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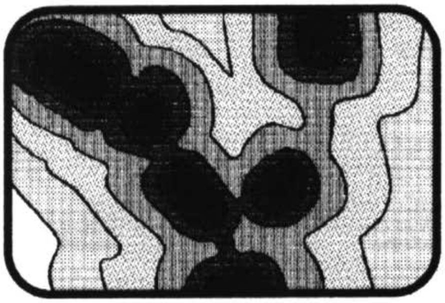
Article abstract

Conventional approaches to environmental site characterization usually involve drilling of relatively dense networks of continuously sampled and geophysically logged bore holes. Inglaciated terrains, problems are often encountered in determining the lateral continuity and three-dimensional sub-surface geometry of sediments between bore hole locations. An improved and potentially more cost-effective approach combines drilling and bore hole sampling with high-resolution shallow seismic reflection profiling. This approach is illustrated with case studies from candidate landfill sites. Seismic data provide critical information regarding the lateral continuity and geometry of sediments and pathways for groundwater and contaminants.



Shallow Seismic Reflection Profiling of Waste Disposal Sites

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SUMMARY
Conventional approaches to environmental site characterization usually involve drilling of relatively dense networks of continuously sampled and geophysically logged boreholes. In glaciated terrains, problems are often encountered in determining the lateral continuity and three-dimensional subsurface geometry of sediments between borehole locations. An improved and potentially more cost-effective approach combines drilling and borehole sampling with high-resolution shallow seismic reflection profiling. This approach is illustrated with case studies from candidate landfill sites. Seismic data provide critical information regarding the lateral continuity and geometry of sediments and pathways for ground water and contaminants.

RÉSUMÉ
Les approches courantes pour la caractérisation environnementale des sites de décharge font appel à l'échantillonnage continu de carottages relativement rapprochés et ainsi qu'à l'enregistrement de diagraphies de ces trous de sondage. Dans les cas des sites de dépôts glaciaires, on éprouve souvent des difficultés à établir l'extension latérale des horizons rencontrés et la configuration géométrique tridimensionnelles des sédiments entre les trous de sondage. Une meilleure approche, peut-être moins coûteuse, consiste à combiner les sondages et leur échantillonnage avec un levé de sismique réflection haute définition des couches peu profondes. Cette approche est illustrée par l'étude d'histoires de cas de sites possibles de décharges sanitaires. Les données sismiques apportent des informations cruciales sur l'extension latérale et la géométrie des sédiments, ainsi que sur les voies empruntées par les eaux souterraines et les polluants.

INTRODUCTION
Detailed subsurface geological information is an important requirement for hydrogeological evaluation of waste disposal sites and other environmental geological investigations carried out in urbanized areas. In the Toronto urban area of southern Ontario (Fig. 1), applied investigations are dependent on a detailed understanding of the subsurface stratigraphy and geometry of thick Pleistocene sediments (up to 200 m) which overlie bedrock across the region. Conventional site characterization typically involves intensive field programmes of drilling and core sampling, downhole geophysical logging, well monitoring, and hydrochemical analysis. However, even with closely spaced networks of continuously sampled boreholes, significant uncertainties can arise in determining the lateral continuity and true subsurface geometry of glacial sediments between drilling locations.

Stratigraphic resolution can be significantly improved in applied investigations by integrating conventional borehole information with continuous subsurface-imaging techniques such as shallow seismic reflection profiling and ground-penetrating radar (GPR;

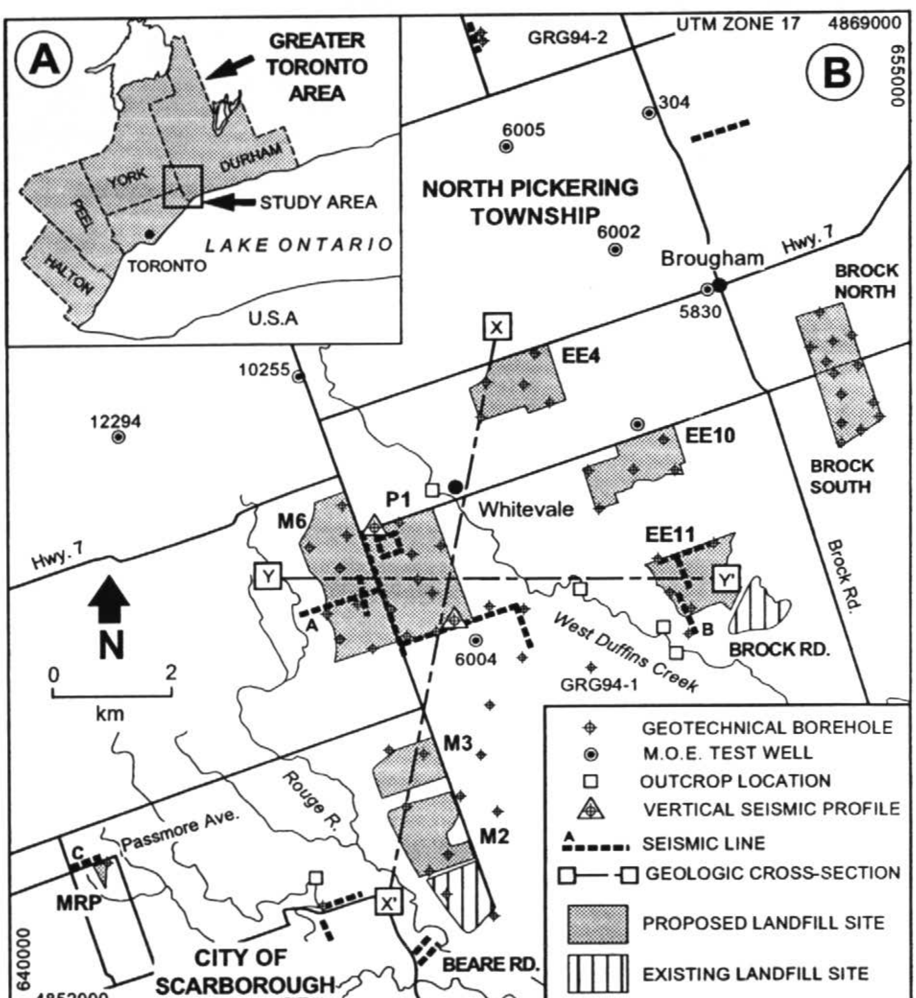

Figure 1 (**A**) *Location of study area.* (**B**) *Location of proposed and existing landfill sites, geologic cross-sections and seismic reflection profiles.*

Scaife, in press). Shallow seismic reflection methods are now employed routinely in Pleistocene geological studies (Pugin and Rossetti, 1992; Genau *et al.* ,1994; Koseoglu, 1995; Boyce *et al.*, 1995) and in regional ground-water investigations (Hunter *et al.*, 1987; Pullan *et al.*, 1994). With the advent over the last decade of less expensive, more powerful seismographs and PC-based processing software (e.g., Somanas *et al.*, 1987), shallow seismic reflection surveys have become efficient and cost-effective for private sector use.

This paper presents an overview of shallow seismic reflection methods and illustrates their application in case studies from three candidate landfill sites and a low-level radioactive soil remediation site in the Greater Toronto Area (GTA; Fig. 1). Searches for new municipal and hazardous waste sites are being carried out in many other parts of Canada and the northern United States where thick glacial sediments are widespread (*e.g.*, Curry *et al.*, 1994). The seismic reflection methods and results reported here, therefore, have a wider relevance for landfilling and applied ground-water investigations in other urbanized areas.

SEISMIC REFLECTION METHODS

The seismic reflection method has been used in the petroleum industry for more than 60 years for evaluating the deep subsurface structure and oil and gas potential of sedimentary basins (Telford *et al.*, 1990). Artificial seismic sources (most commonly explosives or mobile vibrators) are employed to introduce elastic waves (principally compressional or p-waves) into the subsurface (Fig. 2). In a manner similar to sound echoing in air, reflections are produced in the subsurface, where p-waves impinge upon boundaries between geological layers with contrasting densities and/or seismic velocities. The reflectivity of a formation boundary is a function of the change in acoustic impedance which is given by the product of the bulk density and velocity of a formation. Reflected waves arriving at the surface are detected with a linear array of geophones (Fig. 2) or other seismometers (*e.g.*, accelerometers) which output a voltage signal proportional to the vertical velocity of the ground motion. The signals from the receivers are amplified, converted to digital words, and recorded on a multi-channel seismograph. The ground motion recorded by each receiver is displayed as an individual trace on a seismic field record which is a plot of time *versus* signal amplitude. The travel time-amplitude data are then manipulated in a number of processing stages which culminate with the production of a seismic reflection section. The latter outwardly resembles a geological cross-section (with the time axis corresponding qualitatively with depth). The important difference is that the changes in the vertical position of reflecting horizons may be due to changes in either velocity, reflector depth, or both. In order to generate a true geological section, showing the location and structural attitude of reflectors, time-domain seismic sections need to be converted to depth using the average seismic velocities and travel times of reflections.

