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Applications of Shallow Geophysics in a Regional Geological and Hydrogeological Investigation, Oak Ridges Moraine, southern Ontario

S.E. Pullan[1], A. Pugin[2], J.A. Hunter[1], S.D. Robinson[1],
M.A. Annecchione[3], and G.E. Leblanc[4]

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Abstract:

Geophysics has played a critical role in a multi-disciplinary research program in the Oak Ridges Moraine area, southern Ontario, designed to improve understanding of the regional geological and hydrogeological framework of a significant Quaternary aquifer complex. Geophysics was particularly important because of the large study area, complex glacial stratigraphy, and thickness of overburden sediments (up to 200 m). Borehole, surface and airborne geophysical surveys have provided information on the subsurface at scales of investigation varying from sub-metre to kilometre. A suite of geophysical logs were obtained in eleven, deep (90-190 m) stratigraphic boreholes. These data were particularly important in identifying downhole stratigraphic relationships and effecting regional correlation. Ground probing radar was used extensively in glaciofluvial sand and gravel deposits of the ORM to obtain depth to water table and very-near-surface structural and sedimentological information. Electromagnetic techniques were tested, but not used extensively during the project. Over 50 line-km of land-based, shallow seismic reflection profiles provided a means of investigating the subsurface architecture and stratigraphic relationships of the complete sequence of unconsolidated sediments. These surveys were instrumental in identifying the regionally extensive and eroded nature of the Newmarket Till beneath the ORM deposits. Data from a regional gravity survey consisting of over 5500 stations were inverted to obtain an interpretation of bedrock topography. Though as yet unproven, high-resolution airborne magnetic data have identified anomalies which may be related to channel features within 200 m of the surface. Overall, the combined geophysical data have provided high-quality control for a large set of archival data, and have allowed an assessment of the lateral continuity of major hydrostratigraphic units. This paper outlines the objectives and applications of these geophysical surveys in the Oak Ridges Moraine study, and assesses their potential applications in other regional hydrogeological investigations.

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[1] Geological Survey of Canada, Ottawa, Ontario, Canada
[2] Illinois State Geological Survey, Champaign, IL
[3] École Polytechnique, Montreal, Quebec, Canada
[4] present address: National Research Council of Canada, Ottawa, Ontario, Canada

INTRODUCTION

The Oak Ridges Moraine (ORM) and underlying sediments form a thick, extensive Quaternary aquifer complex that supplies groundwater to more than 200,000 people within the Greater Toronto Area (GTA) in southern Ontario (Fig. 1). However, increasing pressures of rapid urbanization (e.g., Regional Municipality of York, 1993) have led to questions relating to the long-term sustainability of this groundwater resource. A better understanding of the regional geology and architecture of the complex glacial sedimentary deposits in the area is required to adequately evaluate regional groundwater resources and flow, and to allow cost-effective searches for additional groundwater supplies.

During the last several years, considerable effort by university groups, federal, provincial, and municipal agencies has been directed towards improving our understanding of the geological and hydrogeological framework of the Oak Ridges Moraine area. Work has included the analysis of a large quantity of archival surface and subsurface data (e.g. Hunter and Associates and Raven-Beck Environmental Ltd., 1996; Russell et al., 1996; Brennand, 1998), geological mapping (e.g., Sharpe et al., 1997), stratigraphic drilling (e.g. Barnett, 1993), hydrogeological studies (e.g. Gerber and Howard, 1996; Howard et al., 1997; Hinton et al., 1998), analysis of remote sensing data (e.g. Kenny et al., 1996; Kenny, 1997; Skinner and Moore, 1997), and geophysical surveys (e.g. Todd et al., 1993; Pilon et al., 1994; Pullan et al., 1994; Boyce et al., 1995, Pugin et al., 1999, Taylor et al., 1999; Annecchione, 2000).

Because of the large area and the thickness and complexity of glacial sediments in the ORM area, surface and borehole geophysical surveys have played critical roles in subsurface investigations. An attempt was made to test and apply a wide variety of geophysical techniques to the ORM study; early results were reported by Pullan et al. (1994). This paper examines and evaluates the contributions made by geophysics to the ORM research, provides a summary of the major results, and assesses each technique's potential application to similar investigations in other regions.

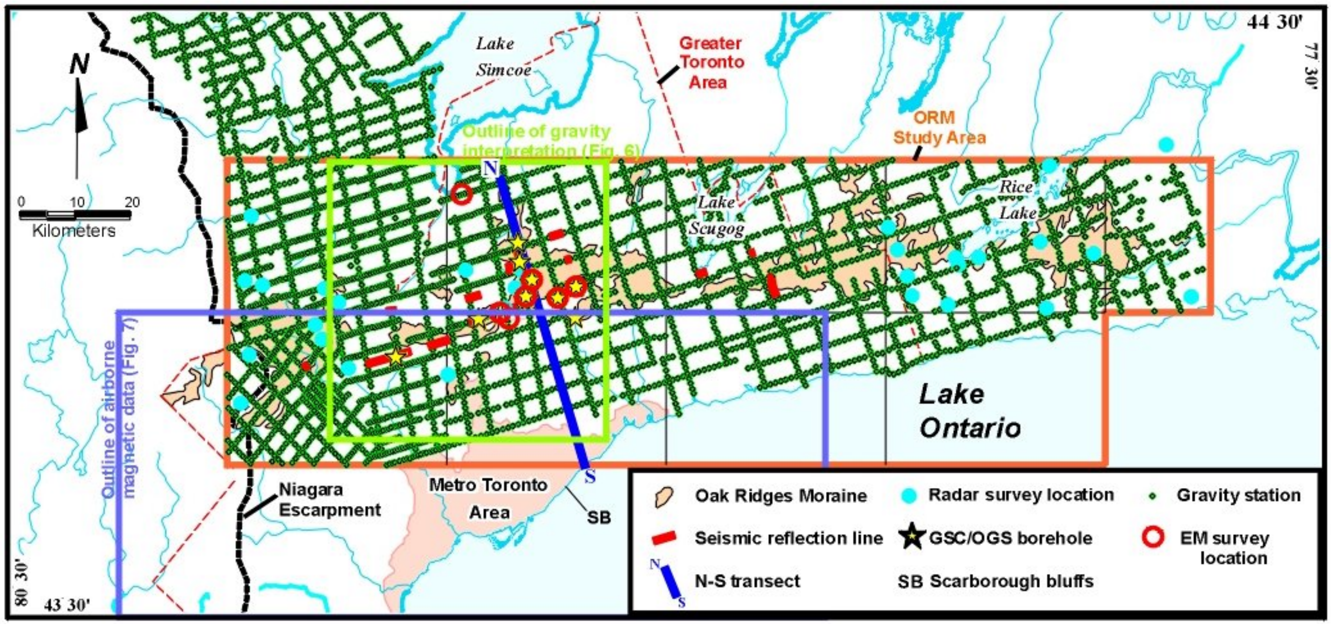

Figure 1: Map showing the location of the geophysical surveys conducted in a regional hydrogeological investigation of the ORM area. The north-south (N-S) transect is the cross-section shown in Fig. 2.

