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Application of high-resolution seismic-reflection techniques in Champlain Sea sediments near Lachute–Saint-Benoît, Quebec

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Abstract: High-resolution seismic-reflection techniques have been tested and applied at several sites northwest of Montréal where thick Quaternary deposits were suspected. This work was conducted as an aid in determining the three-dimensional structure of the Holocene and Pleistocene stratigraphy in the area for ongoing NATMAP and groundwater studies. Initial test seismic arrays indicated areas with substantial thicknesses of overburden above bedrock, several reflecting horizons interpreted as distinct lithological contacts, and high-frequency reflection signals providing good vertical resolution. From the initial testing results, specific survey lines were selected, and common mid-point reflection techniques were designed to optimize the rate and quality of data acquisition. A modified form of 'centre-spread' shooting was adopted, that not only provided adequate stacking (12 fold), but also allowed improved estimates of subsurface velocities required for seismic processing. An example of processed seismic section shows excellent stratigraphic detail.

Résumé : Des techniques de sismique réflexion haute résolution ont été mises à l'essai et appliquées sur plusieurs sites au nord-ouest de Montréal où se trouveraient des dépôts de forte épaisseur du Quaternaire. Ces travaux ont été effectués pour faciliter la détermination de la structure tridimensionnelle de la stratigraphie de l'Holocène et du Pléistocène dans la région où sont réalisées actuellement des études du CARTNAT et des études sur les eaux souterraines. Les premiers essais sismiques ont indiqué des zones où l'épaisseur de la couverture était importante au-dessus du substratum rocheux. Plusieurs horizons miroirs sont interprétés comme étant des contacts lithologiques distincts, et des signaux de réflexion haute fréquence offrant une bonne résolution verticale. En se basant sur les résultats de ces premiers essais, on a sélectionné des lignes de levés particulières et conçu des techniques de réflexion à point milieu commun afin d'optimiser la quantité et la qualité des données acquises. Un formulaire modifié de réflexion «à écart par rapport au centre» a été adopté; il permet non seulement d'obtenir un diagramme d'addition adéquat (12 plis), mais également d'améliorer les estimations des vitesses souterraines nécessaires pour le traitement des données sismiques. Un coupe sismique traitée à titre d'exemple a révélé des données stratigraphiques détaillées d'excellente qualité.

INTRODUCTION

As part of the NATMAP surficial mapping and groundwater studies northwest of Montréal, shallow seismic surveys were performed to delineate subsurface Holocene and Pleistocene sedimentary structure in areas where there was a paucity of drill-hole control, and where the subsurface structure was largely unknown. These areas included locations where buried valleys were suspected beneath a thick cover of Champlain Sea and Pleistocene sediments. Regional test sites were initially established throughout the area (Fig. 1) in order to determine the thickness of overburden and quality of high-resolution reflection events as well as to establish recording parameters (source-receiver geometry, time scales, filters, etc.) for follow-up high-resolution seismic-reflection profiling. From these preliminary observations, seismic line locations were selected that would yield results in key areas (Fig. 1).

INITIAL TEST SPREADS

Figure 2 shows an example of data from test site 23 indicating the quality of data observed throughout the survey area. At each site a 24-channel array of 50 Hz vertical geophones at 3 m spacing was laid out in the ditch along side the road, and records were obtained for shots in the centre of the spread, and at 3, 4.5, 28.5, and 30 m off each end. The compressional wave seismic source was a 12-gauge "Buffalo gun" (Pullan and MacAulay, 1987) with a 180-grain blank, black-powder load detonated at 1 m depth in a shallow borehole. The seismic data were recorded with a Geometrics Strataview^{TM} engineering seismograph. The filtered record shown on the left side of Figure 2 is the centre-spread shot with the source position midway between geophone 12 and 13. The entire suite of nine records can be processed to produce a seismic section (two-way traveltime image of subsurface structure) such as shown on the right side of Figure 2. A detailed description of the field method and processing is given by Pullan et al. (1995).

