Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

Borehole geophysical log signatures and stratigraphic assessment in a glacial basin, southern Ontario

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2017-0016.R1
Manuscript Type:	Article
Date Submitted by the Author:	26-May-2017
Complete List of Authors:	Crow, Heather; Geological Survey of Canada, Natural Resources Canada Hunter, James; Geological Survey of Canada, Natural Resources Canada Olson, Laura; Geological Survey of Canada, Natural Resources Canada Pugin, Andre; Geological Survey of Canada, Natural Resources Canada Russell, Hazen; Geological Survey of Canada, Natural Resources Canada
Is the invited manuscript for consideration in a Special Issue? :	Quaternary Geology of Southern Ontario and Applications to
Keyword:	borehole geophysics, seismic velocity, stratigraphic interpretation, glaciated terrains, southern Ontario

SCHOLARONE™
Manuscripts

**Borehole geophysical log signatures and stratigraphic assessment in a glacial basin,
southern Ontario**

Crow, Heather L.
Geological Survey of Canada, Natural Resources Canada
601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
Heather.Crow@Canada.ca

Hunter, James A.
Geological Survey of Canada, Natural Resources Canada
601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
Heather.Crow@Canada.ca

Olson, Laura C.
Geological Survey of Canada, Natural Resources Canada
601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
Laura.Olson@Canada.ca

Pugin, André J.-M .
Geological Survey of Canada, Natural Resources Canada
601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
André.Pugin@Canada.ca

Russell, Hazen A.J.
Geological Survey of Canada, Natural Resources Canada
601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
Hazen.Russell@Canada.ca

Corresponding author's contact information:
Heather Crow
Geological Survey of Canada, Natural Resources Canada
186-601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
Heather.Crow@Canada.ca
Tel.1- 613-992-2331
Fax not available.

KEY WORDS – borehole geophysics, seismic velocity, stratigraphic interpretation, glaciated
terrains, southern Ontario

ABSTRACT

Over the past two decades, the Geological Survey of Canada has used a standardized suite of slim-hole geophysical tools to log 57 PVC-cased boreholes drilled in the glacial sediments of southern Ontario. This article documents downhole tool responses (natural gamma, apparent conductivity, magnetic susceptibility, and seismic velocity) in the context of mineralogical characteristics of the region and grain size data from 28 of the 57 boreholes. Characteristic geophysical properties and/or patterns are identified within the units of a regional hydrostratigraphic framework in southern Ontario. The importance of a calibrated suite of tools is emphasized, as stratigraphic units may have variable response from site to site. The use of a high-sensitivity magnetic susceptibility induction probe is shown to be an important tool in the log suite for lithostratigraphic interpretation, and more broadly, for provenance studies of source rock across the region. Ranges of compressional (P) and shear (S) wave velocities and their ratios are provided for each of the hydrostratigraphic units. Case studies are presented to demonstrate how logs may assist in the interpretation of glacial processes at lithological boundaries.

1. Introduction

Regional groundwater studies are often faced with limited data to resolve hydrostratigraphy and aquifer heterogeneity. Water well records are commonly the only widespread dataset available for hydrostratigraphic studies, but this information lacks geological resolution, integrity, and reliability (e.g., Russell et al. 1998). The most cost effective means to supplement the water well dataset is through applied geophysical techniques. Geophysical logs provide a continuous method to identify downhole variation in lithology based on changes in physical and chemical properties of sediments. Downhole geophysical logging (wireline logging) has a long history of applications in the petroleum industry (e.g., Cant, 1984) for characterization of basin stratigraphy, stratigraphic and formation correlation, characterization of scale and nature of reservoir heterogeneity, and estimation of reservoir properties. It has also been applied for over 35 years to similar problems in groundwater studies (e.g. Paillett et al., 1996; Keys, 1997; Paillett and Reese, 2000). Prior to the 1990's, geophysical logging was conducted using analogue tools, but manufacturers have since migrated to digital data collection and storage. This greatly enhances the value of the logging data, and offers an opportunity for quantitative (re)analysis, and integration of datasets for regional analyses. This increased level of interpretation, however, raises the significant issue of tool calibration and collection protocols.

Much of the groundwater research conducted in Canada is focused on glaciated basins within a glacial stratigraphy (e.g., Rivera, 2014). Interpretive knowledge gained from petroleum well logging studies has been in sedimentary bedrock environments where relatively slow rates of deposition are dominated by chemical weathering, rather than physical weathering and erosion

(e.g. Hearst et al, 2000). Following two million years of glaciation during the Quaternary, northern North America has been largely denuded of chemically weathered bedrock (e.g., saprolite) by the Late Wisconsin. Rapid and voluminous deposition of glacial detritus common to many glacial settings (glaciofluvial, glaciolacustrine, ice-marginal) is accompanied by little time for mineralogical partitioning during formation of distinctly different horizons. Furthermore, glacial erosion produces a greater proportion of grains that are abraded to terminal mineral size. This has contributed to an abundance of “rock flour” (silt and clay-sized particles) dominated by the primary mineralogy of the provenance lithologies (e.g., quartz, feldspar, calcite) rather than by secondary alteration minerals (e.g., phyllosilicates). Consequently, there is an absence of mineralogical distinction between muds and the coarser grain size fraction, which can lead to challenges when interpreting variation in downhole stratigraphy using only one or two of the traditional geophysical logging techniques, such as natural gamma and electrical conductivity.

Over the past two decades, a standard suite of logs including natural gamma, apparent conductivity, magnetic susceptibility, and compressional (P) and shear (S) wave velocities has been collected by the Geological Survey of Canada (GSC) in 226 cased wells across Canada (Crow et al., 2015a). In southern Ontario, 57 PVC-cased wells were sampled and geophysically logged (Figure 1). This dataset was collected using the same suite of tools, calibrated at the Bells Corners Borehole Calibration Facility in Ottawa, Ontario (Bernius, 1996; Mwenifumbo et al., 2005), and other sediment reference boreholes to ensure that the log suite provided consistent results over time. This unique dataset therefore allows for an interpretation of similarities and differences in depositional settings, chemistry, and provenance in locations across Canada.

The primary objective of this article is to document the response of downhole geophysical tools (gamma, conductivity, magnetic susceptibility, and velocity) in glacial sediments of southern Ontario. The paper places the geophysical signatures within the context of known mineralogical characteristics of the area and detailed grain size data available for 28 of the 57 logged holes. A second objective is to relate patterns in the log responses to the range of depositional environments present within the glaciated succession. The paper summarizes how the characteristic geophysical properties and/or patterns can assist in placing glacial sediments within the regional hydrostratigraphic framework.

2. Geological Context of Southern Ontario.

The 74,000 km² of Southern Ontario in the Great Lakes basin is underlain by Paleozoic sedimentary rocks that are overlain by up to 200 m of unconsolidated Quaternary sediment. The Niagara Escarpment, extending from Manitoulin Island southward into the United States, forms a major division between outcropping and subcropping Ordovician and Cambrian bedrock to the east, and Silurian and Devonian bedrock to the west. These sedimentary rock units are dominated by limestones and shales east of the escarpment, and dolomites, limestones and shales to the west. A background clay mineralogy signal is available from a limited suite of samples for outcropping and subcropping shale formations across southern Ontario (e.g. Martin and Kwong, 1986; Sadler, 1962; Béland Ottis, 2013). A broader literature does exist; however, results are commonly reported in a qualitative fashion (e.g., Guillet, 1977). Shale formation mineralogy generally consists predominantly of illite and chlorite minerals, with smaller amounts of vermiculite and inter-layered clays. For the formations presented in Martin and Kwong (1986)

and Béland Otis (2013), clay minerals can be up to 55 % of the rock mineralogy. Sadler (1962) presents combined results of illite, chlorite, and feldspar of up to 77 % for the Queenston Shale and 92% for the Dundas in Etobicoke, Toronto. Dolomite in bedrock is the principal constituent in the Silurian cap rocks of the Niagara Escarpment and westward (Armstrong and Carter, 2010).

To the north on the Canadian Shield, the Grenville province forms a mosaic of diverse metasedimentary and crystalline rocks grouped into two belts: the Central Metasedimentary Belt north of Lake Ontario, and the Central Gneiss Belt northeast of Georgian Bay. Saprolites can contain alteration minerals which produce elevated geophysical responses, but their extent for Late Wisconsin erosion are poorly constrained. Areas to the east in New Brunswick and Quebec, and to the west in Michigan and Minnesota have reported saprolites (e.g., Bouchard and Godard, 1985), but there are no such deposits documented for the hinterland of Southern Ontario. This suggests minimal saprolite occurrence as source rock potential for Late Wisconsin deposits in Southern Ontario.

The surficial deposits of Southern Ontario have a well-documented Late Quaternary succession of Illinoian, Sangamoian and Wisconsin sediment (e.g. Eyles and Williams, 1992). The pre-Late Wisconsin stratigraphy is most completely described from the Scarborough Bluffs, (Karrow, 1967), Toronto area (e.g., Karrow et al., 2001), Lake Erie Bluffs (Dreimanis, 1992) and other scattered locations across southwestern Ontario (e.g. Bajc et al., 2015). Fossil remains of the Sangamonian Don Valley Formation constrain underlying deposits to a likely Illinoian age and overlying deposits to early and Late Wisconsin (Scarborough, Thorncliffe formations and associated muddy diamictos). The Thorncliffe Formation is overlain by Newmarket Till, which

is correlated with Catfish Creek Till to the southwest; these tills are considered to have been deposited during the Late Wisconsin maximum (e.g., Karrow, 1974). A succession of overlying Late Wisconsin deposits of glaciofluvial, glaciolacustrine stratified deposits and diamictons complete the glacial succession (e.g., Sharpe et al., 2002).

