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Permanent link: https://doi.org/10.4095/332366

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Recommended citation

Dietiker, B., Pugin, A.J.-M., Crow, H., Brewer, K., and Russell, H.A.J., 2024. Geophysical data interpretation for the York University ATES site investigation, Ontario; Geological Survey of Canada, Open File 9076, 1 .zip file. https://doi.org/10.4095/332366

Publications in this series have not been edited; they are released as submitted by the author.

ISSN 2816-7155
ISBN 978-0-660-69198-5
Catalogue No. M183-2/9076E-PDF

Abstract

Aquifer Thermal Energy Storage (ATES) systems have the potential of reducing heating and cooling energy consumption at institutional and commercial scales. ATES systems are popular in Europe, particularly in areas of extensive glacial and post glacial unconsolidated sediment. Southern Ontario shares numerous similarities with such settings. To support an ATES study at York University, Toronto, Ontario, three geophysical datasets were collected i) Microtremor analysis (the horizontal-to-vertical spectral ratio technique, HVSR), ii) seismic reflection, and iii) borehole geophysics. The three techniques provide different scales and resolution of subsurface investigation and form a complementary suite of tools. In areas with thick sediment cover, depth to bedrock estimations often suffer from sparse data. The HVSR technique is a low cost, non-intrusive, rapid approach to estimating depth to bedrock. ATES systems commonly require enhanced information on the succession of surficial geological units, and aquifer geometry and heterogeneity. Seismic reflection data collection can provide insights into all these characteristics and consequently provide greatly enhanced target information for follow-up drilling. The confidence in seismic interpretation can be improved through collection of subsurface information from drilling, either through the combination of drill core logging (sedimentology), core testing, and downhole geophysics. Multiple downhole geophysical data were collected to support i) lithological characterisation (gamma, conductivity, magnetic susceptibility), ii) seismic velocity analysis (p and s-wave), and iii) hydrogeological characteristics (temperature, and porosity using nuclear magnetic resonance). Collectively, the geophysical data can be framed in a basin analysis methodology. This study shows that these surveys can reduce uncertainty - and potentially the cost - of mitigating a poorly understood geological context that could compromise the full potential of an ATES development.

1 Introduction

Aquifer Thermal Energy Storage (ATES) systems have the potential of reducing energy consumption for heating and cooling at institutional and commercial scales (Miecznik and Skrzypczak 2019). ATES systems are popular in Europe, particularly in areas of extensive glacial and post glacial unconsolidated sediment, and are of growing interest globally (e.g., Bloemendal et al. 2015). Southern Ontario (Fig. 1) shares numerous similarities with such settings. The feasibility of ATES installations in southern Ontario has been highlighted by Ford and Wong (2010). A collaborative study on the geological suitability for the development of an ATES system at York University is underway. An outstanding question regards the extent that geophysical techniques can aid and potentially provide cost effective methodologies for preliminary or reconnaissance site investigations. A review of global, and particularly European literature has failed to identify a clear resolution of this question. Preliminarily, site selection techniques have relied on geological knowledge of the area, water well analysis and geological models developed from water well records - an approach championed by Le Grand and Rosen (1998, 2000) to optimize eventual site-specific evaluation. Based on a review of literature, ATES site investigations have focused on drilling that has commonly employed either continuous coring or water well-style borehole development. Individual or even multiple boreholes provide minimal information to advance site characterization as they only provide a two-dimensional perspective on the stratigraphy and lack an ability to define stratigraphic architecture (geometry) and lateral facies continuity. Nevertheless, sedimentologically logged core is an essential component for identification of sedimentary facies and subsequent development of depositional models as practiced in standard basin analysis approaches to exploration in petroleum studies (e.g. Miall, 2000). Some of this information can be inferred from hydraulic testing; however, such information lacks good horizontal and vertical scale information in the absence of a network of observational wells. Additionally, collection of continuous core to depths >100 m can be expensive. Geophysical techniques provide an opportunity to collect an expanded suite of data on bedrock depth, architecture, seismic facies, and physical properties and hence provide a more informative context for subsequent drill site selection.

1.1 Study Objective

This report provides preliminary documentation on surface and downhole geophysical data collected at the York University, Tennis Canada, and Toronto Regional Conservation Authority (TRCA) campuses, near the intersection of Highways 400 and 407 in Toronto, Ontario (Fig. 2). Three geophysical datasets are described: microtremor analysis (the horizontal-to-vertical spectral ratio technique, HVSR), seismic reflection, and downhole geophysical logging. In this report, the emphasis is on documentation of the technical methods and data results with some interpretation.

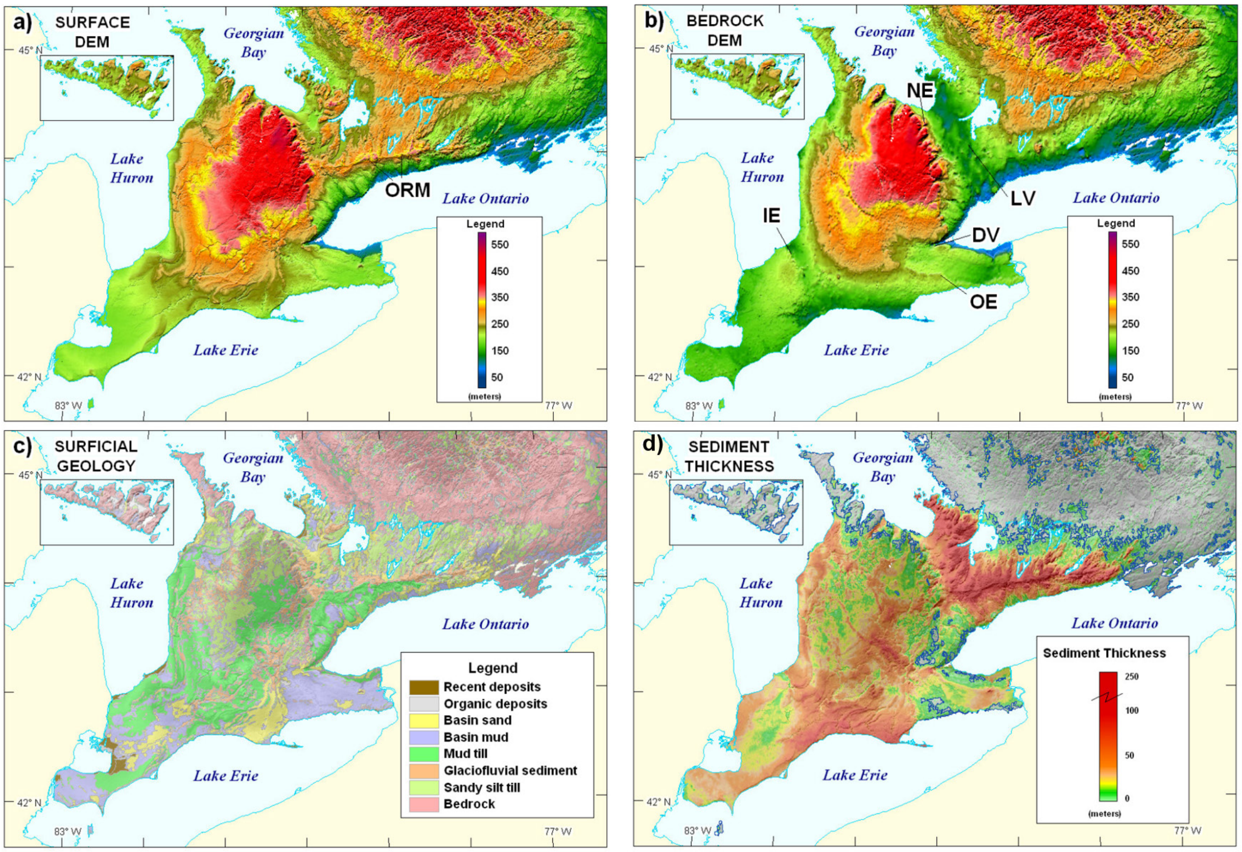

Figure 1. Regional surficial geology context southern Ontario a) Digital elevation model (DEM) of the ground surface. ORM= Oak Ridges Moraine. b) DEM of the bedrock surface. LV= Laurentian Valley, DV= Dundas Valley, NE= Niagara Escarpment, OE= Onandaga Escarpment, IE= Ipperwash Escarpment. c) Simplified surficial geology draped on a ground surface DEM (modified from Barnett et al. 1991; OGS MRD-128). d) Sediment thickness with areas of very thin (<3 m) and no sediment and > 5km^2 outlined in blue. Figure modified from Hinton et al. (2007), landsurface DEM from OMNR (2006), bedrock and sediment thickness from Gao et al. (2006).