GEOLOGICAL SETTING

The Oak Ridges Moraine is a sandy, glaciofluvial-glaciolacustrine landform complex deposited, primarily by meltwater processes rather than active ice processes (e.g. Sharpe and Cowan, 1991; Barnett et al., 1998), near the margin of the Laurentide Ice Sheet towards the end of the last major glacial advance (Late Wisconsinan: 25,000 to 12,000 years BP) (Karrow, 1989; Barnett et al., 1998). It extends approximately 160 km east from the Niagara Escarpment, and is up to 20 km wide (Fig. 1); its crest is approximately 250 m above Lake Ontario (Fig. 2). The last major ice advance deposited a thick widespread till sheet (Newmarket Till), which appears to be continuous under the ORM (Gwyn and Cowan, 1978). Where this till sheet is exposed north of the ORM, it forms NE-SW trending drumlins that are dissected by a network of channels (Barnett, 1995). The ORM rests on this eroded terrain and underlying older sediments (lower deposits) that are related to the thick, tabular sediments exposed at Scarborough Bluffs (e.g., Karrow, 1967) (Fig. 2). The total package of Pleistocene sediments can reach thicknesses of up to 200 m, and is underlain by Palaeozoic shales and carbonates.

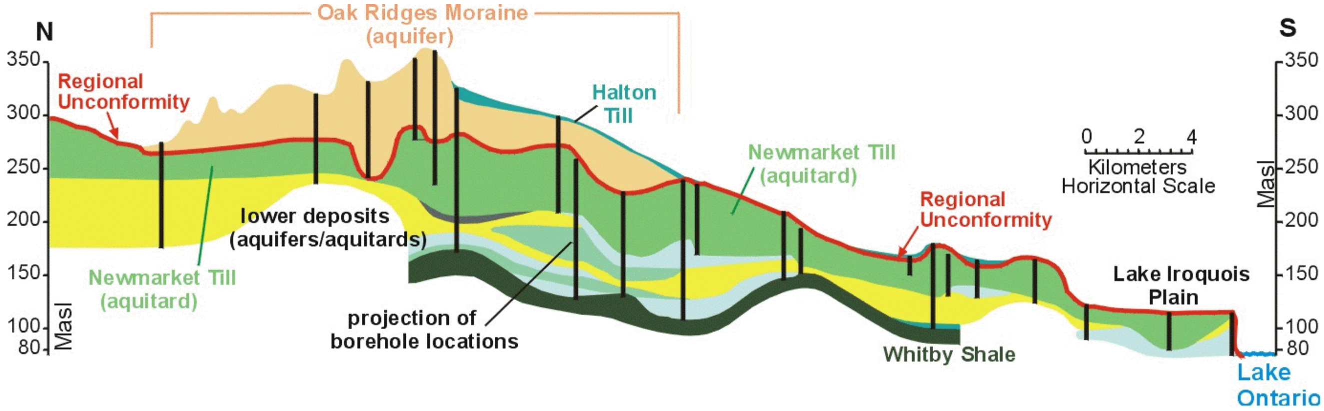

Figure 2: North-south schematic cross section from south of Lake Simcoe to Lake Ontario, based on high-quality borehole data, showing major elements of the geological/hydrogstratigraphic model of the Oak Ridges Moraine area (adapted from Sharpe et al., 1994).

A conceptual geological model has been developed for the glacial deposits of the ORM area (Sharpe et al., 1996; Sharpe and Barnett, 1997). The model emphasizes the extensive nature of the Newmarket Till, and the importance of channels eroded into or through the Newmarket Till beneath the Oak Ridges Moraine (e.g. Fig. 2). The Newmarket Till is a regional aquitard that separates the largely-unconfined ORM aquifer from underlying aquifers found within the lower deposits. Although there is vertical leakage through the till (Gerber and Howard, 2000), where the Newmarket Till is eroded, there is the potential for greater hydraulic connection between these aquifers (Desbarats et al., in press). Thus, the Newmarket Till plays a crucial role in the regional hydrostratigraphy, and much of the work of this ORM project was aimed at delineating this unit.

OBJECTIVES

The Geological Survey of Canada (GSC) in conjunction with the Ontario Geological Survey (OGS) and local regional municipalities, has conducted a multi-year, multi-disciplinary, regional geological and hydrogeological study in the Oak Ridges Moraine area. The primary objective of this work was to identify and assess the geological factors and the stratigraphic elements which influence groundwater flow and the distribution and size of groundwater resources.

The goals of the geophysics program were:

1) to map subsurface structure and stratigraphy to contribute to the development of a regional geological model;
2) to improve the understanding of bedrock topography in the area, and especially to identify channels or topographic highs in the bedrock surface which can influence the distribution of groundwater resources;
3) to enhance the value of boreholes by providing physical properties through borehole logging;
4) to test a wide range of geophysical techniques and demonstrate the value of geophysical investigations to this project and to similar future studies.

Geophysical surveys, used in conjunction with ground truth provided by boreholes, extend our understanding of the subsurface structure into two- or three-dimensions on a wide variety of scales. This fundamental information contributes greatly to the understanding of geological structures which influence groundwater resource potential.

GEOPHYSICAL SURVEYS

The geophysical techniques that were tested and applied in the ORM study are listed in Table 1 along with their particular survey objectives. A brief discussion of data acquisition and results of each of the surveys follows below. The discussion ranges from detailed borehole measurements (sub-metre scale of investigation) to broad regional surveys (e.g. gravity, airborne magnetics).

Table 1: Geophysical surveys applied in the ORM study, their survey objectives, surveys completed, and scale of investigation.

