MULTICOMPONENT VIBROSEISMIC PROFILING OVER HIGH VELOCITY GLACIAL GROUND: AN EXAMPLE FROM SOUTHERN ONTARIO

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Abstract

A 3-D Quaternary mapping project conducted by the Ontario Geological Survey (OGS) in the southern part of Simcoe County involves borehole drilling, airborne geophysics, such as TDEM and magnetics and ground gravity surveys. Geophysical surveys are necessary to define the top of bedrock, including buried bedrock valleys and the architecture of overlying sediments for evaluating groundwater resources. In support of this project, the Geological Survey of Canada (GSC) carried out a three-line 21.2 km seismic reflection survey. Geophysical logging in two deep boreholes was undertaken to assist with the calibration of the seismic sections.

The seismic survey was performed using an IVI “Minivib 1” source with a “landstreamer” three-component geophone array built by the GSC. The landstreamer consists of 72 - 3 kg metal sleds, spaced at 1.5 m, towed using low-stretch belts. Data were acquired with shot points every 4.5 m. The source vibrates a 140 kg mass in in-line (H1) horizontal mode, using a 7 second nonlinear logarithmic sweep of -2 DB/Oct from 20 to 300 Hz. This type of sweep increases the time spent in the low end of the sweep which has the effect to increase the low frequency energy to enhance shear body wave energy. Data were recorded using seven 24-channel Geometrics Geode engineering seismographs operated in the cab of the Minivib. Only the vertical component of the 24 geophones, furthest from the source, was recorded in order to obtain a better coverage of the P-wave data acquisition window. Uncorrelated records were collected to allow pre-whitening of the data and careful choice of the correlating function was the first step in the data processing sequence. P-wave sections were derived from processing the first 0.5 sec. (after correlation) of data acquired on the vertical geophones, while S-wave sections were produced using the in-line, H1, component over a correlated window of 2 seconds. Seismic sections were then correlated with borehole geophysical data.

Interpretation of the equivalent compressional (P-) wave section permits delineation of seismic facies sequences. The P-wave velocity is an order of magnitude higher than the shear-wave velocity and as a result, the vertical resolution of the section is lower. However, the acoustic impedance contrast with underlying materials (coarser sediments, tills or bedrock) is lower than in the case of shear-wave. The shear-wave data produce remarkably detailed sections over buried valleys down to 150 m.

Introduction, survey characteristics

As part of this project and in order to help define the sediment-bedrock interface and in particular to map buried bedrock valleys, which have the potential to host significant groundwater resources, a program of geophysical surveys have been carried out in the study area. Following gravity surveys (Bajc and Rainsford, 2010) and an airborne TDEM test survey (Ontario Geological Survey, 2012, Rainsford, 2013), a three-line seismic reflection survey were conducted in 2013 by the Geological Survey of Canada (GSC) under a collaborative agreement with the Ontario Geological Survey (OGS). Downhole geophysical data, that also includes P-wave and S-wave velocities, were acquired in 2014.

The seismic reflection survey totaling 21.2 line kilometers was carried out along three road traverses in the project area (Figure 1). The work was performed by the Near Surface Geophysics Section at the GSC using an Industrial Vehicles International (IVI) Minivib 1 Minibuggy source with a "landstreamer" three-component geophone array built by the GSC (Pugin et al. 2009). This seismic source vibrates a 140 kg mass in either vertical or horizontal mode, and allows the operator to program the sweep through a range of frequencies between 10 and 550 Hz. The seismic source is configured with drive amplitudes set to 70% of the vibrator's range of motion. The minibuggy is equipped with a high-precision distance-measuring odometer linked to a small readout screen mounted in the cab, allowing the operator to move quickly and accurately to the next shotpoint location while the seismograph is saving data. Data were recorded using 7, 24-channel Geometrics Geode engineering seismographs operated in the cab of the Minivib. Uncorrelated records were collected to allow pre-whitening of the data and careful choice of the correlating function was the first step in the data processing sequence. For this survey, the Minivib was operated in the in-line horizontal vibrating mode (H1) using a 7 second linear sweep from 20-300 Hz with a nonlinear logarithm sweep of -2 DB/Oct; this type of sweep increases the sweep time in the low end to increase low frequency energy of shear body waves.

