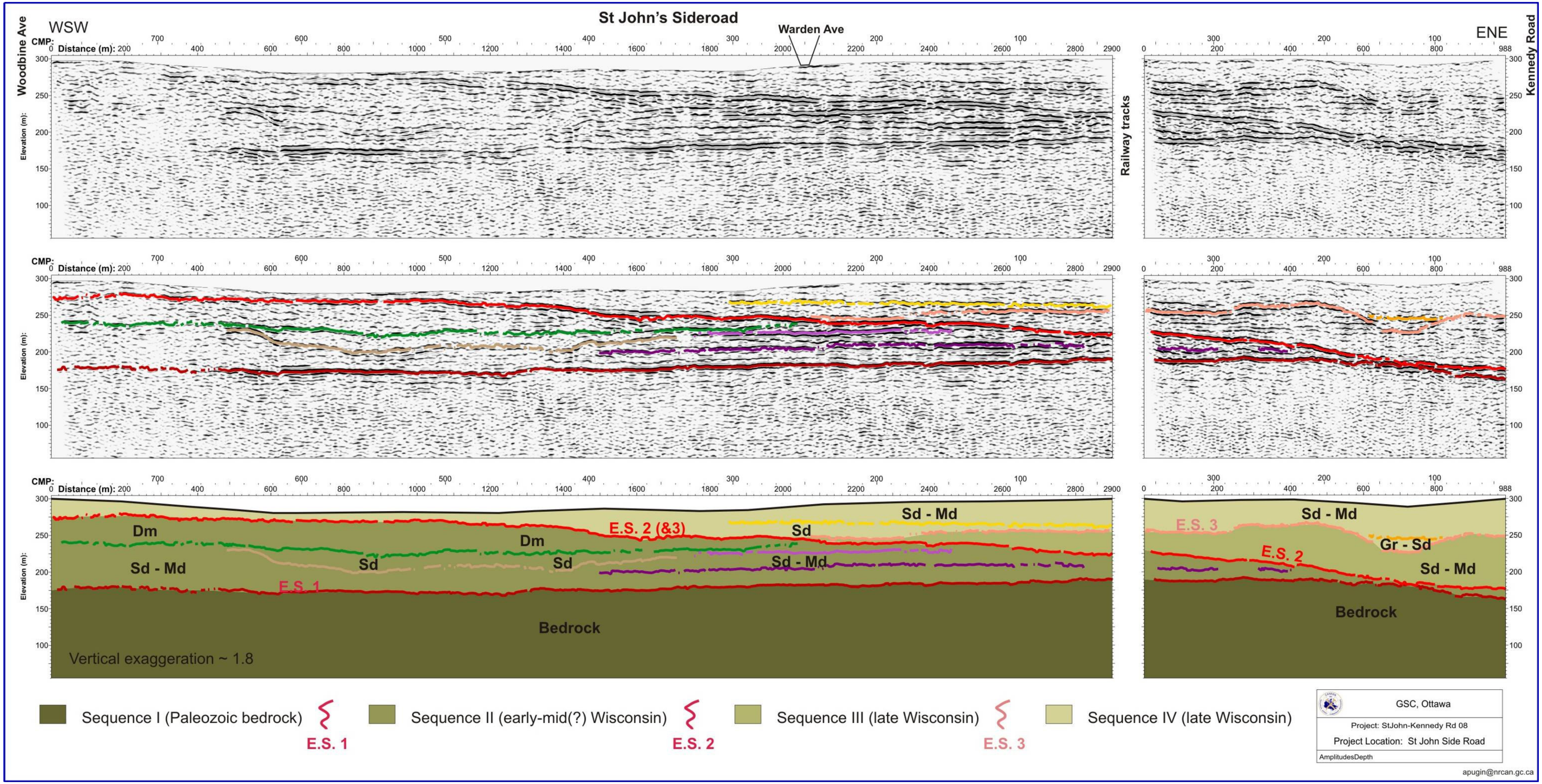

Figure 8: Seismic profile obtained along St John's Sideroad in 2008. The break in the section corresponds to the railway crossing where the array had to be picked up and redeployed. The CMP numbers shown as the upper horizontal scale correspond to the numbers shown on Figure 6. The upper panel shows the processed section after topographic corrections and conversion from two-way travel time to depth/elevation (Table 2). The middle panel shows the profile with major reflection events highlighted. The bottom panel details the interpreted subsurface stratigraphy. E.S. = erosional surface. Md = mud. Sd = sand. Gr = gravel. Dm = diamicton.