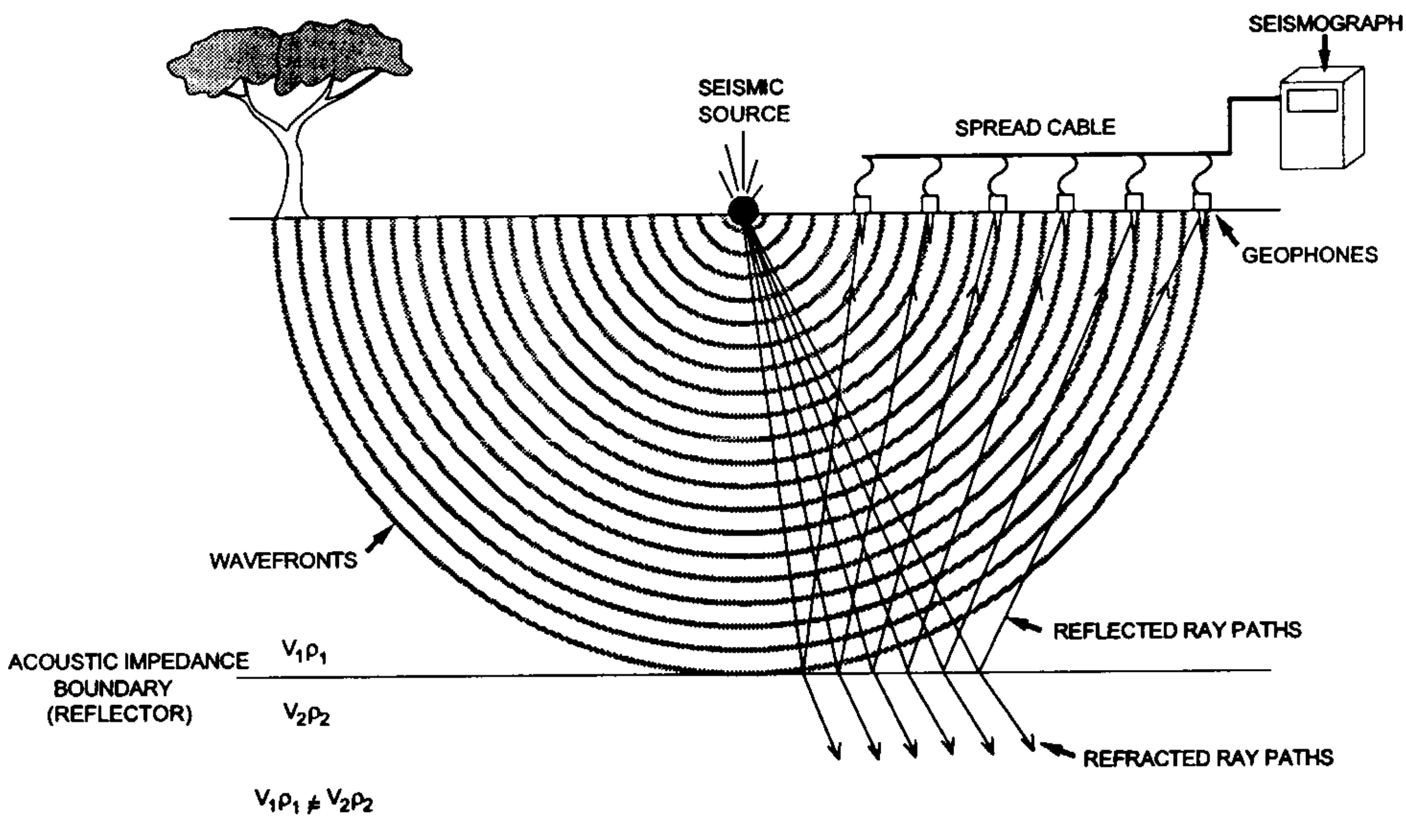

Figure 2 *Basic principle of seismic reflection method. Elastic waves (principally p-waves) are propagated into the subsurface using an artificial seismic energy source (e.g., explosives) and are reflected and refracted at acoustical discontinuities between layers with contrasting mass density and/or seismic velocity (acoustic impedance = Vp). The arrival times and amplitudes of reflected waves are detected at the surface by an array of receivers and recorded by a seismograph. The depth and seismic velocity above the reflecting interfaces are obtained from analysis of the recorded travel time-amplitude series.*

Shallow Seismic Reflection Methods

During the past two decades, seismic reflection methods have been adapted for exploration of the shallow subsurface (≈5 m to 200 m depth) in engineering and ground-water investigations (Schepers, 1975; Hunter *et al.*, 1984, 1987; Miller and Steeples, 1994). Resolution of layering down to about 1 m in thickness is now routinely achieved in shallow seismic work although, under near-ideal substrate conditions, beds as thin as 0.5 m have been imaged (*e.g.*, Jongerius and Helbig, 1988). Shallow seismic methods have been used to locate faults, sinkholes and void spaces (Steeples *et al.*, 1986; Branham and Steeples, 1988; Treadway *et al.*, 1988).

Among the most important requirements for shallow reflection work are the use of high-frequency energy sources and low-cut filtering of data during field acquisition (Knapp and Steeples, 1986a, b; Hunter *et al.*, 1987). In contrast to petroleum-scale surveys which employ source frequencies in the 10-90 Hz range, frequencies of several hundred Hz are required to obtain high resolution at shallow depths of investigation. This stems from the fact that the vertical resolution, or thinnest bed that can be successfully imaged, is dependent upon the wavelength of the seismic impulse (wavelength = velocity/frequency). In theoretical terms, reflecting boundaries must be a minimum thickness of a quarter wavelength apart in order to be resolved; below this limit, destructive interference between reflections from the top and bottom of a layer results in greatly reduced reflection amplitude (Sheriff, 1985). Field filtering involves the use of pre-emphasis low-cut filters on the recording instrument to counter the selective attenuation of high-frequency signals which occurs in the subsurface (Knapp and Steeples, 1986b). In general, fine-grained, water-saturated sediments are more conducive to transmission of high frequencies and collection of high-resolution seismic data than dry, coarse-grained overburden materials (Hunter *et al.*, 1987). Besides low-cut filtering, high-frequency geophones with high natural resonant frequencies (between 50 Hz and 100 Hz) can be used to reduce some of the unwanted low-frequency components. The instrumentation and optimal field parameters for high-resolution seismic work are discussed by Knapp and Steeples (1986a, b) and Hunter *et al.* (1987). Generally, steps must be taken to prevent low-frequency signal components from dominating the recording.

The necessity for preserving high-frequency components of the seismic record has led to much development and testing of source types, in particular, downhole rifles and shotguns which are now widely employed in shallow reflection work (*e.g.*, Miller *et al.*, 1986; Seeber and Steeples, 1986; Pullan and MacAulay, 1987; Miller *et al.*, 1992). Two acquisition strategies are employed routinely in shallow seismic reflection work, the common-depth point method and the optimum-offset method, both of which are reviewed here.

