Geological Survey of Canada

CURRENT RESEARCH
2001-E7

Near-surface seismic methods applied to site-response characterization at an earthquake monitoring station near London, Ontario

B. Benjumea, S.E. Pullan, J.A. Hunter, R.A. Burns, M. Douma, and D. Eaton

Natural Resources Canada
Ressources naturelles Canada

Canada

Catalogue No. M44-2001/E7E-IN
ISBN 0-662-30771-2

Available in Canada from the
Geological Survey of Canada Bookstore website at:
http://www.nrcan.gc.ca/gsc/bookstore (Toll-free: 1-888-252-4301)

A copy of this publication is also available for reference by depository libraries across Canada through access to the Depository Services Program's website at http://dsp-psd.pwgsc.gc.ca

Price subject to change without notice

Near-surface seismic methods applied to site-response characterization at an earthquake monitoring station near London, Ontario

B. Benjumea, S.E. Pullan, J.A. Hunter, R.A. Burns, M. Douma, and D. Eaton[1]
Terrain Sciences Division, Ottawa

Benjumea, B., Pullan, S.E., Hunter, J.A., Burns, R.A., Douma, M., and Eaton, D., 2001: Near-surface seismic methods applied to site-response characterization at an earthquake monitoring station near London, Ontario; Geological Survey of Canada, Current Research 2001-E7, 15 p.

[1] Department of Earth Sciences
University of Western Ontario
London, Ontario N6A 5B7

Abstract

Near-surface seismic methods have been applied in an area south of London, Ontario, in order to image subsurface structure of the overburden and bedrock surface and to obtain estimates of elastic parameters of these sediments. This work was conducted as a pilot study to determine the seismic site response at a future seismograph site for earthquake monitoring. Two seismic refraction-reflection profiles were acquired on two different terraces cut by the Thames River. The results show two major acoustic impedance boundaries, one within overburden related to the presence of a buried overconsolidated till and the other at the overburden-bedrock contact. The elevation of these two contacts is the same for both studied terraces. A 1-D model has been used to obtain estimates of the variation of fundamental site periods in the survey area. The results of this survey provide the basic information needed to evaluate the site response effects.

Résumé

Des méthodes sismiques à faible pénétration ont été utilisées dans une région située au sud de London (Ontario) afin d'obtenir une représentation graphique de la structure de faible profondeur du mort-terrain et de la surface du substratum rocheux et d'obtenir une évaluation des paramètres d'élasticité de ces sédiments. Ce travail a été exécuté dans le cadre d'une étude pilote visant à déterminer la réponse sismique à un site où sera installé éventuellement un séismographe pour la surveillance des tremblements de terre. Deux profils de sismique-réfraction et de sismique-réflexion ont été enregistrés sur deux terrasses entaillées par la rivière Thames. Les résultats ont révélé l'existence de deux importantes limites d'impédance acoustique : l'une se trouve dans le mort-terrain et est liée à la présence de till surconsolidé enfoui, l'autre est située au contact du mort-terrain avec le substratum rocheux. L'altitude de ces deux contacts est la même pour les deux terrasses étudiées. Un modèle unidimensionnel a été utilisé pour évaluer la variation de la période fondamentale en différents endroits du site à l'étudie. Les résultats de cette étude fournissent des données de base indispensables pour évaluer les divers effets entrant dans la réponse sismique du site.

INTRODUCTION

Estimation of the effects of near-surface geology on seismic motion is a critical component of seismological research, as it is necessary to separate site effects from the source and path effects in interpreting the nature of the ground motion. Furthermore, near-surface conditions play an important role in earthquake hazard analysis. In particular, it is well known that thick soil sites are subject to increased ground motion in comparison to the rock sites (e.g. Aki, 1993).

The first-order effects related to near-surface properties and geometry of thick soil sites are impedance contrast amplification and resonance amplification (Shearer and Orcutt, 1987). In addition, localized, large surface amplifications are possible due to the focusing of body waves by topography on the buried bedrock surface (Frankel and Vidale, 1992). Surface topography can also influence the interaction of seismic waves producing complex patterns of amplification and deamplification (Sánchez-Sesma and Campillo, 1993). Knowledge of the elastic parameters of the overburden-rock system and the geometry of the basement are essential to both understand and estimate these amplification effects. Techniques based on microtremor measurements (Bard, 1998) and near-surface geophysical methods (e.g. Hunter et al., 1998) can be used to obtain this information.

In this paper we focus on the application of high-resolution surface-seismic techniques at a future POLARIS site. POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity) is a multi-institutional $10 M program recently funded by the Canada Foundation for Innovation for the creation of a network of portable, satellite-linked geophysical observatories in Canada. One aim of this research project is to improve the understanding of earthquake ground motions and their related hazards. A component of this research includes the deployment of a subarray of 30 three-component broadband seismometers in southern Ontario, many of which will be located in areas of thick overburden. Information on the near-surface characteristics of these sites will be a critical input to the analysis of the data acquired in this project.

The work reported in this paper was a pilot near-surface characterization study at the Delaware site, south of London, Ontario (**Fig. 1**). Shallow seismic methods were used to provide information on the near-surface velocity structure, to identify major acoustic impedances within the overburden, to estimate bedrock depth, and to delineate any local subsurface structure. This study demonstrates the applicability of near-surface geophysical techniques to such site characterizations and stresses the importance of determining near-surface characteristics when planning the installation of, or interpreting data from, these seismological monitoring stations.