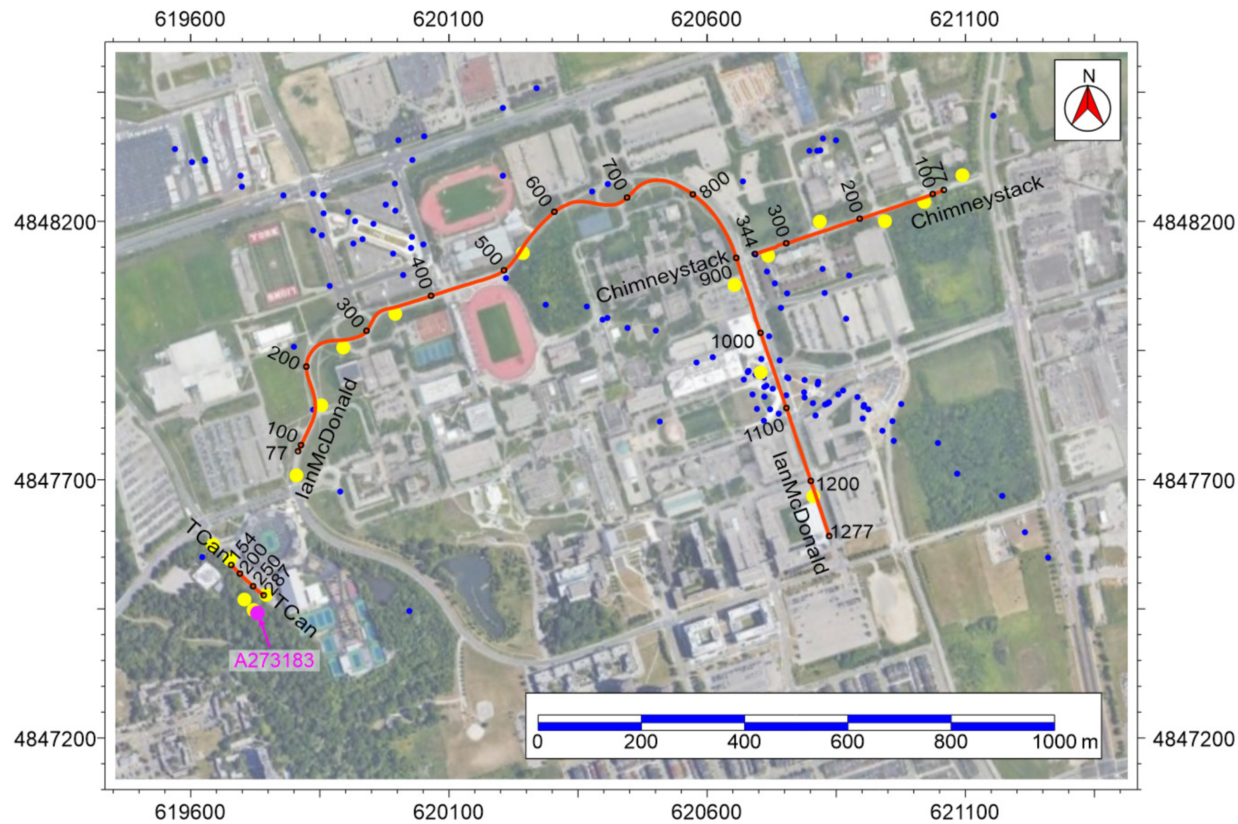

Figure 2. Map of the York University campus study area with the three seismic reflection profiles (red lines with black CMP numbers) and 18 HVSR sites (yellow circles). Dark blue dots represent wells in the Groundwater Information Network (GIN) and Ontario Geological Survey (OGS) databases that provided material (mud, sand, gravel, till) information for the study area. The TRCA observation well (A273183) used for seismic calibration is marked with a pink dot south of the Tennis Canada (TCan) profile. Coordinates are shown in UTM NAD83 zone 17.

2 Geological Setting of Southern Ontario

Southern Ontario is underlain by Paleozoic bedrock buried by Quaternary sediment that can exceed 200 m in thickness (Gao et al. 2006, Figure 3). The buried bedrock surface has a series of escarpments (e.g., Niagara Escarpment) that are flanked to the east by bedrock troughs (e.g., the Laurentian trough). The bedrock surface also has secondary valleys that are smaller in scale and were formed by a combination of fluvial, glacial, and glaciofluvial processes with possible lithologic and structural control (Gao 2011; Russell et al. 2007). In the study area, Georgian Bay Formation shale commonly subcrops beneath a thick cover of surficial sediment.

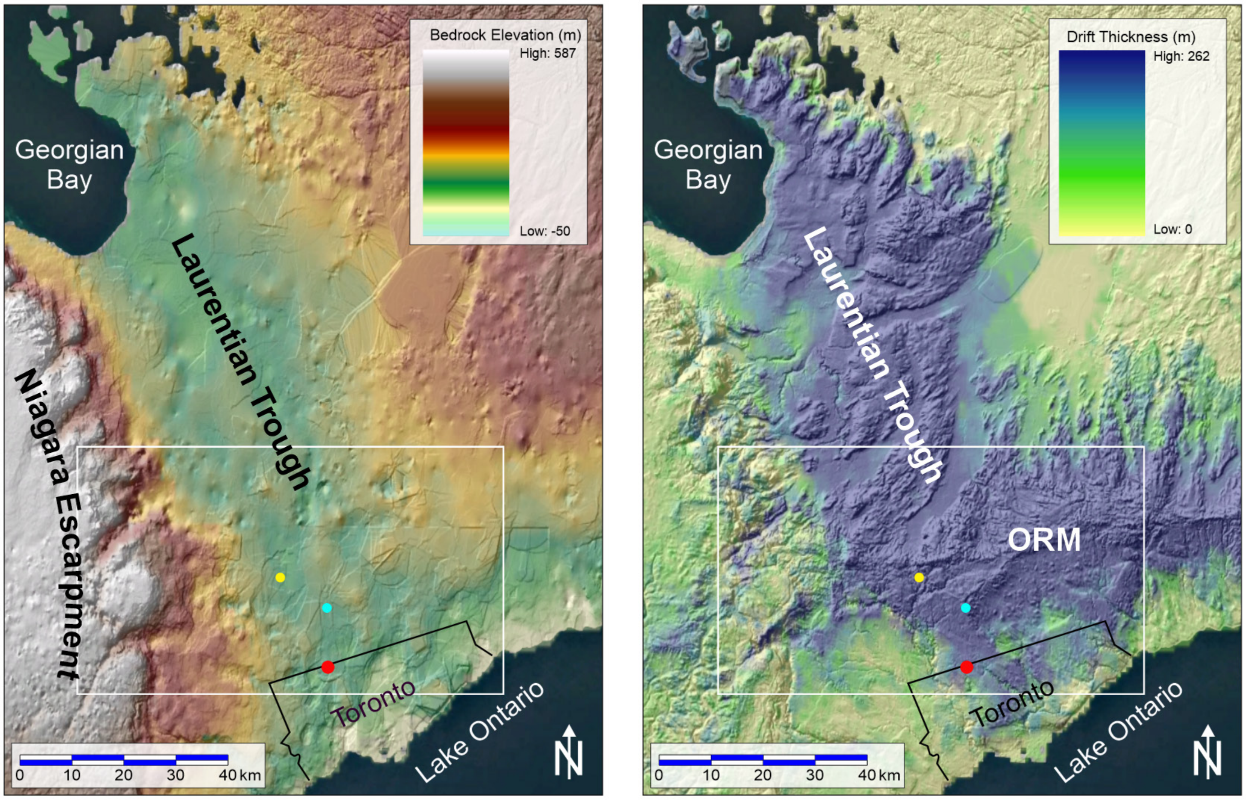

Figure 3. Left: Map of bedrock topography model between Georgian Bay and Lake Ontario with York University location indicated by red circle. Light blue and yellow circles indicate Keele Valley landfill and the Nobleton borehole sites, respectively. Right: Drift thickness model highlighting Laurentian trough and Oak Ridges Moraine (ORM), OGS MRD-207. The white rectangle indicates the area depicted in Figure 5.

The thickest surficial deposits east of the Niagara Escarpment are coincident with the Laurentian trough and the Oak Ridges Moraine (ORM). The Quaternary stratigraphy for the area is presented in Fig. 4. Important sub-Newmarket Till units include Scarborough and Thorncliffe formations (e.g., Gerber et al. 2018). Scarborough sediments are most extensively described at the Lake Ontario bluffs (Kelly and Martini 1986) and Thorncliffe and Scarborough equivalents have been identified in core north to Barrie (Eyles et al. 1985; Mulligan and Bajc 2018). Thorncliffe Formation sediments form up to a 100 m thick sequence across most of the Laurentian trough (Sharpe et al. 2018) and vary from cross-bedded to cross-laminated fine sand and mud at Scarborough Bluffs (e.g., Eyles and Eyles 1983) to thick successions of rhythmites in the Nobleton – Schomberg area (e.g., Logan et al. 2008). Seismic reflection data at Aurora, Nobleton, and Schomberg reveal truncated seismic stratigraphy. Channels truncate tabular Lower sediment with an axial north–south direction and can exceed 2 km in width and 80 m in depth and are likely of Upper Thorncliffe Formation age (e.g., Sharpe et al. 2011; Sharpe et al. 2018; Gerber et al. 2018).

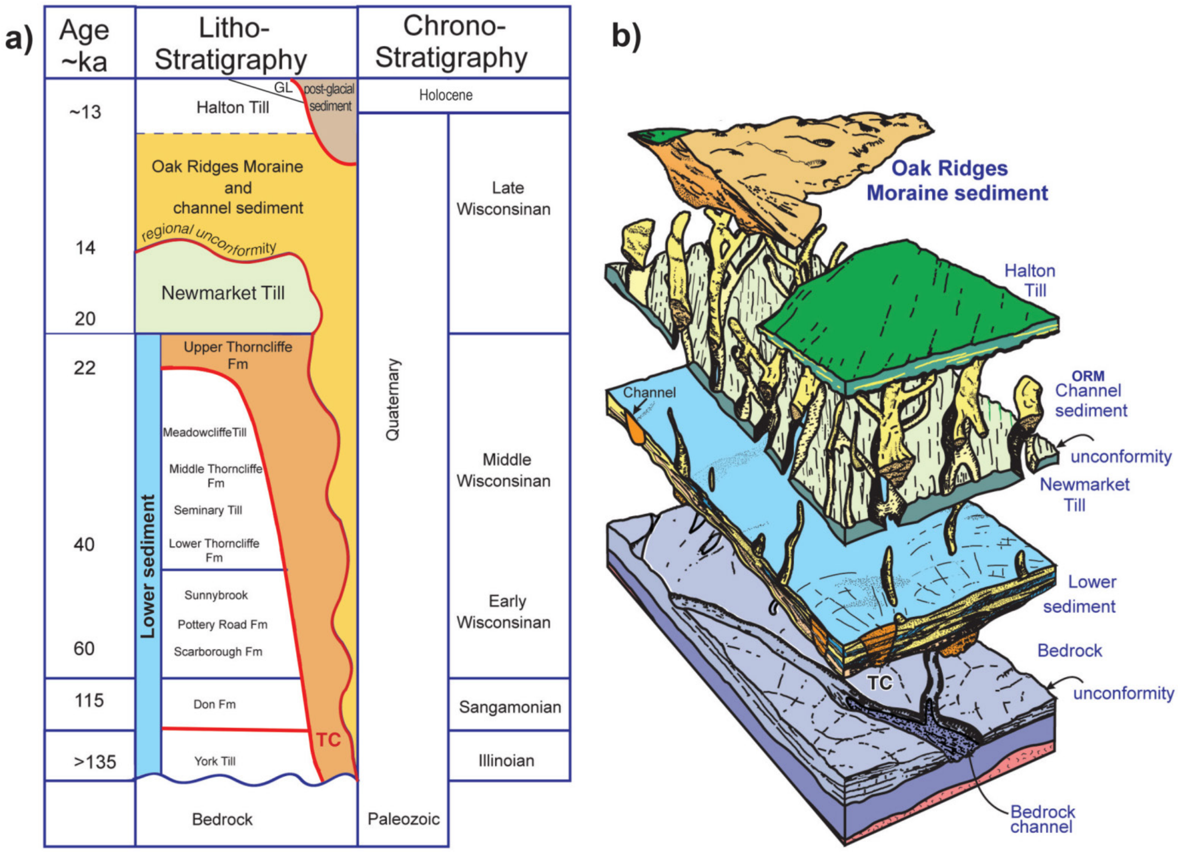

Figure 4. Regional stratigraphy for the York University Oak Ridges Moraine area. From Gerber et al. 2018. The abbreviations TC and GL represent tunnel channel and glaciolacustrine, respectively.