To facilitate data integration and regional 3D mapping across the Greater Toronto Area (GTA), a simplified regional stratigraphic framework was developed by Sharpe et al. (2002). With minor modifications, this framework is applicable to the Waterloo region (Table 1; Bajc et al. 2014). The bedrock surface forms the lower unconformity and is characterized by a range of valley scales containing a complex succession of glacial sediments (Gao, 2011; Russell et al., 2007). The Lower Sediments (also referred to as the lower deposits) is a grouping of ten pre-Late Wisconsin deposits that can be up to 150 m thick. West of the Niagara Escarpment, the lower sediments consist of glacial (e.g. Canning Till) and non-glacial deposits (e.g. Bajc et al., 2014). The sandy silt textured Newmarket Till and fine-textured, stone-poor facies of the Catfish Creek Till have been recognized regionally and are commonly characterized by a high velocity (e.g. Pullan et al., 2002; Bajc and Hunter, 2006). The surface of these tills is characterized by a drumlinized and channelized surface which forms a second regional unconformity (Sharpe et al. 2002; Bajc et al. 2014). Coincident with this undulating surface are tunnel channels that can be incised down to bedrock and host a range of fills depending upon location (e.g. Russell et al., 2003a, 2004). Where only partially infilled, knowledge of the fills is sparse, but near surface units are dominated by glaciolacustrine deposits and organics (e.g. north of the Oak Ridges Moraine). Where filled and buried by stratified moraines, the fill can consist of gravel, sand, and localized mud intervals (Russell et al, 2003a, Pugin et al. 1999). Areal extent of stratified

moraines (Waterloo, Orangeville, Oro, and Oak Ridges) consist predominantly of sandy sediment with proximal gravel deposits and distal mud (e.g. Barnett et al 1998; Bajc et al., 2014; Sharpe et al. 2002). Sedimentary units are organized by an ice-confined depositional meltwater process of conduit flow, flow expansion, and proximal glaciolacustrine deposits (e.g. Russell and Arnott, 2003). Overlying and flanking the stratified moraines are a series of late-glacial, fine grained tills and younger glacial lacustrine deposits, which can contain sandy interbeds (e.g. Sharpe and Russell, 2016; MacLachlan and Eyles, 2011). This grouping of mud rich tills is attributed to multiple glacial lobes and includes approximately 17 tills mapped across southern Ontario by the Ontario Geological Survey (OGS) at 1:50,000 scale, as detailed by Barnett et al (1991).

Much of the chemical and mineralogical characterisation of Southern Ontario sediments has focused on tills (e.g. Dreimanis et al., 1957) with commensurately less attention on stratified sediments. Regional bedrock lithologies and weathering history impart a first order control on geochemistry. Carbonate content and calcite and dolomite percentage has been calculated expensively using Chittick apparatus since the early 1960s (Dreimanis, 1962). An extensive reference dataset exists for diamicton units as part of OGS surficial geological mapping and subsurface investigations (e.g. Karrow, 1987; Bajc and Shirota, 2007). Heavy mineral data is considerably less abundant but exists across the region for till units, and locally within core data (Bajc et al., 2015). An illustrative example is available in Karrow (1987) from the Hamilton to Cambridge area which describes a common suite of heavy minerals: magnetite-ilmenite, 8 %; hornblende, 47 %; clinopyroxene, 17 %; hypersthene, 3 %; white and purple garnet, 5 %; and red-orange garnet, 8 %. Elemental geochemistry data is available across southern Ontario (e.g.

Sharpe et al., 2016) and in the GTA from core data (e.g. Knight et al., 2016) for the range of mapped surficial materials and subsurface stratigraphic units, respectively. Geotechnical studies in the Sarnia area have documented the clay mineralogy of glaciolacustrine deposits to range from approximately 21 to 45% (Quigley and Ogunbadejo, 1973). This range of clay mineral concentrations is approximately one-half to one-third of that found in the shale units (see above).

3. Data Distribution and geological setting

A suite of downhole geophysical logs was collected in 57 continuously cored boreholes within three stratified moraines within Southern Ontario (Figure 1). Table 1 provides a generalized description of the key sediments found in the stratigraphic units, and identifies the formation names used in the different study areas.

3.1. Greater Toronto area (GTA)

Downhole data were collected in 29 boreholes ranging in depth from 18 – 187 m in the GTA (Figure 1). These boreholes were drilled predominantly in the Oak Ridges Moraine between 1993 and 2006, with an additional two boreholes near Wasaga Beach and two in South Simcoe County (Pullan et al., 2002; Crow et al., 2015a, Crow et al., 2015b). The dominant landform in the area is the Oak Ridges Moraine, a 160 km-long ridge of sediment which forms the drainage divide between Georgian Bay and Lake Ontario. The stratigraphy of the GTA is Ordovician bedrock (limestone and shale) overlain by ten formations of the Lower Sediments. These formations of Illinoian to mid-Wisconsin age are primarily made up of sequences of silt-clay rhythmites and sand units, with minor sandy silt diamicton and muddy diamictons. These

deposits are overlain conformably and unconformably by Newmarket Till, which is a regional lithological and geophysical marker horizon. The top of Newmarket Till is both drumlinized and channelized and is, in turn, overlain by a range of late glacial (<13,000 BP) sediments, most notably Oak Ridges Moraine, Halton formation (Sharpe and Russell, 2016), and glaciolacustrine deposits (e.g. Peel Ponds, lakes Schomberg and Algonquin).

3.2. Oro Moraine

In the region of the Oro Moraine, downhole logging was conducted in 2004-2005 in 14 boreholes ranging in depth from 20 – 116 m (Burt and Dodge, 2011). The moraine is underlain by Ordovician limestones although Precambrian gneisses of the Grenville Province outcrop a short distance to the north. A gravel lag and weathered bedrock overlie the limestone and form a basal aquifer. In the Oro area, the Lower Sediments consist of multiple units that are tentatively correlated with Scarborough and Thorncliffe stratigraphy and are overlain by Newmarket Till, which is commonly less than 20 m thick, drumlinized, and locally channelized. Sediments of the Oro Moraine (165 km²) unconformably overlie Newmarket Till and consist of sand and gravel units with some beds of silt to sand diamicton. The moraine was predominantly deposited in a series of ice-marginal environments as subaqueous fans, with evidence of esker conduits and occasional fine-textured glaciolacustrine sediments. The uppermost deposits found primarily west and north of the moraine are intersected in only two of the logged boreholes. A silty-clay aquitard underlies more permeable (sandy to gravelly) postglacial to modern sediments deposited in Lake Algonquin (Burt and Dodge, 2011).

3.3. Waterloo Moraine

Borehole logging in the Waterloo moraine was completed in 2003-2004 in 14 boreholes ranging in depth from 15 – 98 m (Bajc and Hunter, 2006). Bedrock in the area is Silurian-aged

dolostone, shale, and evaporite (gypsum) bedrock. Overlying bedrock are a suite of units referred to as pre-Canning glaciofluvial deposits and tills, Canning Till, and Pre-Catfish Creek Till glaciofluvial deposits - all Lower Sediment equivalents. West of the Niagara Escarpment, the Catfish Creek Till (Newmarket Till equivalent) is a regional sandy silt till sheet which can have a stone-poor fine-textured facies, commonly referred to by water well drillers as hardpan (e.g., Dreimanis and Gibbard, 2005). The Waterloo Moraine unconformably overlies Catfish Creek Till, and is a complex sequence of interbedded (gritty, pebbly) mud, sand, gravel, and muddy diamicton. Surface tills (Port Stanley, Upper Maryhill, Tavistock, and Mornington) form a nearly continuous cover surrounding the moraine but become discontinuous over, and adjacent to, the moraine's centre (Bajc et al., 2014).

4. Previous Borehole Geophysical Studies in Southern Ontario

In the late 1970's and early 1980's, geophysical logging was first applied to the study of Quaternary stratigraphy in southern Ontario in the Laurentian Channel at sites south of Barrie by Sibul et al. (1977) and Fligg and Rodriguez (1983). In early days, drillers' logs were not sufficiently detailed to permit close comparisons between sediment descriptions and downhole geophysical logs, so a number of studies were undertaken to recover high quality cores to compare log responses with sediment textures in different regions throughout southern Ontario, east and west of the Niagara Escarpment (Eyles et al, 1985, Farvolden et al, 1987, Karrow et al, 1990; Greenhouse and Karrow, 1994; Schneider et al, 1994). In these studies, downhole logs identified geophysical marker horizons which could be used to interpret downhole variation in stratigraphy where core did not exist, and to correlate horizons from hole to hole within study areas.

The Canadian development of a slim-hole induction (apparent conductivity) logging tool in the early 1980's (McNeill, 1980a; McNeil 1986) and subsequent industry evaluation (e.g. Taylor et al, 1989; McNeill et al., 1990) increased the range of logging applications available for use inside plastic-cased boreholes. When paired with a total count gamma sonde, this allowed geophysical logging to play an increasingly important role in groundwater investigations both in industry and academia, with studies ranging from glacial sediment stratigraphy to the investigation of contaminant impact on pore fluid conductivity. Subsequent development of an induction magnetic susceptibility logging tool proved to be highly useful for shallow lithological mapping where susceptibilities are typically low (McNeill et al., 1996).

As urban growth in regions north of Toronto increased demand on groundwater resources in the 1990's, studies of the Oak Ridges Moraine employed geophysical techniques (surface and downhole) to identify characteristic variations in material properties (e.g. high velocity tills) which could be used to identify geophysical marker horizons, and to map these units over large distances (e.g. Boyce et al, 1995; Pugin et al., 1999; Pullan et al, 2002; Gerrie et al, 2003). This work, along with continuously cored boreholes ("Golden Spikes", e.g. Sharpe et al., 2003; Russell et al., 2003b, 2004; Logan et al., 2008; Sharpe et al., 2011) contributed to the development of a stratigraphic framework and 3D geological hydrostratigraphic model for the region (Sharpe et al 2004; Logan et al, 2005). The development of 3D models in numerous moraine settings in southern Ontario has been assisted by the use of geophysical logs in the correlation of stratigraphy (Bajc and Hunter, 2006; Bajc et al, 2014).

Analytical approaches such as cross plotting of log responses, and more recently, principal component analyses have been used in identifying material type or grain size (Pehme, 1984; Karrow et al, 1990; Kassenaar, 1991; Pullan et al, 2002; Gerrie et al., 2003; Brennan, 2011). It has been recognized that a key requirement for these studies is a collection of calibrated geophysical logs (Gerrie et al, 2003; Crow et al, 2015a).