As indicated in Figure 2, several reflectors were commonly evident on the field records with dominant frequencies of near-surface events being in the 400–500 Hz range, and those at later reflection times in the 300–350 Hz range. With average compressional wave velocities in the range of 1500 m/s, these frequencies yield wavelengths in the range of 3–4.5 m with potential vertical resolution in the range of 1.5–2.25 m.

In total, 33 test sites were located throughout the survey area (Fig. 1). From examination of these initial results, areas were selected where seismic sections of the subsurface would be most useful in defining the subsurface structure.

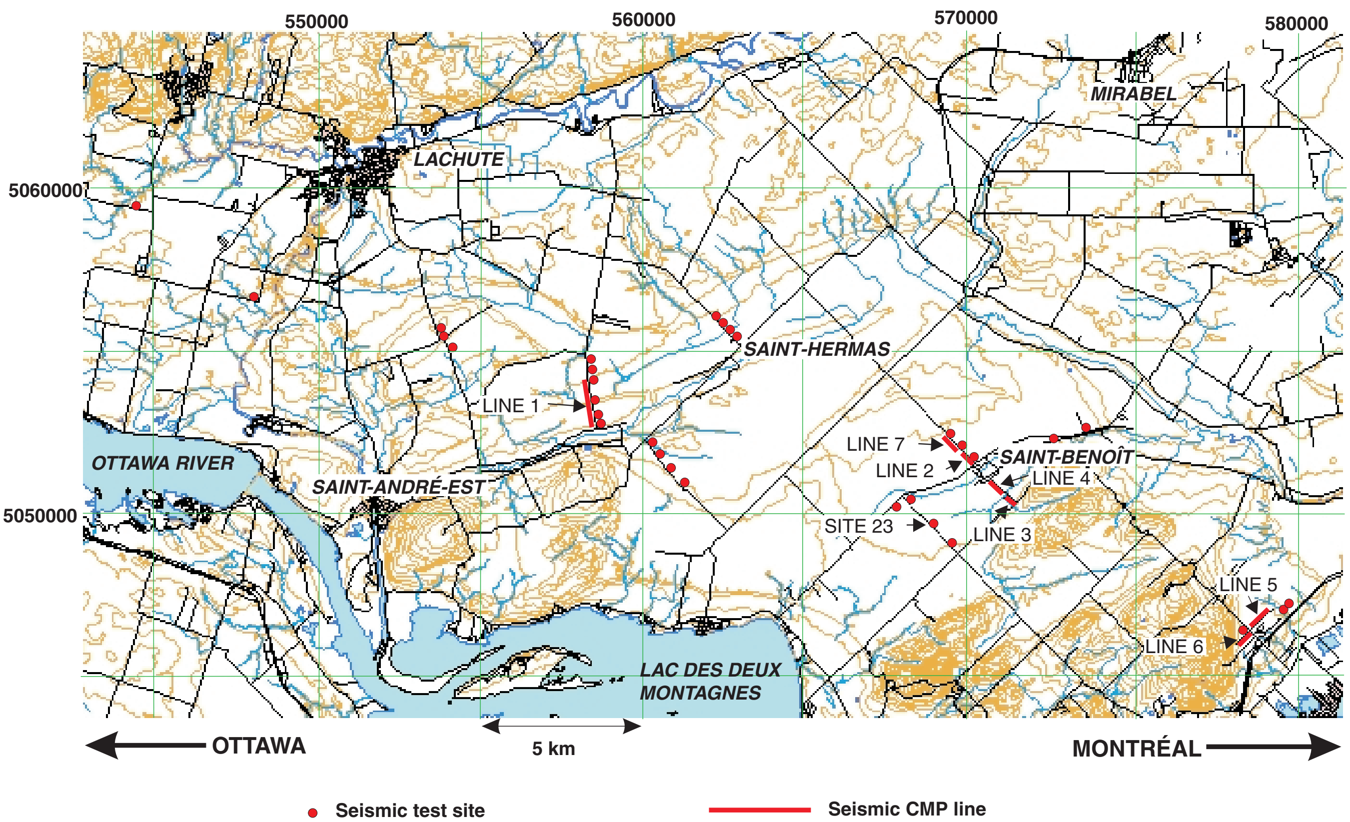

Figure 1. *Survey area near Lachute, Quebec, showing the locations of the test sites and the seismic CMP lines. The grid labels are UTM northings and eastings (zone 18) using the NAD83 datum.*