Geophysical Technique	**Survey Objectives**	**Surveys completed**	**Scale**
Downhole			
Natural gamma, conductivity, magnetic susceptibility	lithology; borehole-to-borehole correlation of stratigraphic units	11 stratigraphic boreholes	sub-metre
Gamma-gamma	estimate density variations downhole	7 stratigraphic boreholes	sub-metre
Temperature	indications of groundwater flow	38 boreholes/water wells	sub-metre
Seismic velocity	lithology; velocity control for seismic reflection survey	11 stratigraphic boreholes (P-wave) 1 stratigraphic borehole (S-wave)	metre
Surface			
Ground probing radar (GPR)	high-resolution, near-surface (0-20m) structural/sedimentological mapping map water table	20 line-km at 25 sites	m-10's m
Electromagnetic (TDEM soundings)	estimate depth to bedrock	testing only - 6 sounding sites plus one 8-sounding profile	10's-100's m
Shallow seismic reflection profiling	subsurface structure - bedrock topography, overburden stratigraphy	50 line-km of land-based CMP profiling	10's-100's m
Gravity	regional bedrock topography	>5500 stations @ ~1x4 km spacing	100's m - kms
Airborne			
High-res. magnetics	Precambrian bedrock structure	82,000 line-km in total, ~30% in ORM study area	100's m - kms

DOWNHOLE SURVEYS

Downhole geophysical logs provide a remote means of characterizing and identifying stratigraphic units based on variations in their physical properties. In this way, geophysical logs can be used to supplement geological drill logs and cores, and often allow detailed lithologic and stratigraphic information to be obtained from non-sampled boreholes. Identification of geophysical "markers" allow correlation between boreholes and with surface geophysical methods.

An extensive suite of downhole geophysical logs have been acquired in eleven deep, continuously-cored boreholes drilled in the ORM area by the Ontario Geological Survey (Barnett, 1993) and the Geological Survey of Canada (Fig. 1). The logs include natural gamma, induced conductivity, and magnetic susceptibility logs acquired with a Geonics EM-39 system, and spectral gamma-gamma (using an uncollimated Cobalt-60 source) and temperature logs acquired with an IFG system. Downhole seismic velocity logs were acquired with a hydrophone (P-wave) or a 3-component, well-locking geophone (S-wave) array and a surface seismic source. Details on the measurements, their radii of investigation and the practical interpretation of these logs are given in Table 2 . The reader is referred to Douma et al. (1999) for further details on the GSC logging systems, and to Hunter et al. (1998) for a complete discussion of the downhole seismic logging system and data analysis.

Table 2: Details on the measurements and interpretation of geophysical logs acquired in the ORM study.

Geophysical Log	Quantity Measured	Radius of Investigation	Practical Interpretations
Natural gamma	Number of gamma rays (produced by decay of K, U, Th)	0.3 m	grain-size (high counts associated with K in clay minerals)
Conductivity	Quadrature component of magnetic field induced by alternating magnetic field in transmitter coil	1-1.5 m	grain size (grain conductivity) and/or porewater conductivity
Magnetic susceptibility	In-phase component of above	0.3 m	magnetite concentration (lithology)
Spectral gamma-gamma density	Number of gamma rays returned to probe due to Compton scattering	0.3 m	water table, relative soil density
Spectral gamma-gamma ratio	Ratio of high-energy/low-energy gamma counts	0.3 m	variation in heavy mineral content, void ratio, or moisture content
Temperature (Temperature gradient)	temperature (+/-0.005^{o} C) (temp. gradient = dT/dz)	within borehole	thermal history (equilibrium T), lithology (as related to thermal conductivity), anomalies due to groundwater flow
Seismic velocity (P-wave)	arrival times of seismic signal from surface (determination of velocity)	metres	variation in lithology, compaction, identification of reflecting horizons
Seismic velocity (S-wave)	arrival times of seismic signal from surface (determination of velocity)	metres	variation in lithology, compaction, identification of reflecting horizons