Annex

Methodology

Shallow Seismic Reflection Methods

Land-based seismic methods are geophysical techniques which use measurements of the time taken for acoustic energy to travel from a source on the surface through the subsurface and back to a series of receivers on the ground. Energy is refracted or reflected at boundaries where there is a change in acoustic impedance (the product of material density and seismic velocity). Because contrasts in acoustic impedance are generally associated with lithological boundaries, seismic techniques can be used to obtain subsurface structural information. This section briefly outlines the application of shallow seismic reflection methods to delineating the structure of unconsolidated sediments and the underlying bedrock surface.

Seismic reflection methods have been the primary geophysical tool used in oil and gas exploration for over 60 years. Because of the tremendous commercial importance of oil, much industrial research and development has been invested in this branch of geophysics. By the 1960s, specialized field procedures, digital magnetic tape recording, and computer processing of the data had become standard in the industry. Conventional seismic reflection techniques are highly sophisticated, but require considerable investment in both data acquisition and processing.

In the early 1980s, the development of digital enhancement engineering seismographs with high-pass filtering capabilities and the proliferation of increasingly powerful microcomputers, began to make the application of seismic reflection methods to "shallow" problems a viable alternative. Over the last 20-25 years, much experience and expertise in the application of shallow high-resolution reflection techniques have been gained, and today these methods are accepted and proven shallow geophysical tools. Seismic reflection techniques can be applied using compressional (P-wave) or shear (S-wave) energy. Compressional waves are those in which the particle motion and direction of wave propagation are the same, whereas shear waves are those in which the particle motion is normal to the direction of wave propagation (Fig. A1-1).

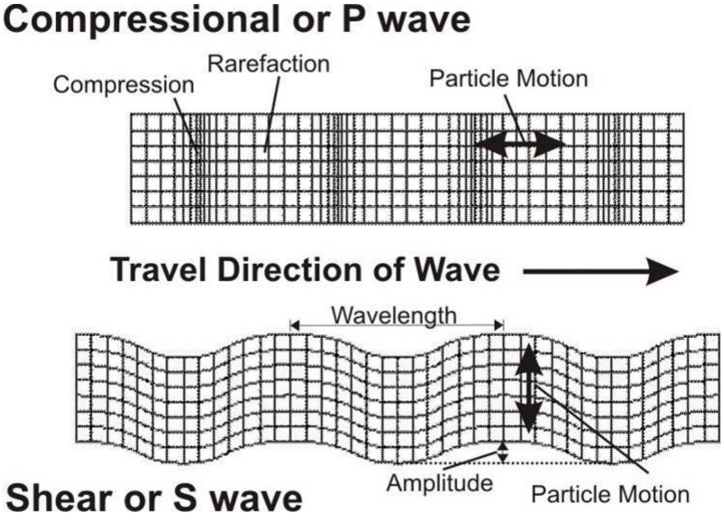

Figure A1-1: Schematic diagram showing the particle motions for compressional or P waves (upper panel) and shear or S waves (lower panel).

Seismic reflection methods involve measurement of the time taken for seismic energy to travel from the source at or near the surface, down into the ground to an acoustical discontinuity, and back up to a receiver or series of receivers on the ground surface (Fig. A1-2a). Data are usually acquired continuously along a survey line, and processed to produce a seismic section which is a two-way travel time cross-section of the subsurface (Fig. A1-2b). Velocity-depth functions calculated from the data, or seismic logging of a nearby borehole(s) are used to translate the two-way travel time into depth.

