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Application of seismic stratigraphy and sedimentology to regional hydrogeological investigations: an example from Oak Ridges Moraine, southern Ontario, Canada[1]

D.R. Sharpe, A. Pugin, S.E. Pullan, and G. Gorrell

Abstract: Hydrogeological models need to be supported by a clear understanding of the subsurface geology to provide effective assessment, flow modelling, or management of groundwater regimes. This paper illustrates how geophysical and sedimentological data can be used to significantly improve watershed-scale hydrostratigraphic models by advancing our understanding of the subsurface through regional hydrogeological investigations in the Greater Toronto Area. The example of a 3 km shallow seismic reflection survey that traverses a buried channel within Bowmanville Creek watershed, Oak Ridges Moraine, Ontario, illustrates a basis for linking geophysical and sedimentological properties to regional hydrostratigraphic parameters. Seismic reflection methods plus seismic stratigraphy and a well-constrained three-dimensional geological framework have helped to (*i*) identify regional hydrostratigraphic units, (*ii*) define properties and trends of these units–facies, (*iii*) improve depositional models that assist hydrogeological analysis, and (*iv*) establish a hydrostratigraphic framework within a watershed. The extent, proportions, boundaries, and variation in internal properties of major hydrostratigraphic units could be identified to greater than 100 m depth. Geostatistical analysis of seismic amplitudes was used to provide a quantitative measure of heterogeneity in a glaciofluvial aquifer with inadequate parameter support. Benefits to engineering practice include improved siting of monitors and tests from portrayal of the spatial organization, geometry, and variability of hydrostratigraphic units based on sedimentary architecture and environments of deposition. Hydrogeological modelling can be improved with better knowledge of the geometry of aquifers and aquitards and grid-cell boundaries that correspond with the defined sediment boundaries that control properties.

Key words: Oak Ridges Moraine, hydrogeology, seismic stratigraphy, southern Ontario, sedimentology.

Résumé : Les modèles hydrogéologiques doivent s'appuyer sur une connaissance approfondie de la géologie souterraine pour fournir de façon efficace l'évaluation, la modélisation de l'écoulement, ou la gestion des régimes des eaux souterraines. Cet article illustre comment les données géophysiques et sédimentologiques peuvent être utilisées pour améliorer de façon significative les modèles hydrographiques à l'échelle des bassins versants en améliorant notre compréhension des conditions souterraines par des études hydrogéologiques régionales dans le Greater Toronto Area. L'exemple d'un relevé séismique de 3 km par réflexion à faible profondeur qui traverse un chenal enfoui à l'intérieur du bassin versant de Bowmanville Creek, Oak Ridges Moraine, Ontario, illustre un principe pour relier les propriétés géophysiques et sédimentologiques aux paramètres hydrographiques régionaux. Les méthodes de réflexion séismique en plus de la stratigraphie séismique et d'un cadre géologique 3D bien cerné ont aidé à: (*i*) identifier les unités hydrostratigraphiques régionales, (*ii*) définir les propriétés et les tendances de ces unités/faciès, (*iii*) améliorer les modèles de déposition qui aident l'analyse hydrogéologique, et (*iv*) établir un cadre hydrostratigraphique à l'intérieur du bassin versant. L'étendue, les proportions, les frontières et la variation dans les propriétés internes des unités hydrostratigraphiques majeures ont pu être identifiées jusqu'à des profondeurs de plus de 100 m. L'analyse géostatistique des amplitudes séismiques a été utilisée pour fournir une mesure quantitative de l'hétérogénéité dans un aquifère glaciofluvial avec une base inadéquate de paramètres. Le bénéfices apportés à la pratique de l'ingéniérie comprend un positionnement amélioré des mesures et des essais sur le site à partir de la représentation de l'organisation spatiale, de la géométrie et de la variabilité des unités hydrostratigraphiques sur la base de l'architecture sédimentaire et des

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environnements de déposition. La modélisation hydrogéologique peut être améliorée avec une meilleure connaissance de la géométrie des aquifères et aquitards, et des frontières des cellules de maillage qui correspondent avec les frontières des sédiments qui contrôlent les propriétés.

Mots clés : Oak Bridge Moraine, hydrogéologie, stratigraphie séismique, Ontario du sud, sédimentologie.

[Traduit par la Rédaction]

Introduction

The need to improve our understanding of the relationship between sedimentary and hydrogeological properties is being increasingly recognized (e.g., Huggenberger and Aigner 1999). The continuity and facies distribution of sedimentary deposits control the geometry and character of aquifers and aquitards. Specifically, these sedimentary attributes have considerable influence over hydraulic boundaries and hydraulic properties (Davis et al. 1997). For example, sediment texture greatly affects permeability and porosity, and when described within a depositional model that defines sedimentary arrangement and lithofacies, these sedimentary attributes can improve prediction of variation in hydraulic properties (Fogg et al. 1998). Depositional models derived from vertical profiles (e.g., borehole data) alone, however, may be inadequate because they may not allow one to interpret the stratigraphic framework, horizontal continuity, scale, or architecture of the depositional environment (Miall 1988).

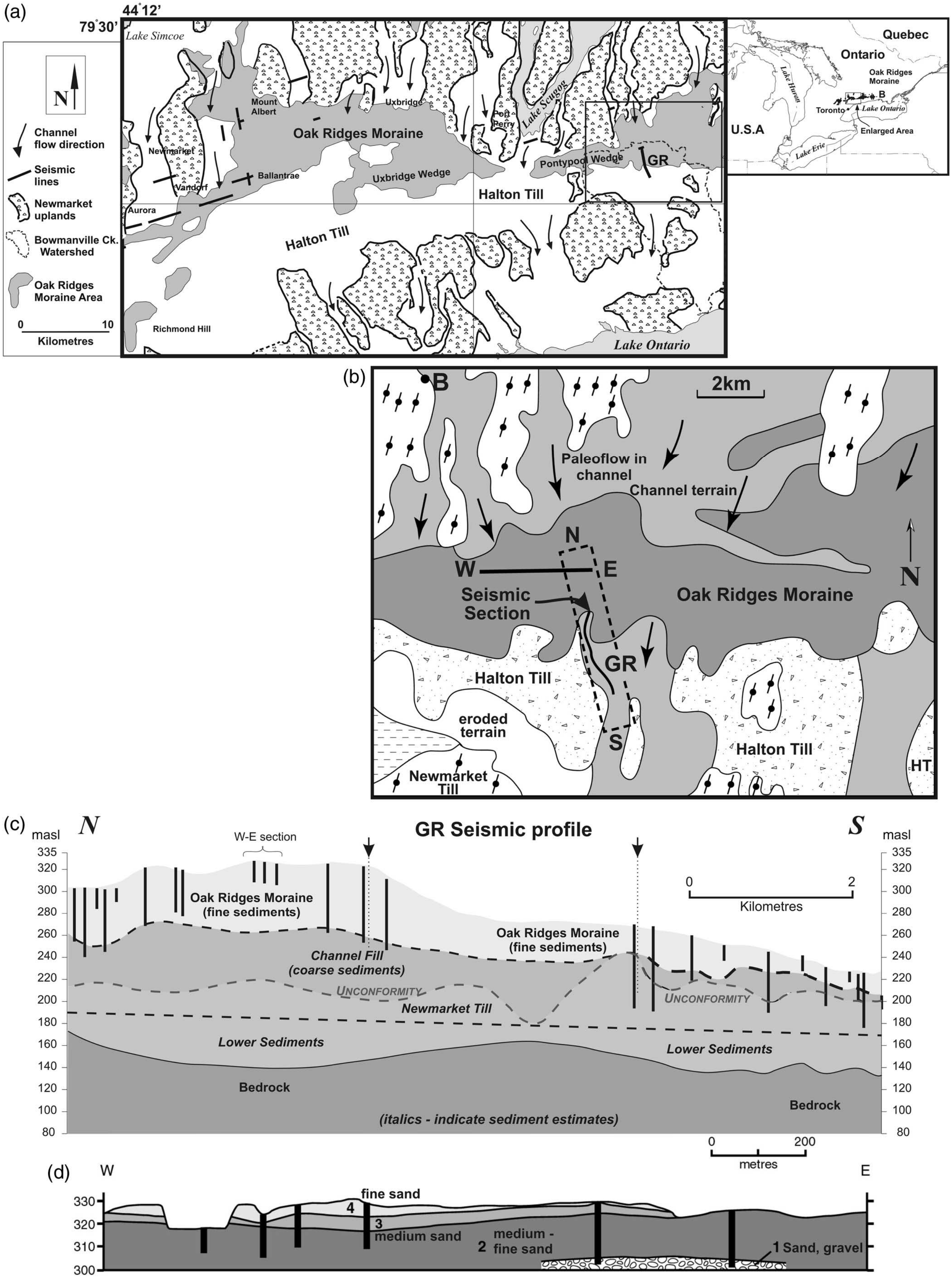
Spatial heterogeneity is a particular characteristic of glacial sediments that makes hydrogeologic analysis challenging. Geological–hydrogeological understanding can be improved by making use of recent advances in the sedimentology of glaciofluvial sediments (e.g., high-energy flood events; Maizels 1997). Lithological facies models have been used to describe heterogeneity and large-scale spatial trends in glacial and glaciofluvial aquifer systems (Anderson 1989). Lithofacies models may also allow an improved geostatistical representation of heterogeneity in glaciofluvial aquifers (Ritzi et al. 1995), but too little of the subsurface is sampled in sufficient detail to fully define hydraulic properties (Dominic et al. 1998). It is clear that the spatial architecture of a heterogeneous porous medium is one of the most difficult characteristics to describe (Fogg 1986).

The form, nature, and extent of sediments within buried valleys are generally not well understood, thus major aquifer systems, such as the Mahomet Aquifer buried valley (e.g., Pugin et al. 2003), often lack a sound sedimentologic basis for their continued development. Poorly defined, buried glacial channel systems may require additional subsurface information to help determine the heterogeneity of hydraulic properties and their control on groundwater flow. The link between geophysics and sedimentology provides a potential basis for the prediction of scale, structure, arrangement, and textural trends in sediments, and their associated hydrogeologic properties.

Geophysical surveys can sample an entire aquifer remotely, which affords the opportunity to assess its dimensions and internal variability and provide a coherent plan for future drilling (e.g., Rubin et al. 1992). Seismic reflection profiles are particularly effective at improving definition of lateral spatial variability or uncertainty that results from inadequate borehole spacing. Since the interpretation of seismic signals capitalizes on the contrasts between strata, reflection images tend to provide good structural and architectural information to aid hydrostratigraphic analysis. Seismic signals may not provide resolution of sediment properties, but seismic facies analysis can improve the definition of these sediment properties (Syvitski et al. 1997), especially with good ground control (Pugin et al. 1999). Nevertheless, the relationship between hydrogeologic or geologic attributes (hydraulic conductivity *K* or sediment facies) and surface geophysics is as yet incompletely understood (Fogg et al. 1998).