Channel fills consist of fining-upward sequences of gravel, sand, and mud (Sharpe et al. 2011). The regionally extensive Late Wisconsinan Newmarket Till is stratigraphically younger than Lower sediment (Fig. 4) and has a drumlinized and channelized upper erosional surface (Sharpe et al., 1997; Brennand et al. 2006). Newmarket Till can be up to 50 m thick (Boyce and Eyles 2000). It is very dense to the south of the ORM where it forms a regional seismic marker horizon with seismic compressional (P) wave velocities exceeding 2000 m/s (Pugin et al. 1996). The drumlinized surface of Newmarket Till (Fig. 4) and valleys, (subglacial ORM (tunnel) channels - TC) form a regional unconformity). The unconformity channels locally truncate Newmarket Till and Lower sediment (Pugin et al. 1999) and are mapped as features linked to the ORM (Russell et al. 2004). This unconformity is overlain locally by thick ORM channel, ridge, and fan sediments (Fig. 4), which extend from the Niagara Escarpment eastward to Trenton (Sharpe et al. 2007). ORM sediment is generally a productive aquifer consisting of 50–100 m thick silt, sand, and gravel with only minor clay and diamicton (Sharpe and Russell 2023). Along the flanks of the ORM, muddy lacustrine-rich Halton/Kettleby tills form the final episode of moraine sedimentation (Sharpe and Russell 2016). Adjacent to the ORM, glaciolacustrine sand and silt were deposited in post-glacial lakes.

Of particular import to the York University setting is recent understanding of the Yonge Street Aquifer (YSA, Fig. 5; Gerber et al. 2018) which may provide paleogeographic context. That is, deposits beneath the Newmarket Till at York University may be analogous to those in YSA which contain channel fills within a glaciolacustrine basin.

2.1 York University Setting

York University is located to the southwest of the intersection of Steeles Avenue and Keele Street in the city of North York (Fig. 2). The campus is bounded to the west by Black Creek and covers an area of approximately 2 km^2 (~500 acres). The campus is situated 195 to 200 metres above sea level, and slopes gently to the west. The north edge of campus is located approximately 8 km south of the Maple Spur of the Oak Ridges Moraine and the former Keele landfill site. Context on the sediments in the region are provided by Golden Spike boreholes in the area which include Earl Bales, approximately 6 km to the south-east and Kleinburg, ~16 km to the north-west, sites which have basin sediments below Newmarket Till (Sharpe et al., 2013). The site is located south-southwest of an area characterized as the Yonge St Aquifer (Gerber et al. 2019), which appears to be part of a channel network that yielded this long term, high-capacity aquifer.

A continuously cored borehole at the TRCA property terminated at 125 m depth in sand without reaching bedrock (Ford unpublished; see sediment log in Fig. 10). The regional stratigraphic units intersected were Lower sediments inferred to be Scarborough Formation sands (125-110 m), overlain by Thorncliffe Formation sand and diamicton (110–45 m), succeeded by diamicton (15–5 m; Newmarket Till) and surficial sand. Geological mapping of the area indicates Newmarket Till as the surface diamicton unit (Sharpe et al. 1997).

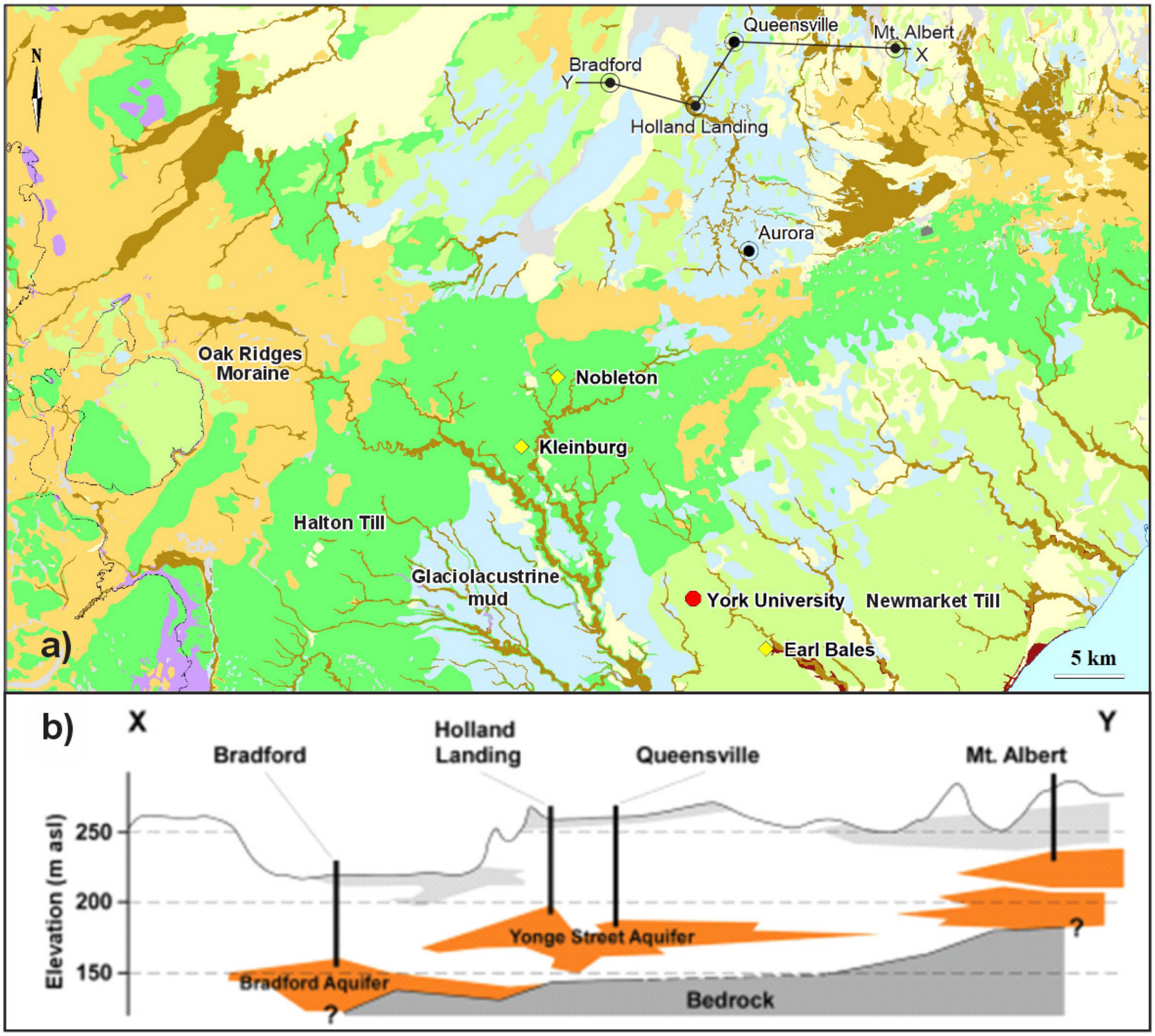

Figure 5. (a) Surficial geology in the Oak Ridges Moraine area from Logan et al., 2023. (b) West-east cross-section (X–Y shown on Figure a) shows a historical depiction of the Bradford, Yonge Street, and Mount Albert aquifers, from International Water Consultants Ltd. 1991. Adapted from Gerber et al. (2018). The Younge Street Aquifer and aquifer at Mt. Albert both occur below Newmarket Till whereas the Bradford aquifer does not.

3 Geophysical Methods

To demonstrate the application of multiple geophysical methods for optimization of ATES system installation in an urban setting, the GSC conducted microtremor Horizontal-to-Vertical Spectral Ratio (HVSR) measurements, a seismic reflection survey, and downhole geophysical logging on the York University campus (Fig. 2). The work was carried out in November 2020 (reflection survey, HVSR) and May 2022 (borehole logging); field delays caused by Covid-19 led to the gap in time between the surface and downhole data collection. At the time of the surveys, several York

University ATES boreholes had already been drilled but were metal-cased and therefore not candidates for geophysical logging. Plastic casing diameter of the TRCA borehole was inadequate to permit Nuclear Magnetic Resonance (NMR) logging so a Golden Spike borehole (Nobleton, indicated in Figures 3 and 5) north of the York University campus with a similar succession of sediment was logged to illustrate the types of downhole data that can be obtained for ATES investigations.

3.1 Data Collection

Passive seismic data were recorded at 18 stations along the seismic reflection alignments using a digital seismograph (Tromino®, manufactured by Moho LLC., Fig. 5). The seismograph was placed on bare soil and recorded vibrations in three directions (N–S, E–W and vertical) for 30 minutes. A calibration HVSR station was located at the TRCA well (well tag A273183). Sediment descriptions and geophysical logs collected in this well during the project provided the lithological and shear-wave velocity information required to convert the HVSR curve amplitudes, measured in frequency, to depth. During the survey wind strength was high and gusty. The proximity and concentration of large buildings might therefore require further post-processing to eliminate the effect of buildings in the current interpretation.

Reflection seismic data were acquired on the York University campus along three profiles ranging from 85 m to 1790 m in length for a total length of 2.26 km (Fig. 2). The Tennis Canada (TCan) profile is 85 m long and was acquired in the parking lot next to the TRCA observation well thus providing the link between lithologies identified during the core logging and the seismic signatures. The Ian McDonald (IMCD) profile is 1790 m long and follows the winding road from west to north-east and southwards. The Chimneystack (CHIM) profile is 388 m long and was acquired from east to west along Chimneystack Road. The western end of CHIM is 36 m east of the line IMCD.

Borehole geophysical data were collected in the TRCA's 2.5" PVC-cased observation well using the GSC's borehole geophysical logging system (see Crow et al. 2015, 2021 for description). The following suite of instruments were run: high-resolution temperature, inductive bulk conductivity and magnetic susceptibility, natural gamma, and downhole triaxial geophones to calculate shear-wave velocities. The integration of new, industry-developed slim-hole nuclear magnetic resonance (NMR) technology into the suite of tools was the first known deployment in the glacial sediments of southern Ontario, which is an innovative aspect of this project. As the NMR tool diameter is too large for the 2.5" TRCA well, the NMR tool was run in a 3" PVC borehole located 25 km to the north in a comparable glacial sediment setting.