Optimum-Offset Method

The optimum-offset method was developed by the Geological Survey of Canada as a method that could be implemented with a minimum of equipment and computing facilities (Hunter *et*

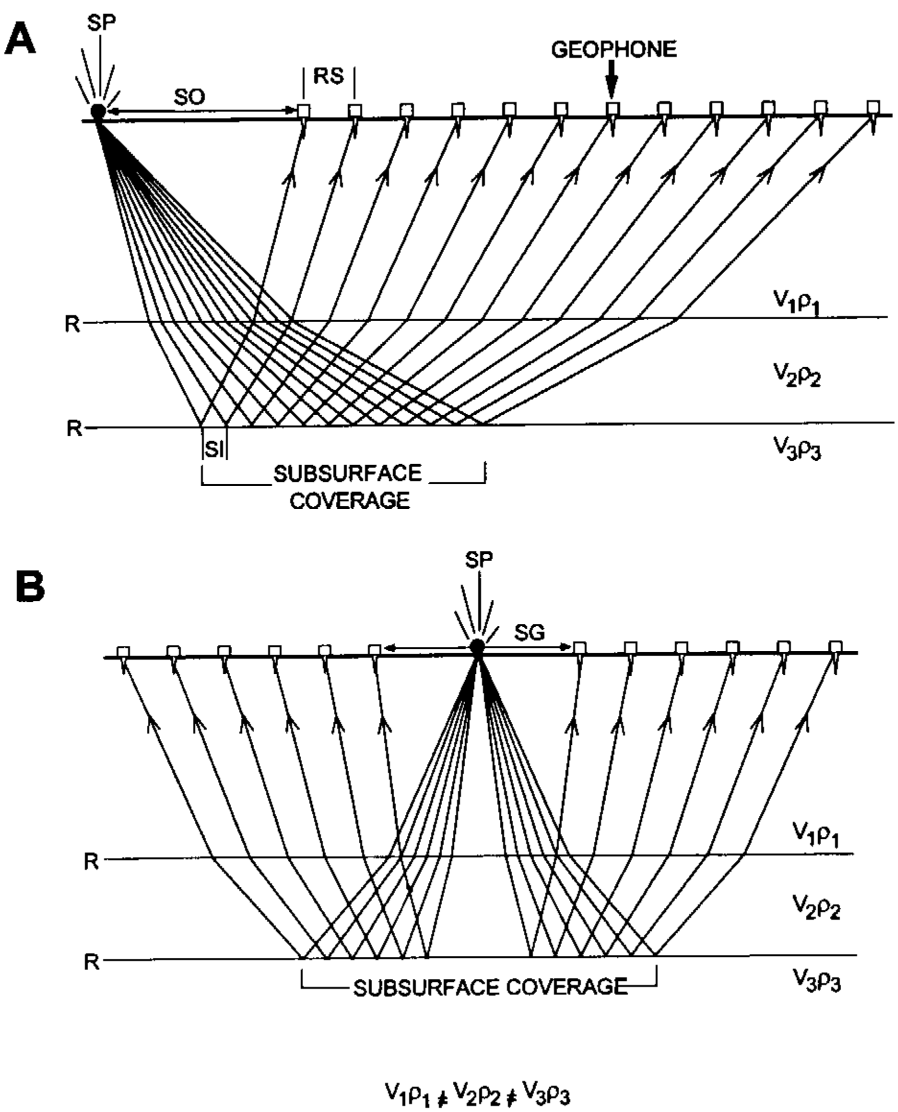

Figure 3 *Two field layouts commonly used in acquisition of CDP seismic reflection data with idealized reflection raypaths shown for a simple horizontally layered case.* (**A**) *End-on geometry. Shot point (SP) is positioned at set source offset (SO) and fired into line of receivers which are moved incrementally along the line using a roll-box or by repositioning of receiver spread. The reflection sampling interval (SI) is one-half the receiver spacing (RS). Continuous roll-along shooting using the 12-channel arrangement shown and with a shot interval equal to the receiver spacing would result in a maximum 6-fold (600%) subsurface coverage.* (**B**) *Split-spread geometry. Shot point is positioned mid-spread and a shot gap (SG) is used to separate near-shot receivers from energy source. Spread is rolled-along in same manner as in end-on layout to provide continuous subsurface coverage.*

al., 1984). This method involves collection of end-to-end single-fold spreads, using an optimized source-receiver offset that allows reflections to be recorded with minimum interference from groundroll and shallow refraction events. The optimum-offset range is determined by performing a series of walk-away noise tests with increasing source-receiver separations. A single offset is then selected within this window, and the survey proceeds by shooting one trace at a time, using the same offset for all traces. Alternately, multichannel records are collected and the traces corresponding to the selected offset are assembled later during processing. In the optimum-offset method, each subsurface reflection point is sampled once, providing single-fold, or 100%, coverage. Case studies demonstrating the successful application and some potential pitfalls of the optimum-offset method are discussed by Hunter *et al.* (1987) and Slaine *et al.*, (1990).

Common-Depth Point Method

The common-depth point method (CDP) is a continuous-profiling technique in which subsurface reflection points are sampled repeatedly over a range of source-receiver separations (Mayne, 1962; Knapp and Steeples, 1986a, b; Steeples and Miller, 1990). The strategy employs roll-along shooting in which the shot point and geophones are advanced along the survey line at increments equal to the geophone spacing or some multiple of this distance (Fig. 3). The resulting overlap between spreads leads to a redundancy of data collected for each reflection mid-point in the subsurface (Fig. 3). These mid-points are variously referred to as common-depth points (CDP) or common mid-points (CMP) and have a spacing which is one-half the surface shot station separation. Figure 4 illustrates the CDP concept for a case where a reflection point is sampled from six different source-receiver separations.

Continuous profiling in CDP surveys is usually facilitated with a roll-along switch which is used to increment a number of live recording channels through successive spreads. For example, during roll-along shooting with a spread of 24 geophones and a 12-channel recording instrument, geophones 1-12 would record shot 1, geophones 2-13 shot 2, geophones 3-14 shot 3, and so on. The fold, or redundancy, of subsurface coverage is determined by the number of active channels and the shot and receiver intervals; for the 12-channel setup described, six-fold or 600% coverage (*e.g.*, Fig. 4) would be obtained where shots are performed at every geophone location, and three-fold data where the shot spacing was set at twice the geophone interval. Exploration seismographs available at the present are commonly equipped with 24, 48 or 96 channels and 12-, 24- or 48-fold coverages are now employed routinely in shallow seismic reflection work.

CDP surveys are usually acquired using either end-on or a split-spread field layout (Fig. 3). For a fixed number of channels, the end-on layout has the advantage of providing a wider range of source-receiver offsets for a given geophone spacing when compared to the split-spread design. This additional offset information is often critical for accurate determination of moveout velocities of reflectors (see below) and, in most instances, permits a larger number of traces to be recorded without interference from groundroll energy (*e.g.*, Fig. 5A).

Figure 5A shows two raw field records, or shot gathers, collected with shotgun and hammer sources. A number of events can be identified on the field records including reflections, shallow refractions, surface waves and a ground-coupled airwave (air blast from source). Reflection events are identified by their hyperbolic curvature, which is a result of the increasing ray path length as the source-receiver separation is increased (*e.g.*, Figs. 3, 4). The degree of curvature of the hyperbola is also determined by average seismic velocity above a reflector as well as its depth and dip angle. The time difference between a reflection arrival time at a geophone remote from the source compared to a detector at the source is referred to as the normal moveout (NMO). The normal moveout of a reflector is used to estimate the average seismic velocity above the reflecting horizon, and must be removed prior to stacking of CDP data. Refractions, in contrast, are recognized as linear arrival events which are characteristically lower frequency than reflections and show a number of cycles (Fig. 5A). The first arrivals on the records in Figure 5 represent shallow refractions from the water table and base of the surface low-velocity layer (weathering layer).

The chief advantage of the CDP method over single-fold techniques (*e.g.*, optimum-offset method) is the significant increase in signal-to-noise ratio that potentially can be achieved through the stacking (summation) of redundantly sampled reflection points. Before

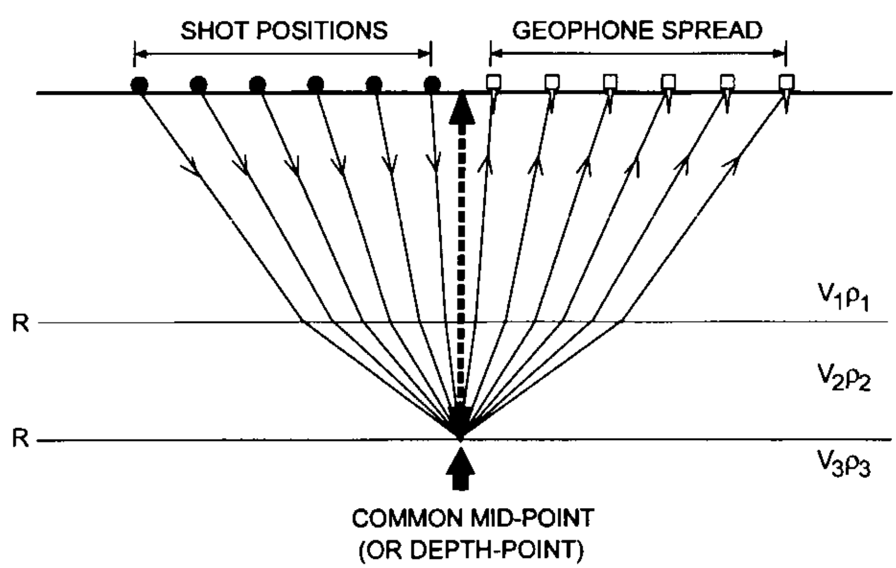

Figure 4 *The common-depth point (CDP) concept. Reflector is repeatedly sampled with source-receiver pairs centred over a common-depth point (or common mid-point) in the subsurface. The example shown is for the case of a 12-channel seismograph with shots fired at all geophone locations (e.g., Fig. 3) which results in a maximum 6-fold subsurface coverage. Bold dashed line shows the vertically incident ray path simulated by normal moveout (NMO) correction of CDP data during processing.*