5. Geophysical Logging Methods

Geophysical logs recorded by the GSC in southern Ontario sediment boreholes between 1993 and 2013 include passive (natural) gamma, active gamma (relative density, spectral density ratio), induction (apparent conductivity and magnetic susceptibility), fluid temperature, and compressional wave velocities (V_p) calculated from vertical seismic profiles. In many boreholes, shear wave velocities (V_s) were also calculated using horizontally polarized shear wave VSPs. Neutron logs were additionally collected by non-GSC personnel in 19 boreholes in the Waterloo (9), Oro (8), and GTA (2) study areas. All digital log data, along with logging procedures and systems, can be found in Crow et al. (2015a). In the present study, natural gamma, induction, and velocity (V_p , V_s) logs were selected to characterize hydrostratigraphic unit responses as they were collected in nearly all the boreholes. These non-radioactive tools have a radius of investigation beyond the grout present in these holes and do not require specialized licenses, allowing for wider application within the hydrogeological community.

Gamma Methods

Natural gamma (or gamma ray) logs measure naturally occurring radioactivity by converting gamma rays emitted from the formation into electronic pulses using a scintillator crystal in the tool, recorded in counts per second (cps). Scintillator crystals differ from probe to probe, resulting in differences in sensitivities between count levels; thus unless calibrated, a tool's counts represent relative changes in downhole lithology. The instrument used to collect all of the gamma log data presented here was Geonics Ltd.'s Gamma39 probe (with the exception of the two boreholes in the south Simcoe County area).

The most common natural radionuclides in rock and sediment are potassium (K), uranium (U), and thorium (Th). In total count logging, the number of cps are summed across the entire 3000 kiloelectron volt (keV) energy window. To gain insight into the contributions from the K, U, and Th energy windows in each total count reading, a spectral gamma tool must be used. In these instruments, the amplitude of each received pulse over a given time interval is binned into energy windows to determine whether the gamma ray energy corresponds with the windows for K, U, or Th. Although gamma rays from decaying isotopes of K, and to a lesser extent, U, and Th are present in the spectrum, the majority of the counts come from a lower energy band both in sediment and rock (Figure 2).

In southern Ontario where mineralogical composition of the sediments can be similar between muds and the coarser grain size fraction, often subtle changes in total count rates can be used in a qualitative manner to estimate changes in grain size, where <2 micron-sized grains exhibit higher count levels than the coarser grain size fraction. These trends are discussed in Section 6.0 where log response is examined alongside particle size analyses.

Induction Methods

The apparent conductivity logging tool (Geonics Ltd.'s EM39) uses an alternating 40 kHz AC current in a dipole transmitter to generate a magnetic field which induces electric fields in the formation. A dipole antenna receiver, in turn, measures the responding signal, which is proportional to the conductivity of the materials intersected by the borehole (McNeill et al., 1990). In studies of electrical conductivities in shales, clay minerals have a higher cation exchange capacity (CEC) due to water bound to the surface of the grains, and are therefore more conductive than coarser grained materials (Patchett, 1975; Hearst et al, 2000). Cation exchange capacity in soils and sediments increases with clay mineral content (McNeill, 1980b), hence although the percentage of clay minerals can be relatively low in the <2 micron fraction in the study areas, adsorbed ions on the surface of the <2 micron grains contribute to the increased conductivity, relative to the coarser grained silts and sands. In soil and bedrock logging, the mineral grains and pore water both contribute to the total (bulk) conductivity values measured. In the absence of conductive (saline, or leachate-impacted) pore water, the conductivity tool provides a method to identify lithological changes downhole associated with variation in mineralogy. The log generally follows the trends of the natural gamma log, where fine grained materials (<2 micron size) are more conductive than coarser grained materials.

The magnetic susceptibility logging tool (Geonics Ltd's EM39S) records the ratio between the primary magnetic field, and the in-phase component of the magnetic field caused by the presence of magnetically susceptible material in the formation. Although traditionally used for downhole

mineral exploration due to its sensitivity to magnetic minerals (e.g. magnetite, pyrrhotite, ilmenite), the susceptibility tool is extremely useful for lithological logging in unconsolidated sediments of low susceptibilities (McNeill et al, 1996). This requires a very sensitive logging tool in the sub-parts-per-thousand (ppt) SI with a high degree of temperature compensation. Therefore, induction susceptibility loggers require a slightly different coil configuration than the apparent conductivity tools, with enhanced temperature compensation electronics. Due to the differing coil configurations between the EM39 and EM39S induction tools, the effective sphere of influence from the formation on the magnetic susceptibility response is approximately 0.5 m diameter, while the apparent conductivity is approximately 1.0 m. In sediments derived from the Canadian Shield, we observe that the log response generally inversely mirrors the conductivity and gamma logs, as coarse grained materials have retained a higher percentage of heavier magnetic minerals than fine grained materials. In this setting, magnetic susceptibility also provides an indication of variation in sediment provenance, as the log responds positively (5 – 20⁺ ppt SI) in sands and gravels derived from the Canadian Shield, but remains low (1 – 4 ppt) in materials derived from carbonate and shale bedrock.

Seismic Methods

Downhole compressional (V_p) wave and shear (V_s) wave velocities were calculated by measuring the traveltimes of waves propagating from a surface source to a series of downhole receivers. The entire wave train was recorded following the procedures described in Hunter et al. (1998), which allowed for the interpretation of later arriving events (e.g. reflections from horizons below the bottom of the borehole, converted waves, tube waves, etc.). P-wave logging

was carried out in fluid-filled portions of the boreholes using a high-frequency in-hole surface shotgun source with a 24-channel hydrophone array (0.5 m geophone spacings) pulled up-hole at 1m intervals. Shear wave logging was carried out using a wall-locking instrument containing a 3-component geophone block, pulled up-hole at 1 m intervals. A loaded metal plate struck horizontally with a sledgehammer was commonly used as a source. In addition to providing interval velocity characteristics of the sediments intersected by the borehole, downhole seismic data was used to correlate depths to reflections from surface seismic datasets. Shear waves are proving to be highly effective for lithological mapping of near-surface unconsolidated sediments, as slower velocities translate into shorter wavelengths, which have the potential to create higher resolution images of the subsurface. P-waves, although lower in resolution due to longer wavelengths, can penetrate more consolidated or coarser-grained sediments to image the underlying bedrock (e.g. Pugin et al., 2013a; Pugin et al., 2013b).

It is common to observe highly variable V_p and V_s in glacial tills, reflecting the poorly sorted, highly heterogeneous (chaotic) nature of the sediment deposition. V_p in unconsolidated materials are strongly affected by the velocity of the pore fluids, while V_s are transmitted through the material grains, making them much less sensitive to pore water composition, but strongly influenced by overburden pressures and the degree of consolidation. Although much more detail can be noted about velocities, the current discussion is limited to the V_p to V_s ratio. This ratio is a very useful indicator for depositional setting (i.e. lower ratios in glacially-loaded sediments versus higher ratios in deglacial valley-fill and glaciolacustrine environments; Hunter et al, 2007; Crow et al, 2015b).

6. Results

Using the suite of geophysical tools presented here, log response within the glacial stratigraphy across southern Ontario can assist in placing logged intervals of boreholes within a hydrogeological context. As a first step, the correlations between grain size and geophysical tool response were examined, and from these observations, some characteristic geophysical properties and/or patterns within each stratigraphic unit have been described.

6.1. Correlations between geophysical log response and grain size

Datasets of weight percent (%) sand (2 mm - 63 micron), silt (63 – 2 micron), and clay (<2 micron), are plotted alongside a suite of geophysical logs from a GTA borehole. Gamma and conductivity responses closely track the measured <2 micron size fraction, while the magnetic susceptibility log follows the sand content (Figure 3). At 2 cm recording intervals, the downhole logs allow for a more continuous qualitative interpretation of grain size variation than from grain size analyses (core sampling) alone. Instrument response to subtle changes in grain size (e.g. upward coarsening clay into silt, or silt into sand) provide important complementary information for studies of depositional processes and stratigraphic successions.

To examine these relationships of weight percent grain size versus log response, a few representative cross plots are presented from the logged interval (Figure 3). The evident scatter in the plots is primarily the result of the varied composition of the remaining grain size sample volume (i.e. a sample of 40% silt is also some combination of 60% sand and clay), but also the variability of material types sampled, the choice of sampling location in the cores, borehole conditions, and the vertical sonde resolution versus the thickness of the sediment layer sampled in the core. In addition, log response overlap, particularly with silt and sand, cautions an

429 interpreter against making a quantitative assessment of sand-silt-clay distribution from the logs.
430 Despite these considerations, the plots indicate that conductivity response (and gamma, not
431 shown) is most strongly influenced by the presence of <2 micron-sized particles than silt or sand,
432 even though the sampled sediments do not contain more than 40% clay-size fraction by weight.
433 The correlation coefficient of <2 micron versus conductivity in this borehole is relatively high (ρ
434 = 0.81; ρ = 0.64 for gamma). Silts do not appear to have a strong correlation with conductivity
435 (ρ =0.28) and response tends to remain below 25 mS/m unless clay-sized particles are present in
436 amounts greater than 20% as indicated. In this borehole, the relationship between susceptibility
437 and sand content is weakly positive (ρ =0.51), as the sediments do not appear to contain elevated
438 amounts of magnetic minerals (response range 1-10 ppt SI).

439
440 Grain size analyses conducted by the OGS and GSC were available for 28 of the 57
441 geophysically logged boreholes: 9 from the Waterloo Moraine, 11 from the Oro Moraine, and 8
442 from the Oak Ridges Moraine. Regional cross plots show more scatter than for an individual
443 borehole due to the larger dataset and wider geographic coverage, but the trends are similar
444 (Figure 4). The plots primarily indicate that sediments sampled throughout the region rarely
445 contain more than 40% <2 micron size fraction by weight, but that gamma and conductivity
446 responses are most strongly influenced by the presence of these particles. Regionally, gamma
447 and conductivity responses to <2 micron content tend to be slightly more elevated west of the
448 Niagara Escarpment than east. The magnetic susceptibility versus sand plot has a very low
449 correlation value when examined as a regional dataset. When broken down by region, however,
450 the plots reveal that magnetic susceptibility response is systematically lower west of the Niagara

Escarpment than east, suggesting different mineralogical characteristics which should be examined independently.

