BOREHOLE GEOPHYSICS AND ITS POTENTIAL FOR MAPPING THE GEOLOGICAL FRAMEWORK OF THE OAK RIDGES MORAINE, SOUTHERN ONTARIO

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ABSTRACT
A borehole geophysical logging program was initiated in 2002 as part of the York Peel Durham (YPD) Groundwater Management Strategy Study in southern Ontario, Canada. The key objective was to systematically assemble geophysical data from a suite of boreholes across the Oak Ridges Moraine area with a view to building a database that can be used for ongoing regional hydrostratigraphic studies.

The key hydrostratigraphic units of the Oak Ridges Moraine region were targeted in several boreholes and characterized using a full range of borehole physical property measurements. Statistical analysis and parameter cross-plots were used to identify regional stratigraphic units and evaluate which parameters were most diagnostic. Coarsening and fining-upward sequences in the extensive lower sediment package can be identified across the survey region, indicating the potential exists to correlate these sediments over tens of kilometres using geophysical logging techniques.

RÉSUMÉ
Un programme de géophysique de diagraphie en forage a été initié en 2002 faisant partie de l'Étude du Stratège d'Aménagement d'Eau Souterraine de York Peel Durham (YPD) du sud d'Ontario. L'objectif principal était d'initier un programme pour rassembler, de façon systématique, les donnés géophysiques d'une série de forages recoupant la région du Moraine d'Oak Ridges, ayant le but de construire une banque d'information qui serait utilisée pour des analyses hydrostratigraphiques régionales à long-terme.

Les unités hydrostratigraphiques clefs de la région du Moraine d'Oak Ridges ont été ciblés par des forages spécifiques pour qu'ils soient caractérisés par des mesures in-situes de propriétés physiques. Les caractérisations et corrélations statistiques de ces donnés géophysiques ont été utilisées pour identifier les lithologies communes sur toute la région YPD. Certaines séquences d'augmentation et de diminution vers le haut de la grosseur des grains ont pu être identifiés dans le paquet de sédiments inférieurs à travers la région. Ceci indique que la corrélation de sédiments sur une étendue de plusieurs dizaines de kilomètres peut être accomplie en utilisant la diagraphie géophysique en forage.

1 BACKGROUND AND PREVIOUS WORK

Increasing pressures of rapid urbanization have been linked to the sustainability and protection of groundwater resources in the Oak Ridges Moraine (ORM) region (Regional Municipalities of York, Peel and Durham, 2001). A better understanding of the regional geological framework, particularly within the 20-200 m thick Quaternary deposits and aquifer complex in the area is required to manage groundwater resources. Recent multi-disciplinary efforts to map and develop methods to characterize the geological and hydrogeological settings across the ORM area (Sharpe et al., 2002) highlighted the role of surface geophysics (Pullan et al., 1994; Boyce et al., 1995; Pugin et al., 1999).

Borehole geophysical data can also identify significant geological and hydrogeological units across the area (e.g. Sibul et al., 1977; Fligg and Rodriques, 1983; Eyles et al., 1985) and at key sites (Dillon, 1994; Golder Associates, 1994; Fenco MacLaren, 1994). The high quality data from these and recent borehole geophysical surveys (Pullan et al., 2000, 2002; Taylor et al., 1999) have played a prominent role in advancing a regional framework. In particular, a high-quality suite of downhole geophysical logs achieved lithologic characterization and delineation of subsurface hydrostratigraphic units in support of a sound geological model of the area (Pullan et al., 2002). Key elements of this regional geological model include: Paleozoic bedrock, Lower sediment, Newmarket Till, Oak Ridges Moraine sediment, Halton Till, and channel fill materials that have infilled channels cut along a regional unconformity at the top of the Newmarket Till (Sharpe et al., 1999). This study targeted specific boreholes from previous surveys to further investigate these key strata and characterize in situ properties for designing a long-term borehole geophysics program.

2 OBJECTIVES OF THE STUDY

A borehole geophysical logging program was initiated in 2002 as part of the York Peel Durham (YPD) Groundwater Management Strategy Study in southern Ontario, Canada. The key objective of the project was to initiate a program to systematically assemble geophysical data from a suite of boreholes across the Oak Ridges Moraine area with a view to building a library that can be used for long-term stratigraphic analysis. With a library of borehole geophysical results, it is anticipated that the overall understanding of the complex geology and hydrogeology of the Oak Ridges Moraine will greatly improve, both through regional scale stratigraphic correlation, and through the estimation of hydrogeologic parameters from the geophysical results. The borehole logging ultimately is to provide practitioners with greater confidence in the geologic input to numerical groundwater models.