The ultimate usefulness of any hydrogeologic investigation, be it resource assessment, contaminant transport, watershed modelling, or groundwater management, depends on the accuracy and validity of the investigator's understanding of the subsurface, for example, within a sedimentary basin (Sharpe et al. 2002*a*). Our goal is to use geophysical and sedimentological data to significantly improve our understanding of the subsurface to support regional hydrogeological investigations. We hope to demonstrate that hydrogeologic studies can benefit from efforts to integrate stratigraphic, structural, and textural data provided by geophysics and sediment facies mapping, an approach commonly used in hydrocarbon reservoir exploration. The example used is a buried channel aquifer in the complex glacial sediments of the Oak Ridges Moraine (ORM) aquifer system, southern Ontario (Fig. 1). Shallow seismic reflection surveys provide critical data on the extent, type, and geometry of coarse beds. Combining this information with an improved glaciofluvial sediment model (e.g., Shaw and Gorrell 1991) provides support for hydrogeological inferences regarding aquifer thickness, variation, and continuity. The paper also documents experiments with geostatistical analysis

Fig. 1. (*a*) Location of the ORM and geological setting. Other Geological Survey of Canada seismic profiles (Pugin et al. 1999) are shown as black bars. Channels are highlighted as arrows. Box indicates the location of Fig. 1*b*. Inset maps shows the ORM relative to the eastern Great Lakes. B, Brighton; GR, Grasshopper Park Road seismic profile. (*b*) Geological map of the Grasshopper Park Road study area showing north–south (N–S) seismic profile (GR) within a buried channel system that extends under the ORM; HT, Halton Till. (*c*) Section N–S shows the depth of water wells and the limited penetration of the ~150 m thick sediment sequence. The position of the Grasshopper Park Road seismic profile is shown (vertical arrows) and very little water well control is available. (*d*) Line W–E shows locations of shallow borehole profile. 1, coarse sand and gravel (20%); 2, medium fine sand; 3, medium sand with thin pebble layers; 4, medium fine sand with occasional interbeds.


(a)
44°12'
79°30'
N
Channel flow direction
Seismic lines
Newmarket uplands
Bowmanville Ck. Watershed
Oak Ridges Moraine Area
0
10
Kilometres
Lake Simcoe
Mount Albert
Uxbridge
Port Perry
Lake Scugog
Newmarket
Oak Ridges Moraine
Ballantrae
Vandorf
Aurora
Uxbridge Wedge
Pontypool Wedge
GR
Halton Till
Halton Till
Richmond Hill
Lake Ontario
Quebec
Ontario
Oak Ridges Moraine
B
Lake Huron
U.S.A
Toronto
Lake Ontario
Enlarged Area
Lake Erie
(b)
B
2km
Paleoflow in channel
Channel terrain
N
W
E
Seismic Section
Oak Ridges Moraine
N
GR
Halton Till
eroded terrain
S
Halton Till
Newmarket Till
HT
(c)
N
GR Seismic profile
S
masl
W-E section
335
320
300
280
260
240
220
200
180
160
140
120
100
80
Oak Ridges Moraine (fine sediments)
Channel Fill (coarse sediments)
UNCONFORMITY
Newmarket Till
Oak Ridges Moraine (fine sediments)
UNCONFORMITY
0
2
Kilometres
Lower Sediments
Lower Sediments
Bedrock
Bedrock
(italics - indicate sediment estimates)
0
200
metres
(d)
W
E
330
320
310
300
fine sand
4
3
medium sand
2
medium - fine sand
1
Sand, gravel

of seismic amplitudes to provide a quantitative measure of heterogeneity within the buried glaciofluvial aquifer facies.

Regional hydrogeologic and geological setting

Hydrogeologic setting

The ORM is a ridge of sandy sediment found in the cool temperate terrain near the eastern Great Lakes of Ontario, Huron, and Erie (Fig. 1). It's hydrostratigraphic setting consists of a broad, elevated (300–400 m above sea level (asl)), central sandy recharge area that contributes flow to flanking springs and rivers (Turner 1977; Dyke et al. 1996), ultimately discharging into Lake Ontario (75 m asl) to the south and Lake Simcoe (220 m asl) to the north (Fig. 1) (Haefeli 1970). In terms of potable water, shallow ORM aquifers provide most domestic drinking water, and generally deeper, high-yield wells produce municipal supply (Sibul et al. 1977).

The ORM area provides up to 60% of the baseflow discharge to most of the 30 regional streams (Gerber and Howard 1998, 2002). Groundwater discharge varies spatially (Hinton 1996) and is, in part, focused by the underlying configuration of regional aquitards (Gerber and Howard 1996) and buried channels (Fig. 2) (Sharpe et al. 1996). Groundwater flow systems have been identified in portions of the ORM aquifer system (Turner 1977; Sibul et al. 1977; Howard and Beck 1986; Gerber and Howard 1998).

Field area

The study area is situated within a valley of Bowmanville Creek on the south flank of an ORM sediment wedge (Figs. 1*a*, 1*b*) and is supported by detailed geological mapping (Barnett and Dodge 1996). This valley coincides with an inferred buried channel system that extends beneath the moraine from a surface channel to the north (Barnett and Dodge 1996). The Grasshopper Park Road profile is 3 km long (Fig. 1*b*) and provides a longitudinal section along the north–south buried channel (Fig. 1*a*). Geological mapping, shallow boreholes, and water wells provide modest verification for the upper part of the seismic profile (Fig. 1*c*). A recent continuously cored borehole and downhole geophysics provide deep ground control (G. SooChan and J. Hunter, personal communication, 2003).

Geological–hydrostratigraphic model

As a guide for hydrogeological studies, a regional geologic model was developed for the ORM region (Fig. 2) (Sharpe et al. 1996). The model consists of five major stratigraphic units: bedrock (A), lower sediment (B), Newmarket Till (C), channel sediments (D1), ORM glaciofluvial and glaciolacustrine fan and delta sediments (D2), and Halton Till and glaciolacustrine sediment (E). These major stratigraphic units occur regionally and are well-defined as seismic facies on seismic reflection profiles (Pugin et al. 1999). Internal lithofacies have been identified from outcrop and cores (Russell et al. 1998*a*; Barnett et al. 1998) and they are used to interpret seismic facies and seismic facies geometry (Pugin et al. 1999). Regional hydrogeological parameters are summarized for each of the major hydrostratigraphic units (Table 1), along with their dimensions and elevation ranges.

Bedrock (A)

Flat-lying Paleozoic bedrock with inset valleys (Brennand et al. 1998) underlies the region, beneath up to 200 m of glacial and recent sediment (Russell et al. 1998*b*). Across the region, 10% of the wells are in bedrock and have low yields (~5 L/min), typically from the top 5 m of weathered shale bedrock (Singer 1974).

Lower sediment (B)

These deposits are widespread and well exposed along Lake Ontario bluffs, ~10 km to the south (Karrow 1967; Brookfield et al. 1982) (Fig. 1). Uppermost are sandy (Thorncliffe) aquifer and silty aquitard sediments (e.g., Eyles et al. 1985). Lower sediment aquifers may be ~10 m thick, and they can be connected to surface aquifers where buried channels (Barnett et al. 1998) eroded confining Newmarket Till (Fig. 2). About 10% of wells draw water from lower sediment, with yields of up to 10 L/min for private wells and >100 L/min for municipal wells (Singer 1974).

Newmarket Till (C)

Newmarket Till is a dense, 10–40 m thick, stony sandy silt diamicton (Fig. 2) (Sharpe et al. 1997; Boyce et al. 1995) that forms a regional marker bed and aquitard (Sharpe et al. 2002*b*). This unit may recharge lower sediment ~30–40 mm/year, apparently related to small-scale structural heterogeneity (fractures; Gerber and Howard 1996). Regional heterogeneity and leakance (leakance = (hydraulic conductivity)/(thickness of the unit)) of the Newmarket Till are controlled by a network of channels eroded into the till (Desbarats et al. 2001; Sharpe et al. 2002*a*) (Fig. 2).

Unconformity

An irregular, continuous surface identified by geological mapping and seismic profiling truncates lower strata and is interpreted as a regional erosion surface or unconformity (Barnett et al. 1998; Pugin et al. 1999) (Figs. 2, 3) consisting of channels and drumlins (Fig. 1).

Channel sediment (D1)

Surface and buried channels are common in the ORM area (Fig. 1*a*) and form an extensive approximately north–south, regional network with valleys 1–5 km across, tens of kilometres long, and 50–100 m deep (Barnett et al. 1998). They are filled with gravel, sand, and silt as identified from continuous drill-core data (Russell et al. 2003) and seismic facies (Pugin et al. 1996, 1999). Detailed sedimentary facies observed in surface outcrop (e.g., Shaw and Gorrell 1991) indicate subglacial formation by meltwater floods in which the (tunnel) channel bases are expected to contain coarse-grained sediments (Brennand and Shaw 1994). The origin, nature, and geometry of channel deposits, however, and their hydrogeological heterogeneity at depth are difficult to decipher without geophysical surveys and continuous drill core (Fig. 1*c*).

ORM sediments (D2)

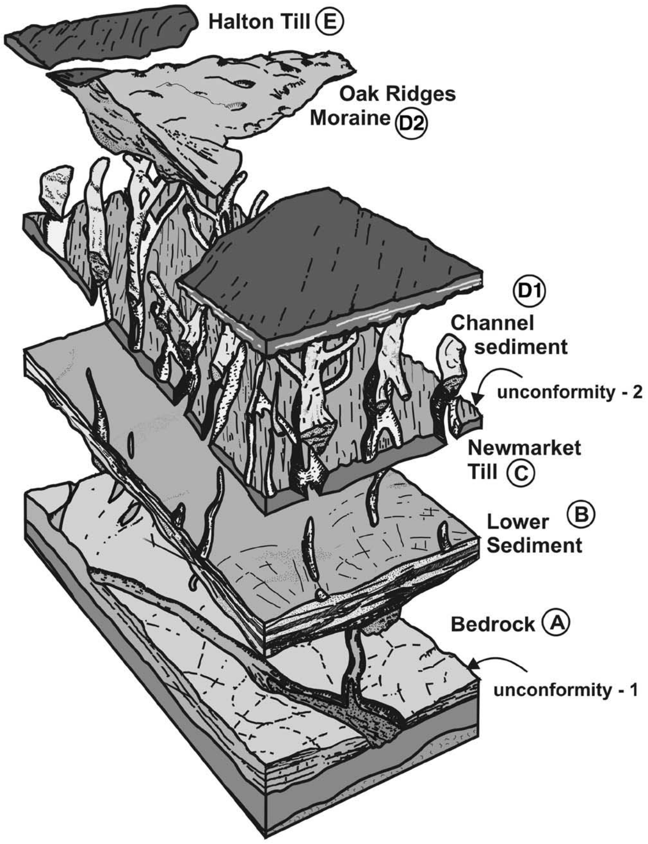
The upper ORM aquifer consists of stratified sand, silt, gravel, and minor clay and diamicton, in places reaching 150 m in thickness (Logan et al. 2001). About 75% of domestic wells in the region draw water from the ORM aquifer

Table 1. Generalized hydrostratigraphy of the study area based on studies of the Oak Ridges Moraine area (Turner 1977; Fenco MacLaren Inc. 1994; Howard et al. 1995; Gerber and Howard 2000; Sharpe et al. 1998).