Little mineralogical data exists for these cores at present, however, mineralogical variation strongly influences log response, and as shown in Figures 3 and 4, the magnetic susceptibility tool plays an important role within the suite. Intervals where magnetic susceptibility response is relatively low but where sand content is elevated suggests a non-igneous (Paleozoic) sand source. Regionally, the higher magnetic susceptibility response east of the Escarpment suggests an increased volume of magnetic mineral content from Canadian Shield-derived sand sediments. Additionally, response to <2 micron-sized grains from the Waterloo moraine area tend to be more conductive with higher gamma counts. This has been interpreted to indicate greater abundance of clay minerals in western sediments, however further mineralogical testing is required to confirm these relationships.

6.2. Geophysical characteristics of the hydrostratigraphic units

Grain size and mineralogical changes reflected in the geophysical logs have been used to identify patterns or characteristic intervals along a borehole. Variation in stiffness (density) of materials revealed from velocity measurements provide another important physical characteristic. Discussed below are common geophysical properties found within the broad hydrostratigraphic units encountered in southern Ontario (Table 1). Within each unit, representative geophysical logs are shown from the three study areas, and cross plots of grain size versus log response demonstrate characteristic responses.

For the quantification of velocity ranges for each unit, basic statistical analyses were carried out. Chauvenet's rejection standard error threshold was used to identify any statistical outliers based on the number of data points in each unit. The data rejection threshold ranged from 2.98 to 3.63 standard deviations of the mean. Data outside the threshold were investigated and determined to be the result of traveltime picking errors or misplaced material boundaries. As a result, 18 velocity records out of 5114 were rejected (i.e. 0.35% of the data set). In boreholes where both V_p and V_s were collected, the ratio of V_p to V_s was calculated using this corrected dataset (Table 2). Of note in each of the units is the wide velocity distribution reflecting the natural variation in the sediments. In these glacial deposits, velocity distributions are often positively skewed, reflecting intervals of elevated velocity randomly present in the units (i.e. gravels, tills). This natural non-normal distribution tends to increase the standard deviation; therefore, one standard deviation is chosen to represent the velocity ranges.

Lower Sediment

Seismic reflection profiles collected in the GTA in the 1990's have been interpreted to indicate that the Lower Sediments are composed of several units which are generally well stratified, horizontal, and laterally extensive. Based on correlations with borehole cores, geophysical logs and outcrops, interglacial formations (Scarborough and Thorncliffe) and diamictons (York, Sunnybrook) could be traced in the profiles over several kilometers (Pugin et al., 1999). In the oldest deposits of this unit, elevated velocities are the characteristic downhole responses in gravels and diamictons (York Till) above the bedrock. In the overlying sand and muds of the Scarborough and Thorncliffe formations, which are commonly interpreted to be delta, lacustrine,

and subaqueous fans (e.g. Eyles et al., 1985; Sharpe et al. 2011), gamma and induction logs produce a particularly distinct funnel-shaped pattern in the upward coarsening rhythmite sequences as clay content decreases upward (Figure 5). This pattern is observed most prominently east of the escarpment in the boreholes drilled in the GTA region (e.g. the Nobleton borehole). Grain size versus log response plots within the Lower Sediment indicate a significant degree of scatter, as it is composed of alternating (1) units, containing glaciolacustrine clays, silts, and sands, and (2) silty-clay diamictos (Figure 6). Clay-sized particles have a strong influence on gamma and conductivity log responses, and are present in quantities greater than in the other hydrostratigraphic units. Magnetic susceptibility response is systematically lower (<4 ppt SI) in the Waterloo region and does not increase with increasing sand content.

As a result of the many grain sizes and textural types (e.g. clays to gravels, laminated muds to tills) found in the Lower Sediment, velocity distributions are positively skewed due to the presence of high velocity diamictos and gravel intervals. Velocity logs in the lower sediment indicate that Vp and Vs are better discriminators of the tills than the lithological logs, but they must be greater than a few metres in thickness to be detected using the seismic techniques described herein.

High velocity tills

Within the high velocity till unit, composed of the Newmarket Till east of the escarpment and Catfish Creek Till west of the escarpment, the lithological log responses (gamma, conductivity, and magnetic susceptibility) indicate characteristically low and stable values, whereas P and S

520 wave velocities increase significantly, in relation to the surrounding sediment (Figure 7). The
521 grain size versus log responses plot in tight clusters (Figure 8), as the matrix grain size of this
522 unit is relatively homogeneous. The till is composed of approximately equal parts of silt and
523 sand (40 – 50%) with <10% <2 micron size, accounting for the relatively low gamma and
524 conductivity responses. Even with the significant sand content, however, magnetic susceptibility
525 has a relatively low response which forms another distinguishing feature of this unit. Recent
526 GSC mineralogical studies from a core north of Oshawa, ON have found the Newmarket Till
527 matrix assemblage to be composed of (in decreasing abundance) quartz, calcite, potassium
528 feldspar, plagioclase, dolomite, amphibole, and clinopyroxene (Kjarsgaard et al. 2016) which
529 accounts for the low response. Clasts larger than gravel-size were found to be limestone or
530 granite, the latter may cause occasional spikes in magnetic susceptibility leading to some
531 variability in this log relative to gamma and conductivity. If sand content increased relative to
532 the underlying Lower Sediments, an abrupt increase in magnetic susceptibility was observed at
533 that interface; however, the gamma, conductivity and magnetic susceptibility logs alone may not
534 readily identify this unit from others in the sedimentary sequence. These observations
535 corroborate earlier work by Pehme (1984) and Farvolden et al. (1987) in a study of geophysical
536 responses in Catfish Creek Till.

537
538 The key geophysical signature of the typical Newmarket and Catfish Creek tills is the elevated P
539 and S wave velocities (Table 2). Core measurements in a borehole north of Oshawa indicate the
540 till density is similar to that of soft rock ($2.2 - 2.4 \text{ g/cm}^3$), which could result from over-
541 consolidation due to glacial loading, the presence of a secondary cement, or a combination of
542 these processes (e.g. Kjarsgaard et al. 2016). The mean V_p of this unit is 20 – 30% greater than

the other hydrostratigraphic units of the region, and similarly, the mean V_s is 15 – 45% higher. The high density of the Catfish Creek Till has also been noted as a geophysical characteristic of this unit by Farvolden et al. (1987). Based on seismic velocities, the two tills of this unit form a regional marker horizon throughout southern Ontario.

A large standard deviation in the velocities of this marker unit led to a further examination of the till east (Newmarket) and west (Catfish Creek) of the escarpment (Figure 9). Mean V_s in the Catfish Creek till is 15% higher than the Newmarket Till, which suggests a slightly greater cementation-consolidation in the Catfish Creek Till. A comparison of V_p measured in high velocity tills intersected in 10 GTA boreholes and 9 Waterloo region boreholes indicates that the mean values are similar (V_p is 5% higher in the Waterloo region). In the GTA, the thickness of the Newmarket Till ranges between 5.0 – 56.0 m with a mean thickness of 27.4 ± 18.7 m. In the Waterloo region, the range is halved in the Catfish Creek Till, measuring only 5.6 – 21.4 m with a mean of 15.2 ± 6.6 m. V_p values in the GTA boreholes have a broader range with a much larger standard deviation than in the Waterloo area boreholes. Thus despite the presence of a high velocity till sheet throughout much of southern Ontario, there are considerable local, regional, and stratigraphic variations observed within this unit.

Moraine and channel deposits

The moraine and channel sediments are characterised by a highly variable magnetic susceptibility log response (Figure 10), which commonly displays a slight upward increase in response through moraine deposits. This could indicate an upward coarsening, and/or could

reflect a preferential sorting of Shield mineralogy. The gamma counts and conductivity levels tend to remain low and unvarying due to limited <2 micron content (typically <5%). The rapid vertical variation of the magnetic susceptibility signal reflects a more chaotic, high-energy style of deposition with alternating coarse-to-fine grained deposits of gravels and sands; this is in agreement with observations from the seismic profiles in the GTA which are characterised by highly reflective, chaotic facies (Pugin et al, 1999).

The variable range of depositional conditions in this unit leads to elevated velocities in a few gravel intervals, resulting in a relatively wide range in the Vp values. The mean Vp:Vs ratio is lower than the overlying unit as the materials contain a greater percentage of sands and gravels (Table 2).

Surficial tills

The late-glacial, <2 micron- and silt-rich surficial tills west of the Niagara Escarpment characteristically exhibit elevated gamma (>100 cps) and conductivity (>20-30 mS/m) and low magnetic susceptibility responses relative to the underlying moraine and channel sediments and high velocity tills. Although a representative example of geophysical log response in the GTA is not presented here due to near surface borehole completion effects, grain size plots show that the surficial (Halton) tills intersected by the boreholes contain more silt, reducing the gamma and conductivity responses (Figure 12). In the GTA, the tills are commonly intercalated with sandy sediment facies with decreased gamma and conductivity responses. The presence of <2 micron grain size strongly influences the gamma and conductivity response (Figure 12). These

geophysical responses are also noted in the Waterloo region by Farvolden et al. (1987) and Karrow et al. (1990), and more recently by Eyles et al. (2011) in gamma logs west of Toronto.

Grain size analyses from over 900 samples in the GTA in a study conducted by Sharpe and Russell (2016) show a clear distinction between the Halton Till, with a clayey-silt to silt matrix containing 1-2% stones, versus the Newmarket Till with a sandy-silt textured matrix and more stones (5-10%). North of Hamilton, the Halton Till has been described as having a silt-rich matrix interstratified with silt and sand with a high shale content (Karrow, 1987).

While the Vp and Vs velocities tend to be low in the muddy diamictons, the Vp-to-Vs ratio is characteristically higher (mean of 4.0) than in the underlying sediments (mean of 3.5 or less, Table 2); this is due to reduced Vs with a lower degree of consolidation than the underlying materials.