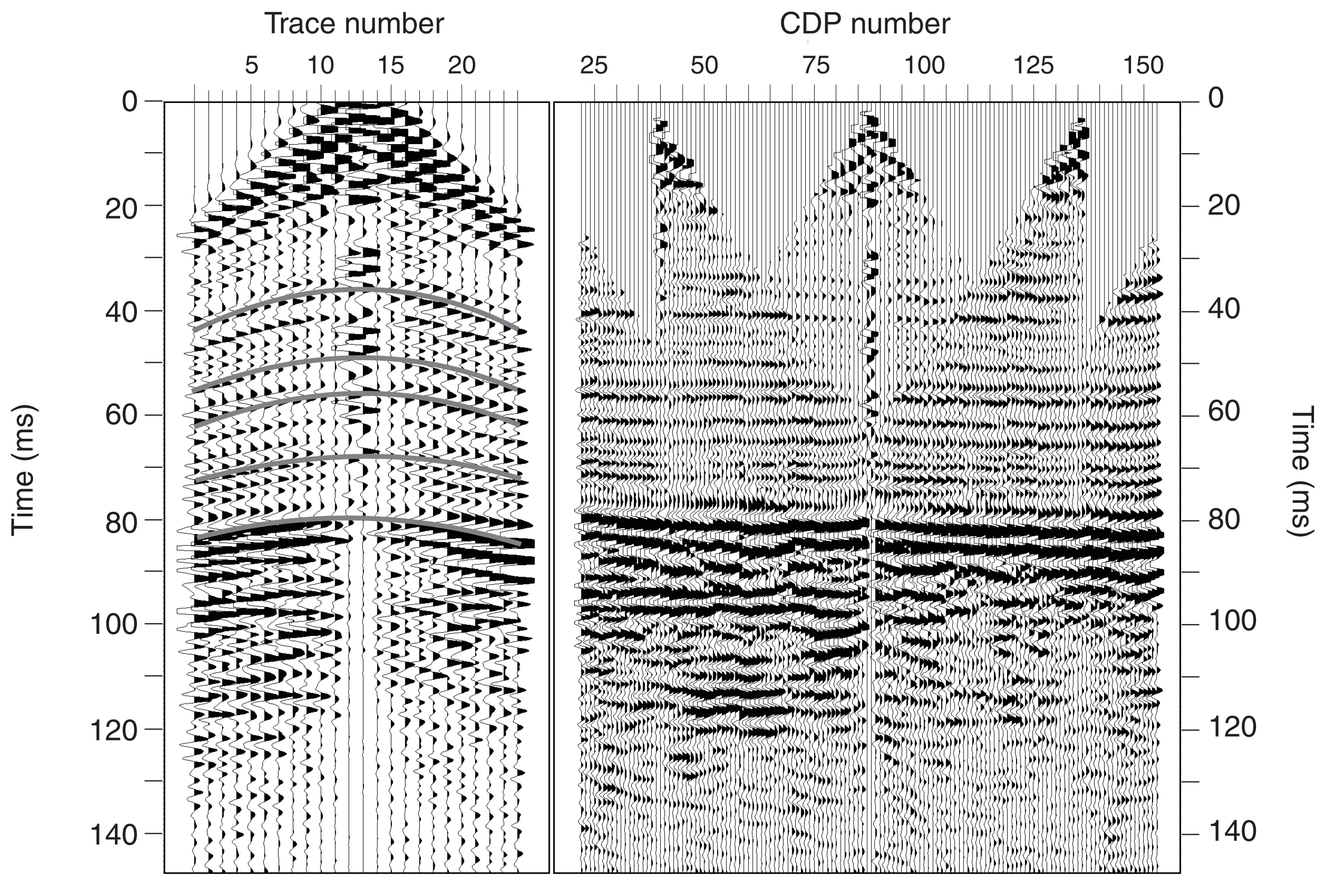

Figure 2. Centre-spread record (left) and stacked section (right) corresponding to the site 23 (Fig. 1). Some of the high-frequency reflections from within the interpreted Champlain Sea sediments (see below) are indicated with grey lines on the shot record (left).