The GSC's landstreamer is designed for use along paved or gravel roads and is built with 72, 3 kg metal sleds connected using wire or low-stretch rope or belt. The number of receivers and the receiver spacing can be varied depending on the near-surface velocities and the targeted depths of observation. For this survey, the landstreamer sleds were spaced 1.5 m apart. Each sled was equipped with a 3-component (3-C) geophone unit constructed in-house with 30 Hz omni-directional geophone elements oriented in three directions: one vertical and two horizontal, in-line and cross-line. Only the vertical component of the last 24 channels were recorded in order to obtain a better coverage of the P-wave data acquisition window. Three-component data were acquired with shotpoints every 4.5 m along the survey lines.

Using the Minivib/landstreamer system, described above, it is typical to collect approximately 1000 records or 4.5 line-km of data per day. An example field record (168 channels) is shown in Figure 2. Channels 1-72 are the vertical (H1, V) geophones; 1-48 the in-line horizontal (H1, H1) geophones; and channels 1-48 the cross-line or transverse horizontal (H1, H2) geophones.

As discussed in Pugin et al. (2009), the reflection data can be processed to provide both P- and S-wave sections even though the mass was vibrated in one orientation. In this case, P-wave sections are derived from processing the first 0.5 sec (after correlation) of data acquired using the vertical geophones, while S-wave sections are produced using the in-line, H1, component. Processing sequences are similar, though different filters and stacking velocities are required for the two data sets (Table 1).

Results

The location of the complete suite of seismic profiles obtained in these surveys is presented in Figure 1. Figure 3 presents examples of processed seismic reflection data obtained along a 5.15 km section of 15th Sideroad in the Town of New Tecumseth, and an explanation of the interpretations of subsurface structure and stratigraphy are provided. The uppermost panels, Fig. 3a and 3b show the compressive wave P and the shear-wave S reflection profiles obtained using the vertical V component data and the in-line H1 component data, respectively (see Fig. 2). The average velocity from ground surface to the reflection event can be calculated by an analysis of the hyperbolic reflection events in the common midpoint (cmp). These data allow the interval velocities to be determined and they are plotted as a cross-section in Figure 3c. Down to the top of the Paleozoic bedrock reflector, the upper sedimentary sequence filling a channel is characterized by low shear-wave velocity (150-250 m/s) as is characteristic for lacustrine sediment, whereas underlying sediments reach velocities of 300 to 700 m/s which may be associated with coarse sediment or till.

Figure 3d shows the shear-wave reflection section after it has been converted to depth (and plotted against elevation) using the velocity functions determined from the analysis of the cmp gathers. The higher velocities of the lower units result in a relative “stretching” of the section with depth and a lower vertical resolution. Water well records warehoused by the Ontario Ministry of the Environment and Climate Change and obtained using the Groundwater Information network (GIN) are plotted along the line (displayed as pink bars). These bars indicate the depth at which water-bearing units occur in the subsurface. OGS cored borehole (SS-11-07) provides a good lithological calibration for this section with a 75 m thick sequence of alternating silt and clay with subordinate sand above a 10 m thick till unit which in turn overlies water-bearing sand and gravel under artesian flow conditions.

Interpretation of the equivalent compressional (P-) wave section permits delineation of seismic facies sequences which are outlined on the section (Fig. 3e). The P-wave velocity is at least an order of magnitude higher than the shear-wave velocity and as a result the vertical resolution of the section is lower. However, the acoustic impedance contrast with underlying materials (coarser sediments, tills or bedrock) is lower than in the case of shear-waves, so the P-wave signal usually penetrates deeper, in particular where thick till sequences are present in the section.