3.2 Horizontal-to-Vertical Spectral Ratio (HVSR)

The geophysical method known as microtremor Horizontal-to-Vertical Spectral Ratio (HVSR) has evolved from earthquake site characterization (e.g., Molnar et al. 2018) to more general subsurface characterization. It is becoming a popular method for estimating the depth to bedrock and more specifically to outline bedrock basins, valleys, etc. (e.g., Seht and Wohlenberg 1999). HVSR utilizes a three-component (two horizontal and one vertical) seismometer to record ambient seismic vibrations (distant earthquakes, ocean waves, traffic, etc). In this study, a small, digital instrument was used (Tromino® by Moho Science and Technology, Fig. 6) to calculate ratios of horizontal and vertical movement at different frequencies. Processed results are presented as curves of horizontal-to-vertical (H/V) ratio amplitudes versus frequency. The highest amplitude (peak) occurs at the fundamental or resonance frequency (f_0) which is related to the average shear-wave velocity and the overlying sediment thickness, which is usually assumed to equal the bedrock depth. The resonance is created in the sediment layer by a strong contrast in density and shear-wave velocity between two layers (e.g., sand over bedrock). Estimation of depth to bedrock can be confounded by shallower units that also have a high-amplitude response. Such layers can mute responses from deeper underlying horizons, particularly if the intervening distance is small (e.g., a thin layer of gravel overlying bedrock). The technique is ideally suited to simple settings with 'soft' sediments such as found in the Ottawa area (e.g., Dietiker and Hunter, 2019).

The HVSR data can be further analyzed to provide directional estimations of subsurface structures. Based on theoretical studies (e.g., Roten et al. 2006, Matsushima et al. 2014) and field observations (e.g., Chandler and Lively, 2016; Cheng et al. 2020), H/V amplitudes can vary in direction (azimuth) depending on the direction of subsurface structures such as steeply dipping layers or basins. The most common association of such dipping surfaces are the walls of buried bedrock valleys. Azimuthal H/V amplitudes are higher in axial direction (parallel to the long axis of a valley or perpendicular to the steepest gradient) hence allowing a rudimentary analysis of the azimuth of the structures.

Figure 6. HVSR data collection. The digital seismograph is portable and designed for one-person use. To minimize the effects of wind and rain, a traffic pylon is commonly placed over the instrument. Photograph by H. Crow. NRCan photo 2023-300.

The raw, three-component time series were processed to improve the signal-to-noise of the frequency spectra by stacking filtered and smoothed, noise-free segments of the signal. The ratio of the combined horizontal amplitudes and the vertical amplitude was then calculated. With a known average shear-wave velocity (V_s) at a site, the resonating layer depth (h, assumed to equal bedrock depth) can be estimated based on the equation:

$$h = V_s / (4*f_0) \qquad \text{eq. 1}$$

The peak amplitude relates to the impedance contrast between the soft, resonating layer and stiff layer which is most often supposed to be bedrock (but can be till or another dense layer). High amplitudes are created from large density and shear-wave velocity contrasts, low amplitudes from low contrasts.

3.3 Seismic Reflection

High-resolution, near-surface seismic reflection surveys are optimized to illuminate subsurface structures down to the bedrock interface, providing detailed 2-D profiles of unconsolidated sedimentary sequences. This method is ideally suited for geotechnical and groundwater investigations (e.g., Pullan et al. 2007; Pugin et al. 2013) as it can differentiate lithologies using seismic facies and velocity analysis.
Seismic facies describe areas of similar seismic reflection pattern, such as amplitude strength, configuration, continuity, and frequency. Their interpretation creates links to depositional settings and lithologies (Pugin et al. 1999).

The survey sites need to be vehicle accessible (roads or gravel trails) and should be free of obstacles like tight curves or train tracks, where the acquisition would have to be interrupted.

Seismic surveys provide seismic reflection images from shear (S) and compressional (P) waves which can be interpreted in terms of lithological horizon interfaces where a contrast of density and/or velocity occurs in the sedimentary or rock column. Information on seismic velocities is computed during the processing of the survey data; subsurface materials can be inferred from these velocities as well as reflection strength and coherence (facies). Seismic downhole velocities from borehole logging are used for calibration purposes and significantly improve the depth conversion compared to using the travel times of reflection events.

Figure 7. Reflection seismic acquisition in progress on Ian McDonald Road at the York University campus. The Microvibe, which produces and transmits the vibrations into the ground, is visible below the door opening of the acquisition van. The three-component geophones that record the reflected vibrations are mounted on sleds and pulled by a high-tension strap behind the Microvibe. Photograph by A. Pugin. NRCan photo 2023-301.

Data collection was carried out by a crew of five people with the aid of a traffic control team (necessary because one traffic lane was occupied by the survey equipment). The seismic source for the survey was an electromagnetic-driven vibrator, a GSC invention called the Microvibe (Brewer et. al., 2013). The Microvibe consists of a mass with 20 tactile transducers which can deliver various types of sweeps from 5 to 800 Hz with up to 2000 W of output power. Transverse horizontal sweeps are used to create S-wave vibrations, and vertical sweeps create the P-wave vibrations. A GPS measures source locations with real-time differential corrections. To record the reflected vibrations, a landstreamer was used which consists of 48 three-kg metal sleds. Each sled carries three 28 Hz omnidirectional geophones mounted in three perpendicular directions: vertical, in-line horizontal and transverse horizontal (Fig. 7).

Data processing was required to improve the signal-to-noise ratio by frequency filtering and stacking of ~24 data traces (see Table 1 for processing details). Conversion of recorded two-way-travel (TWT) time to depth was based on vertical seismic profiling of shear-wave velocities in the

TRCA observation well and on the velocity analysis from the shear-wave reflection data processing. Uninterpreted time and depth sections are provided in the Appendix.

Table 1. Steps for S- and P-wave reflection processing.

Initial processing (all data)	
Format conversion, SEG2 to KGS SEGY	
Spectral whitening	
Pilot trace based deconvolution	
Applying of geometry	
Common Mid Point (CMP) sorting	
S-Wave	**P-Wave**
H2 component (1000 ms)	**V component (500 ms)**
Frequency band pass filter (30, 70, 150, 200 Hz)	Frequency band pass filter (80, 140, 350, 450 Hz)
Scaling (trace normalization)	Scaling (trace normalization)
Top mute (P-, surface waves)	Bottom mute (S-, surface waves)
Velocity semblance analysis	Velocity semblance analysis
NMO corrections	NMO corrections
Stacking	Stacking
Topography correction	Topography correction
Depth conversion	Depth conversion

3.4 Downhole geophysics

Borehole geophysical logs provide a method of identifying and characterizing lithological units based on variations in their chemical and physical properties (conductivity, magnetic susceptibility, mineralogy, density) and the nature of the contacts between the units (e.g., Crow et al. 2018). In the context of unconsolidated sediments, logs can also be used to interpret variation in hydrogeological parameters (porosity, estimates of hydraulic conductivity) (e.g., Dlugosh et al. 2013; Knight et al. 2016; Crow et al. 2022). High-resolution downhole fluid-temperature logs are also capable of identifying potential anomalies caused by fluid movement in aquifer sediments outside the borehole (e.g., Taylor et al. 1999). Velocity logs support the depth calibration of the seismic reflection survey using downhole shear (S) wave travel-time measurements and provide information on variation in sediment consolidation/density. Interchangeable borehole geophysical tools are deployed on wireline logging systems (Fig. 8). In unconsolidated sediment, the tools are run inside a 2.5 inch and ideally a 3-inch PVC-lined borehole, with data traveling up the wireline to be displayed and recorded on a laptop computer. Log data were processed and displayed using WellCAD software (v.5.5). Shear-wave travel-time data were interpreted using SeisUtils software (Kansas Geological Survey) and exported for velocity calculations in a spreadsheet before display in WellCAD.

In southern Ontario, mineralogical composition can be similar between the fine and coarse grain fractions resulting in relatively little variation in the gamma or conductivity logs, although the presence of clay-size grains generally produces increases in both parameters (Crow et al. 2018).

The magnetic susceptibility (MS) log, which responds to changes in magnetic mineral content, is particularly useful in settings like southern Ontario where sediments are in part derived from the Canadian Shield and can contain magnetic mineralogy. The MS log response generally inversely mirrors the gamma and conductivity logs, as coarse-grained sediments have a higher percentage of heavier magnetic minerals than fine-grained materials.

Figure 8. Typical geophysical logging set-up with the GSC's portable wireline logging system. Photograph by H. Crow. NRCan photo 2023-302.

4 Geophysical Survey Results

4.1 HVSR

The HVSR survey maps several resonant layers with the strongest contrast being between 1.44 and 1.78 Hz. An illustrative HVSR curve adjacent to the TRCA borehole highlights two peak frequencies (Fig. 9). Using an average shear-wave velocity of 680 m/s the depth to bedrock equaling the sediment thickness can be estimated by applying equation 1. At the TRCA borehole the strongest impedance contrast is at 101.5 m (main H/V peak at 1.53 Hz, Fig. 9). The secondary resonance (f_1) at 9.4 m (16.2 Hz) coincides with the shallowest strong velocity increase which correlates with the near-surface silty till (Fig. 10). The summary of all resonance frequencies and corresponding bedrock depths can be found in Table 2. The lithological stratigraphic correlation is provided by the collection of data adjacent to the TRCA well (Fig. 10) which also illustrates that the resolution of the HVSR is much lower at greater depths compared to shallow depths and the seismic reflections.

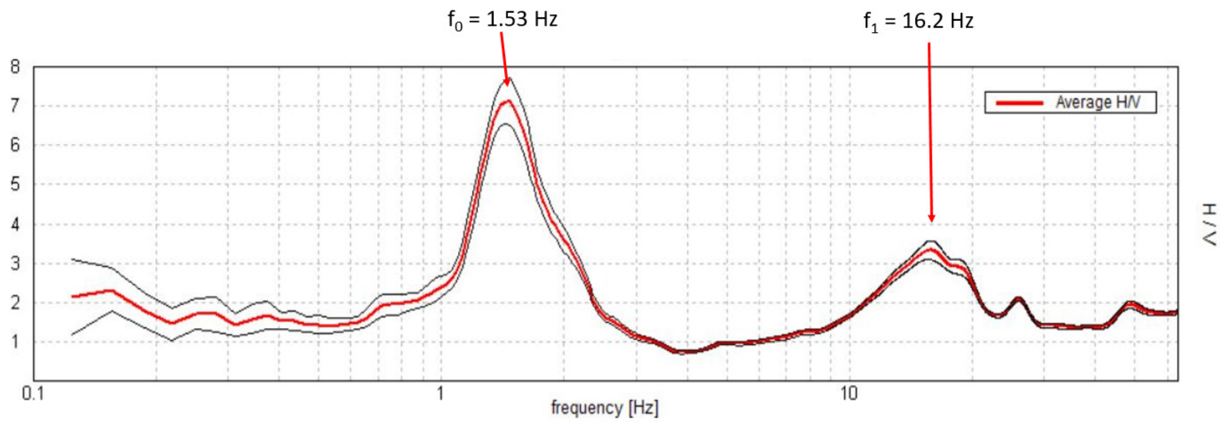

Figure 9. H/V sounding at TRCA well site highlighting frequency and amplitude. The main resonance frequency (f_0) is at (1.53 Hz) with a secondary peak at a shallower depth of ~16.2 Hz.