7. Discussion

7.1. Caveat: the need for multiple logs and mineralogical data in log interpretation

Log signal response has long been interpreted within a scheme of geometric shapes and sedimentary facies analyses of depositional environments (e.g. Cant, 1984; Rider, 1990). Cant reviewed five geometries (cylindrical (blocky), bell, funnel, symmetrical, and irregular) commonly recognized from natural gamma logs. Such geometries are also common elements of

conductivity/resistivity logs, and to a lesser extent, magnetic susceptibility logs. Cant suggests these geometries can be considered as norms against which log signatures can be compared. This type of analysis has also been applied to glacial sedimentary successions in Indiana (Bleuer, 2004). Rider (1990) highlighted the necessity for caution in making the assumption that the gamma signal correlates with clay mineralogy, which in turn correlates to grain size and subsequently to sedimentary facies (e.g. Bleuer, 2004). Rider noted that feldspars are equally capable of influencing the gamma signal and that feldspars may not correlate well with the assumed grain size relationships of higher gamma counts correlating to finer grain sizes. Consequently, as conceptually attractive as it is to complete borehole geophysical analyses using log geometries for both grain size inference and depositional environment analysis, caution is necessary.

A review of geophysical logs and corresponding grain size analyses from the Southern Ontario datasets supports Rider's questioning of the robustness of this approach. Our experience indicates that any geometric log analysis should only be completed by integration of gamma, conductivity, and magnetic susceptibility logs, along with velocity (or density) logs (the latter critical for the identification of the Catfish Creek and Newmarket Tills). Plots of weight percent grain size versus log response indicate response of an individual log signal is not unique to a particular depositional environment, nor characteristic of any stratigraphic unit. A stratigraphic unit may have variable signal depending upon the depositional setting(s) present within its regional occurrence. Characterization thus requires integration of multiple geophysical logs for interpretation of grain size trends, inference of depositional sedimentary facies, and possible stratigraphic assignments.

The suite of gamma and induction logs have responses that reflect changing grain size to varying degrees, however, logs provide only a first order indication of changing mineralogy, both within one borehole, and within a calibrated dataset across the region. In this respect, a high-sensitivity magnetic susceptibility probe is a key instrument to infer mineralogical change, but lab data are also needed to identify assemblages for provenance and depositional process studies. The paucity of subsurface geochemical information presents challenges for developing a robust interpretative framework for interpretation of the logging signals. Emerging data associated with the stratigraphic drilling programs of the Ontario Geological Survey (e.g. Bajc et al., 2015) and Geological Survey of Canada (e.g. Knight et al 2016) are gradually providing the data support for an enhanced geochemical characterization, and hence correlation with geophysical response. For example, the presence of abundant quartz and calcite in the Newmarket Till matrix accounts for the reduced variability and low response of the gamma and induction logs. By contrast, sands of similar grain size in moraine and channel deposits can produce more elevated magnetic susceptibilities. To date, knowledge from mostly near surface sampling indicates the Ontario portion of the Great Lakes basin is largely carbonate dominated, has low amounts of clay minerals, and has a secondary signal of Grenville Province geochemistry and mineralogy, dominated by quartz and minor amounts of feldspar.

The calibrated downhole dataset identified regional differences in log response between common stratigraphic units. In the Lower Sediment, log response versus grain size plots indicate that electrical conductivity and gamma response can be higher in <2 micron and silt grain sizes of the Waterloo region than in the Oro and GTA regions, hinting at the presence of a greater content of

clay minerals. Conversely, the magnetic susceptibilities are systematically lower in Waterloo Region Lower Sediment sand (1 - 3 ppt SI) than in the Oro and GTA regions (3 – 20⁺ ppt SI). This seems to indicate that the sands in the Waterloo area have a higher percentage of Paleozoic relative to Shield-derived sediment and therefore have less magnetic mineral content. Also noted in the borehole log suites from the three study areas are basal tills containing sands exhibiting lower magnetic susceptibilities than sands from shallower depths, suggesting differences in sand provenance. This may explain the low susceptibility readings observed even when sand is present in significant percentages (e.g. 80-100%).

More elevated gamma and conductivity responses in the silty-clay and clayey-silt surficial tills were also noted west of the Niagara Escarpment, relative to the east. In the future, mineralogical data (i.e. clay mineral content) could assist in the interpretation of these responses, as shale from the Queenston Formation has been a noted source material in the Hamilton region (Karrow, 1987).

7.2. Implications for interpretation of glacial processes

The response of geophysical logs at a stratigraphic boundary can provide key information in the interpretation of glacial processes. At the boundary between the Newmarket Till and the Lower Sediments, log responses in three boreholes across the GTA were examined (Figure 13).

In borehole A, the transition at the boundary is sharp in all logs, reflecting a well sorted, fine grained mud unit underlying a poorly sorted diamicton with a sandy silt matrix. The reverse

response in the magnetic susceptibility data compared to the gamma and conductivity data confirms an increase in magnetic mineral content, reflective of the change from muds dominated by suspension sedimentation to the poorly sorted diamicton matrix that is deposited directly from the ice. The upward increase in Vp indicates a density increase within the diamicton. The sharp signal break across all logs suggests that the interface marks an unconformity, and that the depositing ice had integrated a minimal amount of the underlying material into the diamicton matrix. The cores examined below the contact show no evidence of deformation in the underlying laminated muds.

In borehole B, the gamma log has no apparent change across the boundary with an upward increasing (fining) pattern having a slight decrease in amplitude within the diamicton unit. The conductivity log has a sharp drop across the contact but remains stable upward through the diamicton. The magnetic susceptibility and velocity logs increase sharply and stabilize above the boundary. The three lithological logs provide complementary information on the transition from Lower Sediment mud to diamicton; however the signal is not as clear and easily interpreted as (A). There is likely greater similarity in the matrix mineralogy in (B) than in (A). The gamma log suggests that mobilization or cannibalization of mud into the till is possible, but the change in induction logs support a strong contribution of unrelated and more Shield dominated mineralogy. The plateau in the magnetic susceptibility signal indicates that the increase is likely due to matrix mineralogy rather than oversized clasts.

In borehole C, the three lithological log responses remain relatively low and smoothly varying across the boundary, with the indication of the Newmarket Till coming primarily from the

increase in the P-wave velocity log. In this well, a different gamma tool was used for the logging than in A and B, accounting for the more elevated cps. The logs suggest a gradational contact at the base of the Newmarket Till which fines upward into a siltier matrix. Together, the logs suggest a similar matrix material is present in both units, possibly through incorporation of the underlying sediments. The low magnetic susceptibility log does not suggest Shield dominated mineralogy is present in the matrix.

In these examples, the logs provide insight into the nature of the contact between the Lower Sediments and the Newmarket Till. The gamma and induction logs indicate whether the boundary is abrupt or more continuous in nature, from which an interpretation on glacial processes at that location can be made. An examination of this boundary in the borehole dataset indicates that conditions were not uniform across the basin.

7.3. Application of geophysical logs within hydrogeology studies

To advance groundwater understanding requires increased collection of reliable data. The era for reliance on water well records is long past, given the range of data quality and resolution issues (e.g. Russell et al., 1998). Increasing conflict in land use issues and stress on surface and subsurface resources requires increased integration of high quality data in groundwater modelling and decision-making. The need for such a change in data support has been recognized for over 20 years (e.g., Bhatt, 1993) yet both modelling and consequently management decisions continue to be based on inadequate data quality and data support. The use of a regional framework for interpreting downhole geophysical logs presents another cost effective manner of adding hydrostratigraphic context to a borehole dataset.

Currently, a lack of borehole calibration sites has limited the ability of consultants to collect data to a common standard. A requirement by contracting authorities (conservation authorities, municipal and provincial governments) to insist on data collection following a standard calibration protocol would enable data to be normalized for specific tools; hence, individual studies could be more broadly used by the groundwater community. The issue of calibration has been addressed in other jurisdictions with similar geology to Southern Ontario, such as Denmark. A national borehole calibration facility operated by the GSC near Ottawa is freely available for public use, but boreholes do not intersect glacial sediments and the facility is distant from the GTA. A recent leadership example in southern Ontario is the University of Guelph's bedrock aquifer field facility (BAFF) where boreholes intersecting bedrock and glacial sediments are being used to teach and train professional staff in applied groundwater research.

8. Summary

Over the past three decades, a suite of geophysical logs has been collected by the GSC in 57 PVC-cased wells drilled in the glacial sediments of southern Ontario. Rapid deposition of many of these sedimentary units has resulted in reduced time for mineralogical partitioning and associated mineralogical contrast between bedding horizons. Sand, silt and clay-sized grains are dominated by the primary mineralogy (e.g., quartz, feldspar, calcite) of the provenance lithologies (crystalline rocks, limestones) rather than by secondary alteration minerals (e.g., phyllosilicates). Consequently, when the weight percent <2 micron grain size fraction is low (approximately <20%), there can be an absence of mineralogical distinction between the sediments, resulting in a reduced range of downhole log responses. This often causes log

overlap for different grain size distributions when only one or two of the conventional lithological logging tools are used (e.g. gamma, conductivity).

As a result, integration of a wider suite of tools (gamma, conductivity, magnetic susceptibility, and velocity logs) becomes important in distinguishing patterns in hydrostratigraphic sequences. The use of a high-sensitivity magnetic susceptibility induction probe in the log suite is found to be an important tool for lithostratigraphic interpretation, and more broadly, for provenance studies of source rock across the region. Ongoing studies of sediment mineralogy are helping to better understand tool response, such as in the Newmarket Till.

For each of the hydrostratigraphic units, the ranges of P- and S-wave velocities, and Vp:Vs ratios have been provided. Although there is overlap in the velocity ranges found within the units, P- and S-wave velocities are necessary in the log suite to identify Newmarket and Catfish Creek tills which form a key geophysical marker horizon across the region. Vp logs in the Newmarket till indicate that where the unit is thick (i.e. >20 m), a broader range of velocities exist than where it is thin, suggesting that conditions during deposition were not uniform, despite the presence of a high velocity till sheet throughout much of southern Ontario. Velocity profiles also identify the presence of gravel units or basal tills which are otherwise difficult to detect with lithological logging tools alone. In addition to hydrogeological studies, Vs is also an important geotechnical parameter used to predict regional variation in earthquake shaking, making these velocity ranges and ratios valuable for other disciplines (e.g. engineering, geohazards) in this highly populated region of Canada.