SITE DESCRIPTION

The Delaware site is located approximately 15 km southwest of London, Ontario, on the banks of the Thames River (**Fig. 1**). Surface sediments have been mapped as Late Wisconsinan glaciolacustrine silt and sand or silty clay till (Dreimanis, 1963). Bedrock at the site is mapped as grey limestone and shale of the Hamilton Group (middle Devonian; Sanford, 1969).

The river has cut a series of terraces into the drift cover with the current water level at about 200 m a.s.l. The surface elevation on the upper terrace is 240 m a.s.l. and the middle terrace is at about 224 m a.s.l. There is limited control on bedrock elevation in the area, however, estimates range between 190 m a.s.l. (Sanford, 1953) and 175 m a.s.l. (Dreimanis, 1968). Thus, 50–65 m of glacially derived sediments were expected to exist above the bedrock surface at the Delaware site.

DATA ACQUISITION

Two seismic profiles were acquired using both P- and S-wave techniques along the upper and middle terrace (Fig. 1). The difference in elevation between these two profiles is 15–20 m. On each terrace, we deployed a 48-channel spread, 1 geophone per channel, with 5 m geophone spacings on the upper terrace and 3 m spacings on the middle one, resulting in profile lengths of 235 m and 141 m, respectively. The reduced geophone spacing was due to the limited dimensions of the middle terrace. The common recording parameters are listed in **Table 1**.

The geometry used for P-wave acquisition consisted of 47 shots fired between geophones, and at 7.5 m, 5 m, and 2.5 m off each end of the spread on the upper terrace (at 4.5 m, 3 m, and 1.5 m off each end on the middle terrace) for a total of 53 shots. This geometry provides sufficient coverage to produce a seismic-reflection stacked profile, as well as the large source-receiver offsets needed to obtain subsurface seismic velocity information using refraction methods. Shear-wave data were acquired for seven shots into each spread. These shotpoints were located 7.5 m and 5 m off each end of the upper terrace layout (4.5 m and 3 m off each end on the middle terrace) and between geophones 12 and 13, 24 and 25, and 36 and 37. This geometry allows a shear-wave velocity structure to be estimated using refraction techniques, but does not provide enough data to produce a reflection section.

Data were recorded on a stacking seismograph with no preacquisition filters applied. The P-wave source was an in-hole shotgun source (Pullan and MacAulay, 1987), which fires a 12-gauge blank charge into the ground from 1 m below surface in a narrow diameter, drilled hole (water tamping preferred). The polarized source for shear wave acquisition (SH mode) was a heavy steel I-beam aligned along the axis of the geophone array and struck on alternating sides with 6 kg hammer fitted with an electronic trigger. Data were recorded for unidirectional hammer blows as well as stacked blows on opposite sides of the I-beam (using the polarity reversal feature of the seismograph). The bidirectional stacking is designed to reduce non-SH mode signal-generated noise. Usually 16 stacks (8 blows/side) produced a record with the optimum signal-to-noise ratio.

Figure 2 shows an example of raw records from off-end shots for both P- and S-surveys on the upper and lower terrace. P-wave shot gathers are characterized by coherent noise in the low-frequency range on both terraces. Differences in the wavefield character acquired in shear-wave surveys can be seen between the upper and middle terrace. Reflection events can be observed on the upper terrace with little interference with coherent noise; however, high-amplitude Love waves are dominant on the middle terrace. This may be related to the near-surface conditions during acquisition. A frozen layer was detected on the upper terrace, whereas the near-surface materials on middle terrace were water-saturated.

REFRACTION ANALYSIS AND INTERPRETATION

Figure **3** shows the first-arrival traveltime curves for P- and S-wave surveys on the upper terrace. The delay time method (Pakiser and Black, 1957), followed by a series of ray-tracing and model adjustments iterations (SIPQC refraction analysis program), has been applied to determine a 4-layer velocity depth structure. The seven P-wave records used in this refraction analysis are those with source locations coincident to the S-wave data set. In order to enhance the subtle break-over between layers 3 and 4 and improve our confidence in these layer assignments, reduced traveltimes were plotted (Fig. 3, lower panel). It should be noted that the far-offset first arrival picks from the P-wave data are deemed more reliable than those derived from the shear-wave data which have a lower signal-to-noise ratio.

The 4-layer refraction interpretations (both P- and S-wave) for the upper and middle terraces are shown in **Figure 4**. The depth models obtained from the two surveying modes are generally consistent. The calculated P- and S-wave velocities for both terraces are listed in **Table 2** (along with average values that are used in subsequent calculations).

The upper layer (layer 1) is a thin surface layer (maximum thickness of 3 m on the upper terrace and 2 m on the middle one) that is characterized by a very low P-wave velocity (α_1=320 m/s). This layer is interpreted as the unsaturated surface zone.

The contact between layer 1 and layer 2 is characterized by a high acoustic impedance contrast for P-waves (α_2=1675 m/s) and is interpreted as the water table. An increase in S-wave velocity is also shown in this model (β_2=285 m/s), but it is likely that the shear-wave velocity increases gradually in the near-surface, due to increasing load with depth, rather than the sharp contact implied by this layered refraction interpretation. Layer 2 is interpreted as water-saturated glacial deposits. This unit (at least the upper portion) is characterized by a high Poisson's ratio (~0.48).