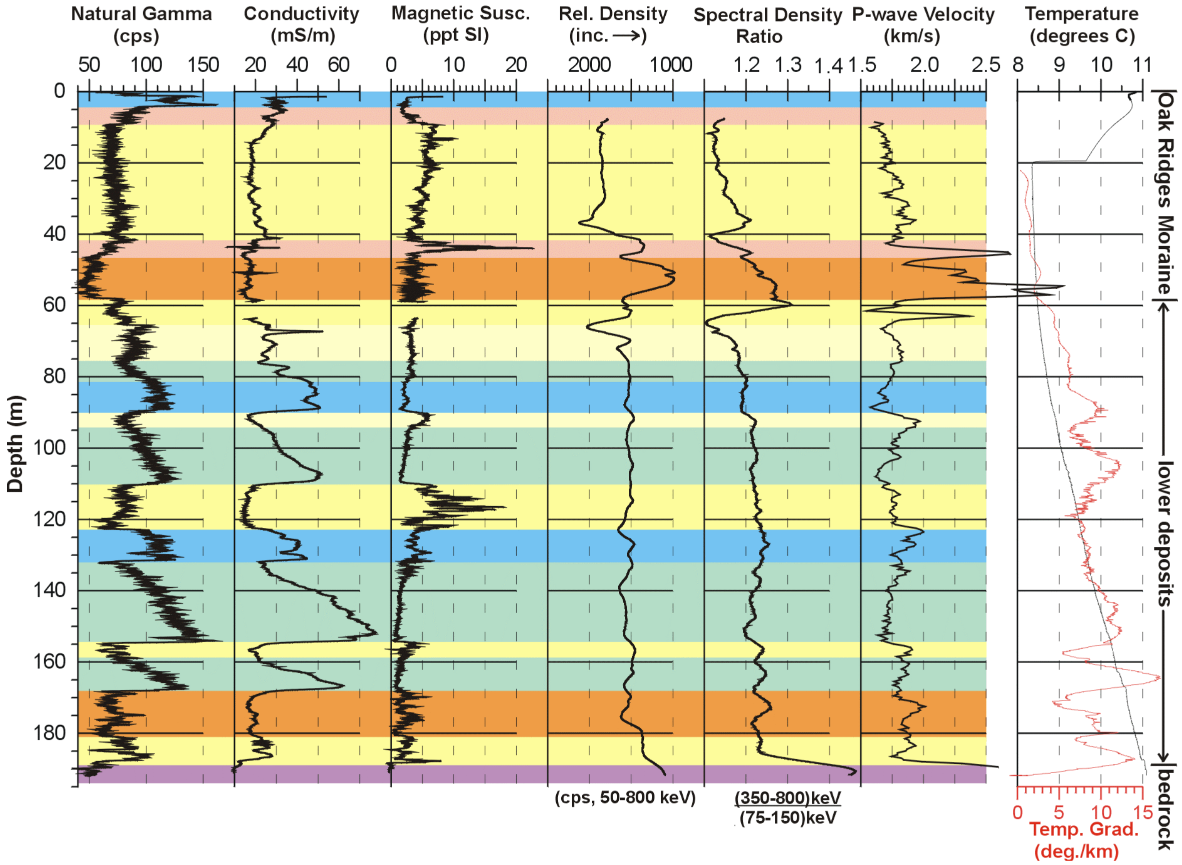

Figure 3: Suite of geophysical logs obtained in borehole GSC-BH-NOB-01. The colour bars show interpreted silty units (blue), fine-sands (light yellow), sands (yellow), coarse sands-gravel (orange), coarsening-upward sequences - silt-sand (green), fining-upward sequences - sands (pink), and bedrock (purple). Velocities in excess of 2000 m/s are associated with the gravel sequence at 45-60 m depth.

Figure 3 shows the logs obtained in the deepest and most westerly stratigraphic borehole (Fig. 1), and they clearly delineate the varying lithologies encountered in this borehole. At this site (Nobleton borehole), the ORM sediments (0-60 m) lie above a complex sequence of lower deposits which are characterized by a distinctive set of coarsening-upwards units which can be correlated across much of the northwestern survey area (Fligg, 1983). No Newmarket Till was encountered in this hole.

However, logs from other boreholes in the central study area (e.g. Pullan et al.1994; 2000) typically do not exhibit the variation in natural gamma and conductivity that can be used to identify varying lithologies in the Nobleton borehole (Fig. 3). In fact, despite its hydrostratigraphic importance in the ORM area, the Newmarket Till has proven to be difficult to differentiate from the overlying ORM sediments or the underlying lower deposits on the geophysical logs usually used for stratigraphic correlation (natural gamma, conductivity and magnetic susceptibility).

In contrast, the P-wave velocity logs obtained from the downhole seismic surveys clearly identify the Newmarket Till as a unit characterized by a high seismic velocity (>2500 m/s; e.g. Fig. 3 of Pullan et al., 2000). Both overlying and underlying sediments are characterized by significantly lower velocities, except for some gravel layers where velocities are greater than 2000 m/s (e.g. Fig. 3), and some basal till units where velocities of 2000-3000 m/s have been observed. The velocity logs also show that seismic velocities can be used as lithologic indicators (note, for example, velocities increase with increasing grain-size in the coarsening-upwards sequences in Fig. 3). Thus, within the Oak Ridges Moraine area, compressional wave velocity can be used as a lithologic indicator, and it is a more diagnostic indicator of the Newmarket Till than several other geophysical logs. The velocity logs from a north-south borehole transect across the ORM (Pullan et al., 2000) show that the Newmarket Till (as indicated by velocities greater than 2500 m/s) can be traced over distances of tens of kilometres beneath the moraine and that the unit reaches thicknesses of more than 50 m. In some holes, there is little or no indication of high velocities (or high velocities are associated with gravels; e.g. Fig. 3) and Newmarket Till is either thin or absent.

SURFACE SURVEYS

Ground probing radar

Twenty line-km of GPR surveys were acquired at 25 sites in Oak Ridges Moraine study area, primarily in glaciofluvial sand and gravel deposits. These resistive coarse-grained deposits often have a water table within 20 m of the ground surface, and are ideal for mapping with ground penetrating radar, especially in areas not capped with till (Pilon et al., 1994; Pullan et al., 1994). Signal penetration was generally possible to depths of 15 m (using 50 MHz antennas). Details of the survey parameters may be found in Pilon et al. (1994). The main aim of these surveys was to map the water table and to provide information on sediment genesis and structural architecture. In many cases GPR survey lines were run within, or immediately above, exposures in aggregate quarries, allowing direct correlation between the radar record and exposed sedimentary structure.

The sites investigated are dominated by coarse-grained materials, where structure is often differentiated on the basis of changes in grain size and their moisture content (Pilon et al., 1994). These physical contrasts are ideally suited for providing the distinctive electrical contrasts that result in radar reflectors (van Overmeeren, 1998). Of structural interest is the delineation of dipping foreset beds (e.g. Fig. 4), subparallel reflectors from sand beds, scour and fill features, lateral textural variations, areas with large boulders, and wavy discontinuous bedding. The variability of reflector geometry and continuity within several profiles may reflect the scale of depositional or erosional processes. In many cases the water table was clearly visible on the radar profiles (e.g. Fig. 4), making this a potentially useful technique for mapping water table over large areas. Mapping the water table in coarse-grained materials is aided by the general lack of a capillary fringe. The GPR data had limited signal penetration in areas with fine-grained diamicton near the surface, even where this unit was thin (1-2 m) and coarser materials were present at greater depths.

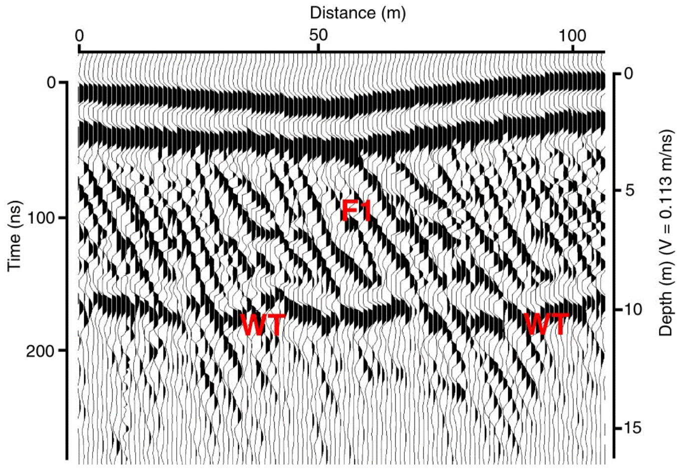

Figure 4: Example GPR profile from an aggregate pit in the eastern survey area (Hope Township) showing foreset bedding to depths of ~15 m below surface (Facies 1 - F1). The large-amplitude, flat-lying reflector at 10 m depth is the water table (WT). Signal penetration below the level of the water table is apparent in some locations along the profile.