Hydrostratigraphic unit	Elevation range (m asl)	Character–setting	Aquifer properties[a]
Halton Till	280–320	Drapes the ORM and restricts recharge; highly variable lithology; may contain sandy interbeds; may locally act as a confining layer or as an aquifer	Hydraulic conductivity K ranges from 2×10^{-9} to 3×10^{-5} m/s; as an aquitard may transmit water vertically 50 to >200 mm/year
Oak Ridges Moraine (aquifer)	250–280	Shallow unconfined “water table” aquifer; water encountered at ~15–40 m depth; saturated zone is ~30 m thick	Hydraulic conductivity K ranges from 3×10^{-6} to 7×10^{-3} m/s; specific yield Sy = 0.06–0.25; effective porosity P = 20–30%
Newmarket Till (Aquitard)	210–250	Thick aquitard; may contain gaps; gaps may transmit significant quantities of water vertically	Hydraulic conductivity K ranges from 10^{-11} to 10^{-9} m/s; fractures may transmit water vertically 30–40 mm/year
Lower sediment (Thorncliffe Formation; aquifer)	170–210	Favoured for municipal wells; confined aquifer; very large potential	Hydraulic conductivity K ranges from 2×10^{-3} to 1×10^{-7} m/s; storativity S = 0.005–0.00001
Lower sediment (Sunnybrook Formation; aquitard)		May be confirmed by recent drilling	
Lower sediment? (aquifer)		Present in deeper parts of bedrock channels (i.e., <140 m asl); not confirmed in study area	

[a] Estimated K is vertical hydraulic conductivity.

Fig. 2. Conceptual 3D stratigraphic model for the ORM region. Letters relate to major hydrostratigraphic units: A, B, and D denote aquifers, and B, C, and E denote aquitards. Note unconformity boundaries on top of bedrock (1) and on top of dissected Newmarket Till (2).



complex, one of the highest producing aquifers in Canada (Turner 1977). The ORM aquifer system contributes significantly to discharge, but no detailed link has been made between its sedimentary architecture and hydrogeological function (Russell and Sharpe 2002).

Halton Till (E)

Halton Till and interbedded lake sediments onlap the southern flanks of the ORM and form local aquifers and discontinuous aquitards.

Study approach

We examine details of a 3 km shallow seismic reflection profile from Bowmanville Creek (Fig. 3), obtained to provide a longitudinal section of a north–south channel buried beneath the ORM (Fig. 1). This shows how seismic and sediment facies help to define flow-parallel sedimentary structure. The clarity and resolution of the seismic data also provide insights into the processes that may have formed the sediments. This knowledge of sediment heterogeneity assists in hydrogeological characterization. An archival borehole database (Russell et al. 1996), outcrop descriptions (Russell et al. 1998*a*), ground-penetrating radar (GPR) profiles, regional mapping (Sharpe et al. 1997), and a three-dimensional (3D) structural model (Logan 2002) are available to help interpret the seismic profile within a well-defined stratigraphic and sedimentological context. This geological context is necessary because few data extend to depths greater than 50 m (Fig. 1*c*). Most water wells are low quality and intersect shallow, discontinuous aquifers. Regionally, high-quality data (~20 000 geological field sites; 50 line-kilometres of seismic reflection data, 10 continuously cored boreholes)

Fig. 3. Grasshopper Park Road seismic sections: (*a*) processed section in variable amplitude (grey scale is relative); and (*b*) interpreted section and seismic unit designations (see Fig. 2). Rectangles show locations of Figs. 4 and 5. Unconformity U1 is at sediment–bedrock boundary, and unconformity U2 is within sediments mainly on Newmarket Till.

were integrated to improve recognition of important seismic and sediment facies (Barnett et al. 1998; Pugin et al. 1999).

Geophysical and geological data may not directly provide a measure of hydrogeologic properties, but they do provide the basis for assessing the scale, extent, and internal variability of hydrostratigraphic units and thus aid in the estimation of more accurate and realistic hydrostratigraphic models. We have in part used geostatistical methods to quantify seismic amplitude data, however.

Methods

The seismic reflection survey in the area was conducted using a 24-channel engineering seismograph, 5 m shot and receiver spacing, and a nominal common midpoint (CMP) stack fold of 12 (Pullan et al. 1994; Pugin et al. 1999). The seismic data described in this paper have an ~2–5 m vertical and ~5–10 m horizontal resolution that can delineate subsurface structure from ~20 m to >100 m depth.

GPR data were also recorded near sand pits in the area using 100 MHz antennae with 1 m spacing (Pilon et al. 1994). GPR profiles allow direct matching of subsurface reflection patterns with sediment facies and structure (Huggenberger et al. 1994). The higher signal frequency in GPR surveys means that the resultant resolution (submetre) is higher than that in land-based seismic surveys. Depth of penetration is typically <30 m using GPR.

GPR and seismic surveys are similar in that both record reflection energy from subsurface features. Seismic data record mechanical propagation of acoustic energy within sediments, whereas GPR data record the transmission of electromagnetic energy within the subsurface. Reflections in both cases relate to impedance boundaries created by variations in lithology and or pore fluids.

Grasshopper Park Road seismic profile

Observations and interpretation of the Grasshopper Park Road seismic profile (Fig. 3) demonstrate the type of subsurface structural and architectural information that can be determined from a seismic reflection profile in conjunction with a regional geological model. In this case, two well-identified unconformities (erosion surfaces) act as marker horizons (Fig. 3), for regional stratigraphic correlation. Such boundaries also mark abrupt changes in hydrogeological properties and help place seven surveyed elements in the appropriate stratigraphic sequence (Fig. 2).

Bedrock (A) and unconformity (1)

The basal reflection at ~140–150 m above sea level (asl) is a continuous, moderately high amplitude reflection characterized by a single, crisp wavelet (facies I of Pugin et al. 1999) that is essentially flat-lying along the section. It is interpreted as the top of Ordovician limestone (A) at a depth of ~100–120 m. This surface shows little topographic relief and no evidence of bedrock channels. The basal reflection forms a regional unconformity (1 in Fig. 2) and a hydraulic boundary between flow in porous sediments and flow in fractured bedrock.

Lower sediment (B)

This 30–60 m thick sequence is continuous across the 3 km profile below 170–180 m asl. The unit is characterized by low reflectivities and shows little coherent internal structure except for weak dipping reflections (e.g., 100 m depth at 0.2–0.7 km, Fig. 3). It is interpreted as a glaciolacustrine sequence of mainly flat-lying strata (B in Fig. 3) (Pugin et al. 1999), likely sand, silt, and clay. Dipping structures are interpreted as cross-beds with inferred paleoflow related to meltwater fluxes within subaqueous fan complexes (Sharpe and Barnett 1985). These deposits are correlated with exposures to the south along Lake Ontario shore bluffs (Brookfield et al. 1982; Brennand 1997), where cross-beds in sand show a northwest paleoflow. The bluff sections show glacial lake sediments 10–40 m thick, similar to thicknesses inferred from these seismic data.

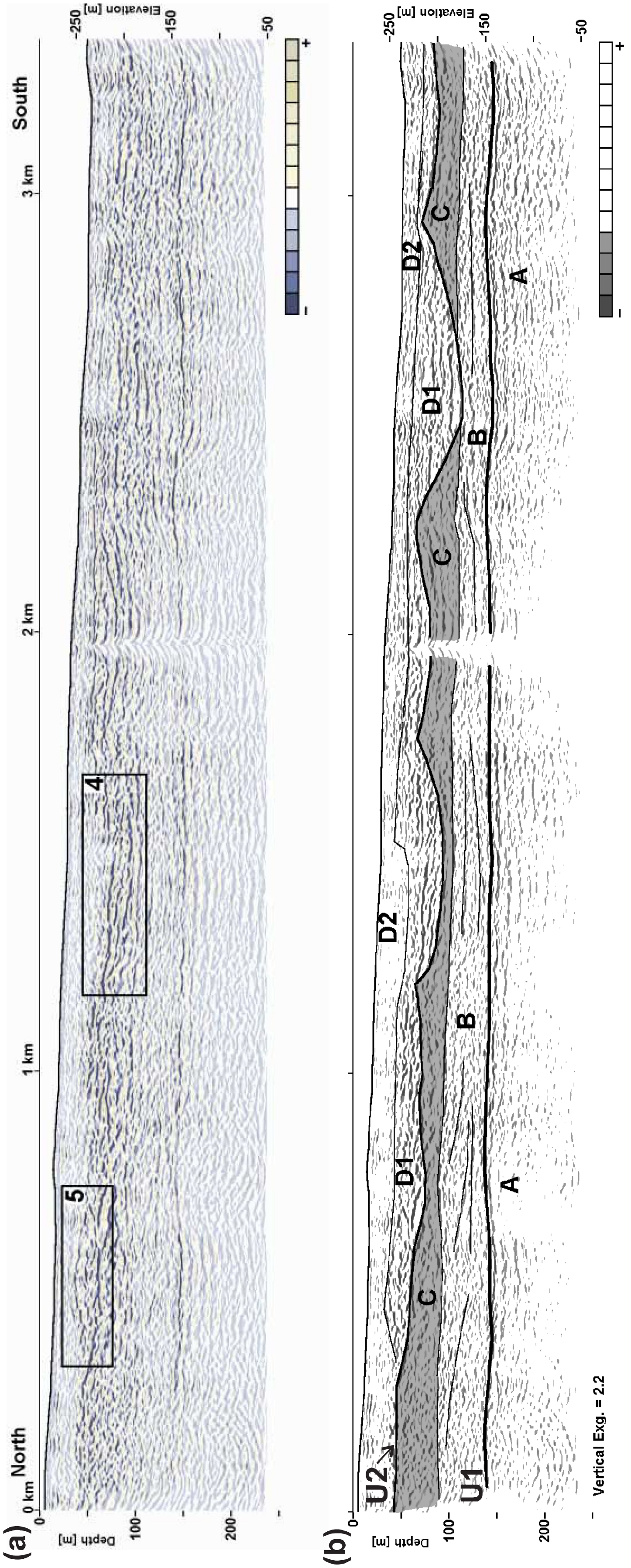
Newmarket Till (C)

This diffuse seismic facies extends discontinuously across the 3 km seismic profile as a 0–50 m thick sequence, exhibiting no coherent internal structure except minor diffractions. It is bounded by a weak but planar contact with the lower sediments (at ~170 m asl) and an irregular upper, high-amplitude reflector. This thick, diffuse reflection package is interpreted as Newmarket Till (C in Fig. 3). The undulating, scoured, distinctive high-reflectivity surface, the diffractoid internal facies, and the characteristic planar base are typical of the Newmarket Till observed on other profiles and identified in boreholes (Pugin et al. 1999). The top of the unit is most clearly defined where it is overlain only by ORM sediments (D2). Interpreted till remnants (Fig. 3) are less certain where they lie beneath another large-amplitude reflection package (coarse sediments, D1).

Newmarket Till is correlated from regional geological mapping north and south of the profile (Fig. 1*b*) (Barnett and Dodge 1996; Brennand 1997), where it consists of drumlinized uplands ~1–4 km wide, dissected by north–south-oriented channels, 1–3 km wide (Fig. 1*b*). Few local wells have been drilled into this dense till aquitard, but it was confirmed with recent core. Nevertheless, the geometry, thickness, and continuity of this aquitard are particularly important to regional hydrogeologic studies (Gerber and Howard 1996; Sharpe et al. 2002*a*), to control on water balance (Gerber and Howard 1998), and to control on regional leakance (Desbarats et al. 2001).