A significant increase in velocity at about 200 m a.s.l. is observed in the P- and S-wave refraction interpretations on both terraces; however, the velocities (α_3=2770 m/s, β_3=1165 m/s) are not high enough to be associated with Paleozoic bedrock. This layer is instead interpreted to indicate the presence of an overconsolidated till unit. This interpretation is based on velocity information from other areas of southern Ontario (e.g. Pullan et al., 2000) where thick, high-velocity (>2500 m/s) till units have been observed within the Quaternary sequence. There are apparently significant differences in the depth to layer 3 in the P- and S-wave interpretations, particularly on the upper terrace between 110 m and 160 m distance from the first geophone; however, these are attributed to the imposition of a simple layered interpretation in the analysis and may not have any structural significance.

The deepest layer (layer 4) is interpreted as bedrock. Only a limited number of first-arrival picks come from this layer, and both the velocities and depths calculated for this layer are subject to a higher degree of uncertainty than those for the overlying layers; however, the velocities (α_4=5000 m/s, β_4=2660 m/s) are consistent with expected values for Paleozoic bedrock (e.g. Beresnev and Atkinson, 1997), and the depth to this layer is consistent with the depth to bedrock expected from the limited borehole control in the area.

These refraction analyses provide simplified P- and S-velocity-depth models for this site. It should be recognized, however, that there are likely to be velocity variations within these layers that cannot be determined from these first-arrival data. In particular, refraction analyses cannot identify the presence of a low-velocity layer within the section. Downhole seismic logging north of Toronto (e.g. Pullan et al., 2000) has shown that lower velocity sediments (α~1800–2000 m/s) often exist beneath the high-velocity overconsolidated till found in that region. The possibility of a similar velocity structure at this site should be considered.

REFLECTION PROCESSING AND INTERPRETATION

P-wave seismic-reflection data have been processed using standard CMP (common midpoint) routines to produce a seismic-reflection section approximately the length of the geophone spread. Most of the coherent noise on the field records could be removed by band-pass filtering (**Fig. 2**). Static corrections after Pugin and Pullan (2000) have been applied to correct for variations in the low-velocity surface layer. Only traces with an offset of 52.5 m or less were included in the reflection processing. The far-offset traces are removed from the processing sequence because of the interference between first arrivals and reflections (Fig. 2). The final sections are shown after two-way traveltime has been converted to depth using the stacking velocities, and after elevation corrections have been made to reference the data to a fixed datum (in this case, the maximum elevation along the upper terrace profile was chosen as the datum). The final P-wave seismic-reflection depth sections are shown in **Figure 5**.

Several different units can be observed within the overburden. Note that the very near-surface structure (0–15 m depth) cannot be resolved on reflection sections because of the interference of shallow reflections and the direct arrivals. The uppermost unit (to ~200 m a.s.l., **Fig. 5**, unit 1) is characterized by a relatively low-amplitude facies with some flat-lying reflections (note particularly the reflection beneath both terraces which suggests a stratigraphic and/or lithological change at ~ 210 m a.s.l.). This upper unit is interpreted as stratified glacial sediments, and is likely to be relatively fine grained (i.e. predominantly clay to fine sand).

The top of the second unit (Fig. 5, unit 2) is characterized by a large-amplitude reflection which is attributed to a large velocity contrast with overlying sediments. This highly reflective and almost flat contact is interpreted as the top of the high-velocity layer (interpreted as overconsolidated till) observed in the refraction analysis. A strong reflection from similar high-velocity till is also commonly observed in the area north of Toronto (Pugin et al., 1999). Below this strong reflector, a sequence of irregular reflections can be found (180–190 m a.s.l.), which may represent the complex structure of the high-velocity till and associated deposits.

At greater depth (Fig. 5, unit 3) there is a series of flat-lying reflections on the middle terrace profile (~160–175 m a.s.l.), but only a low-amplitude reflection on the upper terrace profile (~160 m a.s.l.). This reflection and the lower portion of the reflection package observed on the middle terrace profile is interpreted as the bedrock reflection. The reason for the different reflection character in this depth range is not known, but it is more likely to be related to variations in surface conditions than subsurface structure. The data acquired on the middle terrace, where the water table was closer to surface and there was apparently no frost remaining in the ground, contain significantly higher frequencies than the upper terrace data (**Fig. 2**). It is postulated that these higher frequencies allow the imaging of reflections from thin (several metres) till units directly overlying the bedrock surface, which cannot be resolved on the lower frequency, upper terrace section. The postulated existence of tills (likely characterized by high velocities) overlying bedrock and the reduced signal strength beneath the high-velocity layer at about 200 m a.s.l., may both be factors contributing to the relatively weak bedrock reflection signal. The middle terrace section shows a dipping arrival from the northeast side which is interpreted as sideswipe from the deep ravine located just north of the spread (**Fig. 1**), and not related to subsurface structure.