Electromagnetic

Time-domain electromagnetic (TDEM) soundings were conducted on a test basis to evaluate the potential use of this technique for estimating the depth to bedrock beneath the ORM. Shales underlie much of the survey area, and their low resistivities were thought to be a good target for electromagnetic methods. Soundings were carried out at 6 borehole locations where there was some information on the depth to bedrock, and along one 500 m east-west profile (8 soundings) on the southern flank of the moraine (Fig. 1), using an 80 m square transmitter loop and a central receiver coil (Todd et al., 1993). Commercial software (TEMIXGL, Interpex Ltd.) was used to invert the recorded decay curve into a geoelectric sounding or profile. With these data acquisition parameters, the results tended to underestimate the depth to bedrock (Pullan et al., 1994), likely due to the large target depths (~150m) as compared to the transmitter loop size, and the presence of fine-grained deposits (also low resistivity) overlying bedrock in the area. Larger loop sizes would be required to improve the resolution at depths greater than 100 m and allow more accurate determination of the depth to bedrock. However, in this fairly developed and urbanized area, there was considerable difficulty in finding suitable sites to carry out such soundings and as a result TDEM surveys were not pursued further.

Shallow seismic reflection profiling

Shallow seismic reflection profiling comprised a major component of the geophysics program carried out in the ORM project because of the complex subsurface architecture and the importance of the regional unconformity. Over 50 line-km (Fig. 1) of 12- or 24-fold data were recorded using instantaneous-floating-point engineering seismographs with single 50 Hz geophones at 5 or 6 m spacing, and a 12-gauge in-hole shotgun source. Line locations were chosen on the basis of an extensive series of single-ended test spreads collected throughout the study area. Reflection data quality varied considerably depending on the surface conditions. Good to excellent data were obtained in areas with fine-grained surface sediments and a shallow water table, but attenuation of high-frequency signals was often severe in dry, coarse-grained ORM sediments where the water table was several metres below surface (e.g. Pullan et al., 1994). Details of the data acquisition, processing and interpretation may be found in Pugin et al. (1996, 1999). Variable near-surface conditions made the careful application of static corrections a critical component of the data processing (Pugin and Pullan, 2000).

The seismic reflection sections provide a means of investigating the subsurface architecture and stratigraphic relationships of sediments beneath the ORM. Detailed seismic facies and architectural element analyses of representative 1-3 km seismic sections have been presented in Pugin et al. (1999).

In this paper, a compilation of ~10 line-km of seismic reflection profiles (east-west lines in the most westerly portion of the ORM; see Fig.1) are shown at a compressed horizontal scale (4-trace horizontal stack) to show the regional subsurface architectural structure (Fig. 5). The east side of this profile is dominated by a high-amplitude reflector with variable topography (210-260 masl) which is interpreted as the surface of the Newmarket Till. This reflector is missing across much of the west side of the profile where a large (>3 km wide) channel feature is interpreted. The channel erosion appears to have removed the Newmarket Till and the underlying lower deposits to depths of ~150 m (close to the bedrock surface). The small-scale reflection character within the channel fill is chaotic and discontinuous, and the nature of the chaotic facies is still unknown (Pugin et al., 1999). The borehole in the centre of this profile (see logs in Fig. 3) encountered ~15 m of gravel above the erosional unconformity and a thick sequence of lower deposits above limestone bedrock, though the bedrock in this area is predominantly Whitby Shale. The limestone is clearly visible on the seismic profile as a high-amplitude reflector within a bedrock low that can be traced ~1.5 km in an east-west direction. On either side of this low, where erosion has not completely removed the shale, the bedrock surface offers a much smaller velocity contrast with the overlying glacial sediments and as a result the bedrock reflection is less well defined. The eroded bedrock surface in this area is believed to be the bed of the Laurentian channel system (e.g. Spencer, 1881; Brennand et al., 1997).

Thus, this seismic reflection profile reveals a complex set of large-scale channel systems - a preglacial bedrock channel and a younger (post-Newmarket Till) channel within the glacial sediments. Knowledge of the locations, dimensions and architecture of these features allows geological and hydrogeological interpretations regarding the nature and distribution of aquifers and aquitards as well as possible interconnections between aquifers.

