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Geological Survey of Canada
Open File Report 7346

High-resolution Shallow Seismic Reflection Profiles for Groundwater Studies in the Montérégie region, east of Montreal, Quebec

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Summary

In the Montérégie region, east of Montreal, Quebec, high-resolution compressional (P-) and shear (S-) wave reflection sections were obtained using a vibratory source/landstreamer data acquisition system in two field programs carried out in 2009 and 2010. The work was part of a strategy to improve the knowledge and understanding of groundwater resources within the glacial and post-glacial sediments in the region. Over 100 line-km of seismic profiling provides detailed information on the depth to bedrock and architecture and stratigraphy of the overlying sediments.

Project Overview

As part of a regional, transboundary hydrogeological project on the Richelieu, Yamaska and Lake Champlain basins in southern Quebec, New York and Vermont, the Geological Survey of Canada (GSC) and partners carried out a project that involved testing and developing efficient and novel methodologies for regional hydrogeological characterization. Lefebvre et al. (2011) present an overview of this project; various aspects of the work are described in Blouin et al., (2011), Beaudry et al., (2011a,b), and Laurencelle et al., (2011). One of the geophysical methods evaluated was shallow seismic reflection surveying which is used to provide detailed subsurface architectural and stratigraphic information. This open file report presents the results of the high-resolution shallow seismic reflection surveys conducted for the project in the Montérégie region, east of Montreal, Quebec, during field programs conducted in 2009 and 2010 (see also Pugin and Pullan, 2011).

Survey Description

The GSC has developed a vibratory source-landstreamer data acquisition system which not only greatly improves the efficiency with which shallow seismic reflection data can be obtained, but also allows both compressional (P-) and shear (S-) wave data to be obtained simultaneously (Pugin et al., 2009a,b). In 2009 and 2010 we used a three-component (3-C) landstreamer receiver array coupled to the Minivib vibrating seismic source (Fig. 1) to acquire ~100 line-km of seismic reflection data (Fig. 2) in the Richelieu/Yamaska study area which extends from the St. Lawrence River south of Sorel to St-Jean-sur-Richelieu. Work was carried out along paved back roads or highways with a crew of 5 people plus the aid of a traffic control crew.

Figure 1. Photos of the minivib/landstreamer data acquisition system in operation in the Montérégie region, Quebec.