Sediment unconformity (U2)

An irregular, undulating surface clearly extends across the seismic profile between 175 and 225 m asl (U2 in Fig. 3), characterized by a high-amplitude, relatively coherent reflection. This irregular surface carries three or four, scallop-shaped features about 500 m long and 15–25 m deep and


(a)
0 km
North
1 km
2 km
3 km
South
Depth [m]
0
100
200
Elevation [m]
-250
-150
-50
4
5
+
−
(b)
U2
U1
C
D1
D2
B
A
C
D2
B
C
D1
B
A
D2
C
A
Vertical Exg. = 2.2
Depth [m]
0
100
200
Elevation [m]
-250
-150
-50
+
−

cuts through interpreted Newmarket Till into lower sediments (160 m asl) at 2.5 km (Fig. 3*b*).

This irregular, scalloped surface is interpreted to be part of a regional erosion surface or unconformity (Barnett et al. 1998; Pugin et al. 1999) (Fig. 3*b*) consisting of channels and drumlins. The scallops, by analogy to the form of scours or flute marks produced in flumes, suggest that the surface was eroded by high-energy, turbulent flow (Allen 1971, 1984). Where the scour rises downflow (south, D2 at 2.8 km; Fig. 3), it is inferred to represent erosion under high-pressure subglacial meltwater flow (Brennand and Shaw 1994). Erosion by ice has also been suggested to explain channels eroded in till (Boyce and Eyles 1991; Boulton and Hindmarsh 1987). Identification of the appropriate erosion model will help constrain sediment predictions (till, sand, and gravel) and the heterogeneity affecting groundwater flow paths, fluxes, and boundaries. The distribution and origin of channel sediments that enhance hydraulic connection between near-surface and deeper aquifers are of particular hydrogeologic interest (e.g., Martin and Frind 1998).

Channel sediment (D1)

Overlying the sediment unconformity along most of the seismic profile (U2 in Fig. 3) is another high-amplitude, hummocky to inclined, reflection package, D1 (facies II of Pugin et al. 1999). It is ~40–50 m thick and extends for 2–3 km in the plane of this profile. The top of the reflection package is conformable (CO in Fig. 4) and marks a transition to lower-amplitude facies D2. Gently dipping reflections (GS) and short, inclined reflections (F) form two or three, 10–15 m sets (Fig. 5). These stacked sets appear to climb over one another or over Newmarket Till (at 1.1, 1.7, and 2.8 km; Fig. 3). Dome-shaped reflectors ~40 m high with lateral dimensions of ~300 m (e.g., Fig. 4) also form ~15 m sets with short internal reflections (F in Fig. 4).

This unit is interpreted to be gravelly glaciofluvial sediment (D1 in Fig. 3*b*) that initiated ORM sedimentation (Barnett et al. 1998). These sediments have not been recognized and characterized in previous hydrogeological studies in the ORM area (Table 1). Sediments with south-dipping reflectors are interpreted as cross-beds with southward paleoflow parallel to the channel axis. Gently dipping, highly reflective, moderate-amplitude, continuous reflections are interpreted as sheets of interbedded sand and gravel, perhaps formed as dunes in high-energy, glaciofluvial settings. Reflection amplitudes decrease upwards and indicate upward-fining sediment trends consisting of lower-energy sand and silt (Pugin et al. 1999) observed in outcrop. Above channel scours, rising longitudinal profiles are overlain by 10–15 m cross-sets that climb over the rises (D2 at 2.8 km in Fig. 3), much as ripple bedforms climb over obstacles in high-flow environments (Allen 1984). Dome-shaped structures with internal inclined reflections are interpreted as large bedforms or eskers (Fig. 4). Undulatory scours with coarse-grained infills likely indicate glaciofluvial erosion and deposition during the same event and suggest a correspondence between the regional unconformity and coarse deposition.

Praeg and Long (1997) similarly interpret inclined seismic facies within North Sea tunnel valleys as large cross-sets. Others have resolved inclined seismic facies as 10–15 m thick and 100s of metres long coarse-grained units using reflection seismic data (Roberts et al. 1992). This comparison helps confirm the resolution of decimetre-scale bedding styles (as observed in outcrop) with shallow reflection seismic surveys (see Figs. 3*a*, 3*b*). Such cross-bedded facies can be readily related to high-permeability hydrofacies (Neton et al. 1994).

ORM sediments (D2)

The upper unit, D2, is characterized by low reflectivity and weak, continuous reflections that are typical of many seismic profiles in the area (Pugin et al. 1999). This facies is opaque in the north; more internal structure is visible south of 1400 m (Fig. 3). The thickness of this unit varies along the profile from ~40 m at 0 km to <25 m at 1.6 km.

This low-reflectivity unit (D2) is correlated with sand and silt of the ORM (Fig. 1*d*) that can be found in many nearby pits and recent drill core. The unit is more extensive in the north and shows increasing stratification southwards. This likely marks sediment progradation and a downflow facies variation, in which thick-bedded sandy to silty ORM sediments to the north (Fig. 1*c*) grade towards a layered sand and silt deposit in the south. This lateral and upward-fining facies transition is interpreted as a subaqueous fan sediment, a common depositional environment in the ORM (Barnett et al. 1998; Russell et al. 2003). Such fining-upwards sequences provide important trending heterogeneity to sedimentary aquifers (Freeze and Cherry 1979).

Halton sediments

Halton Till and related sediments (Fig. 2) occur in outcrops close to the Grasshopper Park Road profile (Fig. 1*b*), but they are too thin and shallow to be resolved on the seismic profile. Hence, they are either absent or included as part of seismic facies D2 sediments (Fig. 3).

Channel sediments: supporting sedimentological and GPR data

Outcrops, GPR surveys, and boreholes in the vicinity of Grasshopper Park Road reveal the dimensional, architectural, and textural variation of glaciofluvial sediment found within tunnel channels. Channel sediments observed across the area have similarities to those interpreted from the Grasshopper Park Road seismic profiles (Fig. 3).

The interpretation of glaciofluvial sediments on the Grasshopper Park Road profile (Fig. 4) is supported by the presence of coarse sediment within several large bedforms or mounds exposed in channels to the east (Gorrell and Brennand 1997; Barnett et al. 1998). Eskers are found at the surface in nearby channels (Brennand 1994), and subsurface mounds (Fig. 6*c*) are interpreted as bedforms within channels (Shaw and Gorrell 1991).

Glaciofluvial sediments were traced for more than 200 m in outcrops found within channels ~20 km to the east near Brighton (Fig. 1) (Shaw et al. 1994) and at Trout Creek (Shaw and Gorrell 1991). A 200 m long GPR profile collected at the same Brighton gravel pit (Fig. 6) allows direct comparison of sediment geometry and type, in outcrop (Shaw et al. 1994) and in subsurface radar reflection patterns (Pilon et al. 1994). Laterally continuous, inclined GPR reflectors relate to low-angle sediment wedges, sheets, and

Fig. 4. Detailed segment of seismic profile showing reflector structures of a channel and channel sediments (D1) on Newmarket Till (C). B, C, D1, and D2, seismic units (Fig. 2); CO, conformable; CH, channels; ES, erosion surface; F, foresets; GS, gravel sheets.

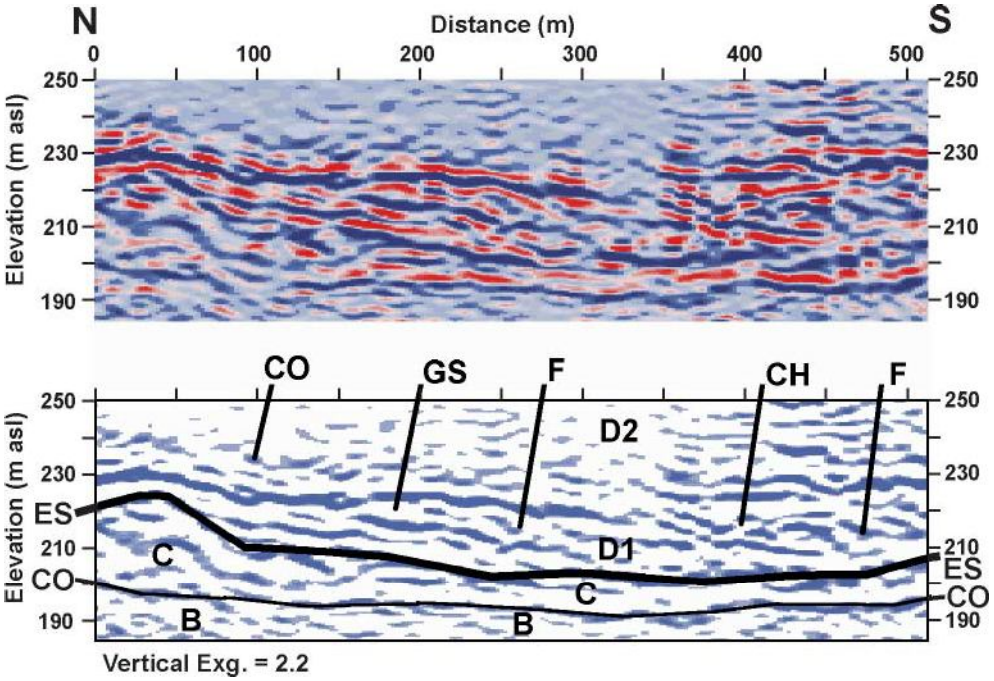
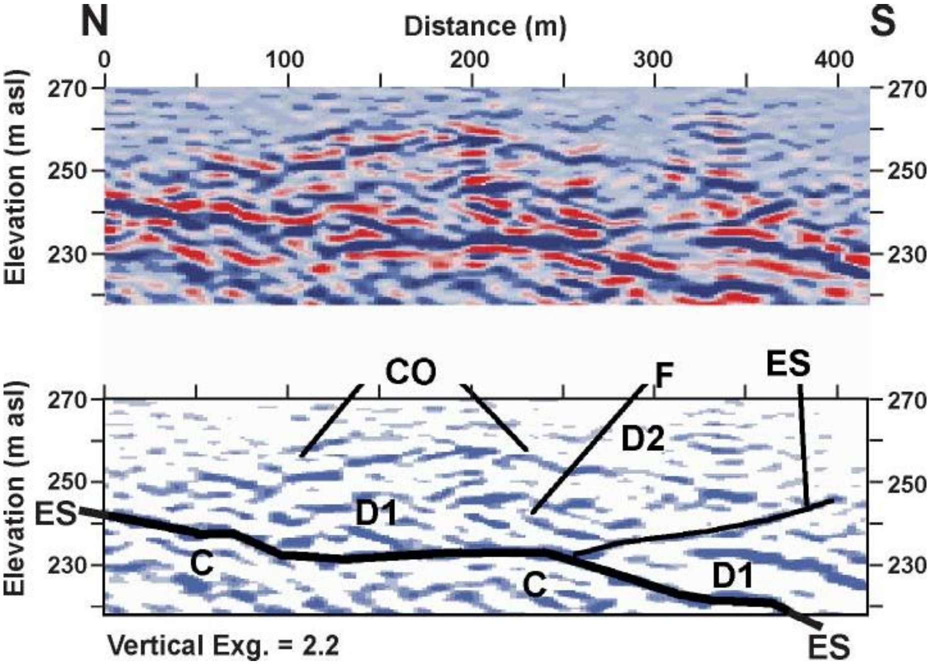