Although water well records are commonly available for hydrogeological studies, these data generally lack the geological resolution and reliability of digital geophysical logs, which allow for quantitative (re)analysis of stratigraphy and marker horizons. It is anticipated that a framework for the interpretation of geophysical logs in southern Ontario will offer a cost-effective method for placing boreholes within a hydrostratigraphic context. This, however, raises the issue of tool calibration and collection protocols for the future standardization of these logs, which will present itself as an important next step for incorporation of geophysical data into large regional analyses for the hydrogeological community.

9. Acknowledgments

We wish to recognize the technique development and dataset collection of R. Good, R. Burns, S. Pullan, M. Douma, T. Cartwright, and K. Brewer. The collaboration with the Ontario Geological Survey and A. Bajc and A. Burt for the drilling of boreholes and sharing of stratigraphic logs and grain size datasets was particularly appreciated. We sincerely appreciate the insights and resulting improvements from comments by anonymous journal reviewers and the guest editor. This work was carried out at GSC–Ottawa under the Aquifer Assessments and Support to Mapping Groundwater Inventory Project of the Groundwater Geoscience Program. This work is a contribution of the GSC-OGS Southern Ontario project on groundwater 2014-2019 (NRCan Contribution 20170073).

10. References

Armstrong, D.K., Carter, T.R., 2010. The subsurface Paleozoic stratigraphy of southern Ontario. Ontario Geological Survey, Special Volume 7.

- 793 Bajc AF, and Hunter JA, 2006. Results of 2003–2004 overburden drilling programs in the
794 Region of Waterloo, southwestern Ontario. Miscellaneous Release-Data 205. Sudbury, ON:
795 Ontario Geological Survey.
- 796 Bajc AF, and Shirota J, 2007. Three-dimensional mapping of surficial deposits in the Regional
797 Municipality of Waterloo, southwestern Ontario; Ontario Geological Survey. Groundwater
798 Resources Study 3.
- 799 Bajc AF, Russell HAJ, and Sharpe DR. 2014. A three-dimensional hydrostratigraphic model of
800 the Waterloo Moraine area, southern Ontario, Canada, Canadian Water Resources Journal
801 <http://dx.doi.org/10.1080/07011784.2014.914794>
- 802 Bajc, A.F., Mulligan, R.P.M., Rainsford, D.R.B., Webb, J.L., 2015. Results of 2011–13
803 overburden drilling programs in the southern part of the County of Simcoe, south-central
804 Ontario. Ontario Geological Survey. Misc. Release—Data 324.
- 805 Barnett, P.J., Henry, A.P., and Cowan, W.R. 1991. Quaternary geology of Ontario, southern
806 sheet. Ontario Geological Survey, Map 2556, scale 1:1 000 000.
- 807 Barnett, P., Sharpe, D., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F., and Pugin, A.J-
808 M., 1998. On the origin of the Oak Ridges Moraine. Can. J. Earth Sci. 35, 1152–1167.
809 [doi:10.1139/cjes-35-10-1152](https://doi.org/10.1139/cjes-35-10-1152)
- 810 Béland Otis, C. 2013. Gas assessment of the Devonian Kettle Point Formation; Ontario
811 Geological Survey, Open File Report 6279, 63 p

- 812 Bernius, G.R; 1996. Borehole geophysical logs from the GSC Borehole Geophysics Test Site at
813 Bell's Corners, Nepean, Ontario, Geological Survey of Canada, Open File 3157, 1996; 38
814 pages, doi:10.4095/207617
- 815 Bhatt K, 1993. Uncertainty in wellhead protection area delineation due to uncertainty in aquifer
816 parameter values. *J. Hydrol.* 149, 1–8.
- 817 Bleuer, N. K. 2004, Slow-logging subtle sequences the gamma-ray log character of glacial
818 and other unconsolidated sedimentary sequences: Indiana Geological Survey Special
819 Report 65, 39 p., 27 fig.
- 820 Boyce J.I, Eyles N.E, and Pugin AJ-M, 1995. Seismic reflection, borehole and outcrop geometry
821 of Late Wisconsin tills at a proposed landfill near Toronto, Ontario, *Can. J. Earth Sci.*, 32:
822 1331-1349
- 823 Bouchard, M., Godard, A., 1985. Les altérités du bouclier canadien : premier bilan d'une
824 campagne de reconnaissance. *Geographie Physique et Quaternaire*. 38, 149–163.
- 825 Brennan AN, 2011. Characterizing the Quaternary hydrostratigraphy of buried valleys using
826 multi-parameter borehole geophysics, Georgetown, Ontario. Unpublished MSc thesis,
827 McMaster University, London, Ontario
- 828 Burt, A.K. and Dodge, J.E.P. 2011. Three-dimensional modelling of surficial deposits in the
829 Barrie–Oro Moraine area of southern Ontario; Ontario Geological Survey, Groundwater
830 Resources Study 11.

- 831 Cant, D.J., 1984. Subsurface Facies Analysis, in: Facies Models. Geological Association of
832 Canada, pp. 297–310.
- 833 Coffin LM, Knight RD, Popovic N, Prowse ND, Russell HAJ, 2017. Sedimentology and
834 geochemistry of the Purple Woods borehole, southern Ontario; Geological Survey of Canada,
835 Open File 7899, 2017; 1 sheet, doi:10.4095/299433
- 836 Crow HL, Good RL, Hunter JA, Burns RA, Reman A, and Russell HAJ, 2015a. Borehole
837 geophysical logs in unconsolidated sediments across Canada. Geological Survey of Canada,
838 Open File 7591, 39 pages, doi:10.4095/295753
- 839 Crow HL, Brewer KD, Bajc AF, Pugin AJ –M, Mulligan RPM, and Russell HAJ, 2015b.
840 Downhole geophysical data from two boreholes in the south Simcoe County, Ontario.
841 Geological Survey of Canada, Open File 7883, 18 pages (2 sheets), doi:10.4095/296884
- 842 Dreimanis, A., 1962. Quantitative gasometric determination of calcite and dolomite by using
843 Chittick apparatus, *Journal of Sedimentary Petrology*, v.32, p.520-529.
- 844 Dreimanis, A., 1992. Early Wisconsinan in the north-central part of the Lake Erie basin: A new
845 interpretation. *Geol. Soc. Am. Spec. Pap.* vol. 270 109–118.
- 846 Dreimanis, A., Gibbard, P.L., 2005. Stratigraphy and sedimentation of the stratotype sections of
847 the Catfish Creek Drift Formation between Bradtville and Plum Point, north shore, Lake Erie,
848 southwestern Ontario, Canada. *Boreas* 34, 101–122.
- 849 Dreimanis, A., Reavely, G.H., Cook, R.J.B., Knox, K.S., Moretti, F.J., 1957. Heavy mineral
850 studies of tills of Ontario and adjacent areas. *J. Sediment. Petrol.* 27, 148–161.

- 851 Eyles, N. and Williams, N.E.1992. The sedimentary and biological record of the last interglacial
852 glacial transition at Toronto, Canada. Geological Society of America Special Papers, vol. 270,
853 p. 119-138.
- 854 Eyles N, Eyles C, Menzies J, Boyce J. 2011. End moraine construction by incremental till
855 deposition below the Laurentide Ice Sheet: Southern Ontario, Canada. Boreas, Vol. 40, pp.
856 92–104. 10.1111/j.1502-3885.2010.00171.x. ISSN 0300-9483.
- 857 Eyles NE, Clark BM, Kaye BG, Howard KWF, and Eyles CH, 1985. The application of basin
858 analysis techniques to glaciated terrains: an example from the Lake Ontario Basin, Canada.
859 Geoscience Canada 12:1, 22 - 32
- 860 Farvolden RN, Greenhouse JP, Karrow PF, Pehme PE, and Ross LC, 1987. Ontario Geoscience
861 Research Grant Program, Grant No. 128, Subsurface Quaternary stratigraphy of the
862 Kitchener-Waterloo area using borehole geophysics; Ontario Geological Survey, Open File
863 Report 5623, 76p
- 864 Fligg, K, Rodriguez, B, 1983. Geophysical well log correlations between Barrie and the Oak
865 Ridges Moraine; Water Resources Branch, Ontario Ministry of the Environment, Map 2273.
- 866 Gao C, 2011. Buried bedrock valleys and glacial and subglacial meltwater erosion in southern
867 Ontario, Canada; Can. J. Earth Sci. 48: 801-818
- 868 Gerrie V, Holysh S, Boyce J, Pullan SE, Blasco K, and Collins S, 2003. Borehole geophysics
869 and its potential for mapping the geological framework of the Oak Ridges Moraine, southern
870 Ontario; in *proceedings of the 56th Canadian Geotechnical Conference and the 4th Joint IAH-*
871 *CNC/CGS Conference, Winnipeg, Manitoba, Canada, September 29-October 1, 2003*

- 872 Greenhouse JP, and Karrow PF, 1994. Geological and geophysical studies of buried valleys and
873 their fills near Elora and Rockwood, Ontario; Can. J. Earth Sci., 31; 1838-1848
- 874 Guillet, JR, 1977. Clay and shale deposits of Ontario: Ontario Geological Survey Mineral
875 Deposits Circular, MDR 15, Ministry of Natural Resources
- 876 Hearst JR, Nelson PH, and Paillett FL, 2000. Well logging for physical properties. New York,
877 NY: John Wiley and Sons Inc.
- 878 Hunter JA, 2007. Measurements of compressional and shear wave velocities and formation
879 porosities in Quaternary sediments; *in proceedings of* the 60th Canadian Geotechnical
880 Conference (GeoOttawa), October 21 – 24, 2007, 491-498
- 881 Hunter JA, Pullan SE, Burns RA, Good RL, Harris JB, Pugin AJ-M, Skvortsov A, and Gorianov
882 NN, 1998. Downhole seismic logging for high-resolution reflection surveying in
883 unconsolidated overburden. Geophysics 63:4, 1371-1384
- 884 Karrow, P.F., 1967. Pleistocene Geology of the Scarborough Area. Ontario Ministry of Natural
885 Resources. Toronto, Report 46 ,108 p.
- 886 Karrow, PF, 1974. Till stratigraphy in parts of southern Ontario, Geological Society of America
887 Bulletin, v 85, p 761-768
- 888 Karrow, P.F. 1987. Quaternary geology of the Hamilton-Cambridge area, southern Ontario.
889 Ontario Geological Survey, Report 25, 94 pp.