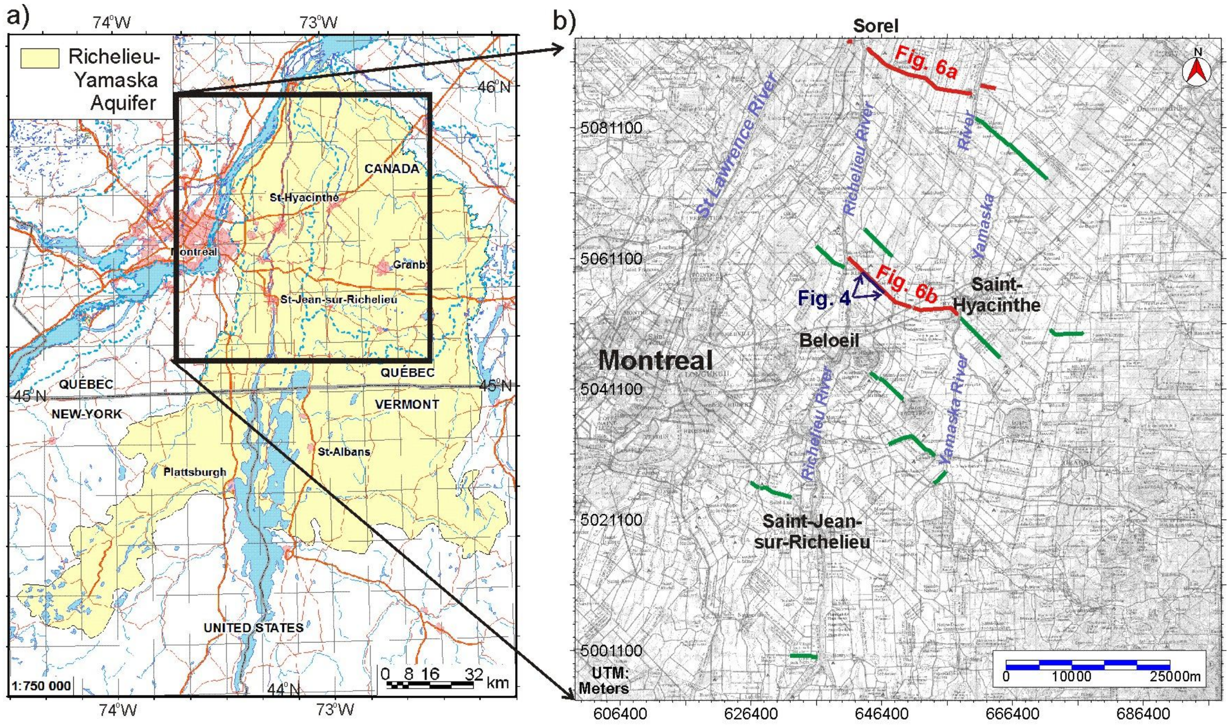

Figure 2. a) Map of the Richelieu-Yamaska transborder aquifer region which covers ~9000 km^2. b) Topographic map of the Canadian portion of the study area (Montérégie region, south-east of Montreal) showing the lines of shallow seismic reflection data acquired in 2009 and 2010. The location of the seismic section shown in Fig. 4 is indicated by the blue line; the red lines indicate the sections shown in Figure 6. The green lines indicate all other lines surveyed.

Shallow Seismic Reflection Data Acquisition

Our seismic source is an IVI (Industrial Vehicles International, Inc) "Minivib" vibrator mounted on a "minibuggy" (http://www.indvehicles.com/minivibminibu.pdf). This 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. For these shallow applications we use it with very low "drive amplitudes" (i.e. 20-40% of the vibrator's possible motion). We have equipped it 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 while the seismograph is saving data. Data were recorded using 6 24-channel Geometrics Geode engineering seismographs operated in the cab of the Minivib. We record uncorrelated records to allow prewhitening of the data and careful choice of the correlating function is the first step in the data processing sequence. For the Montérégie surveys the Minivib was operated in the inline horizontal vibrating mode using a 7 second linear sweep from 20-310 Hz.

The GSC's landstreamer is designed for use along paved or gravel roads, and is built with 3 kg metal sleds connected using wire or low-stretch rope. The number of receivers and the receiver spacing can be varied depending on the near surface velocities and the targeted depths of observation. For these surveys the landstreamer array consisted of 48 sleds spaced 0.75 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. Three-component data were acquired with shotpoints every 3.75 or 4.5 m along the survey lines.

Using the Minivib/landstreamer system described above, we typically collected ~1000 records or ~3.5-4 line-km of data per day. An example field record (144 channels) is shown in Figure 3. Channels 1-48 are the cross-line or transverse horizontal (H2) geophones; 49-96 the in-line horizontal (H1) geophones; and channels 97-143 the vertical (V) geophones.