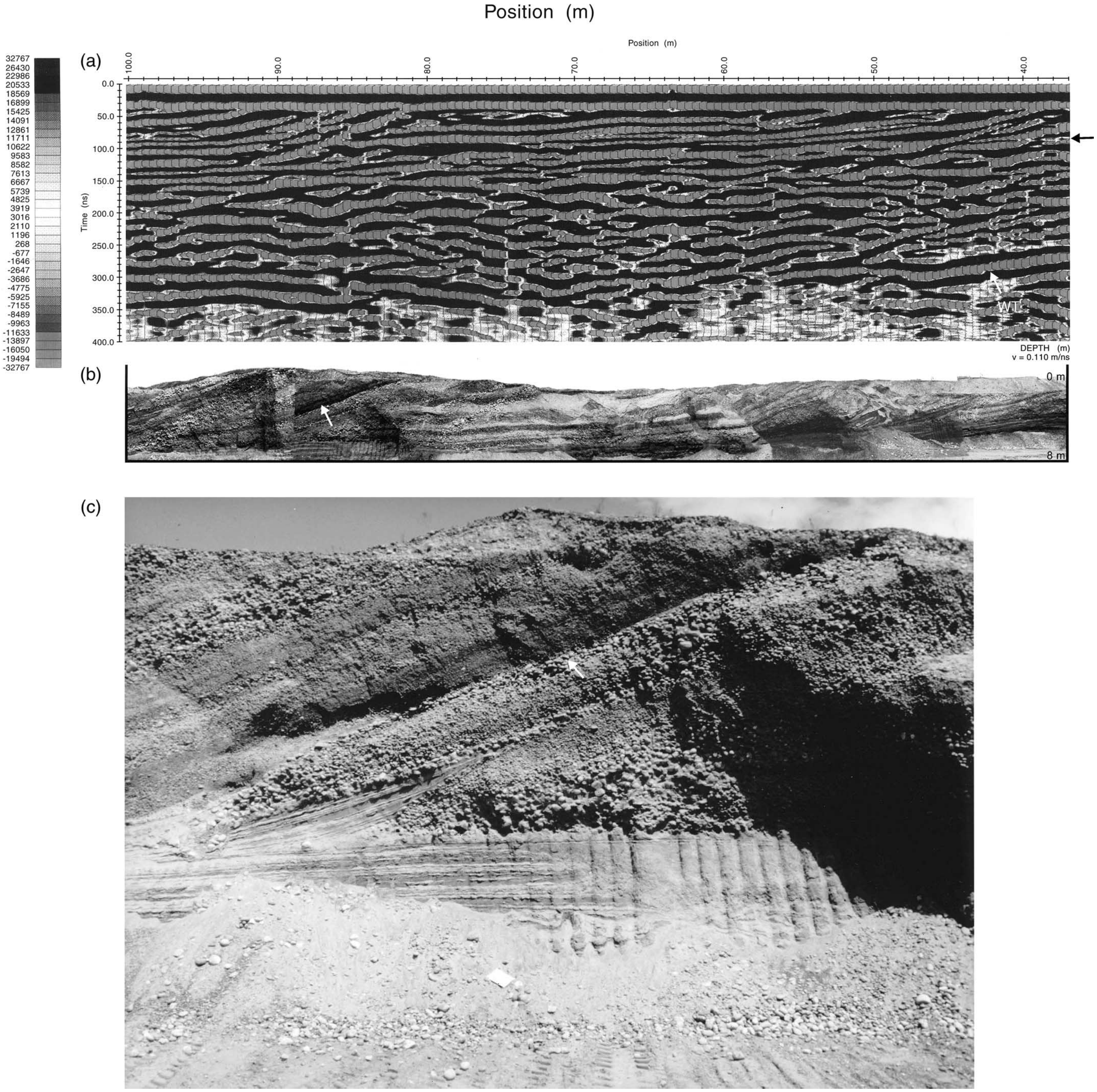
Fig. 5. Detailed segment of seismic profile showing reflector structures found on a regional erosion surface (ES) or unconformity. CO, arched reflectors interpreted as a bedform or possibly an esker. See Figs. 3 and 4 and the text for notation and further explanation.



large cross-beds (Fig. 6), containing bimodal gravel and planar sand units. Dark sand beds (base of the large cross-sets and centre view; Figs. 6*b*, 6*c*) are moist and show up clearly on the GPR profile (Fig. 6*a*). The large cross-beds and adjacent tabular sand and gravel units are similar to the large cross-beds inferred from seismic data at Grasshopper Park Road. At both sites, the alternating, inclined, sandy, and gravelly sets (Figs. 6*b*, 6*c*) would provide large acoustic-impedance contrasts yielding significant reflection energy at seismic wavelengths.

Directional trends provide further sedimentological support and a source of heterogeneity within these glaciofluvial sediments. For example, the Brighton GPR profile shows southwest paleocurrent indicators (cross-bed; Fig. 6), similar to the directional trends from seismic data at Grasshopper Park Road. At each site, channel sediments likely possess

Fig. 6. (*a*, *b*) GPR profile and section oriented west–east at Brighton, Ontario (see Fig. 1): (*a*) large (~8 m high), dipping reflectors map cross-bedded gravel sets, and black arrow indicates depth of exposed section; (*b*) exposed section (~75 m long). Reflector definition is best at sand–gravel breaks (white arrow). Cobble gravel beds (left of arrow in *b*) are bimodal. Prominent reflector at ~20 m depth (~300 ns) is the water table (WT and white arrow in *a*) (v = velocity; relative intensity of reflections is shown at the left of the figure). (*c*) Photograph of sedimentary structure in the Brighton area pit, east of the Grasshopper Park Road section. Large, gravel cross-beds rest on tabular plane-bedded sand. Gravel beds show fining-upward size arrangement. Permeability contrasts of several orders of magnitude are probable between open-work cobble gravel and underlying sands. White arrow is at same gravel bed as white arrow in (*b*). (Notebook in foreground = ~25 cm (long-axis)).



enhanced permeability in a north–south direction. These Grasshopper cross-bedded facies may extend as sets 15 m high and 100 m wide for more than a kilometre downflow.

Thus, supporting sedimentological and GPR data indicate that, in this area, gravelly channel sediments, up to ~40 m thick (confirmed by recent drilling), occur in channels ~1–3 km wide and many kilometres long. Channel elements contain individual gravel sets 5–15 m thick, >100 m wide, and hundreds of metres long. Several gravel sets may be stacked (Fig. 6), yielding a thickness of 30–40 m for coarse channel sediments. Borehole data reveal coarse sandy gravel near Grasshopper Park Road at ~310 m asl and gravel between 250 and 275 m asl on water well records (Fig. 1*d*). The gravel at ~200 m asl and lower confirms high-amplitude facies, D1, in the seismic profile as the top of channel gravel. Gravel buried beneath fine sands is exposed in a gravel pit ~10 km east of the seismic profile. This gravel is tabular in form with 1–2 m cross-beds that indicate a paleoflow to the west.

This comparison of geophysical data, outcrop sediment texture, and architecture (Fig. 7) adds strength to the interpretation of gravel facies and structures within the Grasshopper Park Road channel sediments. The identification of 25 m of gravel from recent coring confirms the gravel inference. The proportions and hydrogeological context of these glaciofluvial sediments and geophysical facies are summarized in Table 2.

This facies architecture allows us to identify hydrogeological variability at several scales as seen in Fig. 7. It highlights architectural elements in the Grasshopper Park Road area using the different field methods considered in this paper. For example, seismic data allow resolution of stratal boundaries at a watershed scale (~10 km^2) (Pugin et al. 1999). GPR and outcrop data map low-angle sediment wedges, sheets, and large cross-beds (at a sub-watershed, <1 km scale). Seismic images of similar deposits at depth would likely be characterized by high, and perhaps varied, seismic amplitudes. Sharp permeability contrasts are expected at the major sediment boundaries (Green et al. 1995).

Hydrostratigraphic model

In the previous section, we demonstrated how a regional geological model and geophysical and sedimentological data can be used to improve our understanding of the subsurface structure, even in areas where borehole information is sparse. Information from seismic architecture and facies helps define boundary conditions and dimensional properties of the sedimentary units, and higher resolution GPR and outcrop data provide detailed information on sediment types and depositional structure. We now assign estimates of hydrogeologic properties based on regional data for major hydrostratigraphic units (Table 1) to develop a preliminary hydrostratigraphic model.

Groundwater investigations in the area by Gorrell Resources Investigations have identified hydraulic properties based on depositional facies (Table 3). Supported by field tests in the area (e.g., water supply and dewatering pumping tests), these estimated values of horizontal hydraulic conductivity (*K*) assume an idealized glaciofluvial sediment sequence displaying lateral directional heterogeneity. Hydraulic estimates derived from depositional facies provide valuable input data for geostatistical modelling (Fogg et al. 1998) because they are tied to predictable and spatially continuous data provided by geophysical profiles and refined glaciofluvial sediment models.

Regional hydrostratigraphic units

Hydrostratigraphic units can be extended beyond the survey area by identifying comparable sediment facies in the same stratigraphic position. Here, lower sediments occur in 20–40 m thick tabular units resting on flat bedrock, ~140–170 m asl. They have a north–south trace of >3 km and extend for >10 km below Newmarket Till along Lake Ontario bluffs (Brennand 1997). Sandy members of lower sediments have hydraulic conductivities (*K*) of ~2×10^{-4} m/s (Table 3).

Previous hydrostratigraphic models in the ORM area adopted a layer-cake design and do not include or recognize erosional gaps or thinning in the regional Newmarket Till (Singer 1974; Sibul et al. 1977; Howard et al. 1995; Boyce et al. 1997). This aquitard is generally assumed to be thick and continuous. In uplands, where it is 30–40 m thick, recharge to underlying aquifers is estimated at 30–40 mm/year and related to small-scale structures (e.g., fractures, Gerber and Howard 1996) (Table 1). Based on seismic data presented here, however, Newmarket Till varies between 0 and 40 m in thickness along the Grasshopper Park Road profile. This lack of aquitard continuity indicates potential for recharge to lower aquifers through gaps or scours in Newmarket Till (Sharpe et al. 2002*b*), an expectation supported by an analysis of leakance in this unit (Desbarats et al. 2001).

Previous hydrostratigraphic models in the ORM area have also failed to include a channel aquifer beneath the ORM (Singer 1974; Sibul et al. 1977; Howard et al. 1995; Boyce et al. 1997), although a channel unit was recognized in the Humber River valley to the west. The sedimentary architecture, seismic facies, and lithofacies from Grasshopper Park Road allow us to discuss the environment of deposition within a glaciofluvial channel system and make advances in hydrogeological understanding of these important buried aquifers.