Based on HVSR depth estimations, bedrock is between 87 to 118m below grade in the study area. Even though these estimates are based on a simplified lithology by using an average Vs, depths match the results from the seismic profiles. Wind may influence HVSR responses near large buildings by creating rocking motions which cause vibrations in the soil (Mihaylov, 2011). Resulting shifts in resonance peaks depend on many factors like wind direction and intensity, building orientation, distance and orientation between station and building. These shifts are difficult to estimate but Mihaylov's measurements suggest that depth differences can reach 16% when natural soil resonance and building's vibrations are in a similar range. In the study area where resonance frequencies are below 2 Hz, they are less impacted by the building vibrations (max. 6%).

Applying the azimuthal H/V analysis to estimate subsurface trends found that most stations show structural orientations in a NNW direction with deviations to N and NW and very few excursions to NE (Fig. 11). These deeper trends are interpreted (preliminary) to outline a deep valley axis. With a much smaller likelihood, they may indicate the direction of major low frequency noise sources like buildings moving in the wind.

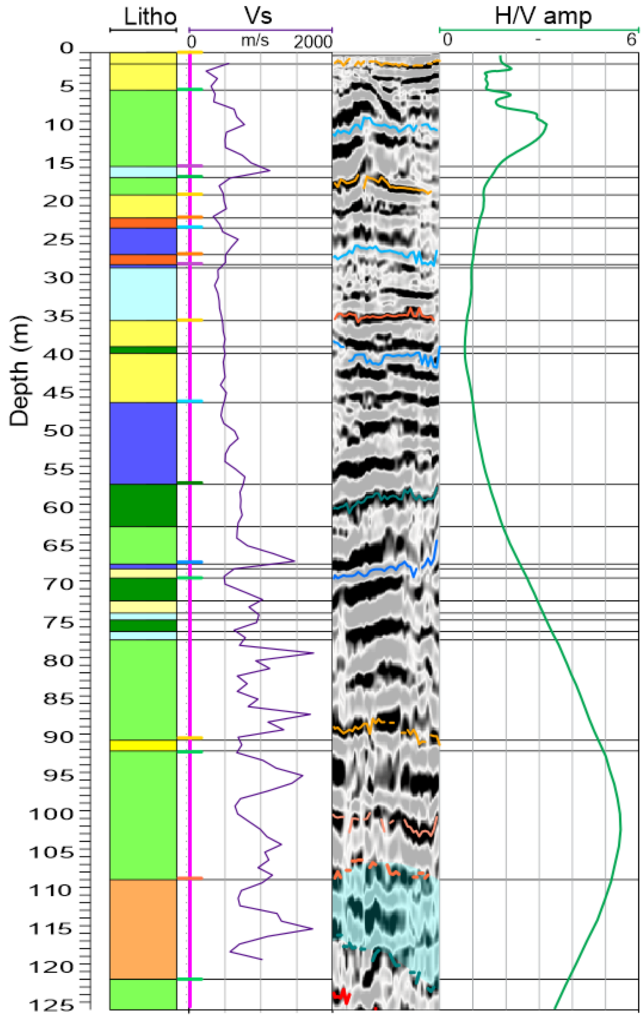

Figure 10. (From left to right) Lithology from the TRCA observation well (Don Ford, pers. com.), shear-wave velocity from VSP logging, shear-wave seismic reflections (patterned) and the HVSR amplitude curve converted to depth. Note the VSP data was collected at one metre vertical interval, seismic reflections are from a dedicated energy source of 30–200 Hz and the HVSR relies on ambient noise measured up to 60 Hz, hence the lower resolution of HVSR relative to the other signals.

Table 2. Summary of HVSR station locations and depth estimates of bedrock.

Easting (m)	Northing (m)	Site Name	f_o	Amplitude	Depth (m)
619704	4847468	Well1_N	1.59	4.85	97.40
619721	4847448	Well2_TRCA	1.53	5.58	101.50
619643	4847574	BOL_TC	1.62	5.45	95.50
619676	4847546	TC_mid	1.53	5.78	101.50
619746	4847477	EOL_TC	1.59	5.66	97.40
621094	4848289	Chimney 6	1.53	4.99	101.50
621020	4848238	Chimney 7	1.66	5.18	93.70
620944	4848200	Chimney M8	1.75	5.08	88.60
620818	4848199	Chimney W9	1.72	3.57	90.20
620718	4848133	Chimney W10	1.62	4.72	95.50
619805	4847708	IanMcDo_BOL	1.69	4.48	91.90
619853	4847844	IanMcDo15	1.78	5.68	87.00
619895	4847956	IanMcDo16	1.72	5.07	90.20
619996	4848021	IanMcDo17	1.72	5.66	90.20
620243	4848138	IanMcDo18	1.78	5.20	87.00
620653	4848077	IanMcDo11	1.62	4.95	95.50
620704	4847907	IanMcDo19	1.66	5.47	93.70
620805	4847668	IanMcDo20	1.44	4.21	118.60

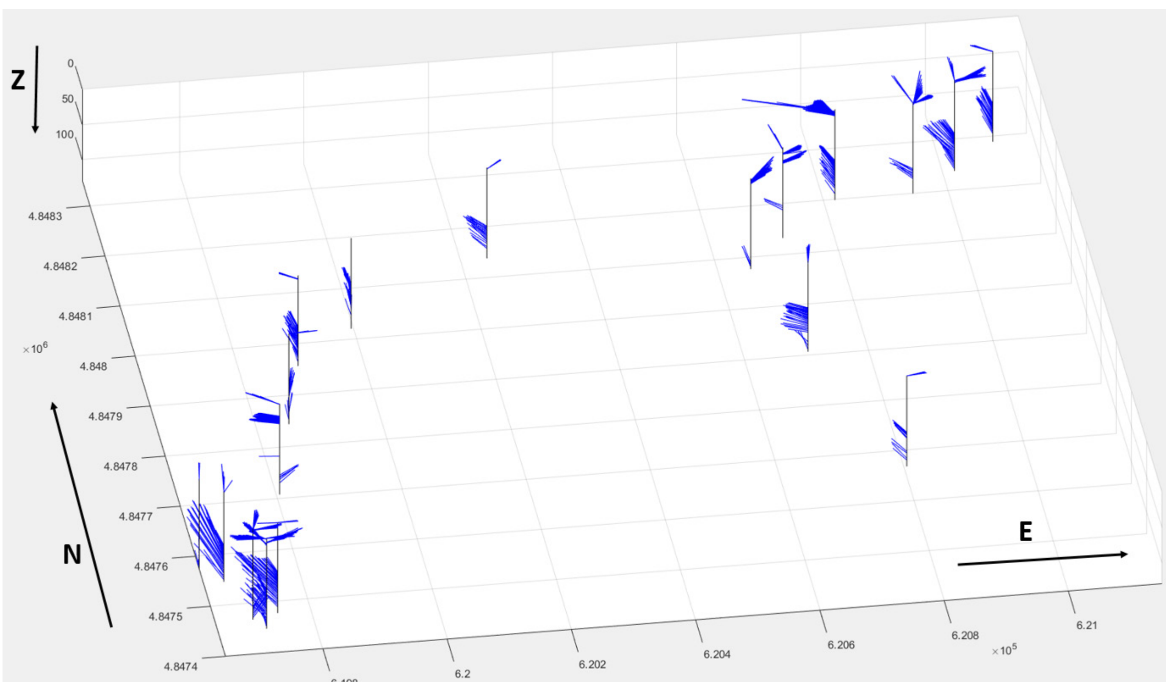

Figure 11. Arrow plot showing subsurface directional trends as estimated from azimuthal HVSR analysis. Deeper trends are predominantly oriented in NNW direction, possibly outlining a deep (bedrock) valley orientation. Depth is shown by distance from top of black vertical shafts.

4.2 Seismic Reflection

An interpretation of seismic facies is performed following the seismic facies characterisation (Pugin et al. 1999). Up to five seismic units are here described from depth to the surface: **A**: limit of high-resolution seismic penetration, no facies characterisation (Bedrock); **B**: high amplitudes of semi-continuous reflections (diamicton, Don Beds/York Till Fm); **C**: continuous to semi-continuous, medium to high-amplitude reflections (Silt, clay, sand, Scarborough Fm.); **D**: semi-continuous reflections, low to medium amplitudes (Silts, clay, sand fine gravel, Thorncliffe Fm.); E: high amplitudes, semi-continuous, complex reflections onlapping on an erosional surface (Silt, sand, gravel, Thorncliffe channel); **F**: high amplitudes, continuous to discontinuous reflections (diamicton, silt, sand, Newmarket Till Fm.)

Data for the three sections are of intermediate to exceptionally high quality with one or two exceptions. On the Ian McDonald (IMCD) road section significant interference occurs between 1400–1500 m distance (Figs. 13, 14), and on the Chimneystack line below 80 m depth the signal-noise ratio is poor (Fig. 15). The three sections highlight varying depths of interpretable data and considerable variations in seismic facies and stratigraphic continuity (Table 3). The bedrock surface is interpreted in all the sections, and to the east it is at ~80–100 m depth and deeper at 135 m at Tennis Canada. Relief on the bedrock surface is generally < 20 m; however, on the IMCD section it can be as large as 40 m. The sedimentary stratigraphy is dominated by several laterally continuous, sub-horizontal reflector horizons, which can be traced across the entire profile, with a few horizons pinching out. The Chimneystack section (Figure 15) displays an exception to this previously described geometrical trend with a distinct 150 m wide, ~50 m deep asymmetric trough, a channel-like structure which truncates horizontal reflections.

Table 3. Principal seismic features.