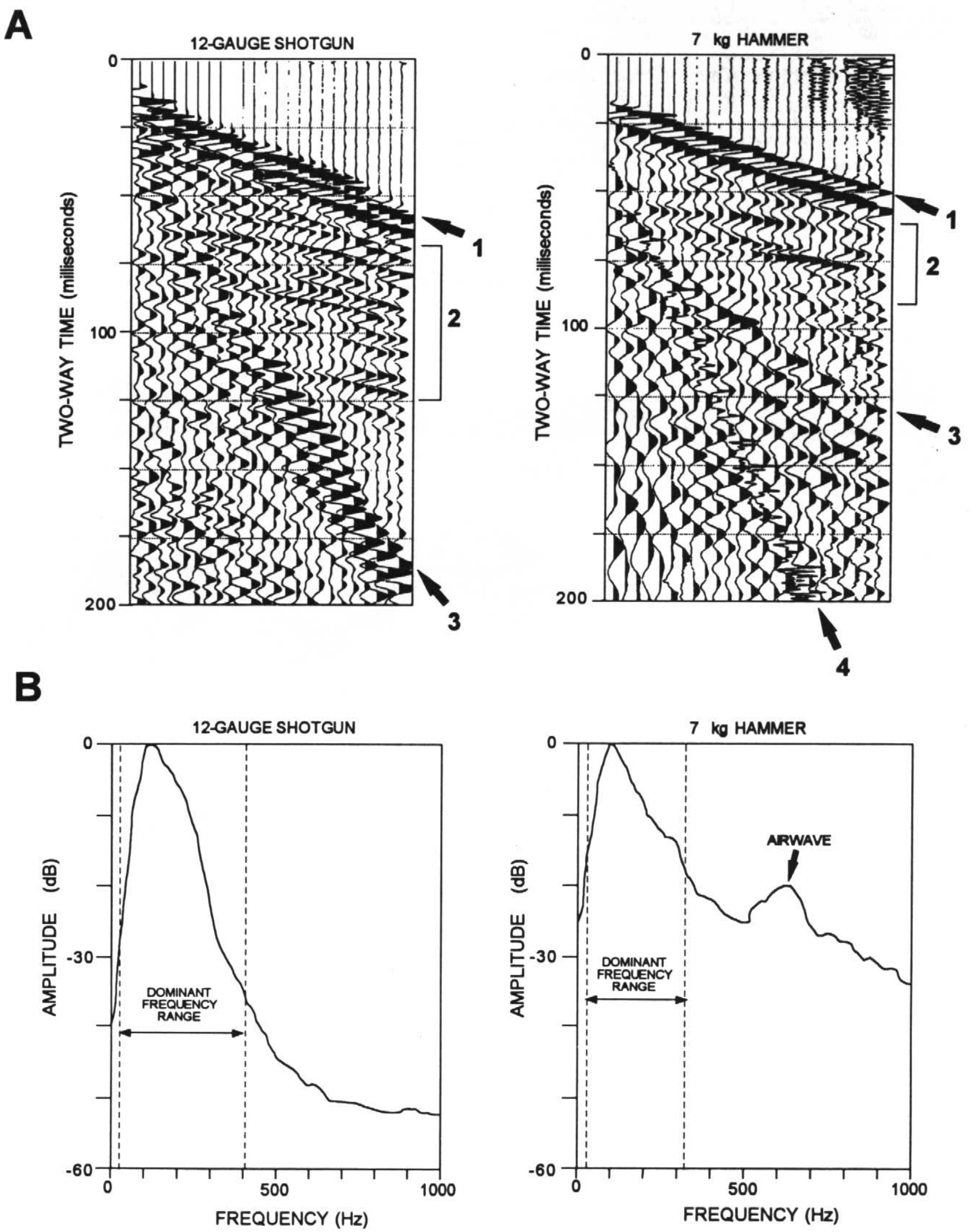

Figure 5 (**A**) *24-channel shot gathers acquired with shotgun (left; single shot) and hammer source (right; 5 stacks) with reflection (1), refraction (2) and groundroll (3) arrivals identified. Ground-coupled airwave (4) records sound energy of hammer impact carried through the air.* (**B**) *Frequency amplitude spectra for field records shown in A above.*

data can be stacked, a number of processing operations must be performed on CDP data which are summarized briefly here. More in-depth discussions of processing techniques are given by Yilmaz (1987) and others (*e.g.*, Robinson and Treitel, 1980; Sheriff and Geldart, 1982). The main objective of CDP processing is to enhance reflection events at the cost of all other signals and to produce a synthetic zero-offset seismic section in which each trace simulates a vertical-incident ray path between the source and the reflector (Fig. 4). The initial stages of processing carried out on raw shot records involve manual editing of traces, application of static corrections, and muting of refractions and noise events (*e.g.*, airwave) that do not contribute usefully to the reflection stack (Fig. 6A, B). Static corrections involve removal of time shifts which result from differences in the elevations of source and receivers (elevation correction) and the changes in thickness and velocity of near-surface low-velocity layers (weathering correction). Static corrections are calculated from elevation information and analysis of the first-arrival times of refractions from the shallow low-velocity layer (refraction statics). Various types of filtering are applied to remove unwanted frequency components of the seismic signal including surface waves, airwaves and random background noise (*e.g.*, Fig. 5A) which can damage reflection coherency.

The next stage of processing involves sorting of shot gathers into common-depth point gathers (Fig. 6C) and application of normal moveout (NMO) corrections. The latter involves applying time and offset-dependent time shifts to each trace in a CDP gather which corrects for the non-vertical incidence of the reflected ray paths (*e.g.*, Fig. 4). This effectively simulates placing all shot and receivers pairs at a zero-offset position directly above the reflection point, and results in flattening of the reflection curve (Fig. 6D). The required NMO corrections are determined from an analysis of the moveout, or stacking velocities, of individual reflectors on some typical CDP gathers. This is done by fitting curves to the reflection hyperbola or by using constant-velocity stacking and semblance analysis techniques (see Yilmaz, 1987). The velocity analysis is commonly augmented with velocity information obtained from vertical seismic profiles (VSP) collected in boreholes adjacent to the seismic line (see Schneider *et al.*, in press). Once the correct stacking velocities have been determined for selected CDPs, the NMO corrections are applied universally to all CDP gathers in preparation for stacking. Stacking involves summing of the moved-out traces in each CDP gather to produce a single com-