DISCUSSION

Near-surface seismic surveys can provide information about the subsurface velocity profile, related elastic parameters, and subsurface structure. In this study, the refraction models identify a high-velocity contrast (both in P-waves and S-waves) within the overburden. Seismic-reflection sections show this velocity contrast to be a highly reflective interface (**Fig. 5**). This boundary is interpreted as the top of an overconsolidated till layer and does not show any topography or structural variation on the survey scale (~500 m). The overburden-bedrock contact was also identified in these surveys, at a slightly greater depth (~85 m for upper terrace and ~65 m for middle terrace) than expected from the sparse depth to bedrock estimates available in the literature. Differences in the depths to bedrock calculated in the P- and S-wave refraction models are due largely to uncertainty in the first arrivals picks; however, the reflection sections show the overburden-bedrock contact to be essentially flat-lying. The refraction method provides good velocity estimates, while the reflection method is deemed to provide more accurate representations of the subsurface structure.

The results obtained in this study are important for understanding the influence of thick soils in the earthquake ground motion. The two major acoustic impedance boundaries may play important roles in the earthquake site response. As a first approximation, the fundamental site resonance period (T) based on 1-D model can be calculated (Shearer and Orcutt, 1987):

$$T = \frac{4H}{V_{ave}} \quad (1)$$

where H and V_{ave} are the thickness and average shear-wave velocity for the overburden. The model used for this calculation consists of the average shear-wave velocities and depths obtained from refraction interpretation for both terraces (**Table 2**).

Using this equation, the fundamental resonance period due to the surficial sediments-overconsolidated till boundary is 0.6 s for the upper terrace and 0.32 s for the middle terrace. The corresponding values for the overburden-bedrock boundary are 0.76 s (upper terrace) and 0.47 s (middle terrace). These calculations clearly show the significant effect of the thickness of 'soft soils' at a site on the fundamental site period.

As noted above, the velocity structure determined from the refraction analysis cannot include the existence of possible low-velocity layers. We have calculated the effect of including a low-velocity layer (β=800 m/s, 25 m thick) below the high-velocity till (layer 3, **Fig. 4**; now assumed to be only 10 m thick). The error in the fundamental resonance period calculation for the overburden-bedrock contact caused by ignoring (or not knowing about) such a low-velocity layer is only 1%.

In contrast, estimating the fundamental resonance period for the overburden-bedrock boundary by assuming the overburden thickness from water-well information (60 m) and an average value for glacial sediments in a range of 400–600 m/s (as suggested by overburden velocity values from Beresnev and Atkinson (1997)) would lead to a calculated fundamental site resonance period that differs from our estimates by 15–40%. As well, without the survey conducted at this site, the possibility of resonance from an intraoverburden velocity contrast would be missed completely. This demonstrates the importance of knowing detailed overburden velocity and depth information to characterize site effects.

Resonant site periods (T) can also be estimated from the zero-offset two-way traveltime of a near-vertical S-wave reflection T_o ($T=2T_o$). This method is considered more reliable and straightforward since structural information is not required; however, the recognition of the shear-wave reflection is not always possible. At this site, shear-wave reflections from the top of the high-velocity till and bedrock surface can be observed in the upper terrace raw data; however, an f-k filter has to be applied to identify possible reflections for the middle terrace data set. Using the two-way traveltime of the shear-wave reflection for zero offset, we obtain resonance periods of 0.56 s and 0.34 for the top of the till, and 0.69 s and 0.58 s for bedrock for the upper and middle terraces, respectively. These values are consistent with the ones obtained using Equation 1 with the velocity and depth estimates obtained from the refraction-reflection interpretations.

CONCLUSIONS

Near-surface seismic methods provide detailed knowledge of subsurface geometry and elastic properties, and can be used to identify and quantify major acoustic impedance boundaries within overburden and at the bedrock contact. As a first approximation based on a 1-D model, we have obtained fundamental site periods corresponding to a high acoustic impedance boundary within the overburden and for the bedrock surface. Differences between this parameter calculated for the upper and the middle terrace are 0.2 s for both acoustic impedance boundaries. At this site, this is simply a consequence of the difference in thickness of the ‘soft soil’ beneath each terrace. Further studies will develop more complex modelling including topographic effects that could be important in this area.

The results of this pilot study reveal the detailed information on the subsurface that can be obtained from simple, cost-effective shallow seismic surveys. Such information can be significant in both general seismological studies (path and source studies) and earthquake hazard evaluation at thick soil sites. Such site characterizations should be considered for all earthquake monitoring sites where significant overburden is known, or suspected, to exist.

ACKNOWLEDGMENTS

We thank Savka Dineva for her support of this work and for her help in the field. B.B. is supported by a fellowship awarded by University of Granada (Spain) and project AMB 99-0795-C02-01 (Spanish Interministerial Commission for Science and Technology).

REFERENCES

Aki, K.
1993: Local site effects on weak and strong ground motion; Tectonophysics, v. 218, p. 93–111.

Bard, P.Y.
1998: Microtremor measurements: a tool for site effect estimation; *in* The Effects of Surface Geology on Seismic Motion; (ed.) K. Irikura, K. Kudo, H. Okada, and T. Sasatani; Balkema, Rotterdam, Netherlands, p. 1251–1279.

Beresnev, I.A. and Atkinson, G.M
1997: Shear-wave velocity survey of seismographic sites in Eastern Canada: calibration of empirical regression method of estimating site response; Seismological Research Letters, v. 68, no. 6, p. 981–987.

Dreimanis, A.
1963: Pleistocene geology of the St. Thomas area (west half), Southern Ontario; Ontario Department of Mines, Preliminary Geological Map No. 238, scale 1:50 000.
1968: St. Thomas sheet, southern Ontario; Bedrock Topography Series, Ontario Department of Mines, Preliminary Map P.482, scale 1:50 000.