Seismic Line	Interpretable depth bedrock (m)	Stratigraphy	Geometry
Tennis Canada	135 (bedrock)	9 reflectors	Horizontal, minor pinch-out
Ian Macdonald Road	100 (bedrock)	7 reflectors	Horizontal
Chimneystack Road	100 (bedrock)	9 reflectors	Trough, truncated reflectors

Correlations between the profile reflections and borehole stratigraphy are supported by downhole shear-wave velocity (Vs) log of the TRCA well (Fig. 12; green line). Vs shows an increasing trend from about 140 m asl to the first high at the base of till at 120 m asl. The underlying diamicton shows very high Vs variability. High velocities match with high amplitudes (black reflections) in the seismic-reflection data. The silty sand and fine sand layer overlying till at the base of the sediments (marked by high Vs, likely indication of large boulders) are the most likely to have good aquifer properties (highlighted in light blue).

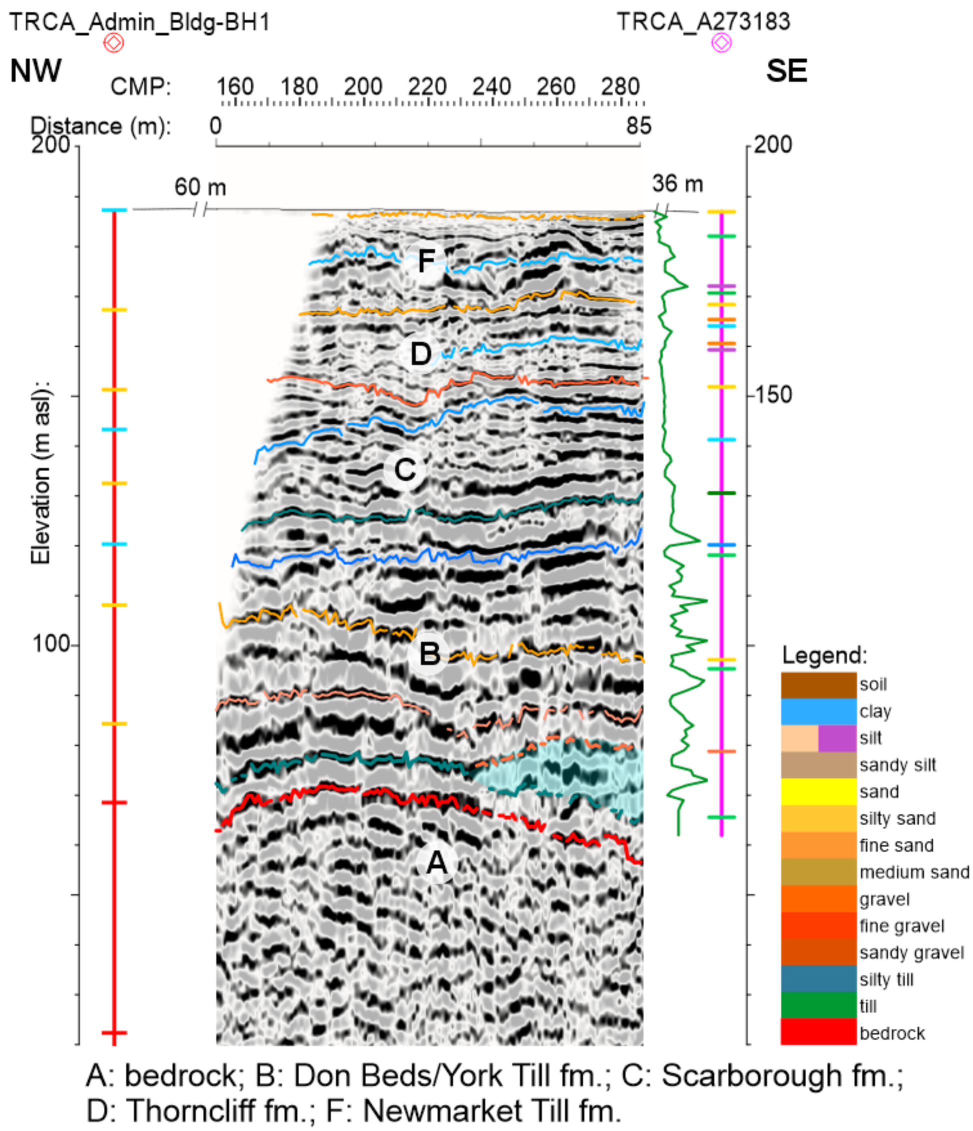

Figure 12. Shear-wave reflection profile at the Tennis Canada facility with horizons interpreted based on the simplified geological units of the TRCA observation well and TRCA_Admin_Bldg-BH1 cored borehole. The shear-wave velocity log (green trace) shows high velocities which match strong reflections, for example at depths of 120 m asl. There is no vertical exaggeration applied. For figures 12–14 two numbered bars occur above the sections; the top bar represents the number of the common midpoint (CMP) gathers, and the lower bar represents the distance in metres along the profile.

The long Ian McDonald profile (IMCD, Fig. 13) has generally well displayed continuous reflections except for a zone between 1400 and 1500 m distance where the large subway station prevents returns of coherent reflections. Outstanding reflection coherence is found at the western end of the profile for up to 400 m distance and between 1100 and 1200 m distance where greenspace dominates on the roadside. Reflections are weaker and less defined at the southern end of the profile where foundations of large buildings cause off-profile echoes which reduce the reflection strength and coherence. This may also be due to the oblique angle of crossing the valley axis interpreted on Chimneystack Road profile.

Most horizons are continuous across the profile, with only a few horizons pinching out in the upper sediment column. The silty sand and fine sand layer overlying till at the base of the sediments which were marked as potentially good aquifer layers in the Tennis Canada profile, vary in thickness and depth along the profile.

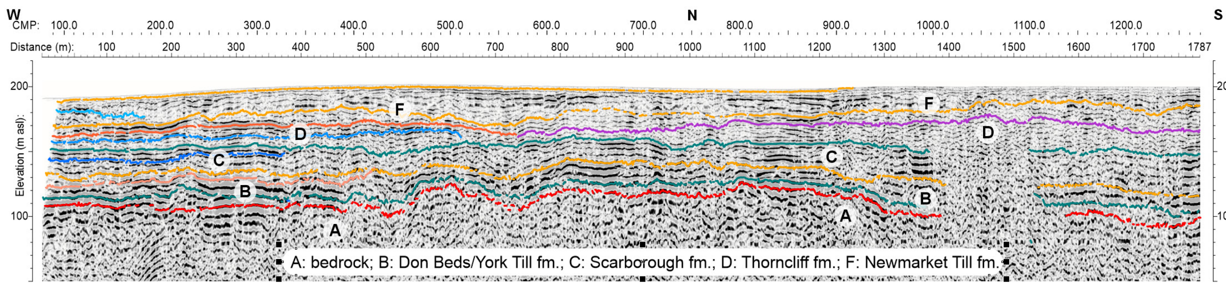

Figure 13. Shear-wave reflection data from the Ian McDonald Road. There is a two times vertical exaggeration applied on this 1.8 km long profile. Letters are defined at the bottom of profile. Horizon colour legend is shown in Figure 12.

The southern end of the IMCD profile (Fig. 14) has available borehole information from GIN and OGS databases (Fig. 4) where few of the water wells are deeper than 50 m. Information about material types is from the drillers' logs and often has confidence issues (e.g., location, depth, vague description; see Russell et al. 1998). The integration of water well logs and seismic data provide a first order comparison and constraint for interpretation of seismic reflection units and associated material characteristics. Notable is the large area of unsampled stratigraphy, depths > 50 m, and laterally.

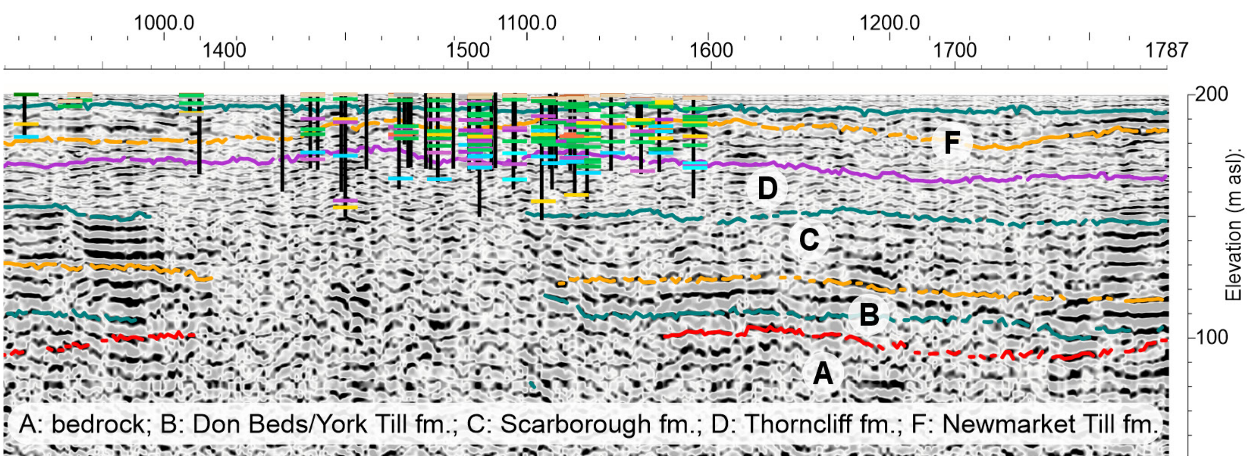

Figure 14. Southern 500 m of IMCD profile showing formation depth information from available wells. No vertical exaggeration is applied.

The shear-wave seismic reflections along the Chimneystack Road (Fig. 15) have high reflection strength and coherence allowing a detailed interpretation down to about 80 m depth below grade (120 m asl). Below this depth, the reflected signal is weaker and more impacted by noise from the off-line echoes of building foundations. Reflections are therefore less coherent, and bedrock is more difficult to interpret at around 80–100 m depth below grade (120 m asl; red line in Fig. 15). A trough structure (or maybe a channel) is recognizable by the high-amplitude reflections of the fill and the terminated reflections on either side of the structure (outlined with yellow lines in Fig. 15). The maximum 55 m depth of this trough structure is present at CMP 215. The structure truncates or cuts the underlying seismic reflectors supporting an interpretation of an erosion feature. This trough (channel) is overlain by the upper diamicton (green horizon) and fine gravel (dark orange horizon) present in the near surface.