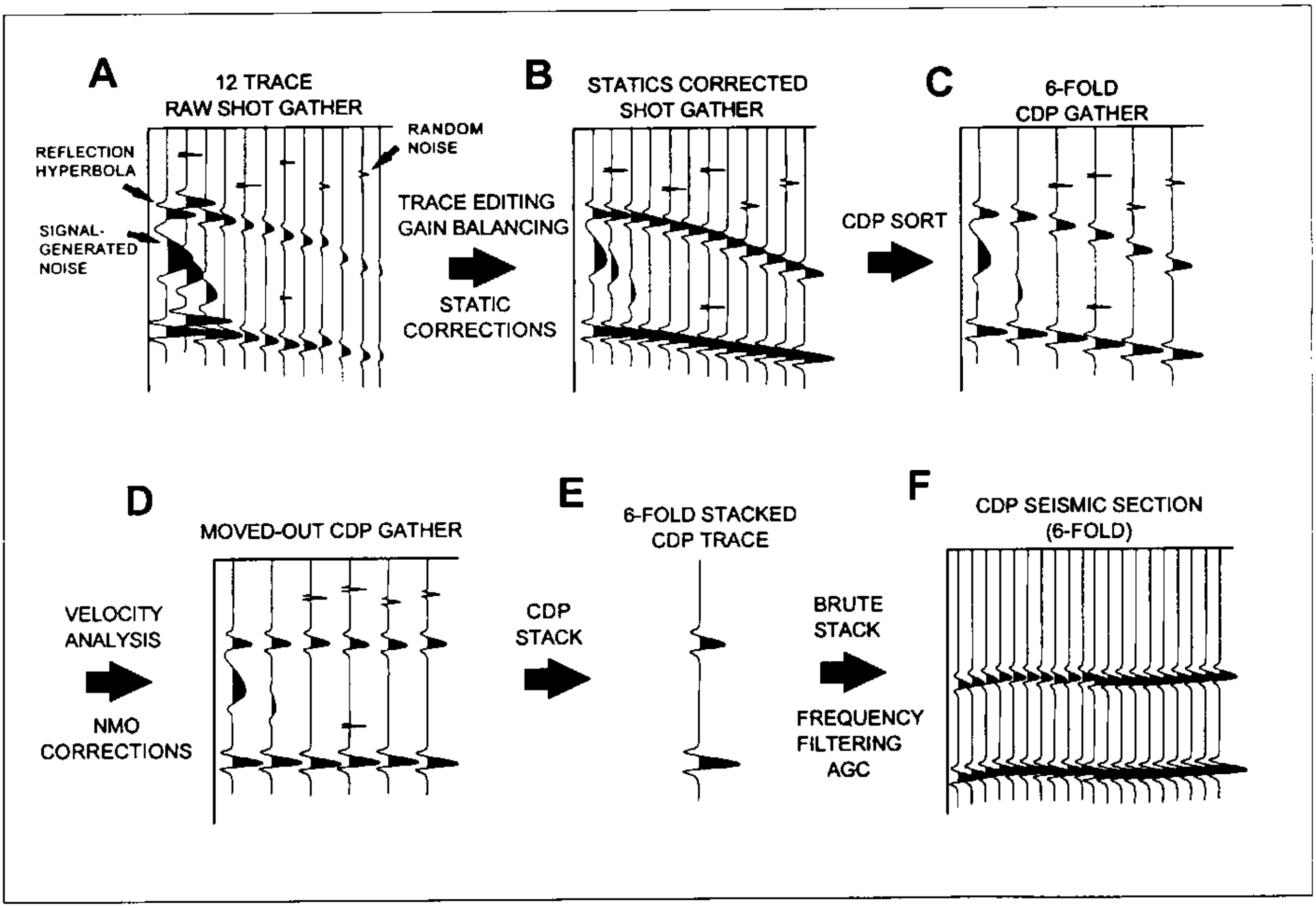

Figure 6 *Principal steps involved in the processing of CDP seismic reflection data: Raw shot gathers* (**A**) *are edited, corrected for elevation and weathering-layer statics* (**B**) *and are sorted into CDP gathers* (**C**) *containing all traces associated with a single reflection point. A velocity analysis is performed and dynamic corrections are made to remove the normal moveouts (NMO) of reflectors prior to stacking* (**D**). *Traces in each CDP gather are then stacked, resulting in re-inforcement of reflections and attenuation of other out-of-phase signals* (**E**). *Filtering and gain-balancing operations (automatic gain control; AGC) are applied to enhance the appearance of the final stacked section* (**F**).

posite trace (Fig. 6E). The combining of traces results in cancellation of out-of-phase noise energy and reinforcement of in-phase reflection events. From a theoretical standpoint, the improvement in signal-to-noise ratio achieved by stacking increases proportionally with the square root of the CDP fold. As final steps, various types of filtering and gain-balancing operations are performed to enhance the appearance of reflection events and to equalize the trace amplitudes on the final stacked section (Fig. 6F).

EXAMPLES

In this section, examples illustrating the application of CDP seismic reflection profiling are presented from work completed at three proposed landfills and other test sites (Fig. 1).

Whitevale Candidate Sites

The Whitevale P1, M6 and EE11 sites (Fig. 1B) were investigated as possible locations for a landfill to accept 6 million tonnes of municipal waste. Site investigations involved intensive programmes of drilling, core sampling, hydrochemical analysis, and hydrogeological field monitoring (M.M. Dillon Ltd., 1990; Fenco MacLaren Ltd., 1994). These studies demonstrated the presence of unsuspected hydraulic windows through a thick (up to 50 m), compact till unit below the site (Northern till; Fig. 7, 8) which had previously been considered to be a highly impermeable aquitard capable of restricting the movement of ground water and landfill leachates to underlying aquifers (Boyce *et al.*, 1995; Gerber and Howard, in press). Seismic reflection investigations were carried out in an attempt to better resolve the internal stratigraphy and nature of potential ground-water pathways in the till.

Seismic Data Acquisition and Processing

Seismic data were acquired using two 24-channel exploration seismographs and 50 Hz geophones. Profiles were collected end-on (*e.g.*, Fig. 3A) with 3-9 m source offsets and a geophone and shot spacing of 3 m. Continuous 12- or 24-fold coverage was obtained using a

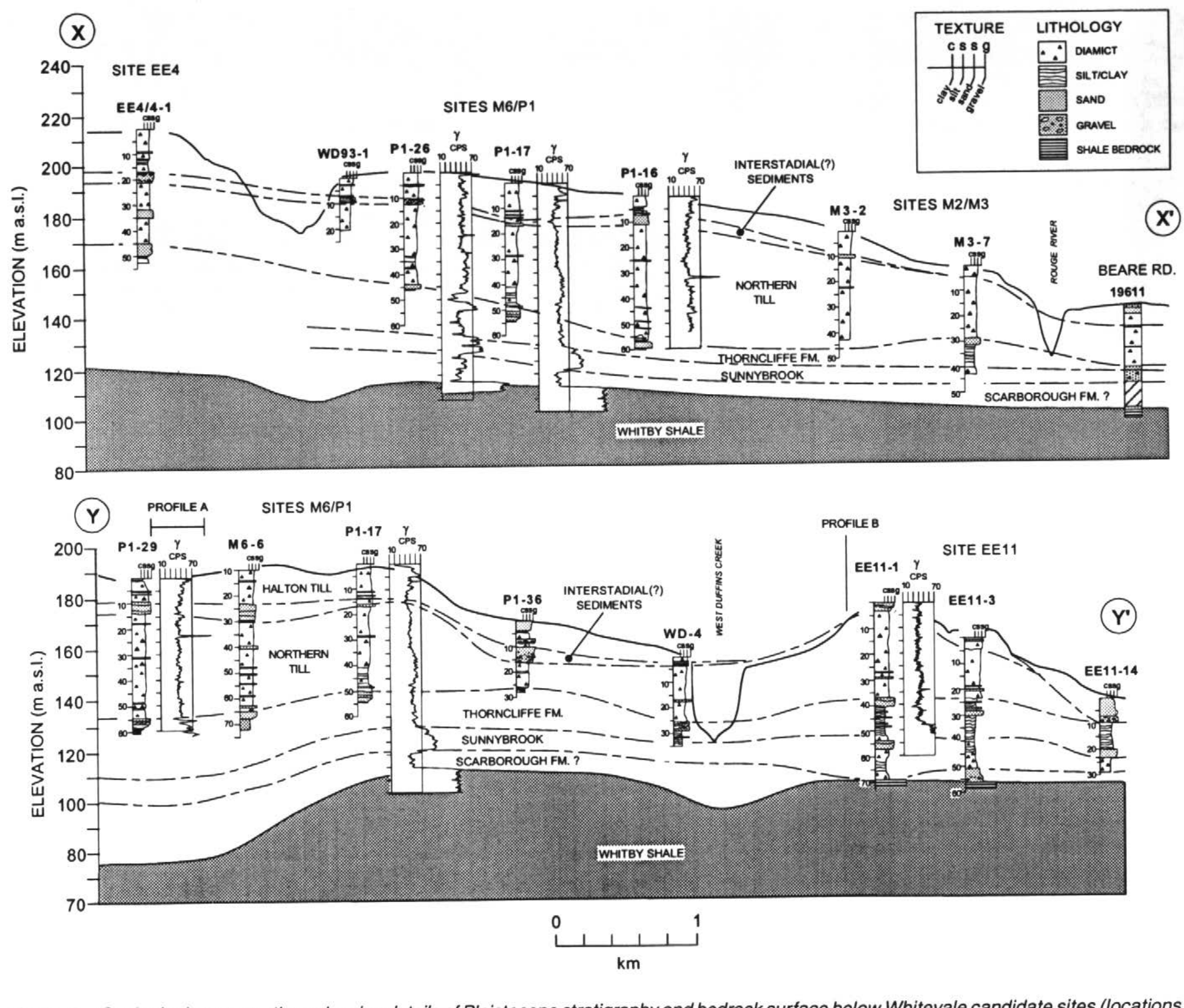

Figure 7 *Geological cross-sections showing details of Pleistocene stratigraphy and bedrock surface below Whitevale candidate sites (locations shown in Fig. 1B). Borehole lithologic and geophysical data (natural gamma; units in counts per second, CPS) also shown. Note presence of thin sands and gravels within Northern till aquitard. Vertical exaggeration is 18:1.*

roll-along switch or by repositioning of receiver spreads (see Koseoglu, 1995). During initial trials of the CDP method at sites P1 and M6, a 7-kg hammer and aluminum plate were used as the source, with five blows stacked per record. The hammer source was found to be highly repeatable, and provided good high-frequency response on the compacted road beds around the sites. The excellent seismic response is in part due to the presence of a shallow water table within 1 m or so of the surface. The hammer source was found to be generally unsuitable for surveying in other off-road areas, due to problems with high-amplitude surface waves and rapid attenuation of high frequencies by a loose surface-weathering layer. In these areas, a 12-gauge Buffalo gun (Pullan and MacAulay, 1987) was found to produce a significant improvement in high-frequency content of the data. The gun was detonated in 1 m deep, water-filled shot holes, with one shot registered for each 24-channel record. Although production rates are somewhat slower than with hammer, the downhole shotgun has been found to provide more consistent frequency response under varying substrate conditions, and is the preferred source for most applications (*e.g.*, Hunter *et al.*, 1987). Band-pass filtering was employed during data acquisition (A/D input filters 140-1000 Hz) to attenuate low-frequency signals and prevent saturation of the records by ground roll energy.