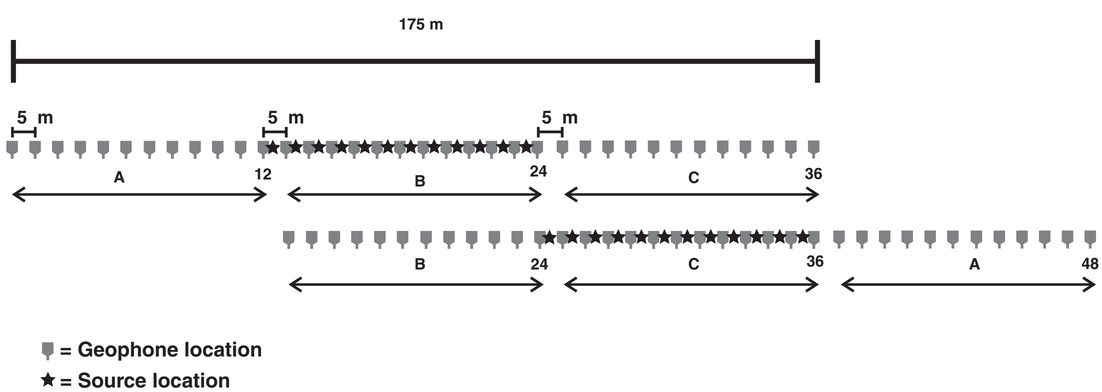

Figure 3. Diagram of geophone array development and shot locations used for the acquisition of the seismic CMP lines. The geophone spread consists of 36 receivers spaced 5 m apart. The 12-channel seismic cables are indicated by A, B, and C. Data were recorded for a series of 12 shots located midway between geophones 12 and 13,..., 23 and 24, as indicated by the stars. Cable A was then moved in front of B and C and the process repeated.

COMMON MID-POINT SURVEYING

A detailed discussion of common mid-point (CMP) seismic surveying is beyond the scope of this paper. For readers unfamiliar with high-resolution seismic-reflection data acquisition and CMP processing, a paper by Steeples and Miller (1990) is highly recommended, especially since this area of geophysics commonly contains much terminology which is inherited technical jargon from larger scale oil-prospecting seismology. Such jargon is indicated by *italics* in this paper.