This high-quality section can be described using seismic facies to infer possible lithology associations (Pugin et al. 1999). The lower 40 to 50 meters (100–50 m depth) are characterized by semi-continuous to very chaotic facies, with relatively strong amplitudes often attributed to either diamicton or gravel lithologies. Low-amplitude and semi-continuous facies situated between the dark green reflection horizon (140–150 m asl) and the yellow unconformity can be associated with more massive sediments like sandy silt or stratified silty clay. The highly reflective seismic facies filling the trough could be associated with highly contrasted lithologies such as alternance of sand, gravel or diamicton layers. The upper seismic facies that extends across the section (Fig. 15) is characterised by more continuous reflections, possibly a finer grained diamicton and sand. It is noteworthy that lateral facies changes are much more common below the unconformity (yellow line) than within the overlying channel fill. This highlights the complications of siting boreholes without high-resolution subsurface information.

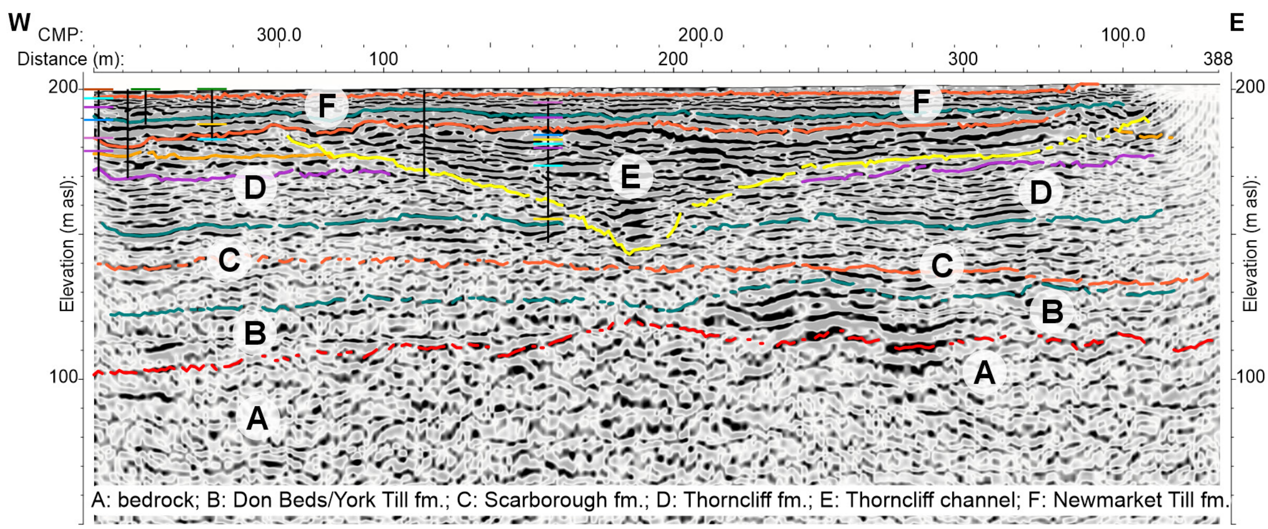

Figure 15. Shear-wave seismic reflections along the Chimneystack Road with interpretation showing a filled-in erosion channel (yellow outline) which is 55m deep. There is no vertical exaggeration applied.

4.3 Borehole Geophysical Logging

The aims of the borehole geophysical logging were to (1) identify variations in lithology and fluid response that would indicate the presence of favourable target zones for the ATES system (high yield aquifers), and (2) allow for the conversion of travel times to depths for the seismic reflection profiles. To support these objectives, six geophysical logs were collected (Figure 16).

4.3.1 Physical properties of stratigraphic units

The combination of natural gamma, bulk conductivity, magnetic susceptibility (MS), and shear wave velocity (Vs) provide information on variation of the mineralogical and physical properties of the sediment column (Fig. 16):

- **Gamma and conductivity logs** follow a common trend, typically rising together in intervals of increased clay content (i.e., more flow-restricted layers).
- **Magnetic susceptibility (MS) log** is relatively low and unvarying (<12 ppt) with the exception of the interval between 28–38 m (MS 15–25 ppt) and the near-surface sand unit between 2.5–3.5 m (MS 10–21 ppt). The highest MS is found in a sand unit (spanning 35–45.7 m) corresponding to an interval of elevated temperature in the borehole. The sand is separated by a diamicton layer, and a drop in counts below the diamicton indicates there are mineralogical differences between the sand horizons. The MS response is lowest in the gravels in the base of the borehole, therefore interpreted to be derived from carbonate–shale bedrock.
- **Shear wave velocities** are relatively low in the upper 50 m of the borehole (Vs <500 m/s) and increase in the more consolidated tills and diamictons in the lower half of the borehole (materials often described as 'hard' or 'dense' in the material description - 50 m and deeper). Velocity peaks occur within the till units, indicating there is variability in density within these tills.

Changes in the geophysical logs are often coincident with unit boundaries identified in the core. Overall, the logs tend to lack sharp contacts, suggesting the boundaries between units are gradational in nature, which could have a diffusive impact on fluid flow through the sediment.

Important features to note as part of the interpretation are influences from the borehole completion. Elevated gamma counts just below ground surface are attributed to a known bentonite plug and an increase in counts as the tool enters the portion of the hole cemented with grout ("B" and "G" on Fig. 16). Spikes in the MS log (indicated with an "M" in Fig. 16) are interpreted to be caused by metal filings from the drill bit as it wore through hard cobbles in intervals of till, diamicton, or gravel.

4.3.2 Groundwater Flow

The temperature log, when interpreted alongside the lithological logs, provides insight into the depth of the water table and groundwater movement within the sediments. There are three main intervals of relatively elevated temperatures identified on Fig. 16 (numbered i, ii, iii). The uppermost interval ("i") is interpreted as being influenced by the groundwater table. Core observation indicates a gradual downward decrease in iron staining with a colour change to grey at a depth of 11.4 m. The temperature log suggests that the water level may have been closer to 9.6 m on the logging date based on a small (0.02°C) temperature increase at 9.6 m followed by a reversal in temperature below. Shallower increases in both temperature and bulk conductivity (4.20–4.90 m) are suggestive of a perched water table in the sand above the till. The fractured and iron-stained nature of the till suggests it can be partially saturated between depths of 4.9 m and 11.4 m, and that the water table depth varies in this interval with changes in precipitation and season. The deeper piezometric water level in the borehole indicates there's a downward gradient at the site.

The two lower intervals of temperature increases are found in the sand interval between 35– 45.7 m (Fig. 16, "ii"), and in the open screen at the base of the well (Fig. 16, "iii"), suggesting these are intervals where groundwater flow is occurring. The screened gravel represents the highest production zone encountered during the drilling. When interpreted together with the lithological logs, these two lower intervals appear to be the main hydrostratigraphic features in the sediment sequence. The till units between these horizons show overall relatively flat and cooler responses where water is less likely to penetrate due to finer grain sizes and sediment compaction; however, smaller temperature anomalies superimposed on the larger trends may be indicative of flow through thinner seams (Fig. 16, "iv"). For example, a small (0.01°C) temperature increase extending about 1 m into the overlying till layer may be indicative of a thermal diffusion halo from flow along the underlying gravelly sand layer.

NMR data provides a more direct picture of groundwater presence in the sediments, both in terms of total water content (porosity in saturated sediments) and how the pore sizes are distributed. The 2.5" diameter of the PVC was too narrow for the NMR tool (requires a 3" PVC for the GSC's tool), so an NMR log was collected in a well-studied GSC sediment borehole 25 km to the north with comparable lithology (Nobleton borehole, see Logan et al. 2008). Results provide clear indications of which intervals would be favourable targets for ATES systems. For example, two ~13m-thick sandy intervals (labeled A, B on Fig. 17) show similar levels of total porosity, but the deeper interval (168–181 m) is predominantly mobile water in larger pores, while the shallower interval (110–124 m) has less free water and more capillary- and clay-bound water, thus making the deeper unit a better target. This type of information would have been particularly useful in the two sandy-gravelly zones identified with temperature increases in the TRCA observation well. The NMR data could be further analysed to estimate the hydraulic conductivity of the material if some site-specific parameters are known as has been done in other locations (see Knight et al. 2016; Crow et al. 2021).

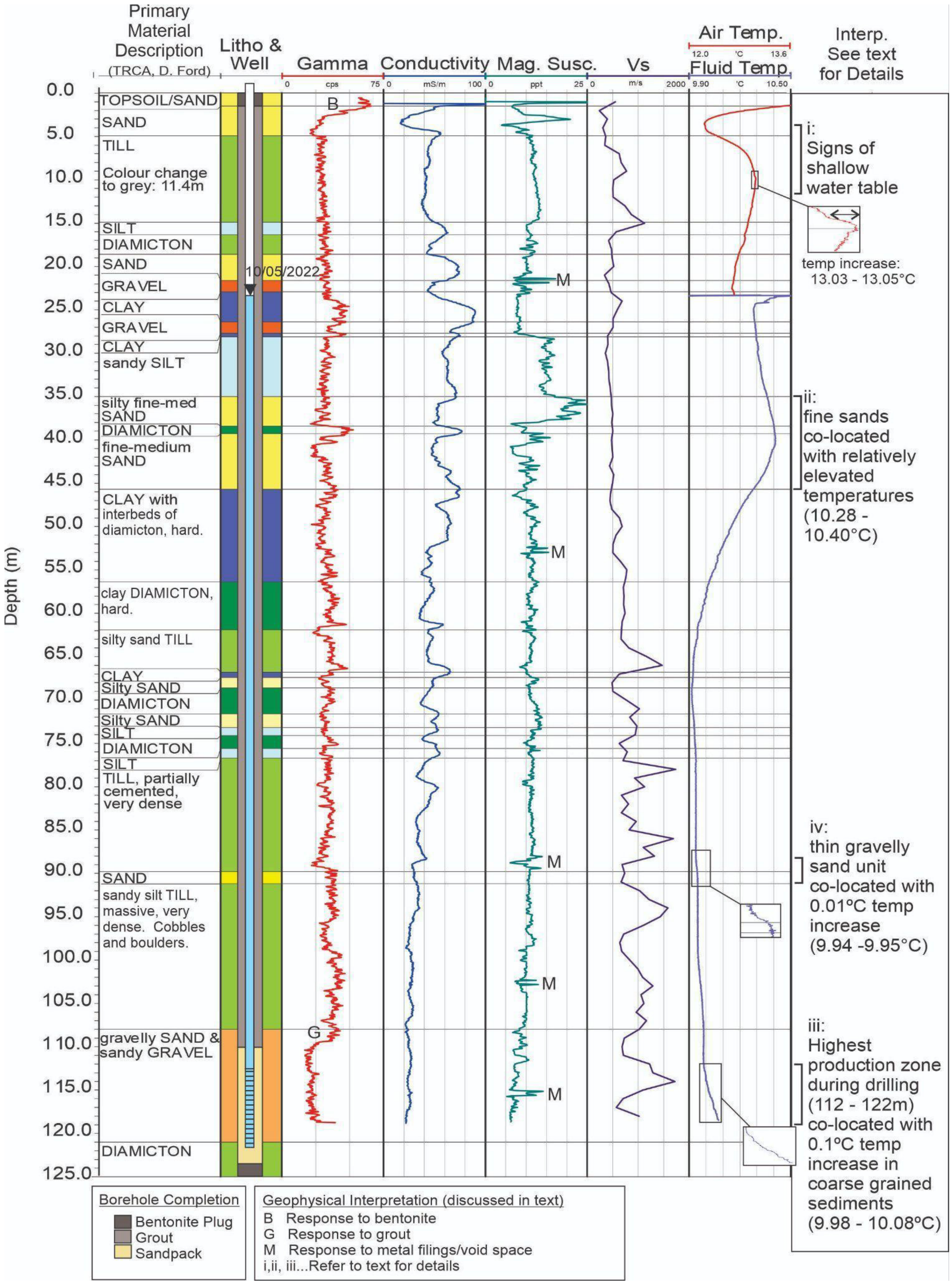

Figure 16. Geophysical logs from TRCA observation well adjacent to seismic profile 'Tennis Canada' on the York U campus. Note the gamma, conductivity, and magnetic susceptibility logs that form the lithological log suite, downhole seismic velocity, and fluid temperature.