Seismic data were processed on Unix and PC platforms using Inverse Theory Applications (ITA) and (Seismic Image Software Ltd.) Vista software packages. The processing, in general terms, followed that described in previous sections. A detailed discussion of the processing methods and parameters employed is given by Koseoglu (1995).

Sites P1 and M6. A 300-m segment of a 1.2 km east-west profile collected at sites P1 and M6 is shown in Figure 9 along with an interpreted depth-converted section (lower panel). A number of laterally continuous reflection events are recognized on the seismic profile (A through F; Fig. 9) which can be correlated with sequence boundaries within Pleistocene sediments and the bedrock interface (Fig. 7). Figure 8 summarizes the lithologic characteristics and range of interval velocities for the seismostratigraphic units defined by these reflection events.

The first coherent event observed on the section is a gently undulating reflection (A; Fig. 9) occurring at a two-way time of 18-20 ms, which is correlated with the top of the Northern till, identified in boreholes P1-29 and M6-6, at depth of 14 and 20 mbgs (below ground surface), respectively. The unit above this reflector consists of a sandy surficial till and underlying sands and gravels (Halton Till complex; Fig. 7) which either lack marked acoustical contrasts or are too shallow to be resolved on seismic sections. The velocity for this uppermost interval is in the range of 1800-2000 $m \cdot s^{-1}$ (Fig. 8), and is consistent with the low level of consolidation and sandy character of the Halton Till complex. Interval velocities within the Northern till are considerably higher (≈2200-2800 $m \cdot s^{-1}$), as a result of the high degree of compaction (bulk density ≈ 2.3 $g \cdot cc^{-1}$, porosity ≈12-14%) and silt-rich texture of this unit. A number of semi-continuous, low-amplitude reflectors are also recognized within the Northern till (Fig. 9). These internal reflectors are correlated with thin (<1.5 m thick) sand and gravel beds. The presence of sand and gravel beds in the Northern till was observed in some core samples (*e.g.*, P1-29, M6-6; Fig. 7), but was more generally indicated during drilling operations by zones of increased drilling rates and poor core recovery (M.M. Dillon Ltd., 1990).

The base of the Northern till is marked by a high-amplitude reflection (B; Fig. 9) at a two-way time of 45-50 ms, which marks the contact with underlying unconsolidated sands and silts (Thorncliffe Formation). The interval velocities

BOUNDING REFLECTORS	SEISMOSTRATIGRAPHIC UNIT	LITHOLOGY	HYDROGEOLOGIC SIGNIFICANCE	INTERVAL VELOCITY (m/s)
-A	HALTON TILL COMPLEX	VARIABLY CONSOLIDATED SANDY TILL AND UNDERLYING INTERSTADIAL SANDS AND GRAVELS	LOCAL AQUIFER	~ 1500 - 2200
A-B	NORTHERN TILL	OVERCONSOLIDATED SANDY SILT TILL WITH THIN (< 1.5 m) SAND AND GRAVEL INTERBEDS AND SAND LENSES	REGIONAL AQUITARD LANDFILL SUBSTRATE	~ 2200 - 2800
B-C	THORNCLIFFE FM.	STRATIFIED LACUSTRINE SILT AND SAND AND LAMINATED SILTY CLAYS	REGIONAL AQUIFER	~ 1600 - 1900
C-D	SUNNYBROOK TILL	WELL-CONSOLIDATED PEBBLY CLAY INTERCALATED WITH LAMINATED SILTY CLAYS AND SANDY GRAVELS	REGIONAL AQUITARD	~ 2200 - 2400
D-E	SCARBOROUGH FM. AND OLDER SEDIMENTS(?)	LAMINATED LACUSTRINE SILTY CLAYS, SANDS AND UNDERLYING COMPACT SANDY DIAMICT UNITS (TILL)	DEEP REGIONAL AQUIFER	~ 2000 - 2800
E	WHITBY SHALE	BLACK SHALE WITH THIN SILTSTONE BEDS	FRACTURED BEDROCK AQUIFER	~ 3000 - 3200

Figure 8 *Seismostratigraphic units identified in the study region with a summary of their lithologic characteristics, hydrogeological significance and approximate range of interval velocities and bounding reflectors* (**A-E**) *depicted in subsequent figures.*

in the Thorncliffe Formation are low in comparison to the overlying till (Fig. 8), and result in a marked acoustic impedance contrast at this boundary. The lower part of the Thorncliffe Formation passes transitionally into a dense pebbly clay (Sunnybrook Till; Fig. 7) which is identified on geophysical logs by a zone of high gamma counts (>80 cps) occurring at depth of 65-80 mbgs. The upper and lower contacts of the pebbly clay are correlated with reflection events at two-way times of about 70 ms and 85 ms, respectively (C, D; Fig. 9).

Bedrock is identified by a high-amplitude reflector occurring between 100-105 ms (E; Fig. 9) which marks a shift to much higher velocities (>3000 $m \cdot s^{-1}$; Fig. 8). This reflector indicates a relatively flat to gently undulating bedrock surface at a depth of about 115 mbgs. A number of deeper internal bedrock reflections are also recorded, including a discontinuous event at 130 ms (F; Fig. 9). These likely result from the alternation of shales with thin siltstone beds known to be present in the Whitby Formation.

Site EE11. Figure 10 shows a 450-m segment of a seismic profile acquired at the southwest corner of the EE11 candidate landfill site (Fig. 1B). This shows a number of reflective horizons that can be directly correlated with seismostratigraphic units identified at sites P1 and M6 (*e.g.*, Fig. 9). The upper surface of the Northern till (Fig. 7) lies at a shallow depth (<12 m), and is not resolved on seismic profiles. The base of this unit is correlated with a gently undulating reflector occurring at two-way time of about 25 ms (B; Fig. 10), which records a shift to much lower velocities (1700-900 $m \cdot s^{-1}$) in the underlying Thorncliffe Formation. A single low-amplitude reflector recorded above this event at about 15 ms correlates with a thin sand and gravel bed identified in the Northern till at a depth of 14 mbgs in borehole EE11-2.

The Thorncliffe Formation at this site shows a number of low-amplitude internal reflection events which record the alternation of sand beds with silty clay units (*e.g.*, EE11-2; Fig. 10). The base of the Thorncliffe unit is marked by a clearly defined reflector at 50 ms, which correlates well with the contact with the Sunnybrook at a depth of 46-50 mbgs. This unit is of hydrogeological importance at site EE11 as an aquitard separating aquifers in the Thorncliffe Forma-