- 890 Karrow PF, Greenhouse JP, and Dusseault MB, 1990. Ontario Geoscience Research Grant
891 Program, Grant No. 312, Subsurface Quaternary using borehole geophysics; Ontario
892 Geological Survey, Open File Report 5734, 249p
- 893 Karrow, P.F., McAndrews, J.H., Miller, B.B., Morgan, A. V, Seymour, K.L., White, O.L., 2001.
894 Illinoian to Late Wisconsinan stratigraphy at Woodbridge, Ontario. Can. J. Earth Sci. 38,
895 921–942. doi:10.1139/e00-108
- 896 Kassenaar, JDC, 1991. An application of principal component analysis to borehole geophysical
897 data; in proceedings of the 4th International MGLS/KEGS Symposium on Borehole
898 Geophysics for Minerals, Geotechnical and Groundwater Applications; Toronto, 18-22 August
899 1991.
- 900 Keys S, 1997. A practical guide to borehole geophysics in environmental investigations; Boca
901 Raton, Florida, CRC Press Inc.
- 902 Kjarsgaard, B., Knight, R.D., Russell, H.A.J., Sharpe, D.R., Crow, H., Olson, L., 2016.
903 Newmarket Till Aquitard: Optimum Grain Packing, With A Pore Filling Cement Generates
904 Pseudo-Concrete, in: Geological Society of America Abstracts with Programs. Vol. 48, No. 7.
905 doi:10.1130/abs/2016AM-285066
- 906 Knight, R.D., Valiquette, L.J., and Russell, H.A.J. 2016. Portable XRF spectrometry, fusion,
907 multi acid, and aqua regia results from the Queensville borehole, Yonge Street Aquifer,
908 southern Ontario. Geological Survey of Canada, Open File 7855, 23 pages.

- 909 Logan C, Russell HAJ, and Sharpe DR, 2005. Regional 3-D structural model of the Oak Ridges
910 Moraine and Greater Toronto area, southern Ontario: version 2.1, Geological Survey of
911 Canada, Open File 5062; 27 pages; 1 CD-ROM, doi:10.4095/221490
- 912 Logan CE, Knight RD, Crow HL, Russell HAJ, Sharpe DR, Pullan SE, and Hinton MJ, 2008.
913 Southern Ontario “Golden Spike: data release: Nobleton borehole; Geological Survey of
914 Canada, Open File 5809; 29 pages; 1 CD-ROM, doi:10.4095/225026
- 915 Maclachlan, J.C., Eyles, C.H., 2011. Subglacial deforming bed conditions recorded by late
916 Quaternary sediments exposed in Vineland Quarry, Ontario, Canada. *Sediment. Geol.* 238,
917 277–287. doi:10.1016/j.sedgeo.2011.04.016
- 918 Martin, P.I. and Kwong, J.K.P. 1986. Geology and Ceramic Properties of Selected Shales and
919 Clays of Southwestern Ontario; Ontario Geological Survey, Open File Report 5583
- 920 McNeill JD, 1980a. Electromagnetic terrain conductivity measurement at low induction
921 numbers; Geonics Limited Technical Note TN-6.
- 922 McNeill JD, 1980b. Electrical Conductivity of Soils and Rocks; Geonics Limited Technical Note
923 TN-5.
- 924 McNeill JD, 1986. Geonics EM39 Borehole conductivity meter – Theory of operation; Geonics
925 Limited Technical Note TN-20.
- 926 McNeill JD, Bosnar M, Snelgrove FB, 1990. Resolution of an electromagnetic borehole
927 conductivity logger for geotechnical and ground water applications; Geonics Technical Note
928 TN-25

- 929 McNeill JD, Hunter JA, Bosnar M, 1996. Application of a borehole induction susceptibility
930 logger to shallow lithological mapping, *J. Environmental and Engineering Geophysics*, 0:2, p.
931 77-90.
- 932 Mwenifumbo, C J; Elliott, B E; Hyatt, W G; Bernius, G R; 2005. Bells Corners calibration
933 facilities for downhole and surface geophysical equipment Geological Survey of Canada,
934 Open File 4838, 2005; 17 pages, doi:10.4095/216755
- 935 Paillett FL, Crowder RE, 1996. A Generalized Approach for the Interpretation of Geophysical
936 Well Logs in Ground-Water Studies—Theory and Application. *Ground Water* 34, 883–898.
937 doi:10.1111/j.1745-6584.1996.tb02083.x
- 938 Paillett FL, Reese RS, 2000. Integrating Borehole Logs and Aquifer Tests in Aquifer
939 Characterization. *Ground Water* 38, 713–725. doi:10.1111/j.1745-6584.2000.tb02707.x
- 940 Patchett J, 1975. An investigation of shale conductivity, *Log Analyst*, 16:6, p.3
- 941 Pehme PE, 1984. Identification of Quaternary deposits with borehole geophysics in the
942 Waterloo Region, Unpublished MSc thesis, University of Waterloo, Waterloo, Ontario, 124p.
- 943 Pugin AJ-M, Pullan SE, and Sharpe DR, 1999. Seismic facies and regional architecture of the
944 Oak Ridges Moraine area, southern Ontario, *Can. J. Earth Sci.* 36, 409-432
- 945 Pugin AJ –M, Pullan SE, Duchesne M, 2013a. Regional hydrostratigraphy and insights into fluid
946 flow through a clay aquitard from shallow seismic reflection data; *The Leading Edge, Special*
947 *Section: Hydrogeophysics*, p. 936-942.

- 948 Pugin AJ –M, Brewer K, Cartwright T, Pullan SE, Perret D, Crow H, Hunter JA, 2013b. Near
949 surface S-wave seismic reflection profiling - new approaches and insights; First Break vol. 31,
950 2013; p. 49-60
- 951 Pullan SE, Hunter JA, and Good RL, 2002. Using downhole geophysical logs to provide
952 detailed lithological and stratigraphic assignment, Oak Ridges Moraine, southern Ontario;
953 Geological Survey of Canada, Current Research (Online) no. 2002-E8, 2002; 12 pages,
954 doi:10.4095/213689
- 955 Quigley, R.M., Ogunbadejo, T.A., 1973. Till Geology, Mineralogy and Geotechnical Behaviour,
956 Sarnia, Ontario, in: Leggett, R.F. (Ed.), Glacial Till. Royal Canadian Society Special
957 Publication, pp. 336–346.
- 958 Rider, M.H, 1990. Gamma-ray log shape used as a facies indicator: critical analysis of an
959 oversimplified methodology, in: Hurst, A., Lovell, M.A., Morton, A.C. (Eds.), Geological
960 Applications of Wireline Logs Geological Society Special Publication No. 48. Geological
961 Society of London, London, pp. 27–37.
- 962 Rivera, A., 2014. Canada's Groundwater Resources. Fitzhenry & Whiteside Limited, Markham.
- 963 Russell, H.A.J., Arnott, R.W.C., 2003. Hydraulic-Jump and Hyperconcentrated-Flow Deposits of
964 a Glacigenic Subaqueous Fan: Oak Ridges Moraine, Southern Ontario, Canada. J. Sediment.
965 Res. 73, 887–905. doi:10.1306/041103730887
- 966 Russell HAJ, Sharpe DR, Hunter JA, 2004. Pontypool “Golden Spike” borehole digital data
967 compilation: sedimentology and geophysical data; Geological Survey of Canada, Open File
968 4540, 2004; 1 CD-ROM, doi:10.4095/214994

- 969 Russell, H.A.J., Sharpe, D.R., Cummings, D.I., 2007. A framework for buried-valley aquifers in
970 southern Ontario, in: Proceedings of the 60th Annual Canadian Geotechnical Society (CGS)
971 and 8th Joint Canadian National Chapter of the International Association of Hydrogeologists
972 (IAH-CNC) Groundwater Specialty Conference. Canadian Geotechnical Society and
973 International Association Hydrogeologists, pp. 386–393.
- 974 Russell, H.A.J., Brennand, T.A., Logan, C., Sharpe, D.R., 1998. Standardization and assessment
975 of geological descriptions from water well records, Greater Toronto and Oak Ridges Moraine
976 areas, southern Ontario. Geol. Surv. Canada, Curr. Res., Current research 1998-E 1998–E,
977 89–102.
- 978 Russell HAJ, Sharpe DR, Brennand TA, Barnett PJ, and Logan C, 2003a. Tunnel channels of the
979 Greater Toronto and Oak Ridges Moraine areas, southern Ontario; Geological Survey of
980 Canada, Open File 4485; 1 sheet, doi:10.4095/214777
- 981 Russell HAJ, Peets J, Gorrell G, Sharpe DR, and Hunter JA, 2003b. Pontypool “Golden Spike”
982 borehole data compilation, Geological Survey of Canada, Open File 1746; 1 sheet,
983 doi:10.4095/214401
- 984 Sadler, A.G., 1962. The Mineral Constitution Of Some Ordovician Shales Of Eastern And
985 Southern Ontario. Dep. Mines Tech. Surv. Ottawa, Mines Branch Res. Rep. R 94.
- 986 Schneider GW, Nobes DC, Lockhard MA, and Greenhouse JP. 1994. Urban geophysics in the
987 Kitchener-Waterloo region; Geoscience Canada, 20: 149 - 156