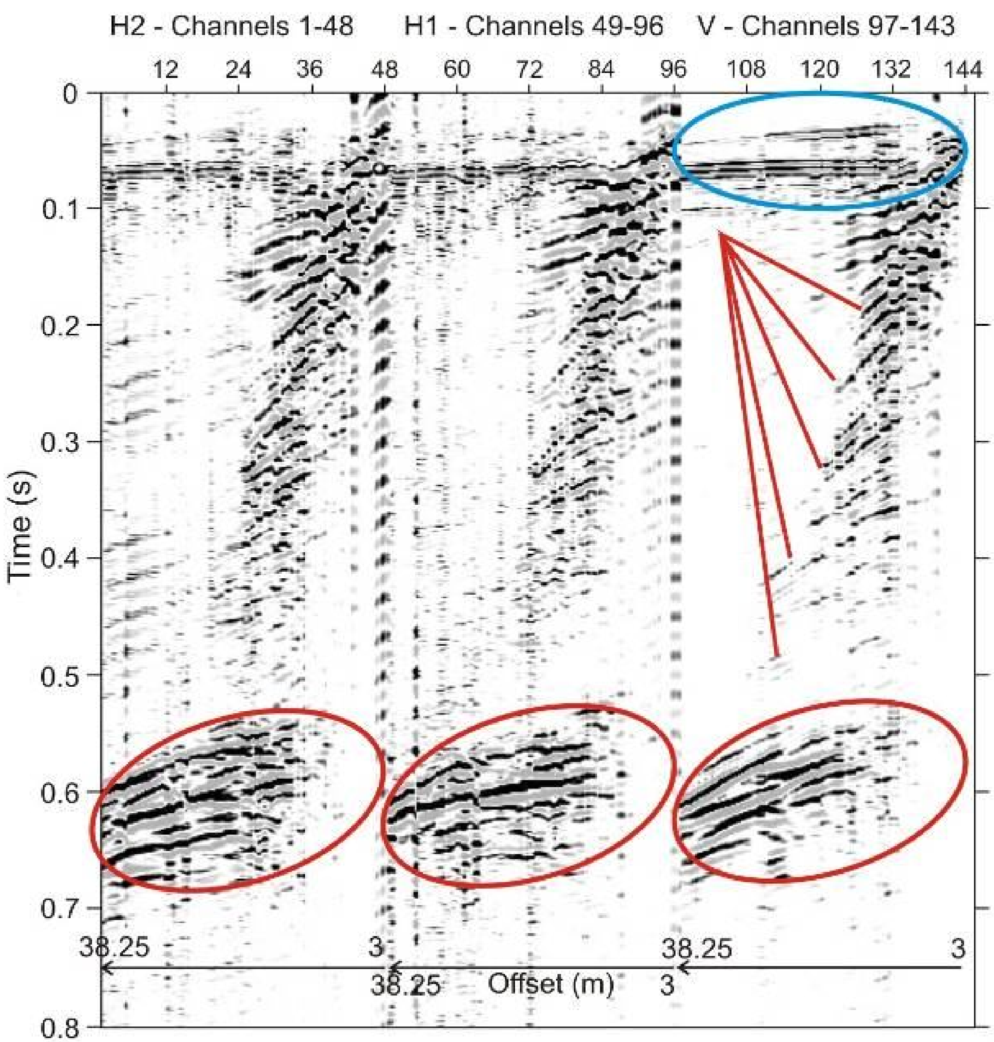

Figure 3. Deconvolved seismic 3-C seismic record from the Montérégie survey. The source was vibrated in the H1 (in-line horizontal direction). The blue ellipse outlines the P-wave reflection data which are best observed on the vertical component. The red ellipse outlines the shear-wave bedrock reflection package – clearly seen on all components. Shear wave reflections from within the Champlain Sea sequence are also seen, particularly well on the vertical component data (red lines).

Line Locations

Details on the survey line locations (see also Figure 2) are provided in Appendix 1.

Data Processing

As discussed in Pugin et al. (2009b), 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 250 milliseconds (after correlation) of data acquired on the vertical geophones, while S-wave sections can be produced from 1.5 sec of any of the three-components of recorded data. In the Montérégie data, the highest resolution S-wave sections are derived from the vertical (V) geophones. Processing sequences are similar, though different filters and stacking velocities are required for the two data sets (Table 1).

Initial processing (all data)	
Format conversion, SEG2 to KGS SEGY Spectral whitening Pilot trace based deconvolution Separation of V, H1, H2 components Editing of the geometry / Sort	
P-wave V component data	**S-wave V component data**
Frequency filter (BP 70-90-270-310 Hz) Scaling (trace normalization) Top mute (refractions) Velocity analysis (cmp gathers: 1.5m bins) NMO Corrections (~1100-1600 m/s) Stack, nominal fold: 16 Correction for ground surface topography Conversion to depth (using NMO velocities)	Frequency filter (BP 40-70-200-300 Hz) Scaling (trace normalization) Top mute (P-wave, surface waves) Velocity analysis (cmp gathers: 1.5m bins) NMO Corrections (~70-400 m/s) Stack, nominal fold: 16 Correction for ground surface topography Conversion to depth (using NMO velocities)

Table 1. Processing flows for Montérégie P-wave and S-wave seismic sections.

Results

The complete suite of seismic profiles obtained in the Montérégie surveys is presented in Appendix 2 (Plates 1-11). The following text and figures (Figure 4-6) present examples of the processed seismic reflection data obtained in this survey, and an explanation of the interpretations of subsurface structure and stratigraphy shown.

The line shown in Figure 4 is ~5.5 km in length and delineates a buried mound, interpreted as a buried esker feature which was unknown before these data were collected. The uppermost panel (Fig. 4a) shows the shear wave reflection profile obtained using the vertical component data (see Fig. 3). Across most of the profile, the upper unit is characterized by high-frequency, low-amplitude, subhorizontal reflections which are the typical seismic reflection signature of Champlain Sea muds (e.g. Pugin et al., 2009a; Cummings et al., 2011). The layering of these sediments is coherent and undisturbed at the SE end of the profile, but appears to be somewhat disturbed to the NW. In the centre of the section is a mound feature with a “flame” structure above parts of the feature within the Champlain Sea sediments.

Analysis of the hyperbolic reflection events in the common midpoint (cmp) gathers allows a determination of the average velocity from ground surface to the reflection event. Those data allow the interval velocities to be determined and they are plotted as a cross section in Fig. 4b. The Champlain Sea sediments are characterized by very low shear wave velocities (70-150 m/s), while the underlying sediments reach velocities of several hundred m/s.

Figure 4c shows the shear wave reflection section after it has been converted to depth (and plotted in 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. The equivalent compressional (P-) wave section is shown in Figure 4d. The P-wave velocity within the Champlain Sea sediments 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 or bedrock) is lower than in the case of shear waves, so the P-wave signal usually penetrates deeper into the section. In this case, the bedrock surface, and some limited indication of structure within the buried mound feature are visible on the P-wave section, whereas little shear wave signal was observed.