Frankel, A. and Vidale, J.
1992: A three-dimensional simulation of seismic waves in the Santa Clara Valley, California, from a Loma Prieta aftershock; Bulletin of Seismological Society of America, v. 82, p. 2045–2074.

Hunter, J.A., Douma, M., Burns, R.A., Good, R.L., Pullan, S.E., Harris, J.B., Luternauer, J.L., and Best, M.E.
1998: Testing and application of near-surface geophysical techniques for earthquake hazards studies, Fraser river delta, British Columbia; *in* Geology and Natural Hazards of the Fraser River Delta, British Columbia, (ed.) J.J. Clague, J.L. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, p. 123–145.

Pakiser, L.C. and Black, R.A.
1957: Exploring for ancient channels with the refraction seismograph; Geophysics, v. 22, p. 32–47.

Pugin, A. and Pullan, S.E.
2000: First-arrival alignment static corrections applied to shallow seismic reflection data; Journal of Environmental and Engineering Geophysics, v. 5, p. 7–15.

Pugin, A., Pullan, S.E., and Sharpe, D.R.
1999: Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario; Canadian Journal of Earth Sciences, v. 36, p. 409–432.

Pullan, S.E. and MacAulay, H.A.
1987: An in-hole shotgun source for engineering seismic surveys; Geophysics, v. 52, p. 985–996.

Pullan, S.E., Hunter, J.A., Pugin, A., Burns, R.A., and Hinton, M.J.
2000: Downhole seismic logging techniques in a regional hydrogeological study, Oak Ridges Moraine, southern Ontario; *in* Proceedings, SAGEEP'2000, Symposium on the Application of Geophysics to Engineering and Environmental Problems; February 20–24, Arlington, Virginia, p. 643–652.

Sánchez-Sesma, F. and Campillo, M.
1993: Topographic effects for incident P, SV and Rayleigh waves; Tectonophysics, v. 218, p. 113–125.

Sanford, B.V.
1953: Elgin County and parts of Middlesex County, Ontario, showing drift thickness and bedrock contours, Maps A and B; Geological Survey of Canada, Paper 53-06, 2 maps, scale 1 inch: 2 miles.
1969: Geology, Toronto-Windsor area, Ontario; Geological Survey of Canada, Map 1263A, scale 1:250 000.

Shearer, P.M. and Orcutt J.A.
1987: Surface and near-surface effects on seismic waves- theory and borehole seismometers results; Bulletin of the Seismological Society of America, v. 77, p. 1168–1196.

Geological Survey of Canada Project 920039

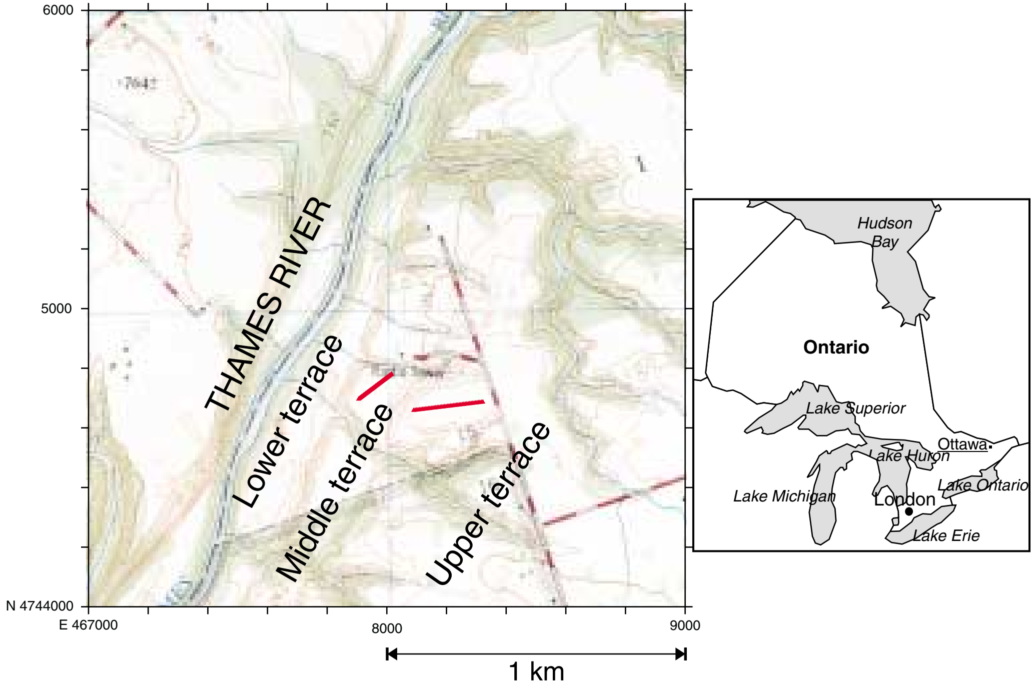

Figure 1. The Delaware site, 15 km southeast of London (Ontario), showing the location of the two seismic lines (solid lines). The profiles are located on the upper and middle terraces of the Thames River valley. The grid labels are UTM co-ordinates (zone 17) using the NAD27 datum. Elevation contours are in feet.