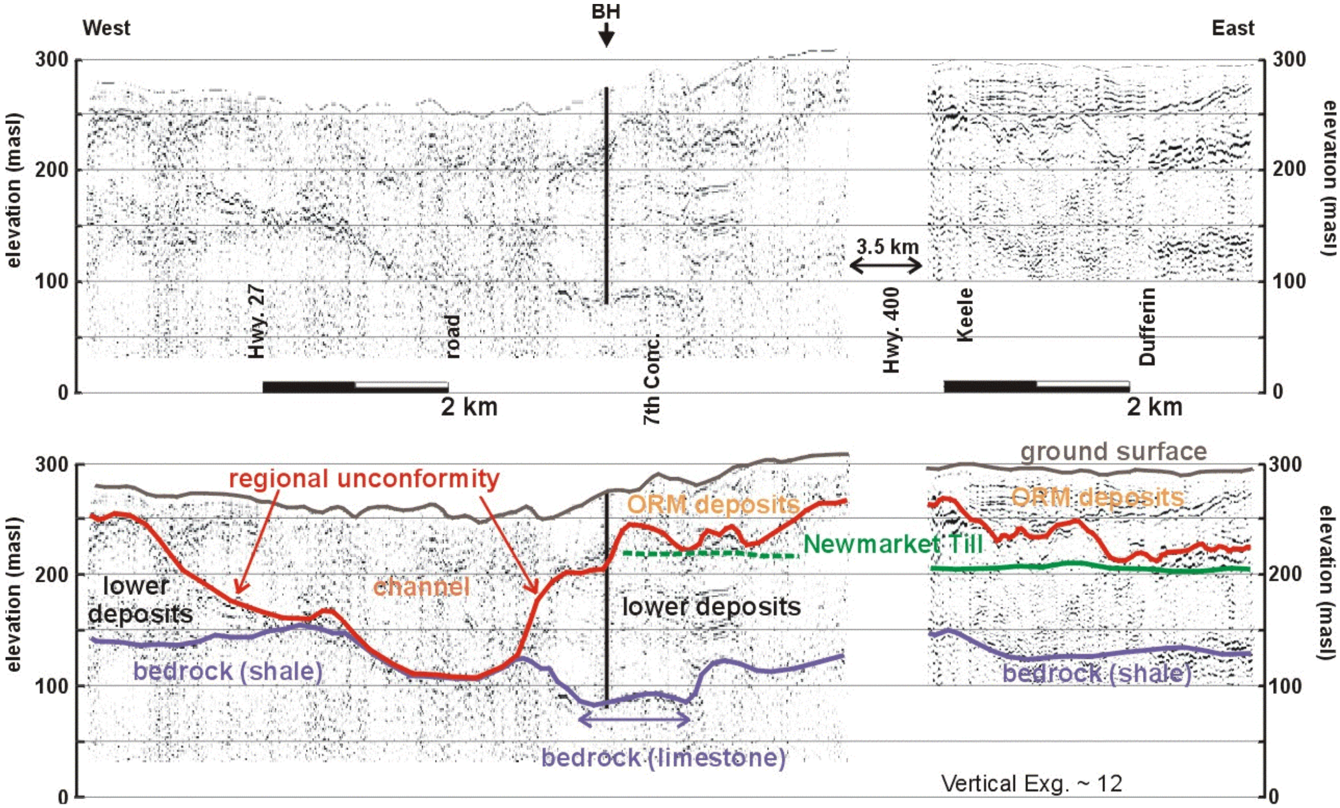

Figure 5: Approximately 10 km of 12-fold CMP reflection profiling data along an east-west profile across the central-western portion of the ORM study area showing the variable topography on the Newmarket Till surface and a large-scale channel feature within the glacial sediments. Logs from the borehole are shown in Fig. 3.

Gravity

Gravity data were collected over the entire ORM survey area in three surveys completed between 1994 and 1996. These data were acquired to provide regional 2D information on bedrock topography. The complete dataset totalled 5681 measurements, with an average maximum error in the gravity measurements of 0.066 mGal, and an average error in station elevation of 1 m (station elevations primarily determined by altimeter measurements). From the raw gravity data, the Bouguer anomaly was calculated using a value of 2.09 g/cm^3 for the average density of the material above the reference ellipsoid. The Bouguer anomaly was then de-trended and kriged to obtain a regular grid with 250 m spacing. The regional gravity field was obtained by upward continuing the Bouguer anomaly to an altitude of 6 km. The residual gravity field was calculated by subtracting this regional field from the Bouguer anomaly (Annecchione, 2000). This procedure served to attenuate signals originating below the Precambrian basement.

Two algorithms were used to invert the residual gravity field. The first is based on the model of a Bouguer slab with topography and a uniform density contrast with overlying material (Parker, 1973; Oldenburg, 1974; Annecchione et al., 2001). The second algorithm utilizes a subsurface volume divided into a 3D grid. The inversion calculates cell densities thus providing a density distribution (Boulanger and Chouteau, 2001). Bedrock topography is obtained from the density distribution by extracting the surface passing through the cells having the estimated bedrock density, 2.6 g/cm³ (Annecchione et al., 2000).

Figure 6 shows inversion images (Fig. 6c,d) obtained for a 50 km by 50 km window in the south-west portion of the moraine (Fig. 1) compared with a bedrock elevation model derived from boreholes (Fig. 6a,b). This window was chosen because borehole coverage providing depth-to-bedrock information is good. Both inversion techniques result in similar structures, but the interpreted relief on the bedrock surface resulting from the topographic inversion (Fig. 6c) is considerably greater than that observed in the borehole model (Fig. 6b), or obtained from inversion for density distribution (Fig. 6d). This is because the topographic inversion requires that the signal be explained entirely by bedrock topography, while the density inversion allows for several structures (e.g. layers whose density increases with depth). Extracting the 2.6 g/cm³ iso-surface from the inverted density distribution isolates a structure contributing to only part of the observed residual field.

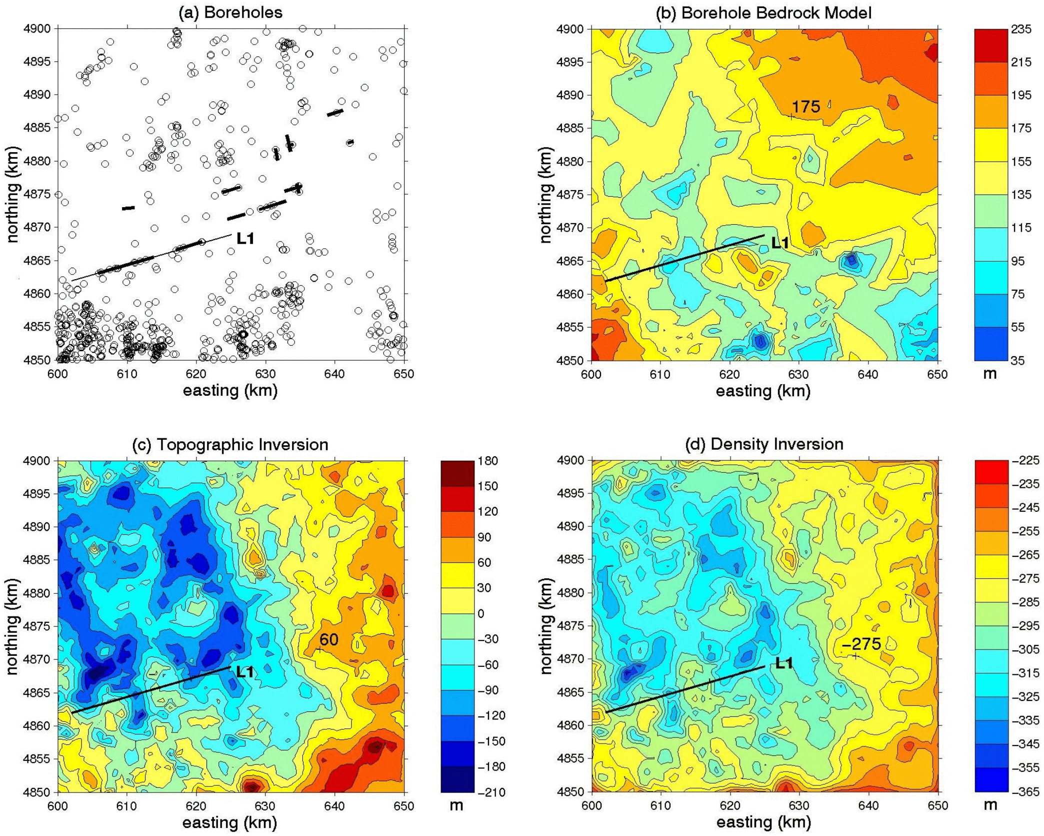

Figure 6: Comparison of inversion results with borehole model in a 50 by 50 km window. Short bold lines in (a) are seismic profiles. L1 is a gravity modelling profile (Annecchione et al., 2000). (b) Bedrock elevation with respect to mean sea level obtained from borehole data. (c) Inverted bedrock topography about datum 250 m below average ground surface (= 236 masl). (d) 2.6 g/cm^3 density iso-surface extracted from inverted density distribution. Depths in metres are measured from average surface elevation datum (236 masl).