The interpreted subsurface structure and stratigraphy along this line is shown in Figure 4e. Based on the seismic signature and some limited borehole control, the buried mound is interpreted as an esker, composed predominantly of sand and gravel. There may be some diamicton above the bedrock surface but it is not well delineated. The main feature appears to be two mounds, with additional smaller deposits of sand and gravel beneath the Champlain Sea deposits to the SE. The main esker deposit is 1.5-2 km wide and reaches a maximum thickness of ~30 m. The entire interpreted sand/gravel deposit is close to 3 km across in the plane of this section. The “flame” structures observed in the shear wave data above the esker are interpreted to be gas and/or water escape features that have disrupted the depositional layering of the muds. Such escape features may also be the cause of the more disturbed Champlain Sea deposits observed NW of the esker feature.

Figure 5 shows a small section of this profile (outlined by blue box in Fig. 4d) to illustrate the many small-scale features in the data which can only be observed at this increased scale.

Figure 6 presents the interpreted sections for two long lines across the central study area. These sections demonstrate some of the main features of this basin that have been revealed by the seismic data. Along these lines, the depth to bedrock increases from ~20-25 m in the east to in excess of 50 m in places further into the basin. Along most of these sections, the bedrock surface is relatively flat-lying at an elevation of -25 masl. It rises gently (Fig. 6a) or steps up (Fig. 6b) to ~0 masl to the east, and dips into a deeper channel south of Sorel (Fig. 6a).

The sediments overlying bedrock on these lines are predominantly Champlain Sea deposits. They increase in thickness from ~20 m in the east to >35 m in some areas in the central part of the basin. Along most of the seismic survey lines, there are often only thin layers (a few metres) of diamicton and/or coarse-grained sediments above bedrock. However, there are significant thicknesses (15-25 m) of diamicton/sand/gravel over bedrock in the northeastern portion of the survey area (Fig. 6a), and the thickness of sand and gravel can reach >30 m in the buried esker (Fig. 6b).