The interpreted subsurface structure and stratigraphy along this line is shown in Figure 3e. Based on the seismic signature and some limited borehole control, the geophysical profile overlying an interpreted Paleozoic bedrock reflector is subdivided into 3 sequences. Sequence 1, which occurs over the upland (described earlier), is characterized by a high-velocity, chaotic and almost transparent seismic facies. Sequence 2 also has a high-velocity signature but presents more down-curved reflections. It may be possible that these first 2 sequences represent part of the same lithological unit with lateral facies changes or that sequence 2 is a younger unit consisting of alternating layers of sand, gravel and till. A truncation is present at the top of these two sequences which extends down to the bedrock surface between 1200 and 2300 m (along line distance). The reflection surface is interpreted to be an unconformity and delineates a buried valley. It may possibly be interpreted as the base of a buried tunnel valley feature. Similar features have been delineated by various authors north of the Oak Ridges Moraine (Pugin et al. 1999, Sharpe et al. 2002, 2004; Russell et al. 2003; Brennand et al. 2006). Based on the S-wave section, the central channel is filled with lacustrine sediments on-lapping on both edges of the channel. Even though surface mapping has not been identified a near-surface till unit in this area, with some higher shear-wave velocities at the surface, it cannot be excluded that a thin layer of till may be present at the surface of this channel.

Conclusions

The GSC vibratory source/landstreamer data acquisition system was used to acquire 21.2 line-km of high-resolution seismic reflection data along three seismic lines. The S-wave seismic profiles obtained provide high-resolution images and a good characterization of the sequences and their lithology while the P-wave profiles, though lower in resolution, can be used to penetrate coarser-grained or more compacted deposits and image the underlying bedrock surface. The data provide detailed information on the depth to bedrock, and on the architecture and stratigraphy of the overlying sediments. Multiple buried valleys have been identified from the seismic investigations. The section presented here shows the architecture of a wide tunnel valley filled with on-lapping stratified sequences. This feature is more than 4 km wide and has a maximum thickness of about 80 m. This feature is likely significant both as a host of potential groundwater resources and for its control on groundwater flow in the region.

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Table 1: Processing flow for P-wave and S-wave seismic sections

<table>
<tr><td colspan="2">Initial processing (all data)</td></tr>
<tr><td colspan="2">Format conversion, SEG2 to KGS SEGY
Spectral whitening using an AGC window of 1 sec
Pilot trace based deconvolution
Separation of V, H1, H2 components
Editing of the geometry / Sort (binning at 2.25 m)</td></tr>
<tr><td>P-wave
V component data</td><td>S-wave
H1 component data</td></tr>
<tr><td>Frequency filter
(BP 80-120-200-250 Hz)
Scaling
(trace normalization)
Top mute
(refractions)
Velocity analysis
NMO Corrections
(~1200-1650 m/s)
Stack, nominal fold: 36
Correction for ground surface topography
Conversion to depth
(using borehole data and NMO velocities)</td><td>Frequency filter
(BP 25-40-75-90 Hz)
Scaling
(trace normalization)
Top mute
(P-wave, surface waves)
Velocity analysis
NMO Corrections
(~100-700 m/s)
Stack, nominal fold: 24
Correction for ground surface topography
Conversion to depth
(using borehole data and NMO velocities)</td></tr>
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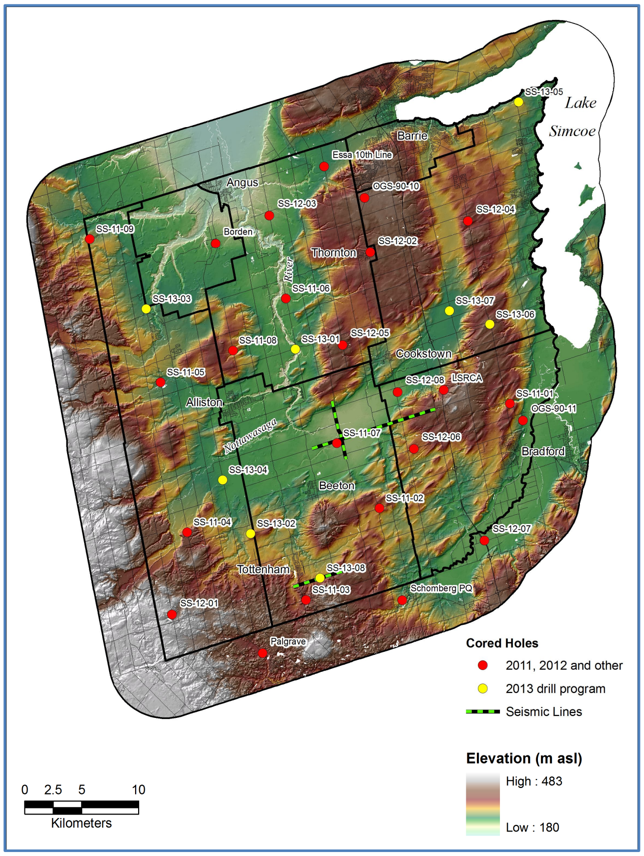