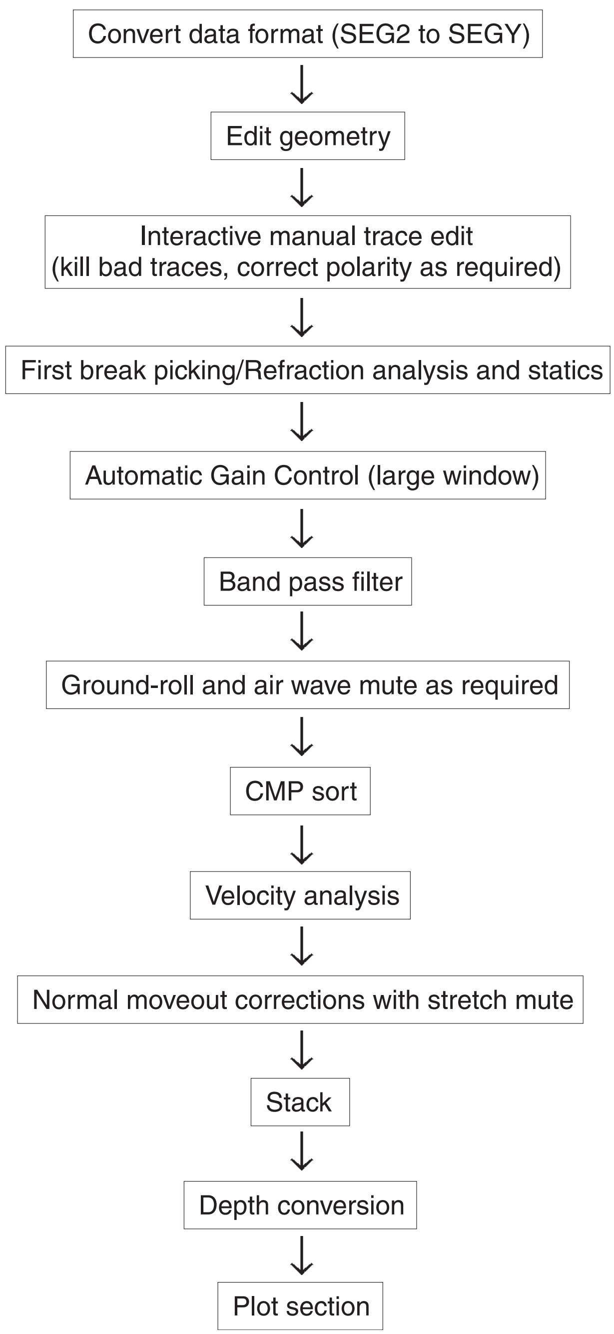

Figure 4. *CMP processing flow.*

Seven seismic lines were shot in the survey area (Fig. 1); the field geometry and recording parameters (Table 1) were held constant throughout. Instead of using a conventional *rollalong* system of *split-spread* data acquisition, an array of 36 geophones at 5 m spacing (175 m active spread length) was laid out, and a series of 12 records were recorded from shots located midway between geophones 12 and 13, 13 and 14, ... 22 and 23, and 23 and 24. At this point, the first twelve geophones were relaid at the leading edge of the spread and the recording process was repeated. The shot-geophone geometry is illustrated in Figure 3.

No internal or external multichannel *rollalong* switching was necessary with this technique. Although only the 24 nearest-offset traces from each record were used for CMP processing (because the long offsets were too wide angle for the target depths in this survey), recording the extra 12 channels gave better velocity information due to enhanced *moveout* (two-way travel time vs. distance) of reflectors. The CMP processing steps are given in Figure 4. The number of summed traces (*fold*) producing 1 trace on the final stacked section was nominally 12 (*12-fold stack*).

RESULTS

All sections show similar seismo-stratigraphy, with high-frequency reflection events predominating throughout, essentially no interference from *ground-roll* or *guided waves*, and only very minor *static* variations caused by changes in the near-surface velocity structure. Though experience has shown that excellent shallow-reflection data are typically acquired when surveying on Champlain Sea sediments, the data acquired in the Lachute–Saint-Benoît area are of exceptionally high quality. This is thought to result from a combination of near-surface conditions (water-saturated silts), and very low attenuation of the higher frequency components of the signal.

Figure 5 shows an example of north-south section from line 1 west of Saint-Hermas (Fig. 1). The horizontal distance between seismic traces is 2.5 m, and the vertical axis has been converted from two-way traveltime to depth. The section has been band-pass filtered with a time-variable filter in the range from 400–800 Hz near surface to 240–800 Hz at depth; as well, an *automatic gain control* (AGC) has been applied. Minimal statics corrections (due to local velocity variations in the unsaturated surface materials) were required.

The seismo-stratigraphy shown on the section can be divided into three major units.

Unit 1 is characterized by relatively flat-lying, low-amplitude reflectors. These events represent the highest frequency content (i.e. highest vertical resolution) in the section. Towards the south side of the section these reflectors are 'draped' on the variable topography of the underlying surface. This unit is interpreted to represent the predominantly silty Champlain Sea sediments and lies unconformably on seismic unit 2. The seismic section (Fig. 5) indicates that unit 1 varies in thickness from less than 20 m to greater than 60 m along this 2 km line.