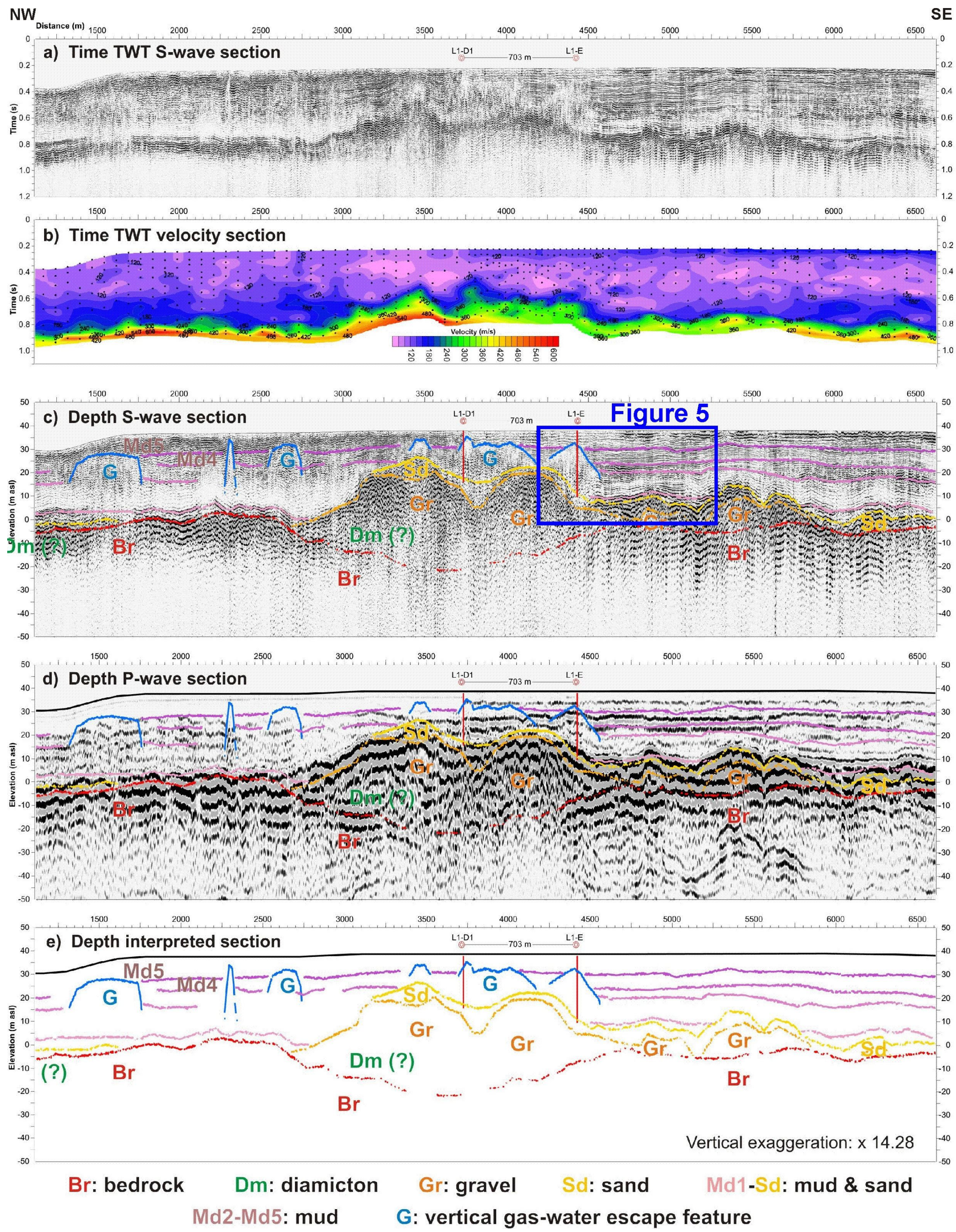

Figure 4. A 5.5 km long seismic reflection line which reveals a buried esker feature. The location of the line, west of Saint-Hyacinthe, is shown in Figure 2. a) A processed shear wave plotted in two-way travel time (TWT) after corrections for surface topography. b) Shear wave velocity cross-section. c) The shear wave section from a) converted to an elevation section using the data shown in b) with interpreted features shown in colour. The blue box outlines the section shown in greater detail in Figure 5. d) The compressional (P-) wave elevation section. e) Interpreted subsurface structure and stratigraphy based on the seismic data and available borehole information.

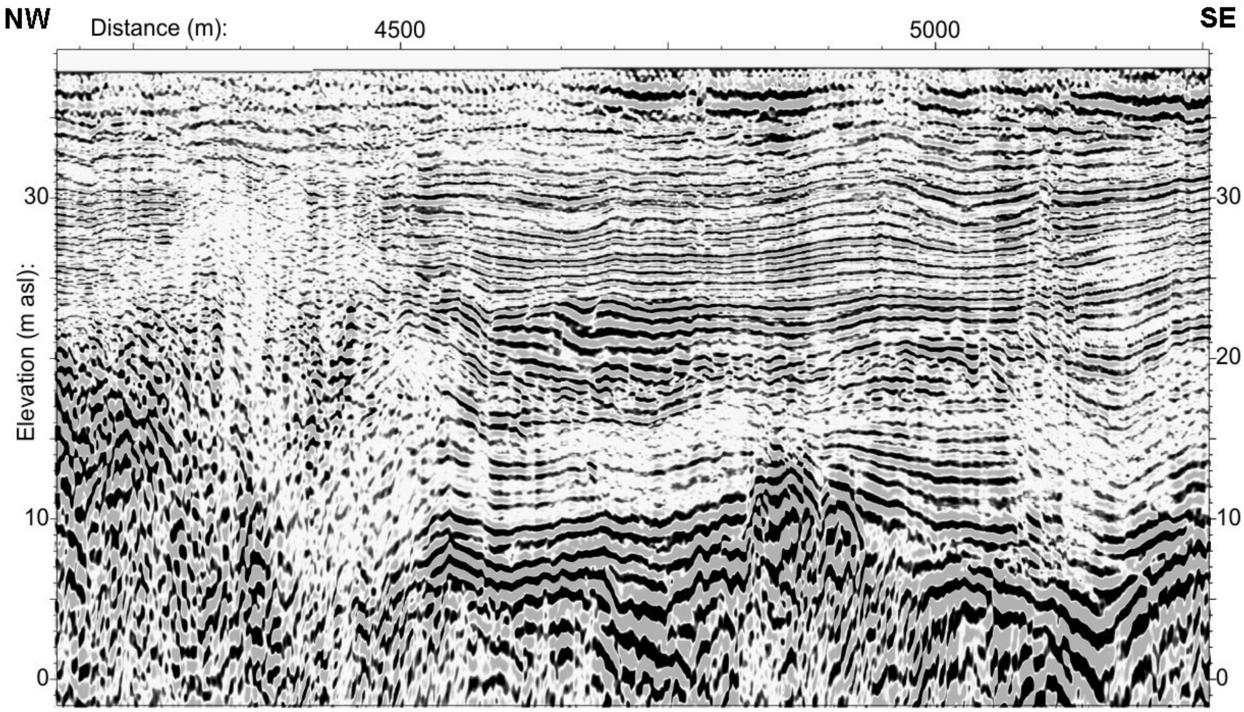

Figure 5. Details of an 1100 m long section of the high-resolution shear wave seismic profile shown in Figure 4. This section is on the southeast edge of the buried esker and shows the structure to a depth of ~40 m (vertical exaggeration x15).