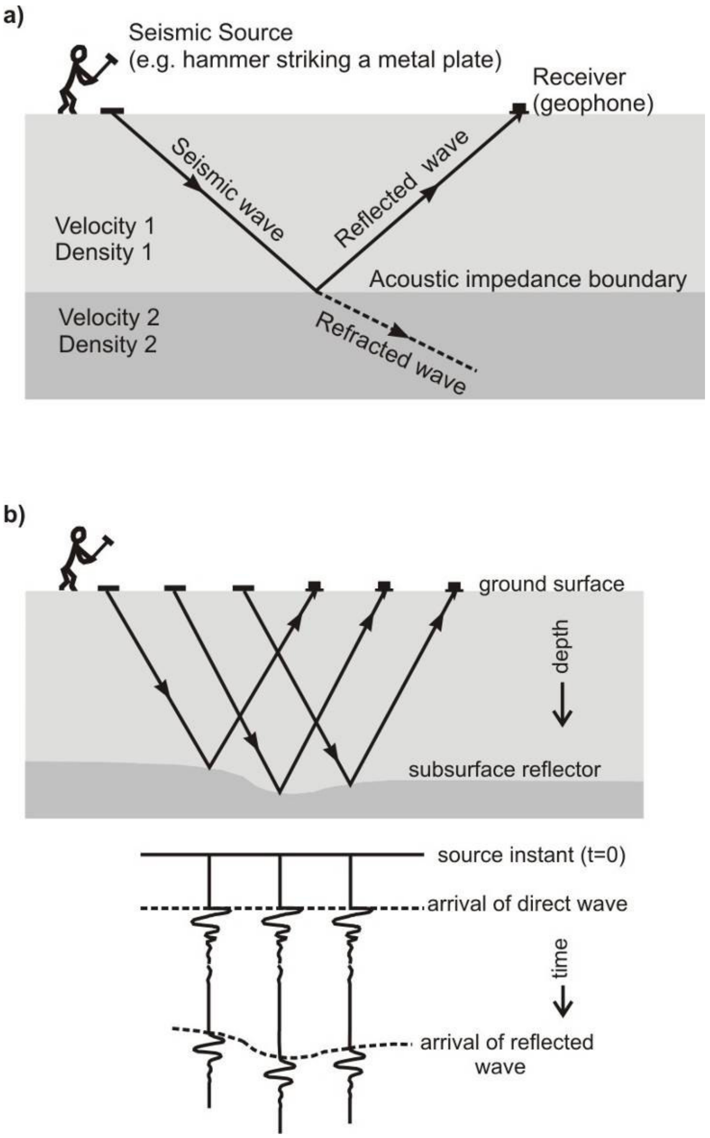

Figure A1-2: Basic premise of seismic reflection methods. a) Seismic energy produced on the ground surface travels from the source down to an acoustic impedance (product of density and velocity) boundary, where it is partially transmitted and partially reflected back towards the surface. b) Data are usually acquired continuously along a survey line and the record of ground motion as a function of time is related to the subsurface structure.

Today, virtually all shallow seismic data are collected and processed based on the common midpoint (CMP) method (often also referred to as the common-depth-point, or CDP, method) which is an adaptation of the methods used by the petroleum industry. In CMP surveys, multi- (12, 24, or more) channel data are recorded for each shotpoint. During processing, the data are sorted according to their common midpoints or common depth points (Fig. A1-3). Each trace is corrected for offset according to a velocity-depth function determined from the data (normal moveout, or NMO, corrections). A standard sequence of CMP data processing steps includes trace editing, static corrections, bandpass filtering, gain scaling, velocity analyses, normal moveout corrections and finally, stacking of the NMO-corrected traces in each CMP gather to create a single trace on the final section. This stacking procedure is the essence of the CMP technique, and allows a potential improvement in the signal-to-noise ratio of the data according to the square root of the fold (number of traces summed to produce the final processed trace at a given point along the seismic profile).