Table 1. Data acquisition parameters for Lachute seismic survey.

Instrumentation/ Equipment	Seismograph	Geometrics Strataview ™, 48-channel, 18-bit A/D convertors
	Source	In-hole ("Buffalo") gun with 12-gauge 180-grain black powder shells fired at 1 m depth in a water-tamped borehole
	Geophone type	Mark Products L-25, 50 Hz vertical coil
Recording parameters	Record length	256 ms
	Digital sample rate	0.125 ms
	Field filters	Out
Geometry	Geophone array	36 active channels, 1 geophone/ channel, 5 m between geophones
	Source geometry	Shot points midway (2.5 m) between geophone locations

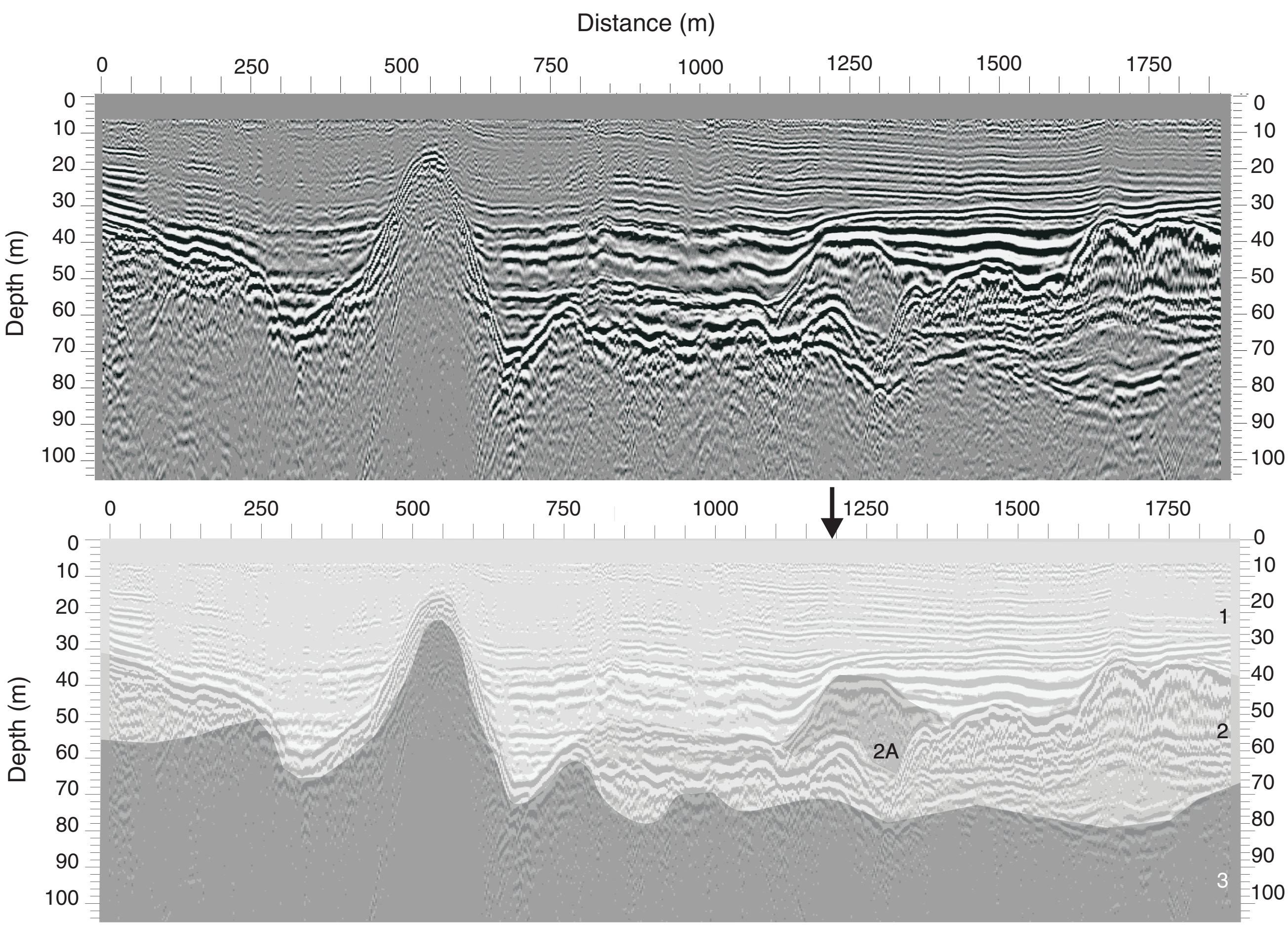

Figure 5. Representative seismic stacked section (line 1) after applying the processing indicated in Figure 4. Lower panel shows the interpretation developed in the text. The position of the borehole is indicated by an arrow.

Unit 2 is a hummocky, highly reflective unit with variable internal reflections, diffractions, and some seismically opaque zones. Where there are large topographic variations along its surface, diffraction events are evident. As well, diffractions and other discontinuous reflections occur internally. Such seismic facies are commonly associated with coarse-grained sediments containing cobbles and boulders, including glacially derived sediments such as diamictons (tills) and ice-contact deposits. Unit 2A has been highlighted as a low-reflectivity subunit having well defined unconformities at upper and lower boundaries. Figure 5 clearly delineates the rough topography of the surface of unit 2, its varying thickness, and the existence of internal stratigraphic variations.