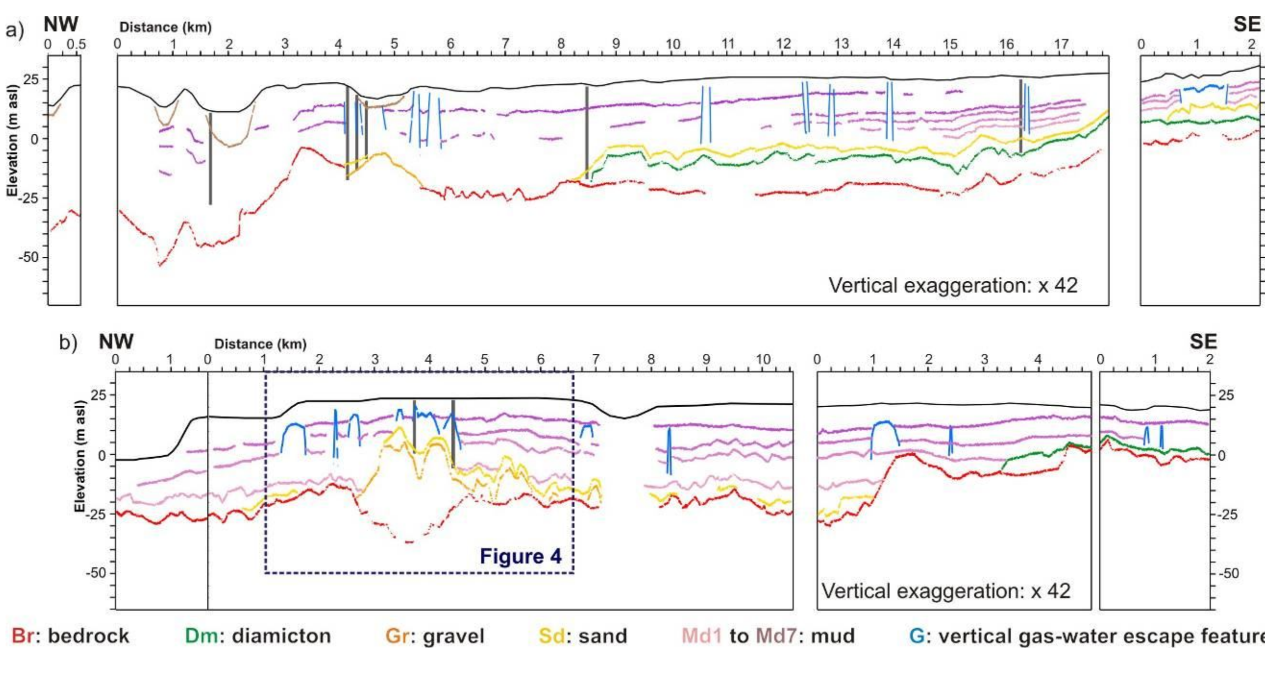

Figure 6. Two NW-SE cross-sections across the central portion of the Montérégie study area obtained from the seismic survey results. The line locations are shown in Figure 2. a) The northern line, south east of Sorel. b) The southern line, west of Saint-Hyacinthe. The location of the data shown in Figure 4 is outlined by a blue box.

Summary

The GSC vibratory source/landstreamer data acquisition system was used to acquire 100 line-km of high-resolution seismic reflection data over two 15-day field seasons in 2009 and 2010. The surveys include two NW-SE cross-basin transects, each ~35 line-km in length.

The S-wave seismic profiles obtained provide very high-resolution images of the Champlain Sea deposits 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. A buried esker has been identified west of Saint-Hyacinthe. The feature is ~1.5 km wide and has a thickness of ~30 m. This deposit is likely significant both as a potential groundwater resource and as an influence on groundwater flow in the region. The very high-resolution shear wave data show what may be gas or water escape features within the Champlain Sea sediments in the vicinity of this esker.

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The work was funded by the Groundwater Geoscience Program of the Geological Survey of Canada. The project is led and coordinated by Christine Rivard (GSC-Quebec) – her support and assistance with logistics has been much appreciated. We also wish to recognize the contributions of many project participants to this work, including Michel Parent and Nicolas Benoit (GSC-Quebec), and Erwan Gloaguen, René Lefebvre, Martin Blouin and Marc-André Carrier (INRS; Institut national de la recherche scientifique, Université du Québec). INRS researchers have generously provided penetrometer results to aid in the seismic interpretation. The collection of the field data was made possible by the outstanding technical support of Tim Cartwright, Kevin Brewer, Marten Douma and Robert Burns, and the help of several students including Shane Ghouralal, Raguvind Gounder, Jonathan Oliver and Malcolm White (GSC), and Patrick Simard (INRS).