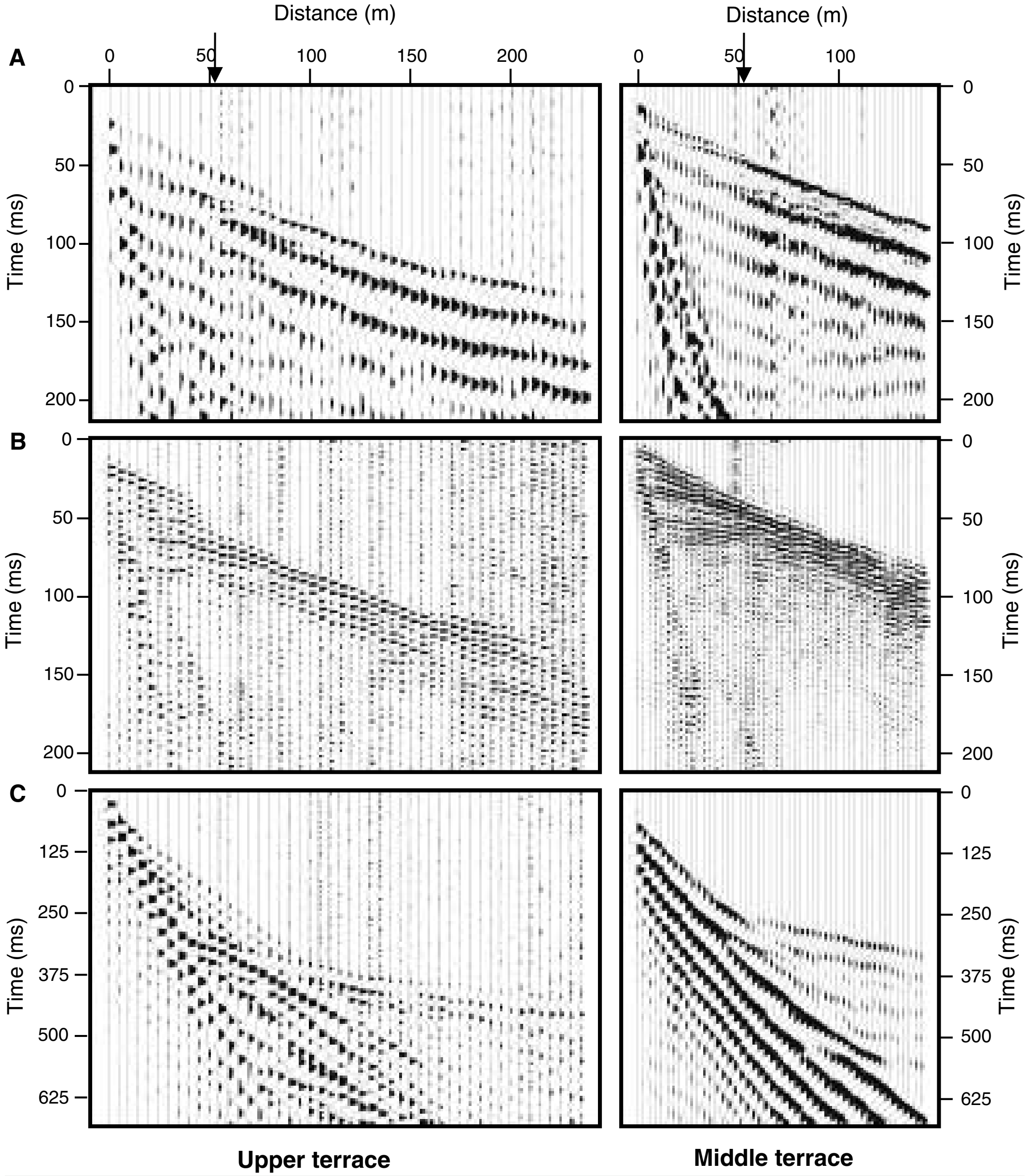

Figure 2. Off-end shot records from the upper terrace (left side) and the middle terrace (right side) displayed with the same horizontal scale. Panel **A)** displays raw P-wave data. The same records, after application of a digital band-pass filter (150–500 Hz) and amplitude scaling, are shown in panel **B)**. Panel **C)** displays the shear-wave records obtained at the same locations. The arrows display the maximum offset for traces that have been used for the P-wave seismic reflection processing (52.5 m offset).