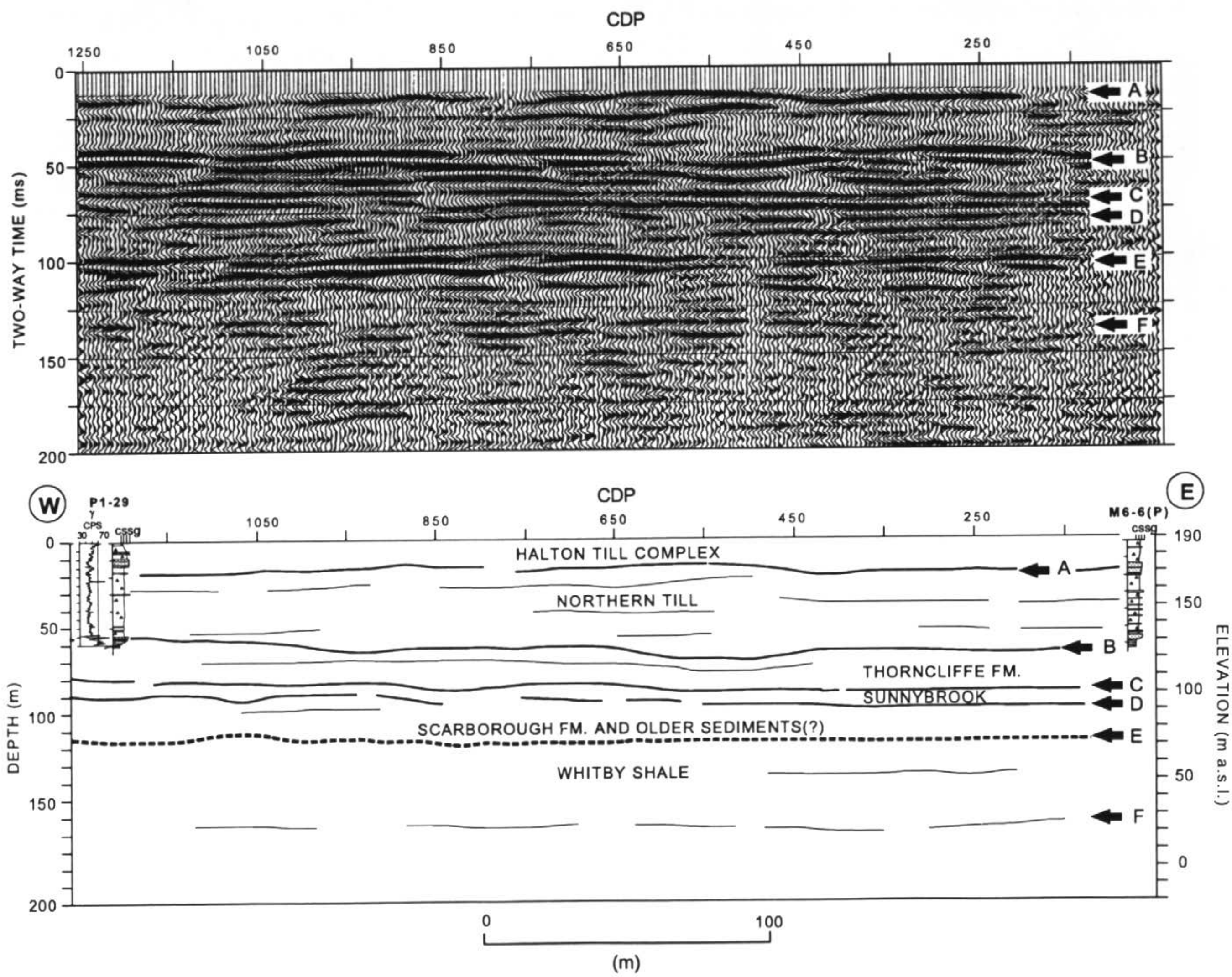

Figure 9 *24-fold seismic reflection profile (A, Fig. 1B) acquired across site M6 and adjacent to site P1. Interpreted section below shows correlations between boundary reflection (labelled A to F; Fig. 8) and lithologic and natural gamma logs from adjacent boreholes. Horizontal and vertical scales on interpreted panel are 1:1.*

tion from a deeper bedrock aquifer system (Fig. 8).

Malvern Radioactive-Soil Treatment Site, City of Scarborough

Work at this Passmore Avenue site (Fig. 1B) is designed to evaluate the feasibility of conducting seismic reflection surveys in urban and industrial areas where surface conditions (*e.g.*, fill, paved surfaces) and cultural noise from roadways, and overhead and underground services (*e.g.*, gas lines, anode-protected pipes, power lines) could potentially limit the use of seismic methods.

The site was investigated in 19931994 for emplacement of a temporary radioactive-soil treatment facility (Acres Ltd., 1994; Je, in press). The site was approved in early 1995, and is currently under use for radium-contaminated soil being removed from a nearby housing project. At this site, only shallow (<25 m) borehole information is available. Interpretation of the deeper seismic stratigraphy is based on comparison of interval velocities and reflection characteristics with seismic data at Whitevale (Figs. 9, 10) and with the regional stratigraphic framework (Fig. 7).

A 300-m segment of a test profile is shown in Figure 11. The data were acquired by shooting in 1-m deep shot holes in a water-filled roadside ditch which provided excellent coupling and penetration of high frequencies. Borehole data show that the near-surface stratigraphy consists of a thin (<5 m) surface till unit (Halton Till) overlying up to 19 m of sand and silt. The first coherent reflection event at 25-27 ms (A; Fig. 11) is characterized by very low stacking velocities (≈1530-1650 m·s⁻¹) which are consistent with the presence of a thick sand unit. The underlying interval, bounded by reflectors B and C (Fig. 11), shows a shift to much higher interval velocities (>2200 m·s⁻¹) which are consistent with the presence of the compact Northern till. A number of gently undulating internal reflection events are recognized in this interval, and are most likely associated with the presence of sorted sediment lenses in the till.

Below the Northern till, the low velocity and thickness (≈25 m) of the interval between reflectors B and C (Fig. 11) suggests a possible correlation with the Thorncliffe Formation. The underlying interval bounded by reflectors C and D shows a marked shift to higher interval velocities, and likely represents the Sunnybrook based on its stratigraphic position. The bedrock interface below the Passmore site is correlated with a relatively strong reflection event occurring at about 115 ms (at about 80 masl).

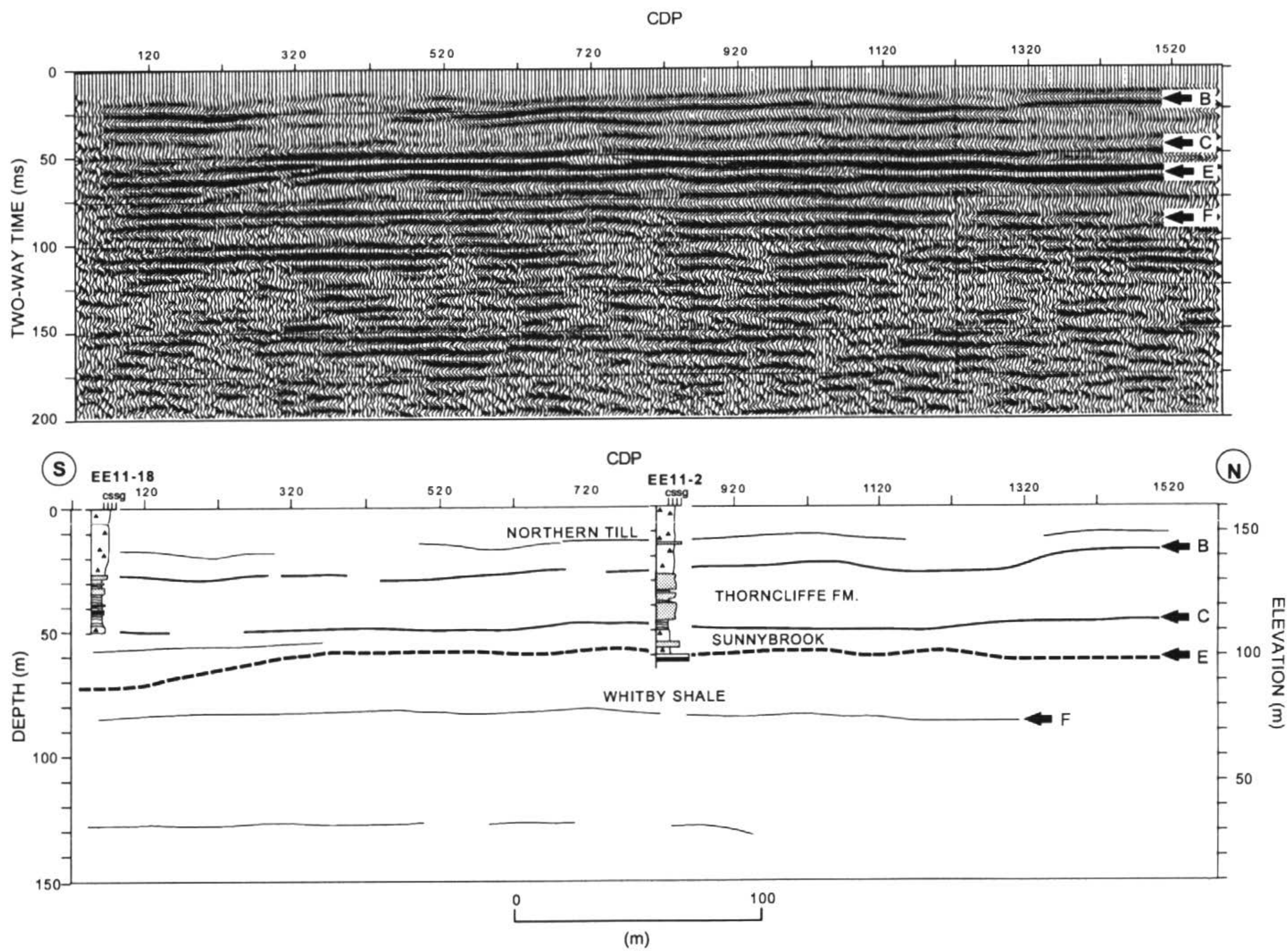

Figure 10 *12-fold seismic reflection profile (B, Fig. 1B) collected on site EE11 with interpreted section. Horizontal and vertical scales on interpreted panel are 1:1.*

Data quality was not degraded significantly by the cultural noise levels at the Passmore site. The use of a 60-Hz notch filter on the recording instrument was found to be effective in suppressing noise from overhead lines and an anode-protected gas pipe which runs along the length of Passmore avenue, about 3 m north of the seismic line. The use of a 140-Hz low-cut filter and careful timing of shots between the passing of vehicles was found to be effective in limiting traffic noise at this site.