The surface of unit 3 is defined by basal reflectors (lowest coherent seismic reflections). Commonly this reflection package is associated with the top of consolidated rock. Along the section, this basal reflection varies in amplitude, and is not always clearly defined. This is attributed to the high reflectivity of the unit 1-unit 2 boundary and the scattering and attenuation of the transmitted seismic signal within unit 2. In some areas common mid-point stacking was required to improve the signal-to-noise ratio of the relatively low-amplitude basal reflection. The seismic section (Fig. 5) indicates that the bedrock surface varies between 25 m and 75 m below ground surface along this 2 km line.

A seismic downhole survey was performed in a borehole located above unit 2A as indicated in Figure 5. A compressional-wave (P-wave) velocity log and an uphole seismic-reflection record were obtained using the hydrophone array method given by Hunter et al. (1998).

Figure 6a is a composite downhole record after the application of an F-K filter to remove the downgoing energy and enhance the reflection events. Prominent reflections mark both the top and bottom of unit 2A. Events later in time, which are reflections from below the bottom of the borehole, are also evident. Figure 6b shows the downhole interval velocity determined from first arrival times picked on the unfiltered data. The upper portion of unit 1 is characterized by relatively low P-wave velocities with a gradual increase from 1300 m/s at surface to 1600 m/s at 32 m depth, values typical of fine-grained sediments (clay, silt, fine sand). A more rapid increase in velocity is noted between 32 m and 37 m at the