- 988 Sharpe, D.R., Russell, H.A.J., 2016. A revised depositional setting for Halton sediments in the
989 Oak Ridges Moraine area, Ontario. *Can. J. Earth Sci.* 53, 281–303. doi:10.1139/cjes-2015-
990 0150
- 991 Sharpe DR, Pullan SE, and Gorrell G, 2011. Geology of the Aurora high-quality reference site
992 and significance to the Yonge Street buried valley aquifer, Ontario; Geological Survey of
993 Canada, Current Research (Online) no. 2011-1; 24 pages, doi:10.4095/286269
- 994 Sharpe, D.R., Hinton, M.J., Russell, H.A.J., and Desbarats, A.J., 2002. The need for basin
995 analysis in regional hydrogeological studies: Oak Ridges Moraine, southern Ontario.
996 *Geoscience Canada* 29, 3–20.
- 997 Sharpe DR, Pugin AJ-M, Pullan, SE, and Shaw, J, 2004. Regional unconformities and the
998 sedimentary architecture of the Oak Ridges Moraine area, southern Ontario, *Can J. Earth Sci.*,
999 41: 183-198
- 1000 Sharpe, D.R., Klassen, R.A., Russell, H.A.J., Logan, C.L., and Garrett, R. 2016. Regional
1001 geochemical survey of soil and sediment in southern Ontario; in Russell H.A.J. and Priebe, E.
1002 (editors) *Regional-scale groundwater geoscience in southern Ontario: an Ontario Geological*
1003 *Survey and Geological Survey of Canada groundwater geoscience open house*; Geological
1004 Survey of Canada, Open File 8022, 17 pages
- 1005 Sharpe DR, Dyke LD, Good RL, Gorrell G, Hinton MJ, Hunter JA, Russell HAJ, 2003. GSC
1006 high-quality borehole “Golden Spike” data – Oak Ridges Moraine, southern Ontario;
1007 Geological Survey of Canada, Open File 1670; 23 pages, doi:10.4095/214289

- 1008 Sibul U, Wang KT, and Vallery D, 1977. Ground-water resources of the Duffins Creek-Rouge
1009 River Drainage Basins; Ministry of the Environment, Water Resources Branch; Water
1010 Resources Report 8.
- 1011 Taylor KC, Hess JW, and Mazzela A, 1989. Field evaluation of a slim-hole borehole induction
1012 tool, Groundwater Monitoring Review, 9:1; 100-104

Draft

Figure 1 – Location map and general surficial geology of Southern Ontario, modified from Barnett et al (1991). Locations are plotted of sediment boreholes geophysically logged by the Geological Survey of Canada between 1993 – 2013.

Figure 2 – Comparison of gamma energy spectrums (kiloelectron volts, keV) plotted against counts per second (cps) from an open bedrock borehole (left) and a PVC-cased glacial sediment (right). On the left, the record was collected at the GSC's Ottawa ON borehole calibration facility in an interval of Grenville-age altered granite consisting of friable clays and altered feldspars derived from syenites, granites, and gneisses. On the right, the record was collected in glacial sediment within the Thorncliffe Formation (clay- and silt-sized particles) of the Lower Sediment unit near Oshawa, ON. The red trace indicates a stacked spectrum summed 10 cm above and below the sensor depth. Although from different regions of Ontario, this comparison, collected by the same spectral tool moving at 1 m/min, illustrates the reduction in spectral amplitudes and count levels recorded in a fine grained glacial sediment of southern ON versus an open bedrock borehole in eastern ON.

20
21 Figure 3 – Geophysical logs (gamma, conductivity, and magnetic susceptibility) from the eastern
22 GTA region, north of Clarington ON (PP02-1), plotted alongside grain size data and sediment

23 descriptions from continuous core in the Lower Sediment hydrostratigraphic unit. The
24 geophysical log responses primarily reflect the changing clay content (gamma, conductivity) and
25 sand content (magnetic susceptibility) as shown in the cross plots. Three different upward
26 coarsening trends are identified based on changing grain sizes: (1) decrease in clay, increase in
27 silt, no change in sand in upward coarsening rhythmites; (2) decrease in clay, no change in silt,
28 increase in sand; (3) decrease in clay, decrease in silt, increase in sand in upward coarsening
29 rhythmites. Sediment descriptions based on Russell et al. (2003b).

30

Draft

Figure 4 – Selected contoured cross plots of grain size versus geophysical log response indicate that despite scatter, trends are present across the study region, with the strongest influence on conductivity and gamma coming from the presence of the <2 micron (μm) size fraction. Sediments from the Waterloo region west of the Niagara escarpment systematically show lower magnetic susceptibilities in sands (also in silt and clay, not shown), and often, higher conductivities and gamma responses in clays versus those east of the Escarpment. Data from 28 boreholes: 9 in the Waterloo region (west of the Niagara Escarpment); 11 from Oro and 8 from the GTA (east of the Niagara Escarpment).

Figure 5 – Sample logs exhibiting the funnel pattern characteristic of upward coarsening rhythmite sequences in the lower sediment (blue intervals). Sediment descriptions from Bajc and Hunter (2006); Logan et al. (2008), and Russell et al. (2004).

Figure 6 – Plots of grainsize versus log response show a significant degree of scatter, as this unit is composed of alternating glaciolacustrine formations and diamictons containing a range of grain sizes. Plots highlight differences in log response between the regions east and west of the Niagara Escarpment; in particular, the lower magnetic susceptibilities in the sands. (Waterloo: 7 boreholes; GTA: 5 boreholes; Oro: 9 boreholes),

Figure 7 – Sample logs showing elevated velocities within the Newmarket and Catfish Creek tills (light green intervals), but relatively low and unvarying lithological log responses. Sediment descriptions from Bajc and Hunter (2006), and Crow et al. (2015a).

Figure 8 – In the high velocity tills, clusters in the grain size versus log response plots reflect a relative uniformity in the matrix grain size, particularly in the Waterloo region (8 boreholes). In the Oro area (7 boreholes), the magnetic susceptibility is more elevated and sand content more variable. Little Newmarket Till grain size data is available in logged boreholes in the GTA (1 borehole). Conductivity (and gamma, not shown) remains relatively low due to little <2 micron grain size content.

70

71 Figure 9 – Comparison of the distributions of Vp and Vs in the Newmarket and the Catfish

72 Creek tills.

73

Figure 10 – Sample logs with characteristic responses in the moraine sediments (orange intervals). Gamma counts tend to remain low and unvarying due to limited clay content, while magnetic susceptibility is elevated and highly varying. Sediment descriptions from Bajc and Hunter (2006); Sharpe et al. (2003), and Russell et al. (2004).

80

81

82 Figure 11 – Sample logs indicating the elevated response of the gamma and conductivity logs,
 83 and reduced velocities, in the surficial tills (green intervals). Sediment descriptions from Bajc
 84 and Hunter (2006); assignment of stratigraphy in Waterloo region from Bajc and Shirota (2007).

Figure 12 – Log response versus grainsize percentage in the surficial silty-clay and clayey-silt tills across southern Ontario. The presence of <2 micron grain size particles, even in quantities <40%, has a stronger influence on the gamma and conductivity response than the other grain sizes. Plots contain data from the GTA (4 boreholes) and Waterloo (9 boreholes).

Figure 13 – Variability in log response at the stratigraphic boundary between Newmarket Till and Lower Sediments (i.e. abrupt vs continuous) can assist in the interpretation of glacial processes. In (A) all logs indicate a sharp transition while in (B), the induction logs are sharp but with less contrast. In (C), logs show little variation across the contact save for the increase in velocity. Sediment descriptions from Coffin et al. (2017), Bajc et al. (2015), Logan et al. (2008).

Borehole geophysical log signatures and stratigraphic assessment in a glacial basin, southern Ontario; Crow et al.

Tables

Table 1 – simplified sediment character within stratigraphic units and formation nomenclature across the region. Fm=formation.

Stratigraphic Unit	Generalized sediment character	Formation Nomenclature		
		GTA	Oro	Waterloo
Surficial tills	Several late glacial tills. Interbedded clayey-silt, silty-clay with sand and gravel and silty to sandy diamictons .	Kettleby and Wentworth Tills, Halton sediments	None identified	Maryhill, Mornington, Port Stanley, Tavistock, Wentworth tills
Moraine and channel sediment	<u>Moraine</u> : extensive stratified complexes, interbedded fine sands and silts with sands and gravels , fining upward successions are common <u>Channels</u> : cut into underlying sediments, contain sandy sediments , some contain cross-bedded gravels , often overlain by mud intervals.	Oak Ridges Moraine	Oro Moraine	Waterloo Moraine
High velocity tills	Dense, stony, sandy silt diamicton , with distinct clay/silt, sand, and gravel/stony interbeds.	Newmarket Till		Catfish Creek Till
Lower sediment	Group of up to 10 formations and tills of Illinoian to mid-Wisconsinan age. Gravel, sand, silt, clay, and tills , and distinctive organic/fossil-bearing beds. Fine-grained sediments can be massive to laminated.	Thorncliffe Fm, Meadowcliffe, Seminary and Sunnybrook tills, Pottery Road Fm, Scarborough Fm, Don Fm, and York Till	Thorncliffe Fm, Sunnybrook and York tills, Scarborough Fm.	pre-Catfish sediment, Canning Till, Pre-Canning sediment
Bedrock	Sedimentary bedrock	Upper and Middle Ordovician limestone, dolostone, siltstone, shale		Silurian limestone, dolostone, siltstone, shale, sandstone, gypsum

Table 2 – Velocity distributions within the hydrostratigraphic units. Data are presented $\pm$ one (1) standard deviation. Number of depth records provided for each calculation.

	Surficial tills	Moraine and channel deposits	High velocity tills	Lower sediments
V _p (m/s)	1855 $\pm$ 235 n°=365	1875 $\pm$ 350 n°=765	2610 $\pm$ 475 n°=366	2075 $\pm$ 360 n°=1874
V _s (m/s)	465 $\pm$ 145 n°=355	540 $\pm$ 165 n°=366	845 $\pm$ 255 n°=154	715 $\pm$ 205 n°=851
V _p :V _s ratio	4.01 $\pm$ 0.86 n°=287	3.50 $\pm$ 0.74 n°=262	2.87 $\pm$ 0.53 n°=154	3.03 $\pm$ 0.57 n°=696

Draft