The Grasshopper Park Road data record the predominance of coarse glaciofluvial sediments in stacked sequences; little diamicton is apparent. Coarse sediment (high-amplitude, hummocky reflectors) fills most of the eroded channel, leaving it with a distinctive geometry and architecture. The reported scour and fill structures (Fig. 3) are not in accord with the expected till facies predicted from an ice erosion and deposition model (e.g., deformation till; Boyce and Eyles 1991). Rather, channel deposits show large (5–15 m high) cross-beds that extend for hundreds of metres over widths of 1–2 km (Table 2). These coarse-grained beds were likely deposited in subglacial channels, under high pressure and high velocities (Barnett 1990; Shaw and Gorrell 1991; Brennand and Shaw 1994), and thus they may be extensive and hydraulically connected over long distances. Such channels are widespread in the area and are likely to contain gravel (Russell and Sharpe 2002), and thus are particularly significant for hydrogeologic representation. This type of channel-sediment process model helps in predictions of sediment type, geometry, and heterogeneity (Fig. 7) for regional hydrogeological analysis in this and other glaciated terrains (Molenaar 1988; Piotrowski 1997).

Geostatistical analysis

Hydrostratigraphic data such as those outlined in this paper can be quantified using geostatistical analysis. Recently, the spatial variability of the Newmarket aquitard was quantified using lithologic indicator geostatistics (Desbarats et al. 2001). A map of Newmarket aquitard leakance (= (hydraulic conductivity)/(thickness of the unit)) was produced using

Fig. 7. Comparison of sedimentary architecture among: (*a*) seismic architecture (Fig. 4), Grasshopper Park Road (box indicates the location of detailed section in *b*); (*b*) channel fill seismic element (box represents inferred location of *c* and *d* in the Grasshopper Park Road depositional setting); (*c*) Brighton surface radar architecture; and (*d*) Brighton surface sediment architecture. Note scale change in (*b*) and (*c*) and (*d*).

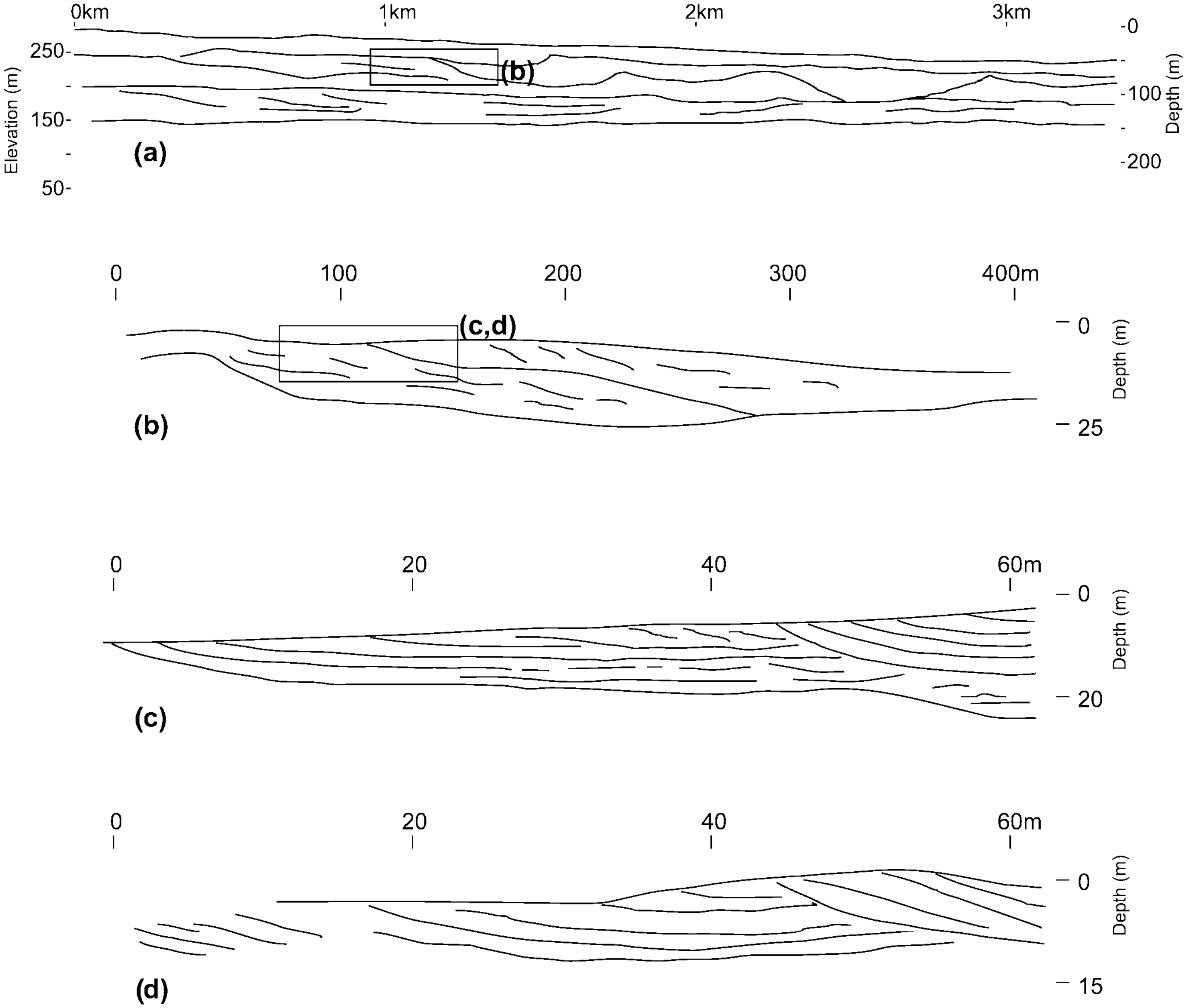


Table 2. Architectural proportions for Grasshopper Park Road glaciofluvial sediments (D1).

	Proportions (minimum; m)					
Information source	Thickness	Length	Width	Spatial correlation	Juxtaposition	Heterogeneity
Seismic	25	400	50–100	Extends >3 km	Overlies regional aquitard	High (cross-beds)
Radar	20	50–100	10–50	Extends >500 m	Overlies thick sand	High (cross-beds)
Outcrop	15–20	50–100	10–20	>100 m	Sand sequence	High (bimodal gravel)

thickness data from over 9000 well records, “trained” in part by seismic profile and sediment facies data. The map of simulated leakance is consistent with sedimentary models of the Newmarket Till and clearly shows regional spatial patterns associated with channel erosion (Desbarats et al. 2001), as discussed previously. At Grasshopper Park Road, one can

Table 3. Variation in hydraulic conductivity (K) and seismic character of glacial sediments in southeastern Ontario.

Facies	Facies association (and texture)	Reflectivity	Seismic facies	K (m/s)
1	Channel bedform or esker core (gravel)	High	Hummocky	$10–10^{-3}$
2	Ice contact – mid-fan (gravelly to silty sand)	Moderate	Inclined	$10^{-3}–10^{-6}$
3	Interbedded fine sand and silt sequence	Low	Planar	$10^{-5}–10^{-7}$
4	Dense till (high K = sand lenses)	High	Diffractoid	$10^{-5}–10^{-11}$

Note: High vertical hydraulic conductivity occurs in specific facies, namely cross-bedded channel gravels and proximal fan environments (facies 1 and 2). Low hydraulic conductivity is probable (facies 3 and 4) where silty laminae are present in a distal part of the subaqueous fans and in regional tills.

model leakance through Newmarket Till directly using detailed thickness data derived from seismic profiling combined with regional values of hydraulic conductivity (Table 1).

The detailed facies character identified within the Grasshopper Park Road channel sediments (Figs. 6, 7) is also well suited for the use of geostatistical analysis to assess spatial and directional variability. Geostatistical methods have been used successfully to describe and characterize heterogeneity within regional channel aquifers in Ohio, using lithological data from water well descriptions (Ritzi et al. 1995). Because seismic profiling samples aquifer media on horizontal and vertical scales on the order of metres (Rubin et al. 1992), there is an opportunity to test whether geophysical attributes can be used to quantify heterogeneity within channel aquifers. Seismic reflectors at Grasshopper Park Road appear to record the interface between coarse- and fine-grained glaciofluvial sediments (Fig. 3). In addition, reflector amplitudes from radar data have been used to characterize aquifer heterogeneity (Rea and Knight 1998). Inasmuch as seismic amplitude can be related to material properties and thence to hydraulic properties, such an analysis can be used to characterize the internal architecture of aquifers for future groundwater flow and transport modelling studies.

In this paper, a geostatistical analysis of seismic reflector amplitudes provides a quantitative measure of spatial continuity and heterogeneity between two glaciofluvial aquifer facies (D1 and D2). A histogram of their amplitudes shows that facies D1 reflectors are much stronger and have a greater standard deviation (×4) than facies D2 amplitudes (Fig. 8). These strong differences in reflector amplitude indicate sediment interfaces of sharply contrasting grain sizes, consistent with a rapidly deposited, coarse, channel sequence (D1). Marked differences in K values would also be expected (variations of ~10^2) within these D1 facies, whereas facies D2 sediment and K would likely be more homogeneous.

The spatial continuity of reflectors can be described using semivariograms of amplitude (Hubbard et al. 1999). The amplitudes in units D1 and D2 have been rescaled to a mean of 0 and a variance of 1 to better compare the spatial correlation in the two units. Both units reveal similar meaningful semivariograms with a horizontal correlation range of 50 m (Figs. 9*a*, 9*b*) and vertical wavelengths of 4.4 m (D1) and 3.2 m (D2; Figs. 9*c*, 9*d*), but there is little distinction between the two units.

Directional, semivariogram maps of the amplitudes of these facies, however, show that the spatial correlation structure of D1 is anisotropic in the vertical plane, with a direction of maximum continuity dipping ~2.5° to the south (Fig. 10*a*) In contrast, the D2 facies semivariogram maps show the direction of maximum continuity to be almost horizontal (Fig. 10*b*). These data provide quantitative confirmation that reflectors in D2 appear to be continuous laterally and are more flat-lying than the inclined beds in D1.

Directional heterogeneity, as identified here and common in alluvial-fan aquifers (Neton et al. 1994), is essential knowledge for correct site characterization and for design of well networks, aquifer tests, and flow models. Hence, the Grasshopper Park Road data and semivariograms are useful as tools for determining favorable locations for new water supply wells, monitoring wells, delineating areas where the lower aquifer system is vulnerable to surface contamination, and preparing for quantitative modelling.

Hydrogeologic implications for Grasshopper Park Road area

Aquifer potential

The preliminary hydrostratigraphic model for Grasshopper Park Road identifies three potential sediment aquifers: lower, channel, and Oak Ridges Moraine (Fig. 2; Table 1). Geophysical and sedimentological data provide aquifer dimensions and their potential interconnectedness. Lower sediment aquifers likely form extensive tabular reservoirs (Fig. 3), despite the fact that hydraulic conductivities are low. Channel sediments form high-permeability north–south bodies that may be kilometres long, tens of metres thick, and hundreds of metres across (Figs. 3*a*, 7).