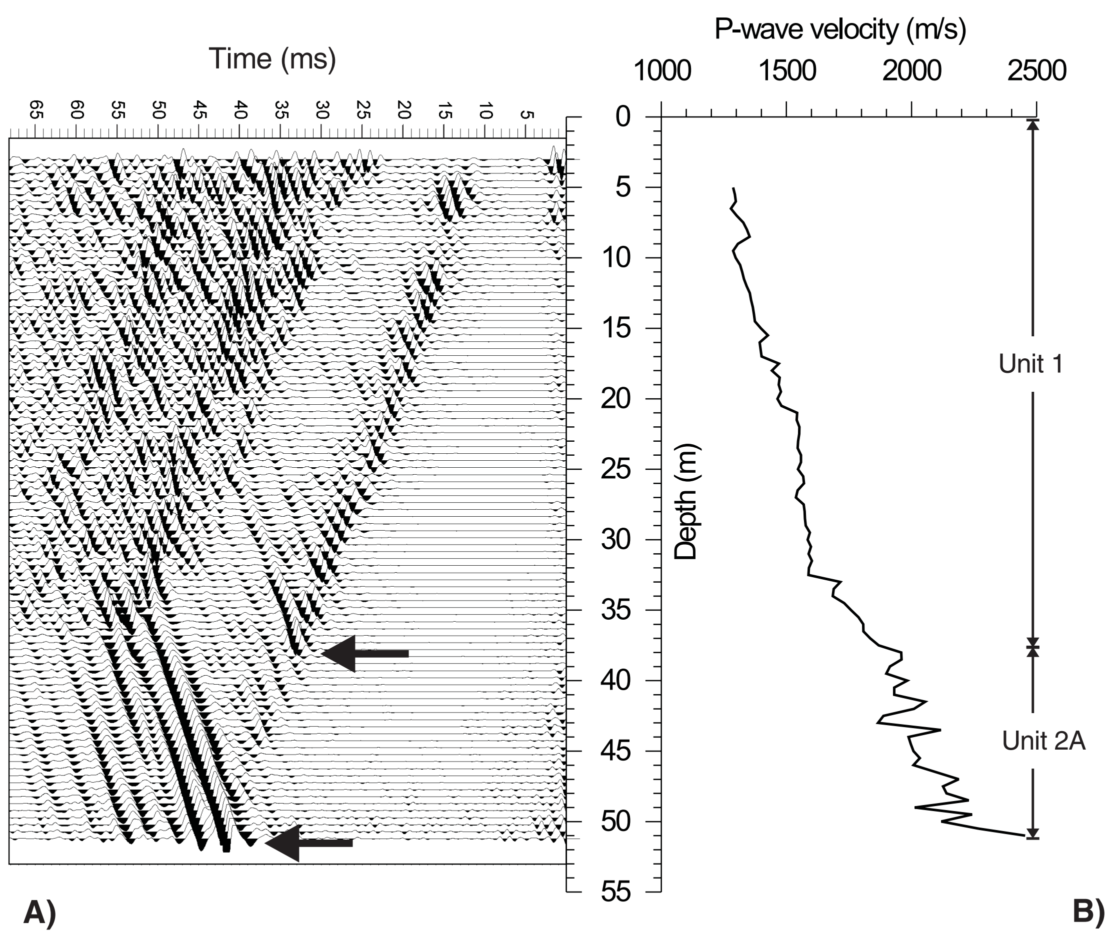

*Figure 6. A) Composite downhole section after the application of an F-K filter. The arrows indicate the reflections from the top and the base of unit 2A (Fig. 5). Figure **B**) shows the interval velocity as a function of depth in the borehole, calculated from the arrival times of the unfiltered downhole seismic data.*

base of unit 1, that may indicate increasing compaction of the sediments. Unit 2A is characterized by velocities of 1900 m/s to 2200 m/s; such values are commonly associated with coarse-grained or well compacted sediments. The reflection events associated with the top and bottom of unit 2A are clearly associated with significant velocity contrasts. At the bottom of the borehole, there is an indication of velocity in the range of 2400 m/s, a value which is typical of compact tills.

The analysis of the downhole seismic data offers a measurement of interval and average velocities at this site, as well as direct correlation between reflection events and depth. These results provide verification and calibration of the seismic section shown in Figure 5.

SUMMARY

High-resolution seismic-reflection surveying carried out in support of hydrogeology and surficial geology studies in the Lachute–Saint-Benoît area northwest of Montréal has contributed to the delineation of subsurface geological structure of surficial materials. The observed high frequencies along with optimal geophone surface arrays combined to yield excellent vertical and horizontal resolution of strata. Three major unconformable seismo-stratigraphic units were identified with unique seismic attributes. Seismic reflectors have been correlated with downhole seismic events and compressional wave velocity variations.

A representative seismic section clearly shows that in this area there can be significant variations in the thickness of overburden sediments above a highly varying bedrock surface. The relatively flat-lying ground surface gives no indication of the subsurface structure that exists below. Shallow seismic-reflection profiling provides details on the overburden stratigraphy and buried bedrock topography that could not be obtained by surface mapping or any feasible drilling program.

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