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Appendix 1 - Line Locations

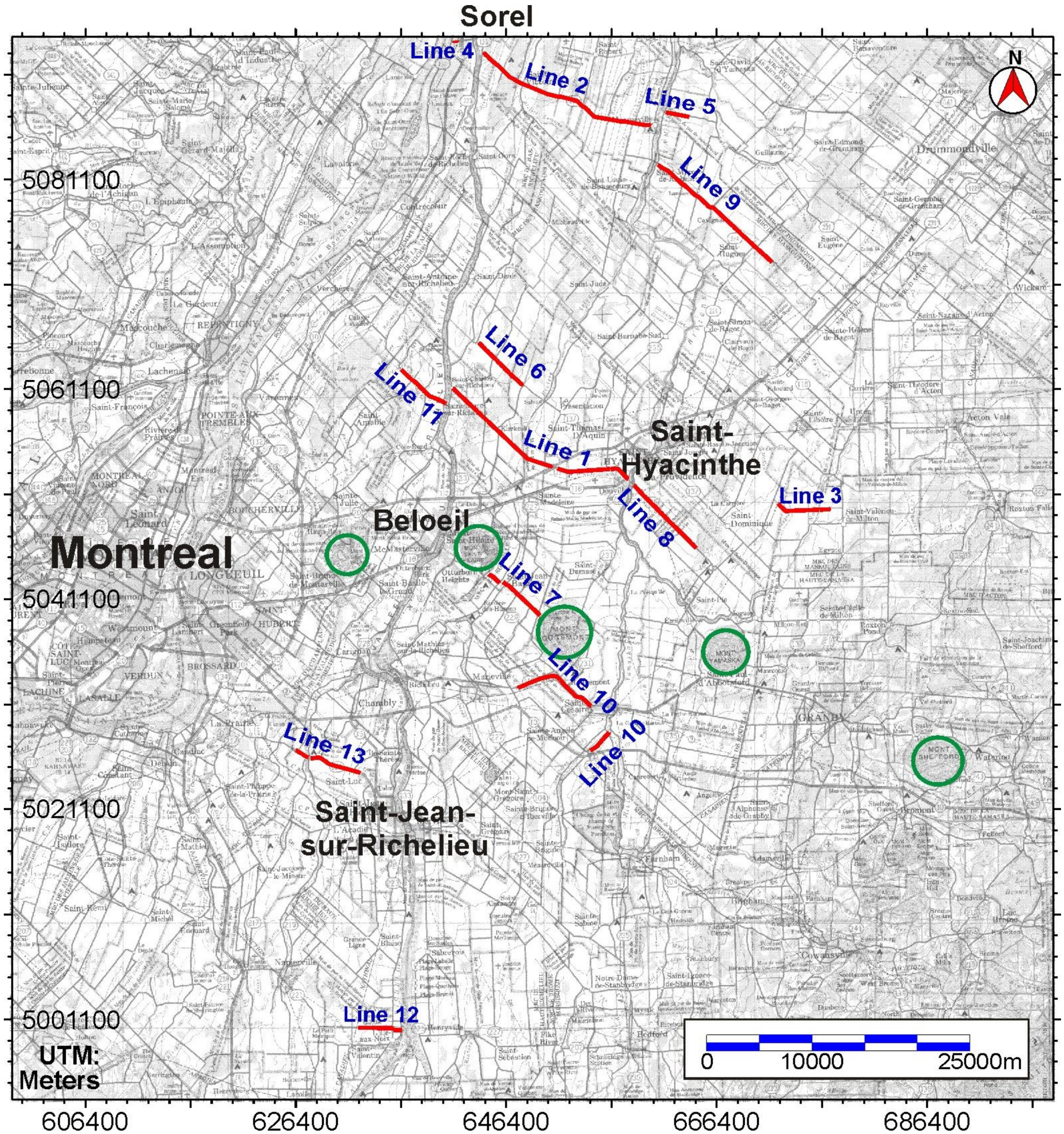

Figure A1. Map showing line locations the for Montérégie seismic survey (red lines). Lines 1-6 (labelled 1000-6000 in this figure) were acquired in 2009. Lines 7-13 (labelled 7000-13000 in this figure) were acquired in 2010. The green circles outline the Montérégie hills.