The Grasshopper Park Road dimensional data (Table 2) may also aid water supply prospecting. Transmissivity (T), the ease of groundwater flow through a sedimentary formation, is easily obtained using the thickness estimates from the seismic data to evaluate favorable aquifers. As a rule, T values of 0.015 m^2/s (Freeze and Cherry 1979) are required if the sedimentary body is to be considered suitable for water well exploitation. Using Table 3 and assuming a conservative T value of 0.015 m^2/s, gravel facies ~15 m thick (e.g., cross-sets in Fig. 3) could perform as high-yield aquifers. Nearby fine sandy facies will have to occur as thicker deposits to be productive municipal aquifers. The facies within these channels, however, can transmit significant quantities of water on a regional scale and increase aquifer reservoir capacity (Easton 1998).

Where channel aquifers intersect lower sandy aquifers (unit B in Fig. 3), higher potential aquifer targets may exist. These sites are identified from seismic data (D1 in Figs. 2*a*, 4) where coarse-grained sediments are connected to extensive lower sandy strata. These lower deposits can be very large (km^2), as they occur in basins or in broad structural

Fig. 8. Histograms of amplitude in glaciofluvial sediments: (*a*) D1 facies, and (*b*) D2 facies.

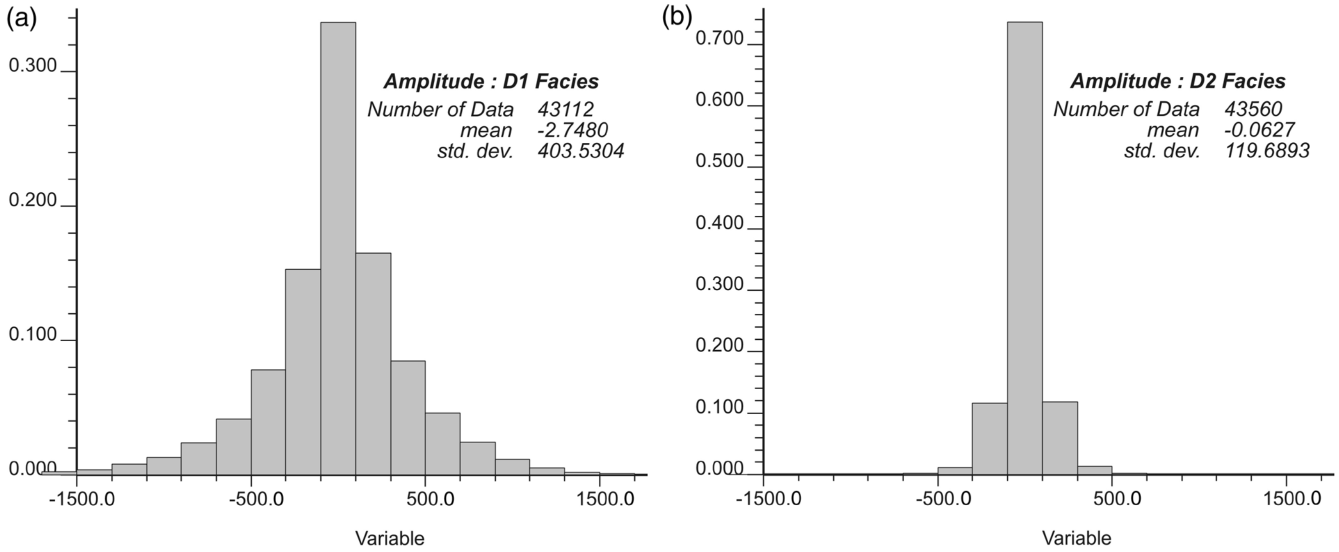


Fig. 9. Semivariograms of normalized amplitude *h* (mean = 0; variance = 1) in the horizontal and vertical directions: (*a*) D1 facies, horizontal; (*b*) D1 facies, vertical; (*c*) D2 facies, horizontal; (*d*) D2 facies, vertical. A processing artifact (vibration) occurs in both D2 facies. (Gamma (h) is a measure of spatial variabity, continuity as a function of distance between sample points).

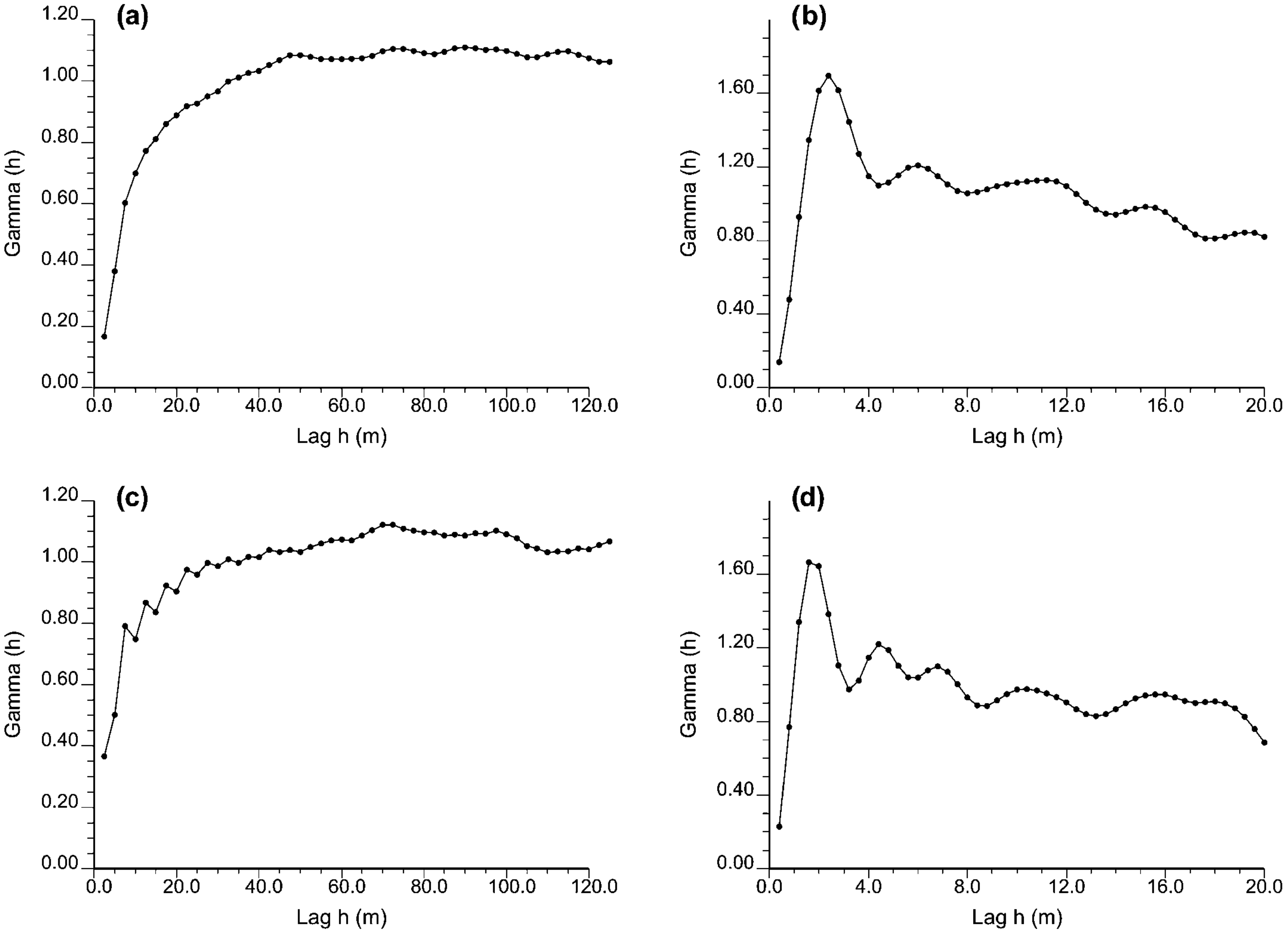
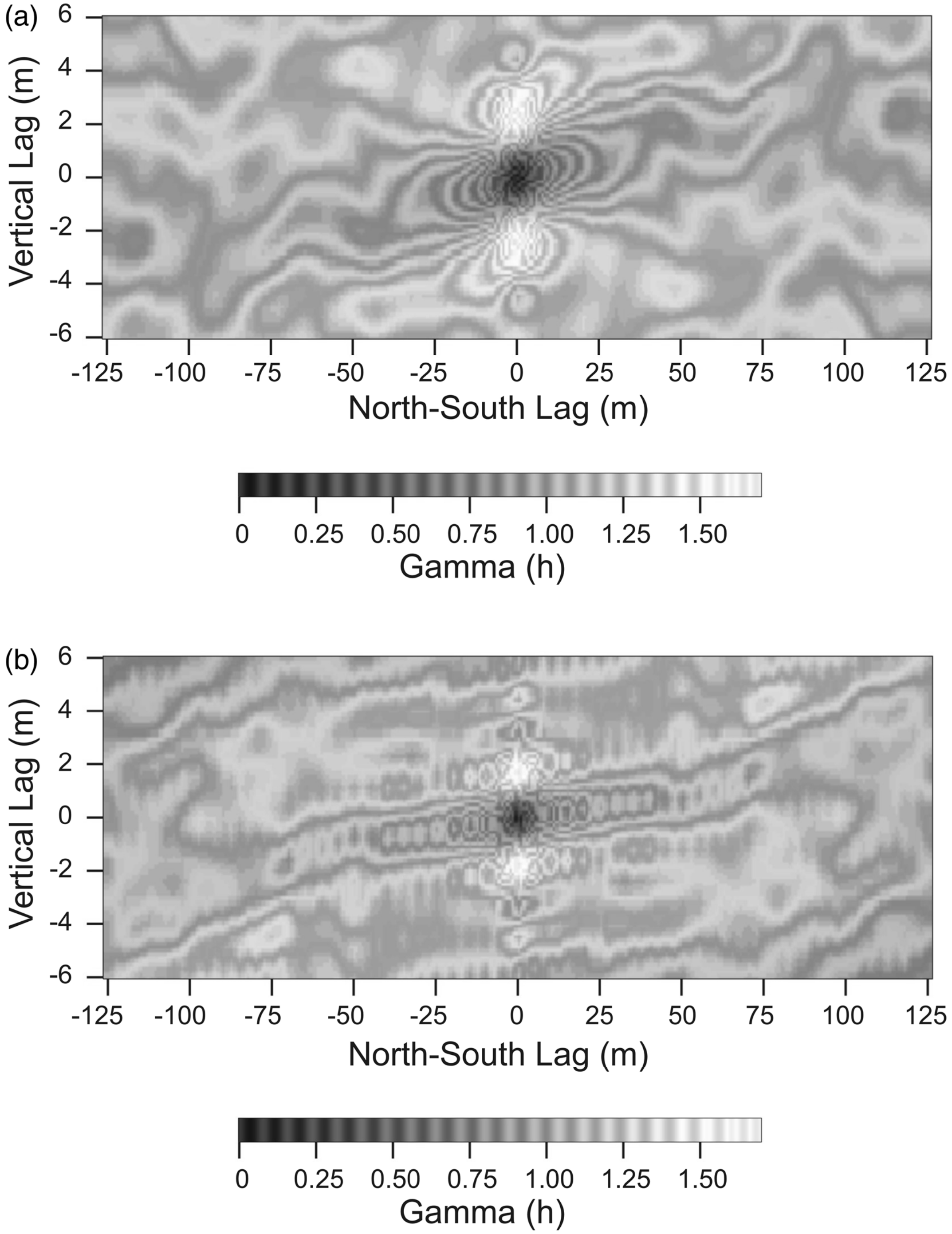


Fig. 10. A semivariogram map of normalized amplitude for the Grasshopper Park Road seismic section: (*a*) D1 facies, (*b*) D2 facies. This figure shows the spatial correlation structure of these two glaciofluvial sediments. D2 facies appear to be continuous laterally and are more flat-lying than the inclined facies in D1.



lows (Fig. 4). Such promising areas for groundwater supply are not always evident from surface mapping or from exploratory boreholes alone. Seismic records, however, reveal that these buried deposits are extensive and interconnected along Grasshopper Park Road (Fig. 3).