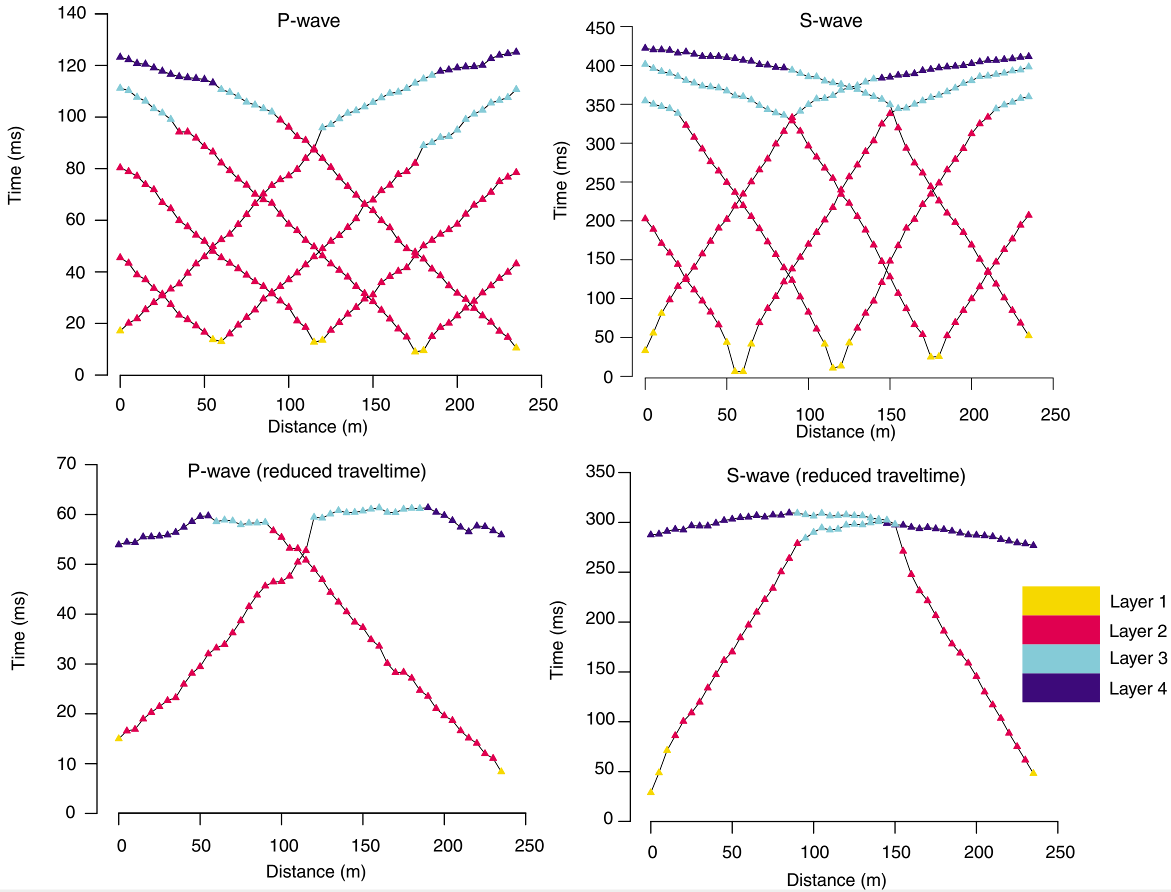

Figure 3. Traveltime versus distance for first arrivals refractions (P-wave on the left and S-wave survey on the right) compiled from records on the upper terrace. The lower panel displays the reduced traveltime versus distance for two off-end records. The reduced traveltime is t_r=t-x/v_r, where t is the arrival time, x is distance between shot and geophone, and v_r is the reducing velocity (in this case v_r=3500 m/s for P-wave and 2500 m/s for S-wave data)