Figure 1: Locations of cored boreholes and reflection seismic lines in the south Simcoe study area . Locations are plotted on a hillshade digital elevation model. Elevation displayed in meters above sea level (m asl).

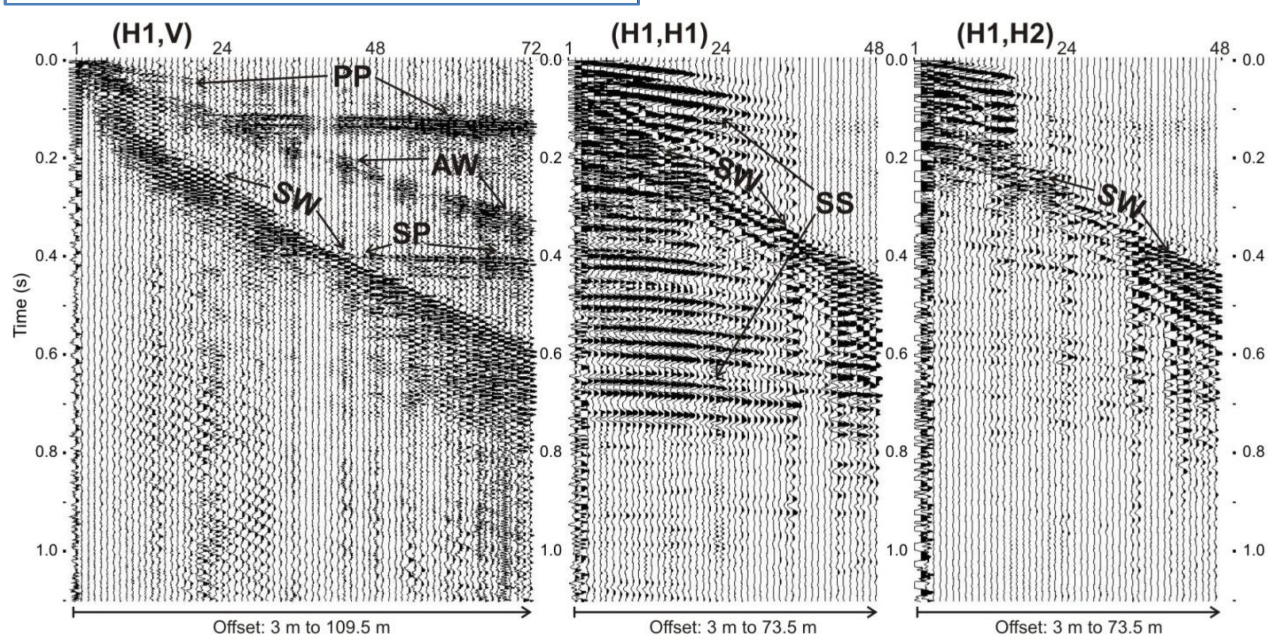

Figure 2: Deconvolved 3-component seismic record from the survey. The source was vibrated in the H1 (in-line horizontal direction). The receivers are vertical (V), in-line (H1) and transverse (H2). **PP**: P-wave reflections, **SS**: S-wave reflections, **SP**: converted, S to P wave, **SW**: surface waves**, AW**: air wave. P-wave reflections are best observed on the vertical component and the S-wave reflections are mostly seen on the H1 component.