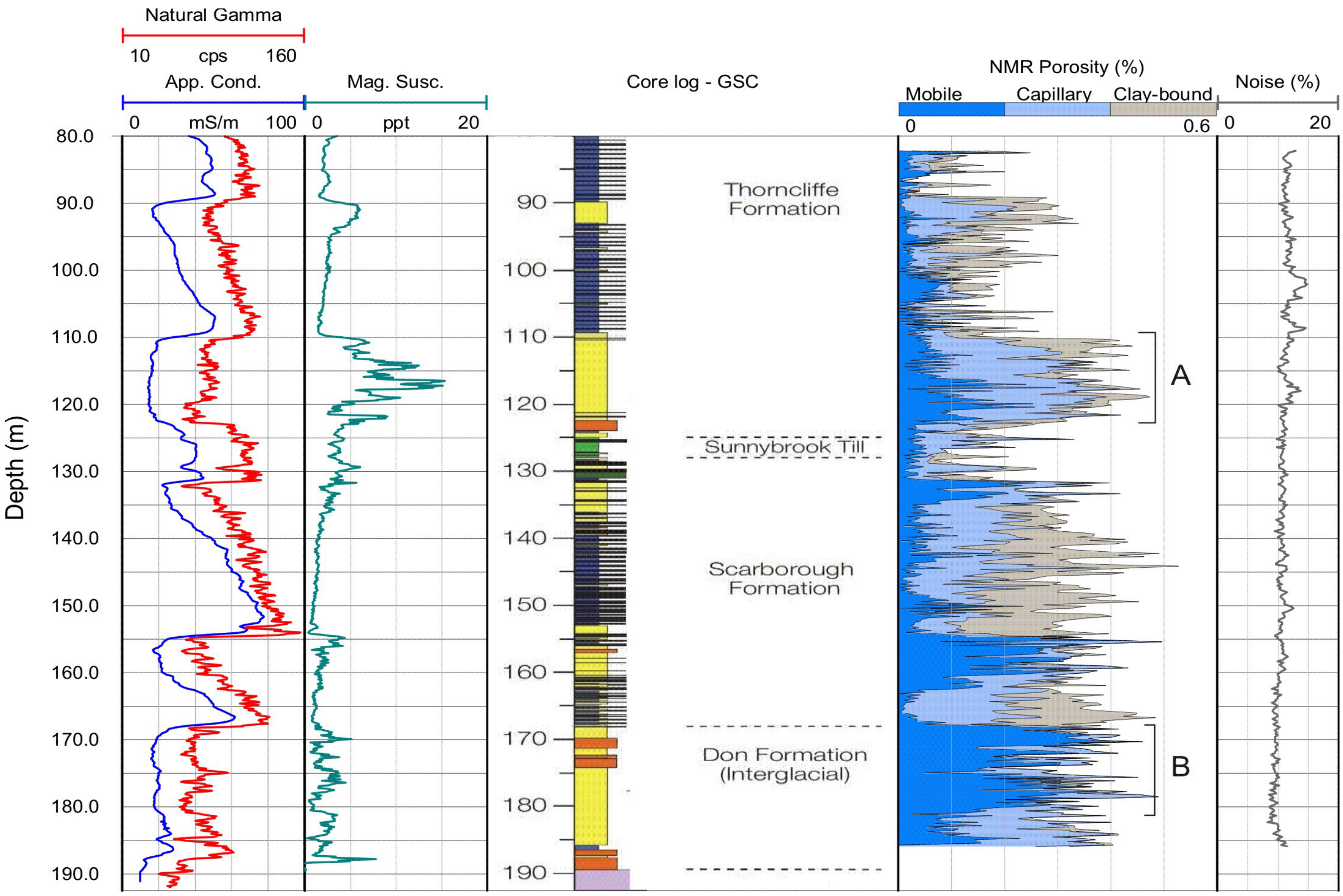

Figure 17. Geophysical logs from the Nobleton well north of Toronto. Letters A, B refer to aquifer intervals described in the text. The lithological log suite is on the left of the sediment log and the nuclear magnetic resonance (NMR) log is on the right. In the sediment log note the intervals of fine-grained sediment marked by the thin black lines and corresponding reduction in mobile water content in the NMR signal. Sediment log from Logan et al. (2008); well surface elevation is 268m asl.

5 Summary

The collaborative study on the geological suitability of an Aquifer Thermal Energy Storage (ATES) system at York University provided an opportunity to address how geophysical surveys could enhance reconnaissance data collection to support ATES site selection. The geophysical program demonstrated the rapidity of data collection, the breadth of 1- and 2-D information gained, and the effectiveness of geophysical techniques versus drilling alone.

The three geophysical techniques deployed for the study individually address specific issues that are critical to successful reconnaissance assessment and subsequent site consideration for an ATES development. The HVSR survey is a non-intrusive, rapidly deployed, low-cost technique capable of providing estimates of depth to bedrock. This technique can be particularly valuable in areas of thick sediment where there may be limited water well intercepts of bedrock. In addition to depth, the orientation of subsurface structures can be mapped to further refine understanding of subsurface geometry. In areas of thick and complex stratigraphic successions, assignment of resonators with bedrock can be complicated, reducing confidence in depth estimates.

Seismic reflection surveying is a well-known non-intrusive, rapid technique used extensively in southern Ontario (e.g., Pugin et al. 1998). In this study, focus was on shear-wave data collection which is less sensitive to fluid contents and images lithologies at higher resolution. The survey successfully imaged bedrock, the stratigraphic architecture, and supports seismic facies assessment. The shear-wave technique provided strong returns from bedrock and permitted mapping of the two-dimensional bedrock relief. Based on the TRCA borehole stratigraphy the seismic stratigraphy mapped lateral continuity of the respective Scarborough and Thorncliffe formations and Newmarket Till. The data provides a first order estimation of unit thickness variability. It also yields information on architecture within the Thorncliffe Formation, specifically a buried channel feature. Such features have been mapped across the region within the Thorncliffe. The Yonge Street Aquifer is interpreted to be such a channel (Gerber et al. 2018). Within the Thorncliffe Formation, inter-channel width and depth scales are poorly constrained as is the full characterization of channel fills. The Aurora borehole study (Sharpe et al. 2011) provides the most complete description of fining upward gravel-sand-mud. The presence of such channels can have significant implications for vertical aquifer connectivity as well as horizontal continuity, orientation, and heterogeneity. Seismic facies can be identified within each of stratigraphic units and further analysis will provide a more complete description. Based on TRCA borehole information and seismic facies analysis, seismic reflection horizons could be identified and linked to stratigraphic horizons. In the progression of site investigation, the seismic data provides a complete stratigraphic architecture and seismic facies analysis that supplies a valuable source of information on aquifer target depths, geometry, and heterogeneity to support optimized selection of drilling location. Integration of water well data along part of the Ian MacDonald Road profile highlights the incomplete understanding provided by water well records due the lack of deep information (as potable water was intercepted at shallow depths). Analysis of the seismic reflection data is greatly enhanced if there is available borehole geophysics to constrain the velocity for conversion from time to depth.

Borehole geophysics can collect valuable data to i) provide velocity constraints for depth conversion of seismic reflections, ii) characterize lithology, iii) identify stratigraphic units, iv) characterize aquifer heterogeneity, and v) estimate sediment and aquifer parameters. Velocity logs allow for the depth calibration of seismic reflection profiles and provide insight into changes in lithology and the variable consolidation of glacial sediments. Logs, with or without core control, including gamma, conductivity, and magnetic susceptibility, support lithological interpretation of the sediment sequence by responding to changes in mineralogy. Gamma and conductivity logs help identify intervals with higher clay content (i.e., those to be avoided as ATES targets because of reduced porosity and flow). Magnetic susceptibility logs can assist with identification of coarser grained units. High resolution fluid temperature logs can identify intervals where groundwater may be flowing outside the casing if the groundwater is in thermal disequilibrium with the surrounding formation. NMR logs provide the clearest indication of the presence of water in the sediments and the size of the pores (mobile water versus clay-bound water). This information greatly enhances the selection of ATES targets.

When planning a site investigation, geophysical data and sequence of collection can provide valuable information that is much greater than one or multiple boreholes. Drilling involving continuous core provides a single point of information on the stratigraphic succession and heterogeneity. Individual or even multiple boreholes will not provide any information on the stratigraphic architecture where horizontal strata may be truncated by channels with completely different fill sediment textures. For reconnaissance the two seismic techniques provide complementary information that will greatly improve drilling site selection. Borehole geophysical logs can reduce the need for expensive continuous core recovery and provide a number of additional datasets on in-situ aquifer characteristics. Integrated with the seismic reflection analysis, the borehole data provide a means of verifying and calibrating the seismic interpretation.

6 Acknowledgements

This project was conducted by the Geological Survey of Canada (NRCan) in collaboration with CANMET Energy (NRCan) under the IESO Grid Innovation Fund (Project 11241, the York University Keele Campus Case Study). We thank Reda Djebbar and Lucio Mesquita at CANMET Energy for project coordination, Steven Prince from York University for logistical and field assistance, and Don Ford from TRCA for borehole access and core information. An internal review was completed by David Sharpe. This work is a contribution of the Geological Survey of Canada Groundwater Geoscience Program, Archetypal Aquifer project 2019-2024.

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