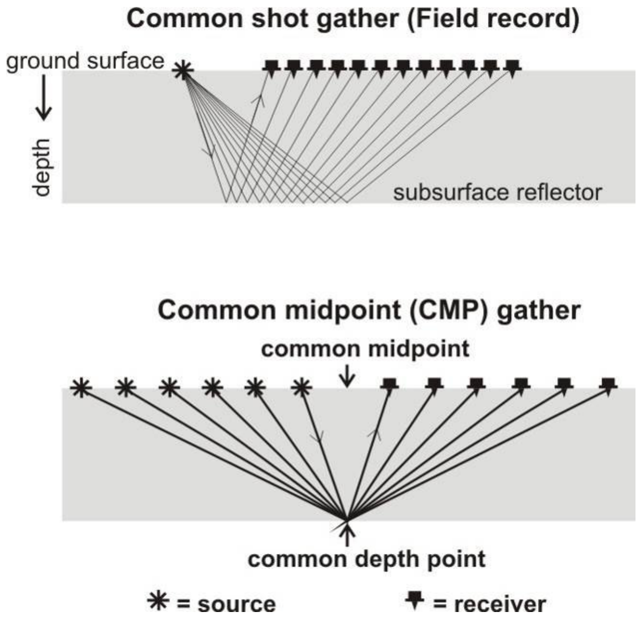

Figure A1-3: Schematic diagram showing a) the subsurface travel paths of reflections from a field record and b) a common midpoint gather. The traces in the CMP gather will be processed and stacked together to form a single trace on the final CMP section (6-fold).

The successful application of any shallow reflection survey depends on the detection of high-frequency energy reflected from velocity discontinuities within the subsurface. However, earth materials, and especially unconsolidated overburden materials, are strong attenuators of high-frequency energy. Thus, compressional (P) seismic waves in the 10-90 Hz range commonly used in petroleum exploration may be reflected from depths of thousands of metres, but energy with frequencies above 100 Hz normally only have travel paths on the order of tens or hundreds of metres. The ability of a particular site to transmit high-frequency energy is a major factor in determining the quality and the ultimate resolution of a shallow reflection survey.

The optimum conditions for shallow reflection surveys (P-wave) are usually when the surface materials are fine-grained and water-saturated; reflections with dominant frequencies of 300-500 Hz can be obtained in such field situations. These frequencies correspond to seismic wavelengths in unconsolidated overburden materials on the order of 3-5 m, with a potential subsurface structural resolution of approximately 1 m. Experience has shown that excellent high-resolution, P-wave, seismic reflection data can be obtained where water-saturated, fine-grained sediment is exposed at the surface (Fig. A1-4).

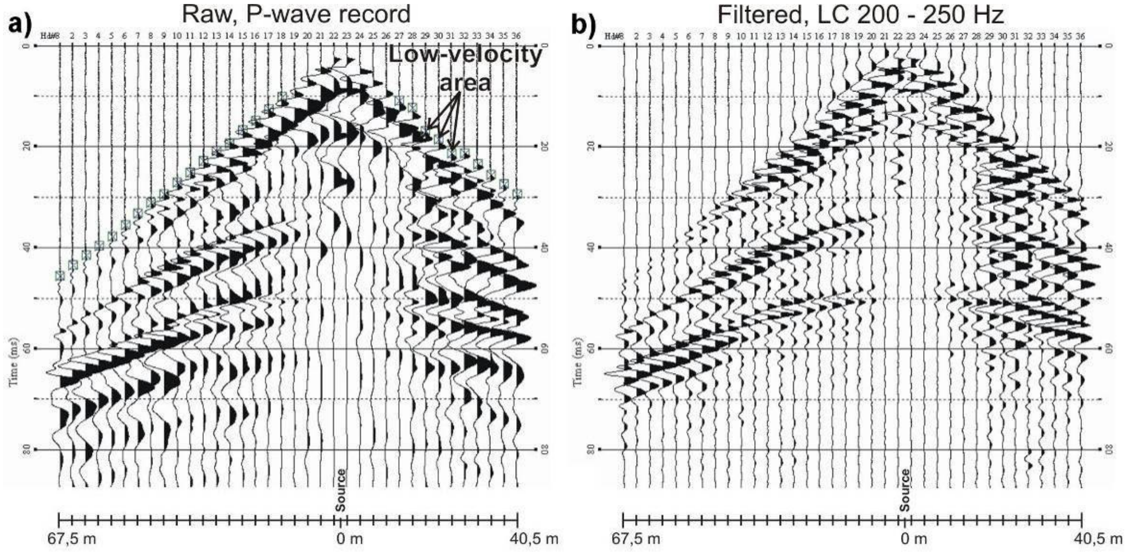

Figure A1-4: Example field shot gather obtained during a P-wave reflection survey using a 12-gauge shotgun source and 50 Hz vertical geophones at 3 m spacing: a) raw record, b) same record after high-pass filtering. These records show excellent reflection energy (hyperbolic events).