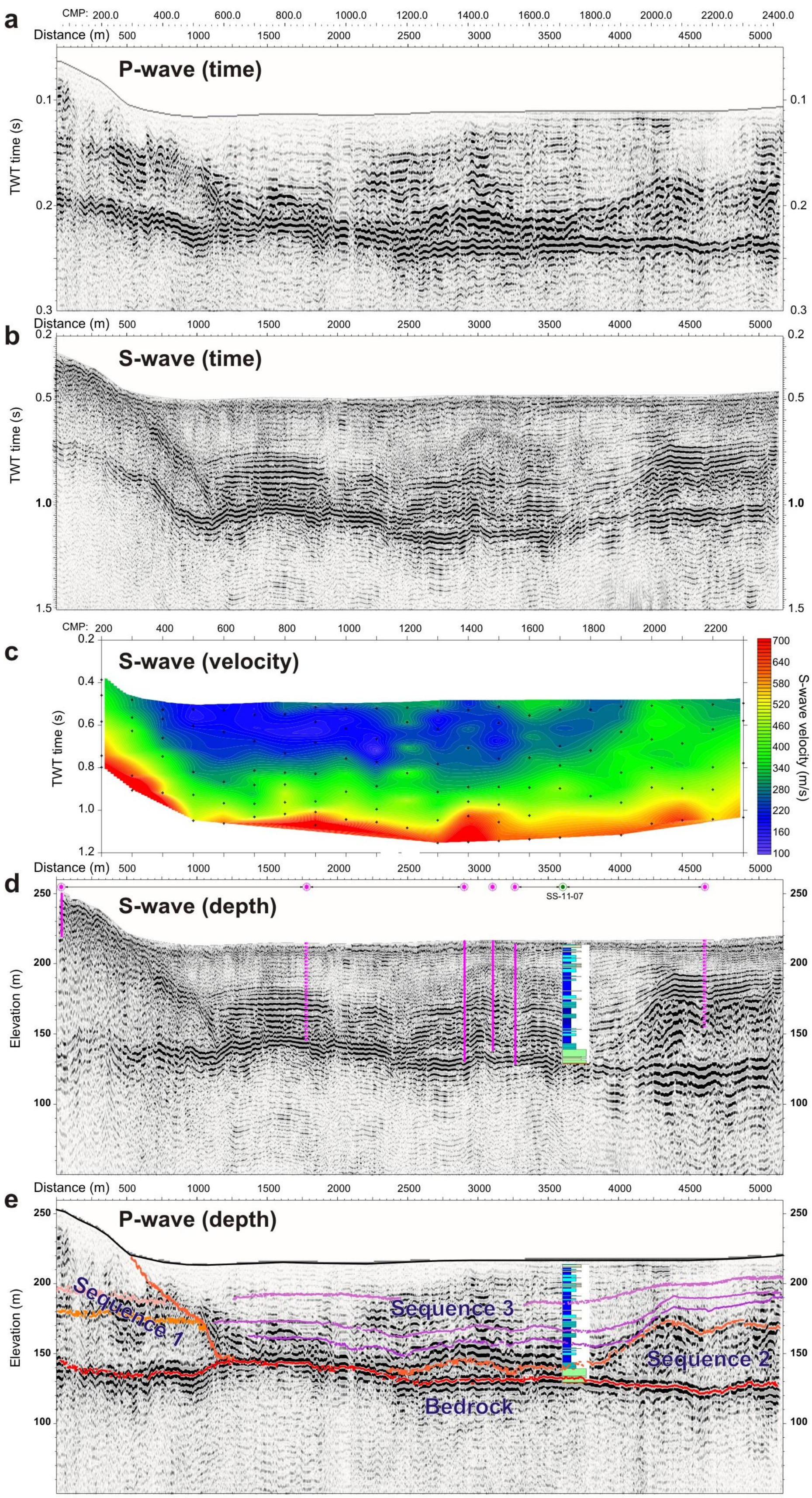

Figure 3: Seismic section along the 15th Sideroad, Town of New Tecumseth. a) P-wave time section, b) S-wave time interval velocity section, c) S-wave velocity section, d) S-wave depth section with projected borehole data, including OGS SS-11-07 borehole log, e) Depth section with seismic sequences.