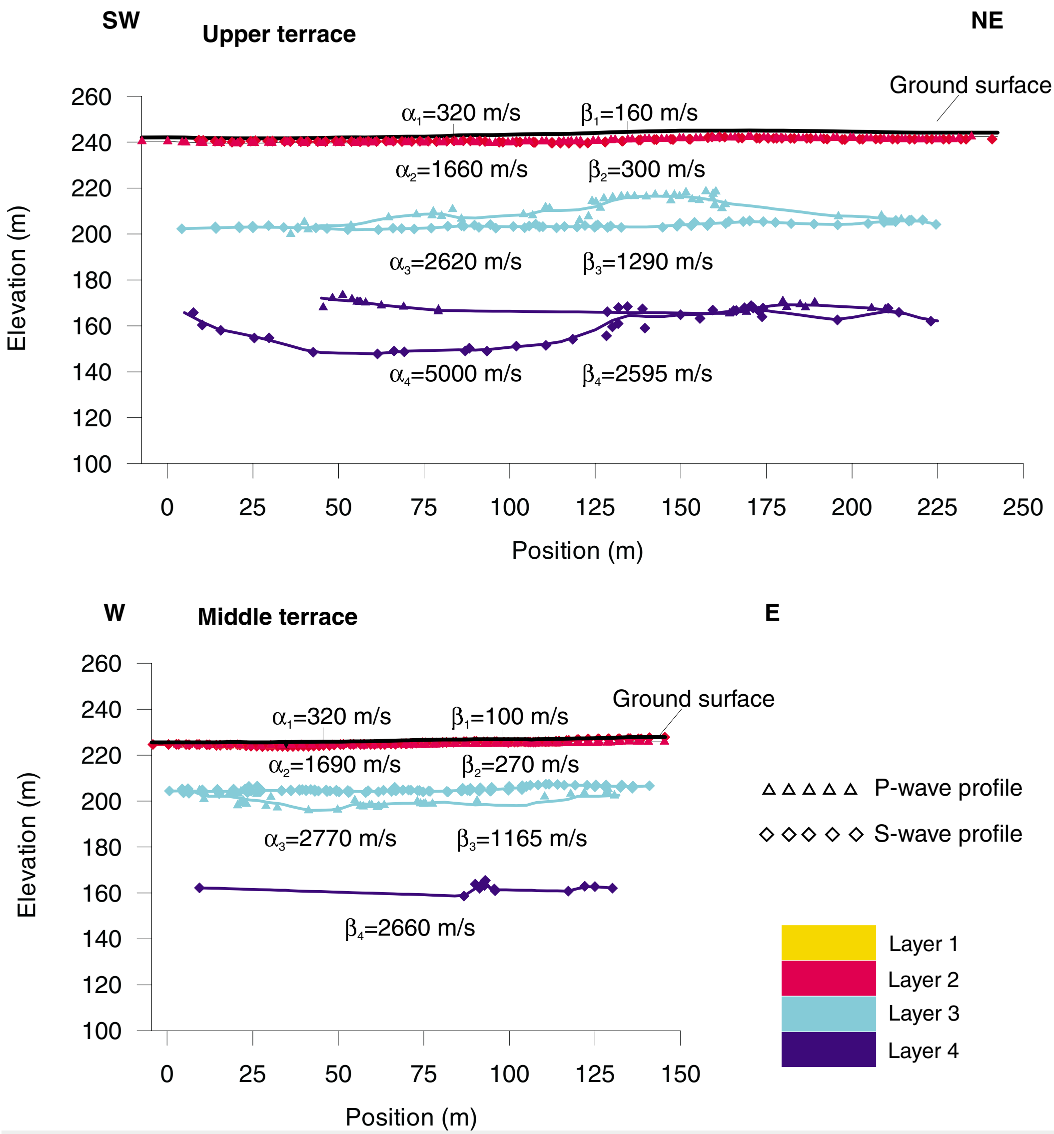

Figure 4. Depth and velocity models resulting from a 4-layer seismic refraction interpretation showing the emergent ray end points from the ray-tracing analysis routine (α = P-wave velocities and β = S-wave velocities). Results obtained from P-wave survey are shown with triangles and for S-wave with diamonds.

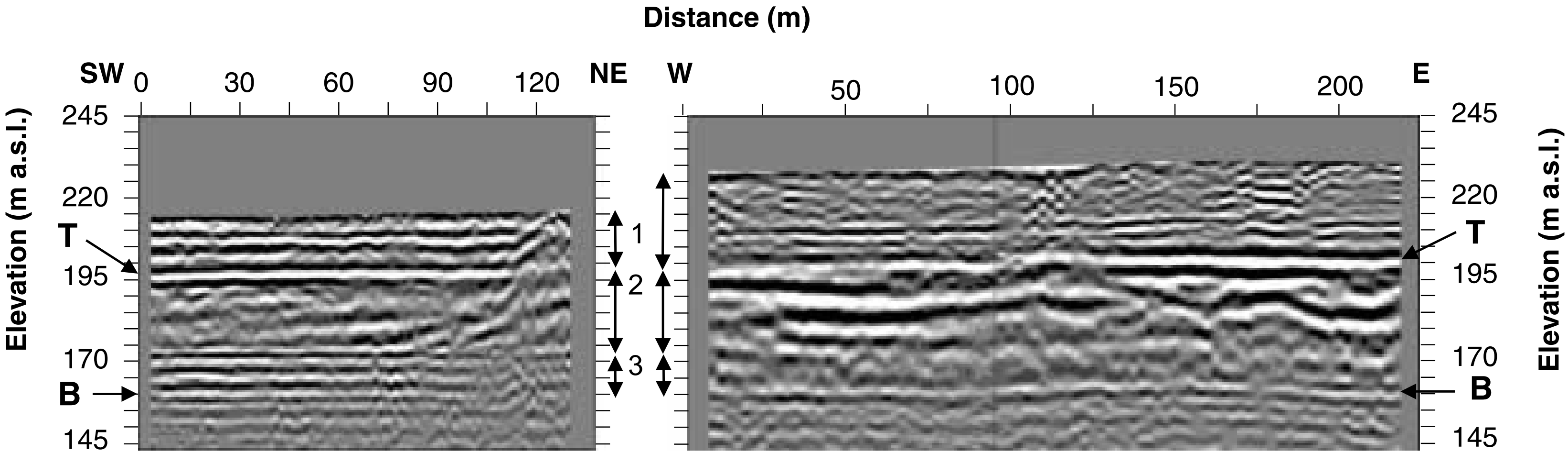

Figure 5. Depth stacked sections for the two seismic profiles. The reference datum is the highest point on the upper terrace profile (245 m a.s.l.) for both sections. The horizontal/vertical distance ratio is 1:1. The different units interpreted for these sections are shown (*see* text for interpretation). Arrows mark the position of the top of the till (T) and top of bedrock (B).

Table 1. Seismic refraction-reflection data recording parameters.

	P-wave acquisition	S-wave acquisition
Recording system	Geometrics StrataView ™	Geometrics StrataView ™
Sampling interval	0.125 ms	0.25 ms
Record length	256 ms	1024 ms
Recording format	SEG-2	SEG-2
Geophones	50 Hz (vertical)	8 Hz (horizontal)
Sources	In-hole shotgun source	Steel I-beam and hammer

Table 2. Velocity model obtained from refraction method.

		α (m/s)	β (m/s)	H(m)*
Upper terrace	**Layer 1**	320	160	2.6
	Layer 2	1660	300	40
	Layer 3	2620	1290	85
	Layer 4	5000	2595	-
Middle terrace	**Layer 1**	320	100	1
	Layer 2	1690	270	20
	Layer 3	2920	1040	65
	Layer 4	-	2720	-
Average values	**Layer 1**	320	130	-
	Layer 2	1675	285	-
	Layer 3	2770	1165	-
	Layer 4	5000	2660	-

* Average thickness determined from S-wave refraction survey