Line (Name/#)	Date Acquired	Location (SOL) Eastings	Northings	Location (EOL) Eastings	Northings	Line length (km)	Remarks
Line 1A	Sept 22-24, Oct 20	641354	5061158	650695	5053736	11.8	Grand Rang: St Charles-sur-Richelieu to Route 20
Line 1B	Sept 25	651298	5053541	656168	5053488	4.9	Grand Rang: Route 20 to railway tracks
Line 1C	Oct 20	656326	5053495	657911	5052583	2	Railway tracks to Douville (intersection with Hwy 116)
Line 2	Sept 26-Oct 1	660103	5086314	644319	5093134	18.1	Highway 239: Chemin des Patriotes to Massueville
Line 3A	Oct 21	672265	5050165	676075	5049630	3.8	Rue Phaneuf - 10e Rang
Line 3B	Oct 21	676203	5049632	677167	5049673	1.5	10e Rang - East of Riviere Noire
Line 4	Oct 1	641857	5094244	641289	5094207	0.6	south of Sorel: Chemin du Golf - west of railway tracks
Line 5	Oct 22	661598	5087498	663715	5087090	2.1	Rang Caroline - east of St Aimé
Line 6A	Oct 19	643802	5065552	645416	5063954	2.3	Chemin Goddu
Line 6B	Oct 23	645500	5063904	647882	5061520	3.4	Highway 137
						50.5	Total line-km

Table A1. Location data for the 2009 Montérégie seismic survey. UTM zone 18. Datum = NAD83 / WGS84. NTS sheets 31H/10,11,14,15.

Line (Name/#)	Date Acquired	Location (SOL) Eastings	Northings	Location (EOL) Eastings	Northings	Line length (km)	Remarks
S07A	Aug 25	645765	5042665	644742	5043484	1.5	field
S07B	Aug 16	646091	5042756	646450	5042451	0.5	Rue Chabot
S07C	Aug 16	646561	5042457	649576	5039602	4.1	Chemin Bédard
S08A	Aug 21	658551	5051927	661000	5049435	3.5	Route 235 (break at railway track)
S08B	Aug 23	661066	5049367	664461	5045976	4.8	Route 235
S09A	Aug 17	660863	5082497	663198	5080588	3.1	Route 239 (break at St-Marcel-de-Richelieu)
S09B	Aug 17-19	663293	5080617	671635	5073248	11.2	Route 239 (break at St-Marcel-de-Richelieu)
S10A	Aug 15	656155	5028442	654411	5026732	2.5	Rng Chaffers
S10B	Aug 20	647568	5032697	651474	5033461	4.3	Route 112
S10C	Aug 24	651533	5033400	654406	5030994	3.9	Route 112
S11	Aug 11	640604	5059765	636432	5062996	5.5	west from St Marc-sur-Richelieu
S12A	Aug 12	636481	5000095	635730	5000104	0.8	73rd Ave
S12B	Aug 12	635609	5000280	632365	5000339	3.3	72nd Ave
S13A	Aug 13	626425	5026727	627542	5026056	1.3	Route 104
S13B	Aug 13	627854	5025937	632468	5024588	5.4	Route 104
						55.7	Total line km

Table A2. Location data for the 2010 Montérégie seismic survey. UTM zone 18. Datum = NAD83 / WGS84. NTS sheets 31H/10,11,14,15.

Appendix 2 – Interpreted Seismic Profiles

Plates 1-11 present detailed maps of the line locations and interpreted seismic profiles for all the high-resolution, shallow seismic reflection data collected for the Montérégie project.

The profiles are presented as time sections (labelled TWT = two-way travel time) and depth sections where depth has been calculated using the velocity-depth functions calculated during data processing. All sections have been topographically corrected to show the variation in ground surface elevation. The depth sections are plotted in terms of Altitude/Elevation (i.e. elevation in metres above sea level).

Plates 1-4 (2009 data) include a cross-section of shear wave velocity, while Plates 5-9 and 11 include a section derived from the analysis of converted waves (labelled PS). These waves are higher frequency than compressional waves (P) but show increased penetration into coarser-grained sediments compared to shear waves alone (S).

Important: Interpretations of the subsurface stratigraphy are based on seismic reflection characteristics and information from available borehole logs (Natural Resources Canada, Groundwater Information Network, Waterwells and Aquifers of Canada:
http://ngwd-bdnes.cits.nrcan.gc.ca/service/api_ngwds:gin/en/wmc/aquifermap.html
and penetrometer logs provided by INRS).
The borehole log information used is presented in the accompanying figures (red lines). These interpretations are deemed to be reliable in most cases, but are subject to reinterpretation as additional calibrated subsurface stratigraphic information becomes available.

The profiles are presented in the accompanying plates as follows:

Plate 1 - Line 1 (2009)
Plate 2 - Line 3 (2009)
Plate 3 - Lines 2, 4, 5 (2009)
Plate 4 - Line 6 (2009)

Plate 5 - Line 7 (2010)
Plate 6 - Line 8 (2010)
Plate 7 - Line 9 (2010)
Plate 8 - Line 10 (2010)
Plate 9 - Line 11 (2010)
Plate 10 - Line 12 (2010)
Plate 11 - Line 13 (2010)