Large-wavelength structures, such as the bedrock low trending to the northwest across the window, are present in both inversions, and in the borehole data. The gravity inversions indicate that the low may actually separate into two channels in the western half of the window. This feature is poorly resolved in the borehole model (Fig. 6b), but this may be a result of the relatively few bedrock depths available in this central area. The south-east corners of the borehole model and the gravity inversions are anti-correlated. This may be explained by the presence of a body below the bedrock surface whose gravity effect was not filtered from the Bouguer anomaly.

Generally, the bedrock topographies resulting from inversion are more detailed than the borehole model, due to the finer and more regular sampling of the gravity surveys as compared to the borehole distribution. The inversion results suggest that this method could be extended to areas where the borehole distribution is too sparse to allow estimates of the bedrock topography to be derived, though at present the results are uncalibrated. Thus the application of gravimetry to regional mapping of bedrock topography shows promise, though some aspects of the present gravity interpretation must be improved before absolute depths can be derived (e.g. including the effect of surface topography in the inverse calculations). In terms of data acquisition, improving the accuracy of station elevation measurements to within 10 cm using differential GPS would improve certainty in the Bouguer anomaly values to within 0.02 mGal.

AIRBORNE SURVEYS

High-resolution magnetics

In 1998 the Geological Survey of Canada, Ontario Power Generation and the Multi-Disciplinary Center for Earthquake Engineering Research acquired a new survey of over 82000 line-km of total field aeromagnetic data in the area of Lakes Ontario and Erie, a portion of which covers the southwestern corner of the ORM project area (Fig. 1). This area of the survey has a high-resolution, down-line sample spacing of 20 m, with an east-west flight line separation of 400 m; north-south control lines were flown at a separation of 5000 m. Mean terrain clearance was 150 m, except in urban areas where it was increased to 300 m. Navigation was accomplished through an on-board differential GPS. The data have undergone removal of the International Geomagnetic Reference Field and manual video editing to eliminate core and anthropogenic sources.

These data were acquired to investigate Precambrian structure, but also contain information from shallower depths. Some particular features related to shallow structures were observed in the original data and a hypothesis as to their possible origin is discussed below.

Figure 7 displays a portion of the residual total field magnetic data, over which, a bedrock Digital Elevation Model (DEM) – determined from borehole data – is plotted. The data show a number of northwest-southeast striking features that are generally curvilinear and, at times, discontinuous (yellow arrow indicates an example anomaly). An important observation is that these features are of short wavelength, indicating that they are, most likely, closer to the surface than the surrounding broader wavelength anomalies. It is suggested here that these anomalies arise from within the sedimentary package (i.e. Paleozoic and Quaternary sequences) rather than from the Precambrian surface. Specifically, it is suggested in this work that the source of the anomalies is found within gravel filled channels of Ordovician-age shale bedrock.

There are several lines of support for this hypothesis. Firstly the Ordovician DEM over the magnetic field (Fig. 7) indicates a spatial association between bedrock channels and many of the curvilinear features in the magnetic data. In fact, the greatest density and best defined of these magnetic features are along the paleodrainage system of the Laurentian channel. Secondly, it is important to note that the majority of these features follow some portion of present-day drainage patterns but generally not the entire length. Finally, forward magnetic modelling (Fig. 8) of possible channel dimensions and magnetic gravel in-fill derived from borehole and shallow seismic data (Figs. 3,5), agree with the observed magnetic amplitude and symmetry. The main objective of this model is to show that near-surface sedimentary features on this scale (in terms of dimensions and magnetic properties) produce considerable magnetic anomalies that can be detected using airborne methods.

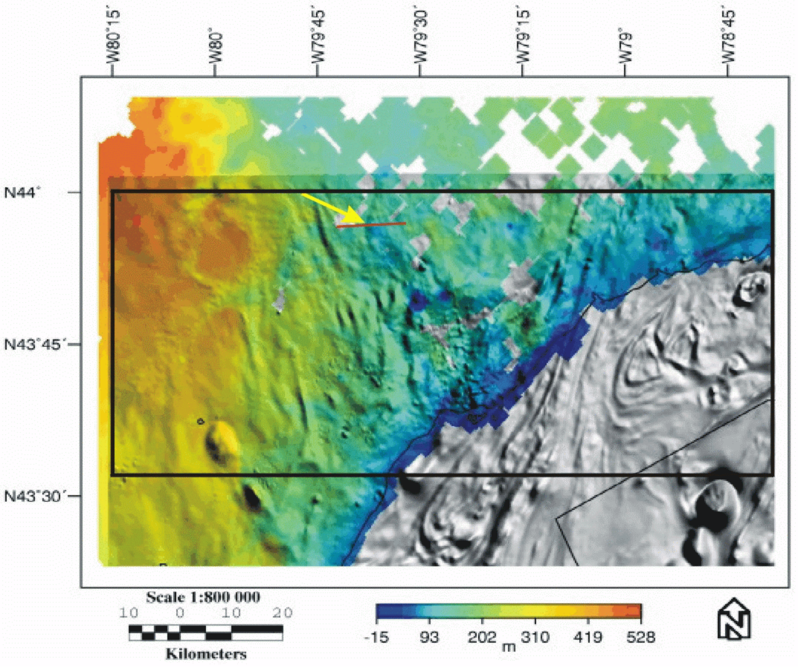

Figure 7: Portion of the aeromagnetic data (greyscale) with a bedrock DEM draped over top (colour). The black box corresponds to the area outlined in purple on Fig. 1. The ***Figure 7:*** Portion of the aeromagnetic data (greyscale) with a bedrock DEM draped over top (colour). The black box corresponds to the area outlined in purple on Fig. 1. The yellow arrow indicates one of the linear anomalies discussed in the text. The red line indicates the location of the data modelled in Fig. 8. yellow arrow indicates one of the linear anomalies discussed in the text. The red line indicates the location of the data modelled in Fig. 8.