Drilling targets

Glaciofluvial sedimentary models, such as a channel-sediment model, can also help in groundwater prospecting. Precise positioning of high-yield drilling targets can be identified from Grasshopper Park Road gravel facies in longitudinal channel profiles. Cross-sectional channel profiles may provide additional resolution. Because channel sediments are transitional upward to sandy ORM fan sediments (Fig. 4), the vertical-permeability distribution of these sediments is expected to change from sandy proximal locales to distal settings where sandy silt units occur. The vertical *K* of the Grasshopper Park Road channel profiles is more predictable, however, because the gravel sequences D1 and D2 can be readily identified and quantified.

Directional properties

Neton et al. (1994) emphasized the directional aspect of variability in *K*, *T*, and storativity *S* as important to understanding aquifer properties and preparing for groundwater flow modelling. The orientation of Grasshopper Park Road channel sediments was gained directly from cross-bedded seismic facies (Fig. 4) and regional mapping (Fig. 1). Total hydraulic variability is revealed by different scales of investigation (Fig. 7): regional analysis relies on landform and stratigraphic architecture; local analysis requires sediment models; and site analysis benefits from high-quality data (seismic and GPR). Although relating geophysical attributes to hydraulic properties remains difficult (Weissman et al. 1999), shallow geophysical methods (seismic and GPR) and sediment facies mapping provide cost-effective watershed-scale methods where a broad network of borehole monitors cannot be established or sparse wells need to be connected.

Vulnerability mapping

Lastly, protection of aquifers is also aided by subsurface geophysical mapping. In particular, where Newmarket Till aquitard has been eroded, channel and ORM sediments are connected to sandy, lower-deposit aquifers (Fig. 2).

Discussion

We briefly discuss the use of detailed geophysical and sedimentary data from Grasshopper Park Road to develop hydrogeological understanding of a watershed. Here, hydrogeologic analysis is advanced with the assistance of a well-developed regional conceptual stratigraphic framework but without the benefit of local high-quality boreholes and hydraulic test data.

Need for structural information in hydrogeological investigations

Buried valley aquifers, important to water supply in glaciated terrain (Stephenson et al. 1988; Lennox et al. 1988), possess significant hydrostratigraphic and sedimentary variability. The Miami buried valley aquifer system in Ohio (Ritzi et al. 1995) and the Mahomet buried valley in Illinois (Stephenson 1967) are longer but otherwise have dimensions (>100 km long, 1–4 km wide, and up to 100 m deep) similar to those of buried channels in the ORM area (Barnett et al. 1998). The buried valleys in Ohio and Illinois may have a more complex and multiage stratigraphy (Krothe and Kempton 1988) that includes significant thicknesses of glaciofluvial sediments. Despite their economic and societal significance, the extent, internal structure, heterogeneity, and sedimentology of these systems have not been studied or revealed in any detail.

Detailed stratigraphic and sedimentary control was shown to be very significant for modelling the Waterloo Moraine (Martin and Frind 1998). This aquifer system is similar in complexity to that of the ORM, but water well records without seismic data control were used to develop a hydrostratigraphic model. Here, aquifer interconnectedness (Fogg 1986) was shown to be critical to the assessment of groundwater flow patterns and capture zones. Model results showed that capture zones are highly sensitive to geological structure, in particular windows inferred in buried aquitards, that allow aquifer connection (Martin and Frind 1998). Comparisons in the ORM area show that known channels that breach aquitards (Sharpe et al. 2002*a*) are resolved by seismic data but not by water well records alone (Russell et al. 1998*a*). Hence, an accurate, detailed 3D stratigraphic model, developed using laterally continuous data, is a necessary basis for field testing and modelling source water protection.

Attributes of laterally continuous data (e.g., seismic surveys) are of particular relevance to hydrogeological analysis of the cited channel aquifers and aquitard continuity. Unit proportions or mean thickness, length, and width, spatial continuity, juxtaposition of differing sediment bodies, and sediment heterogeneity aid prediction of flow and transport in sedimentary aquifers (Dominic et al. 1998). These attributes can identify preferential flow paths and interconnectedness and thus provide input for geostatistical modelling and quantitative estimation (Weissman et al. 1999).

Depositional models and sediment facies architecture

Depositional models have been used to delineate broad trends in the heterogeneity of glacial aquifers. Anderson (1989) showed that regional-scale glaciofluvial sediment distribution affects hydrogeologic variability and regional groundwater flow. At this scale, heterogeneity in the Miami buried valley aquifer was represented by low-permeability facies (till or glaciolacustrine clay) juxtaposed with high-permeability glaciofluvial facies (sand and gravel; Ritzi et al. 1995). This first-order spatial structure or variability in the valley aquifer was quantified geostatistically using indicator variables based on lithologic descriptions from stratigraphically unclassified water well cores (Ritzi et al. 1995). The approach in this paper is to improve this type of analysis using high-quality structural seismic and outcrop data to define sedimentary architecture in the channel system prior to using indicator geostatistics on sediment facies detailed earlier in the paper. In addition, depositional models of channel formation in the ORM support the identified facies: (*i*) coarse sediment from high-energy subglacial deposition (Brennand and Shaw 1994), as opposed to (*ii*) till from low-energy deformation of till layers (Boulton and Hindmarsh 1987).

Generalized facies descriptions and models cannot delineate small-scale heterogeneity within glacial sediments. This critical geometry of interconnected, high-permeability facies creates preferential flow paths of interest to hydrogeologists (Ritzi et al. 1994). Small-scale spatial trends relate to facies variation within architectural elements, such as within channel cross-bedding identified at Grasshopper Park Road (Fig. 6*c*). These gravelly bedforms extend along channel for ~2.5 km within unit D1 as two or three stacked sets with 30–40 m total thickness. Gravel thickness, confirmed by recent drilling, is expected to extend across the channel, a width of ~1.0 km (Table 2). These bedforms are inferred to be similar to gravel and sand cross-beds exposed at Brighton (Figs. 6*c*, 7) and other channels (Gorrell and Shaw 1991). Resolution of sedimentary detail is of increasing benefit to hydrogeologists (Ritzi et al. 1995) because simple textural associations do not adequately record variation and directional attributes in hydraulic properties (Fogg et al. 1998).

Coarse sediments within ORM channels (Sharpe et al. 1996) may prove to be prolific aquifers, but the distribution of these buried aquifer systems is poorly known. Buried channel sediments found north of the ORM (Easton 1998) contain high-yield wells (>400 L/min), and flows up to 4000–8000 L/min have been estimated in channels ~1.0–1.5 km wide. Recent hydrogeological models of the ORM area (e.g., Howard et al. 1995), however, have not recognized the presence or significance of these channels, so their hydraulic character and effect on flow modelling are poorly documented (Sharpe et al. 2002*a*). To date, few data that link sediment facies and hydraulic parameters exist for these sediments (Table 3).

Summary

At Grasshopper Park Road, a seismic profile set within a regional stratigraphic framework and linked to nearby surface exposures reveals several key hydrogeological implications.

(1) Delineating continuity of key hydrostratigraphic units of the stratigraphic architecture — The presented seismic section shows the stratigraphic architecture of two major aquifers (lower sediment B and channel sediment D) separated by a thick regional aquitard, unit C (Newmarket Till). Direct connection between these aquifers occurs through buried channels (D) that incised and breached the regional till sheet.

(2) Definition of unit facies and properties using seismic and sediment facies analysis — High-amplitude and inclined seismic facies (Fig. 3), the likely equivalents of exposed gravelly cross-beds (Fig. 6), record the extent and directional trends of laterally continuous, high-permeability hydrofacies.

(3) Combined knowledge of architecture and sediment facies — This improves the application of erosional and depositional process models to extrapolate subsurface heterogeneity in the watershed. Subglacial meltwater-flow models (Barnett et al. 1998; Sharpe et al. 2002*a*) help define the scale and variation in channel facies and hydrogeologic properties across the area. Meltwater channels are inferred to result from pressurized, high-energy, glaciofluvial erosion that removed portions, or all, of the Newmarket Till aquitard, resulting in hydraulic windows (Desbarats et al. 2001). Coarse glaciofluvial sediment in large cross-beds was rapidly deposited in channels during the waning-flow events (Russell et al. 2003).

(4) Regional parameter estimation — Based on facies analysis, a depositional model, and field tests, we can predict an approximate scale (Tables 1, 2) and hydraulic conductivity (*K*; Table 3) for channel sediments. Table 2 provides parameter estimates for channel and subaqueous fan sediments found in the ORM area. These data are far more accurate and effective for improving hydrogeologic dimensions than analysis of water well data alone (Russell et al. 1998*a*). In addition, the combined datasets may have potential for geostatistical modelling that can quantify and produce probability estimates of hydrogeological unit variability (e.g., Desbarats et al. 2001).

Conclusions

The relevance of hydrogeological analysis often depends on a valid hydrogeological model (LeGrand and Rosen 1998), such as can be provided by information on detailed subsurface hydrostratigraphy. Groundwater investigations, prospecting for water supply, seeking protection for aquifers, or preparing for flow modelling are greatly enhanced by the use of geophysics, hydrostratigraphic, and sedimentological mapping. These data sets also help establish a watershed-scale framework for improved estimation of hydrogeological parameters.

Searches for and delineation of groundwater reservoirs, as is the case for oil and gas prospecting, are improved with seismic profiling and sediment analysis set within a basin-analysis framework (Sharpe et al. 2002*a*). Borehole data, particularly continuous core and downhole geophysics data, are necessary complementary tools for interpretation of seismic surveys. Ideally, borehole locations should be selected on the basis of seismic data to allow specific sampling and monitoring of key hydrostratigraphic structural units and facies. Once experience is gained in an area and tested sedimentological models are available, however, a minimum number of dedicated boreholes are needed to support hydrogeological assessment, as was shown at the Grasshopper Park Road site. Hydraulic windows, important in many hydrogeologic terrains, can be mapped with seismic reflection methods more accurately than can be achieved using water well records or other boreholes alone (e.g., Martin and Frind 1998; Beckers 1998). The Grasshopper Park Road work is also expanding knowledge of the tunnel channel hydrogeology setting, which is becoming recognized in glacial terrains (e.g., Piotrowski 1997; Pugin et al. 1996).

Fogg et al. (1998) state that the relationships between hydrogeologic and geologic attributes and surface geophysical signals (seismic or electromagnetic) are elusive. We believe that this analysis of the ORM area data has shown how to reduce ambiguities, despite the fact that facies-specific hydrogeological parameters are not abundant from local well records.

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