DISCUSSION

In conventional drilling approaches, major stratigraphic boundaries and, in some cases, individual lithofacies can be correlated between drilling locations with an acceptable degree of confidence (*e.g.*, Fig. 7). Delineation of the geometry of bounding surfaces, however, can be problematic, particularly where bed contacts are non-planar or where rapid changes in the thickness of units occur as a result of erosion or non-deposition (*e.g.*, Fig. 7; EE11-14). Problems also frequently arise in correlating relatively thin, (<1 m) lensate beds within otherwise dense tills, and in locating their terminations, or pinch-outs, in the subsurface. When borehole data are integrated with the continuous two-dimensional subsurface coverage provided by seismic reflection profiling, resolution of the continuity and geometry of stratigraphic boundaries is significantly enhanced (Figs. 9, 10, 11).

The vertical resolution achieved at the Whitevale sites, based on the dominant reflection frequencies (150-400 Hz) and velocities within the Pleistocene interval (1500-2800; Fig. 8), is estimated at 1 m to 5 m using the quarter-wavelength criteria. In general, the larger value is associated with later reflection events on seismic sections (*e.g.*, bedrock, E; Fig. 9) due to the attenuation of high frequencies and overall increase in velocity with depth.

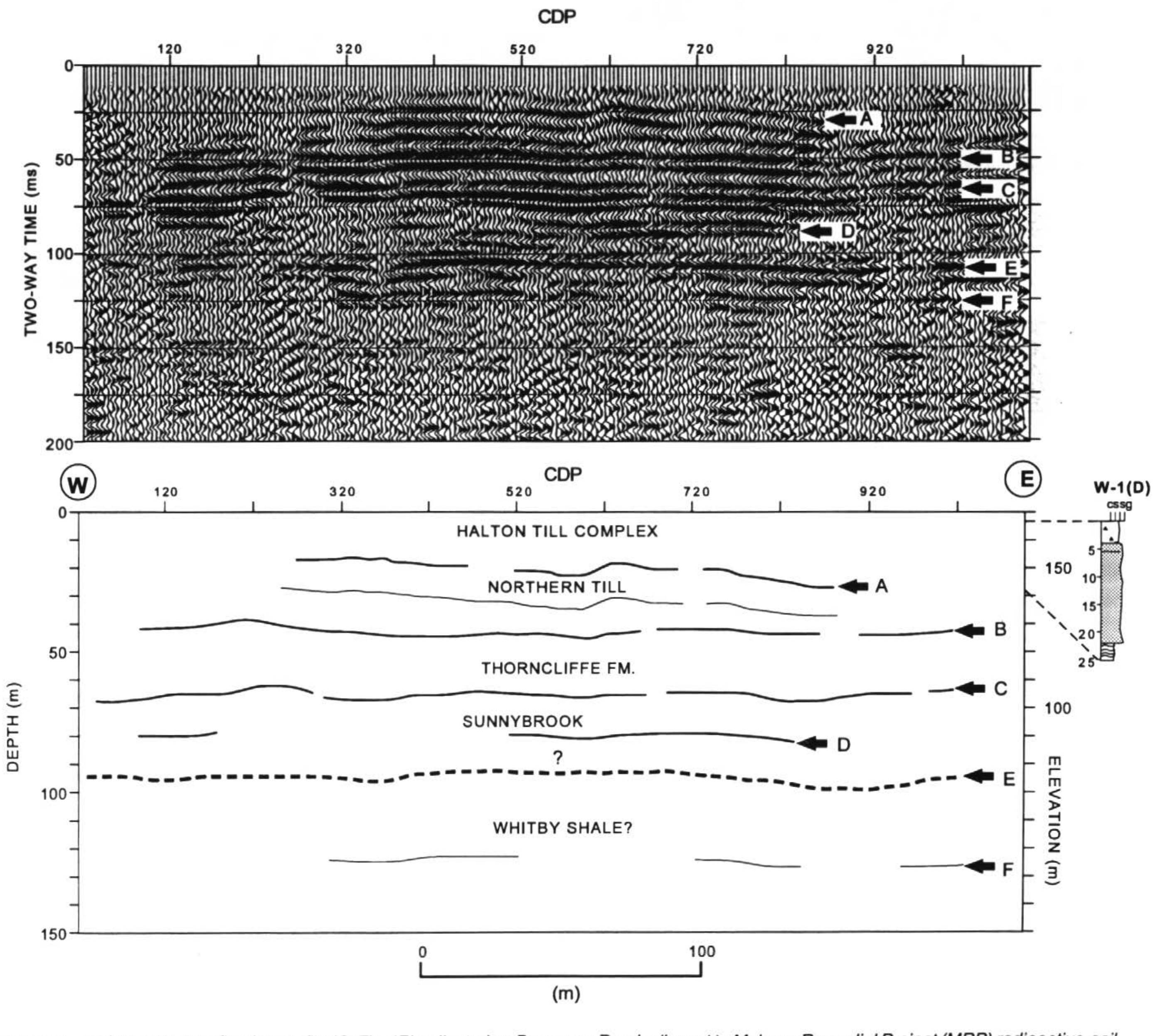

Figure 11 *12-fold seismic reflection profile (C, Fig. 1B) collected on Passmore Road adjacent to Malvern Remedial Project (MRP) radioactive-soil treatment site with provisional interpretation. Horizontal and vertical scales on interpreted panel 1:1.*

It should be noted that the field layout described was designed to resolve the Pleistocene sediments and bedrock surface at depths of up to 110 mbgs. This geometry, however, produced very wide angle reflections and loss of resolution in the near surface (≈15 mbgs). Resolution of the uppermost interval would require use of much smaller geophone spacings (*e.g.*, <1 m) and source-receiver offsets. The resulting reduction in the spread length would considerably increase the time and cost of field acquisition, due to the larger number of shot points, but is technically feasible where information from the very near subsurface is critical. From a practical standpoint, the shallow limit of the seismic method is probably about 5 m for most applications, although reflections from as shallow as 2 m have been obtained (*e.g.*, Birkelo *et al.*, 1987).

Seismic profiles from P1 and M6 demonstrate clearly defined planar to gently undulating reflection events within the Northern till, which can be traced continuously over distances of up to 110 m (Fig. 9). This geometry is consistent with the characteristics of laterally extensive sand and gravel beds, up to 1 m in thickness, identified in the Northern till in outcrop and in core (Fig. 7), which can be correlated with internal reflectors in the till (Boyce *et al.*, 1995). The continuity of these horizons, as suggested by outcrop and seismic data together with their coarse-grained texture and thickness, suggests their importance as ground-water pathways in the Northern till.

In addition to being able to identify small-scale stratigraphic variability, the use of shallow seismic reflection surveys has the potential to reduce the costs of applied investigations by reducing the total number of boreholes required to characterize a site. Landfill investigations at sites P1 and EE11 in the Whitevale area were conducted at a total cost of more than $2 million; drilling costs alone amounted to some 15% of the total expenditure for field studies. During investigations at site EE11, seismic studies were implemented during the last stages of field investigations to confirm the results of drilling operations. A better approach, based on this experience, would be to integrate seismic studies at a much earlier stage and would involve drilling of number of strategically placed test boreholes tied by shallow seismic reflection lines. In this way, the placement of subsequent drill holes could be more effectively selected to target the specific data requirements of the study.

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