Shear wave reflections are commonly much lower in frequency (10-100 Hz) than shallow P-wave reflections. However, resolution of the seismic signals depends on the signal wavelength (higher resolution associated with shorter wavelengths). As the velocity of shear waves in unconsolidated materials can be an order of magnitude lower than the P-wave velocity of the same sediments (particularly if those sediments are water-saturated), the resolution of shear wave data can exceed that obtainable with P-wave data.

Seismic profiles are sections in two-way travel time (not depth). Velocity functions are estimated from the seismic data at intervals along the line during the processing sequence, in order to calculate the normal moveout corrections applied to the data before the stacking procedure, and these velocities can also be used to convert the two-way travel time section to a depth section. However, velocities determined from reflection data can be subject to large uncertainties, depending on the moveout of reflection events. Whenever possible, accurate downhole velocity data from borehole measurements should be obtained in support of the seismic reflection survey (Hunter et al., 1998).

Further discussion on the application of seismic methods to geomorphic and environmental problems can be found in Pullan and Hunter (1999). Steeples (1998) provides an overview of the development of shallow seismic reflection techniques, and the suite of papers in that special issue of Geophysics provides a summary of the state-of-the-art of shallow seismic reflection at that time.

Seismic Landstreamer/Minivib System

Shallow seismic reflection surveys are a powerful tool for mapping detailed subsurface structure, with applications in a wide variety of groundwater, hazard, engineering and environmental investigations. More widespread use of this technique has been limited partly by the time and cost involved in acquiring and processing the data. The efficiency of data collection is largely dependent on the time required to individually plant every receiver (geophone) and to move and reconnect seismic cables as the survey proceeds along a seismic line. As well, the ability to produce and record high-frequency energy for shallow seismic reflection surveys depends on the ground conditions, the effectiveness of ground coupling for both the receivers and the source, the frequency and energy of the seismic source, and the source and receiver spacings (which define the fold – see Fig. A1-3).

The Geological Survey of Canada has developed a Minivib/landstreamer data acquisition system which mates the IVI (Industrial Vehicles International, Inc) minibuggy Minivib source (http://www.indvehicles.com) with a landstreamer receiver array. This system is one way of addressing both the efficiency of data collection and data quality (improvement of signal-noise ratio by decreased source and receiver spacings).

The minibuggy Minivib source (Fig. A1-5) provides a low-impact, vibrating seismic source which can be operated in both P- (vertical) and SH- (horizontal) mode. The vibrating sweeps are programmable in length (seconds) and frequency range (10-550 Hz). The Minivib is used to tow the landstreamer, and is fitted with a distance-measuring wheel which allows the operator to move and set the source at a pre-determined source spacing.

Landstreamers consist of towed arrays of geophones fixed on sleds and have been demonstrated to be an efficient means of recording shear-wave reflection data (e.g. Inazaki, 2004, Pugin et al., 2004). The Geological Survey of Canada's landstreamer array (24 to 48+ channels) consists of small metal sleds on which are mounted the geophone or geophone array (Fig. A1-6). The receiver spacing can be adjusted according to the survey targets; typically, spacings of 0.75-3 m are used. These landstreamers are designed for use along paved or gravel roads. A field record from the 2008 St John's Sideroad survey is shown in Figure A1-7. The signal-noise ratio of the data is very good, and both P- and S-wave reflections are clearly visible.

The small source spacings (typically 1.5-3 m), coupled with the small receiver spacings that are possible (and practical) with the landstreamer, allow high-fold data to be acquired. The short spacing of the sleds avoids spatial aliasing of the surface waves for optimum results when FK spatial filters are applied. Using the landstreamer-Minivib system with the typical source and receiver spacings outlined above, a 4 person crew can acquire several km of line a day. This is an improvement in data acquisition rates of 2-10 times over that possible with the traditional method of planted geophones.

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Figure A1-5: Photos of the IVI minibuggy vibratory source. In the photo on the right, the Minivib is being operated in SH-mode (note cylindrical weight above plate is mounted horizontally).