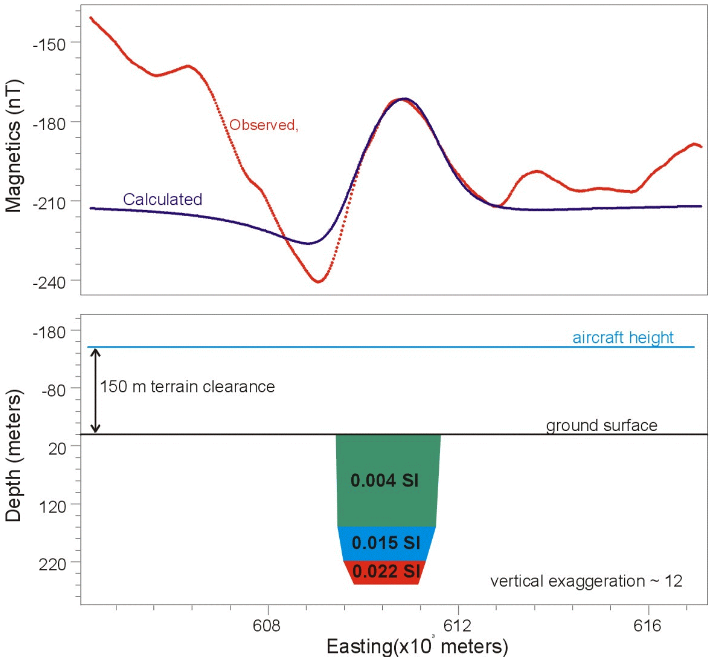

Figure 8: Magnetic forward modelling of a channel feature. The observed aeromagnetic data (a)comes from the line shown in Fig. 7; the calculated values (a) are for the magnetic model shown in (b). The central area of the magnetic profile data can be explained as a channel anomaly, and the amplitude (up to 65 nT) and asymmetric shape agrees with the measured data.

DISCUSSION AND SUMMARY

This paper has presented an overview of the various geophysical techniques that have been applied to the ORM regional geological and hydrogeological project. Geophysics has played a critical role in the study, in part because the size of the study area, the complex glacial stratigraphy and the thickness of unconsolidated sediments make dependence on borehole information impractical. But as well, geophysics has the potential to provide information on the properties and structure of the subsurface that cannot easily or economically be acquired by traditional geological and hydrogeological methods. Some of these have been clearly demonstrated by the ORM study and include:

- identification and delineation of large stratigraphic features (1-10km scale) to establish the regional structural context of the subsurface sediments (e.g. bedrock topography, regional unconformities)
- demonstration of the continuity (or lack thereof) of strata (from m to km scales - e.g. mapping of channels eroded into, or through, the Newmarket Till)
- identification of stratigraphic relationships (from m to km scales)
- demonstration of the scale of variability in physical properties and the provision of quantitative estimates of some properties (e.g. downhole geophysical logs)
- use of geophysical markers to identify geological units and establish stratigraphic correlations (e.g. high seismic velocity of Newmarket Till)
- map of water table (e.g. radar profiles)

The individual contributions of the various geophysical techniques applied in the ORM area are summarized in Table 3. However, in combination, the results have made other substantial contributions to the project. They have played a role in the development and verification of the conceptual geological model of the area, and allowed an assessment of the lateral continuity of major hydrostratigraphic units. The geophysics data have also provided high-quality control for a large set of archival data and significantly enhanced the value of that dataset.

In the Oak Ridges Moraine project, the large study area increased the interest in the potential contributions of regional surveys such as gravity and airborne surveys. The complex subsurface architecture and the importance of the regional unconformity, represented predominantly by the surface of the Newmarket Till, made seismic reflection profiling a particularly useful geophysical technique. Both seismic and radar profiling contributed to our understanding of sediment architecture and genesis.

In contrast, electromagnetic methods were not used extensively in the ORM study. This approach is perhaps surprising for a hydrogeological investigation, where electrical or electromagnetic techniques are commonly used to delineate major hydrostratigraphic units assuming resistive units are aquifers and conductive units are aquitards. However, the sandy Newmarket Till acts as an aquitard due to its compaction, rather than its clay content. Thus, as noted above, the Newmarket Till cannot be readily delineated downhole on the basis of electrical or natural gamma logs, or from the surface in terms of its electromagnetic response.

The ORM experience can help in assessing the potential contributions of geophysics to other similar investigations (Table 3). Geophysical surveys can provide a variety of subsurface information scales varying from the sub-metre to kilometre. Before adopting a geophysical survey program in any regional investigation, it is important to understand a variety of physical properties of the geological/hydrogeological units in the stratigraphic sequence. Downhole geophysical logging (using a suite of tools) can provide some of this information and enhances the value of the boreholes. Surface surveys can provide information on the lateral continuity or variation in stratigraphic units. As the resolution of airborne surveys improves, these surveys may be able to delineate large-scale, near-surface structures.

Table 3: Geophysical surveys applied in the ORM study, a summary of their uses in that study, and their potential uses and primary limitations in other regional studies.

Geophysical Technique	**Applications in ORM study**	**Technique Potential**	**Technique Limitations**
Downhole			
suite of geophysical logs e.g. natural gamma conductivity mag. susceptibility spectral gamma temperature seismic	identification of lithological boundaries identification of Newmarket Till based on high seismic velocity identification of water table correlation between boreholes and with surface surveys	enhanced geol. information from boreholes detailed physical properties (at sub-metre scale) identification of geophysical "markers" regional correlations calibration of surface surveys	requires borehole (PVC-cased for some logs)
Surface			
Ground probing radar (GPR)	mapping water table mapping near-surface structure	mapping water table in coarse-grained sediments detailed near-surface (0-20 m) stratigraphy (extending outcrop-scale mapping into subsurface)	signal attenuation high in conductive materials (e.g. silts, clays)
Electromagnetic	not used extensively	delineation of subsurface electrical structure (e.g. clay aquitards, sandy aquifers)	depends on electrical contrasts in target horizons limited structural resolution
Shallow seismic reflection profiling	delineation of large-scale subsurface architecture identification of erosional surface of Newmarket Till	subsurface architecture (at 10's - 100's m scale)	resolution/data quality dependent on site conditions (poor in dry, sandy soils)
Gravity	assessment of gravity method for mapping regional bedrock topography	improved regional/horizontal resolution of bedrock topography	difficult to separate near-surface gravity signal
Airborne			
High-res. magnetics	mapping buried channels?	improved understanding of shallow regional structures	depends on magnetic properties

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