Figure A1-6: Photo of Minivib/landstreamer system in operation on St. John's Sideroad, 2008.

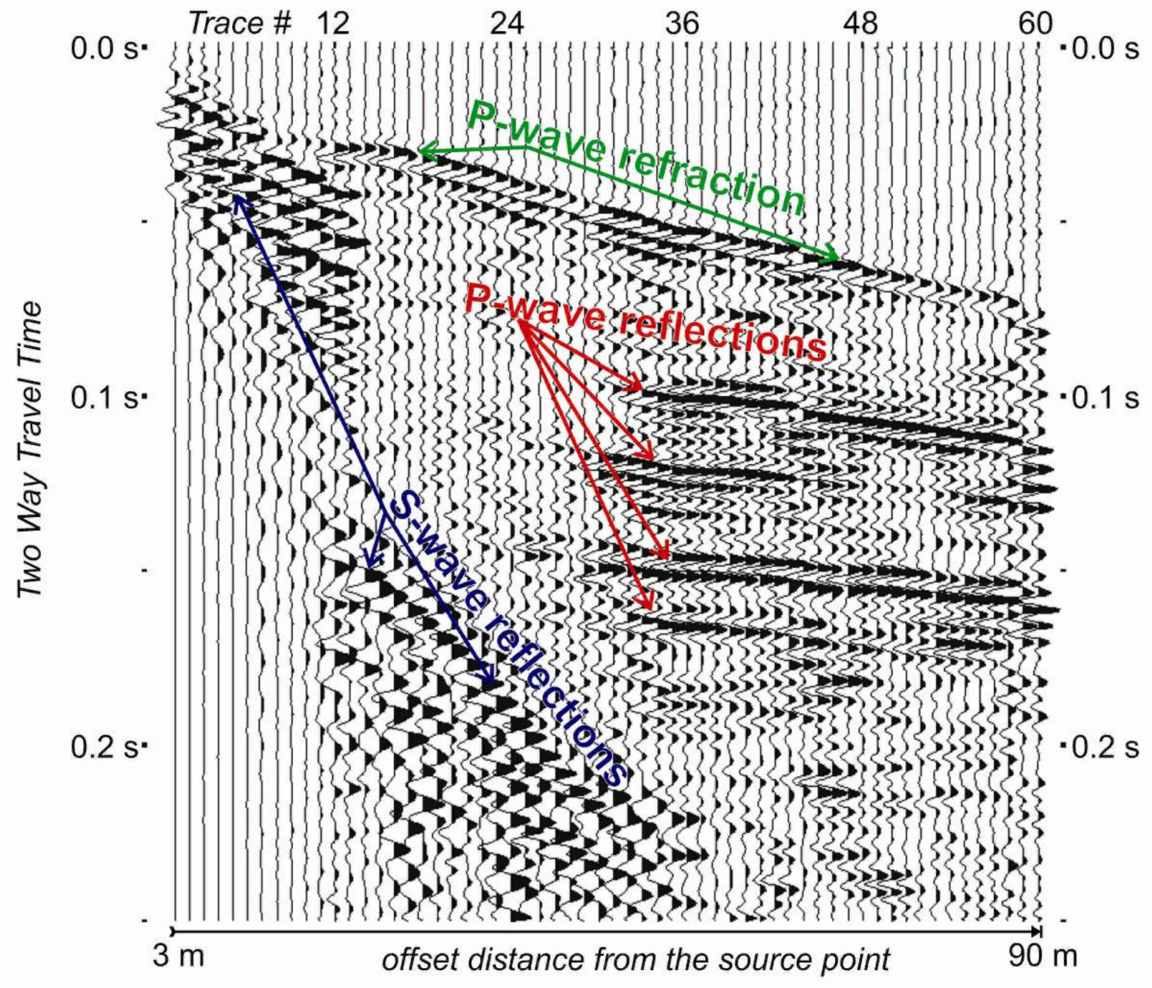

Figure A1-7: Correlated seismic raw record from the St. John's Sideroad line, 2008. P-wave and also hyperbolic-shaped S-wave reflections are visible in this record. A band pass filter of 60Hz-240 Hz was applied before display.