3 SURVEY PLANNING

The initial phase of the logging program focused on survey planning. An MS Access database of existing wells within the ORM area was created to identify and prioritize boreholes for geophysical logging. The database was populated using water well records, obtained from the Ministry of the Environment (MOE), and other borehole records obtained from the regional municipal partner agencies and other sources (conservation authorities, Ontario Geological Survey (OGS), Geological Survey of Canada (GSC), McMaster University). The wells entered into the database were chosen based on their depth, location, construction (casing type, diameter), and the availability of core data (e.g. Sharpe et al., 2003). The database information included location and well construction information. This information was linked to a base map using ViewlogTM software (Figure 1). All available lithologic information and existing geophysical logs were also entered into the database.

4 SURVEY RESULTS

4.1 Overview

The borehole geophysical logging was conducted from June to November 2002 at various locations on the Oak Ridges Moraine and surrounding area (Figure 1).

A total of 16 holes were geophysically logged with some or all of the following parameters:

- natural gamma ray (NG)- measures gamma emissions of naturally-occurring radioactive minerals present within the surrounding lithologies, with potassium typically being the most abundant source of gamma rays. Clays are typically high in potassium relative to other sediments.
- neutron - (a hydrogen indicator) can provide an indication of moisture content within the sediments surrounding the borehole where moisture content has an inverse relationship to neutron count
- dual detector density (DC)- measures the density at locations near and far from the borehole wall. Far density values are more representative of the actual density because the near-field measurements did not significantly penetrate the formation and are affected by grouting and casing.
- full waveform sonic (FWS)- P-wave velocity is calculated from the difference between arrival times at two receivers on the sonic probe. The sonic tool was used in PVC cased holes, but cannot differentiate velocities lower than that of the PVC casing (approx 1900 m/s). The tool is effective in identifying units with relatively high P-wave velocities, such as the Newmarket Till (e.g. Pullan et al., 2002)
- magnetic susceptibility - gives an indication of ferromagnetic minerals present, typically magnetite
- inductive conductivity (dual sensor) - clays tend to be very conductive due to their high moisture content and cation exchange capacity, (Hearst, et al., 2000). The sensors are designed to measure near (medium induction) and far (deep induction). In PVC cased holes the deep induction is less influenced by grouting and casing.
- temperature / temperature gradient
- fluid conductivity

Quantec Logging Services (QLS) consulted with the YPD team and the GSC regarding which holes would be most ideal to log, based on location, penetration depth, well construction, lithologies encountered, and availability / access.

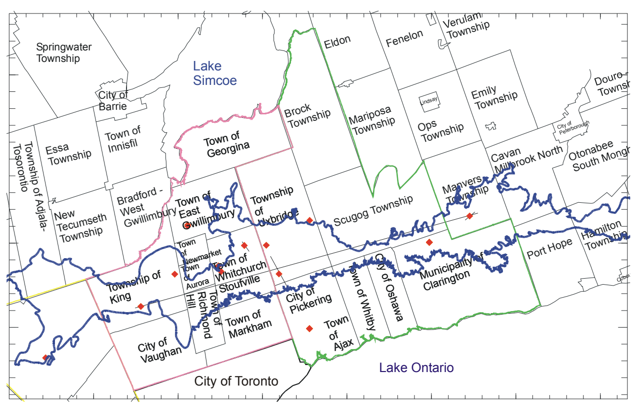

Figure 1: YPD Groundwater Project with Boreholes Logged in 2002. Outline of ORM shown in blue.

This paper focuses on data from 8 of the 16 boreholes logged representing “high quality” survey holes. These boreholes were cored, and cased with PVC allowing for detailed, accurate sediment logs, and a complete suite of downhole geophysical surveys. Steel cased wells are typically not cored (thus lacking accurate sediment logs), and steel precludes the use of many geophysical tools such as magnetic susceptibility, inductive conductivity, and full waveform sonic (FWS). Some PVC cased holes were too small in diameter to accommodate some of logging tools and were therefore excluded from the multi-parameter statistical analysis.

Six of the 16 holes had been logged previously, four by the GSC and two by McMaster University (Table 1). The logging completed in 2002 supplemented the prior work with geophysical parameters not previously logged such as neutron and dual detector calibrated density (described above). This earlier data were used as a quality check and comparison for the QLS data. For example, in Figure 2 the GSC sonic data from vertical seismic profiling (VSP) are overlain with the data collected in 2002 with a FWS tool. The two methods differ in the location of the transmitting source (surface for VSP, in-hole for FWS), and in the bulk of the material sampled for the measurement (cubic metres for VSP, cm of material immediately adjacent to borehole for FWS). The resultant velocities, recorded with different tools and methods, show a very similar trend. The GSC data capture more information in the upper part of the hole (10–25 m) because VSP tools are not limited to measuring velocities greater than that of the PVC pipe (approx 1900 m/s).

Table 1: Borehole Logging Summary (QLS (2002), GSC (Pullen et al, 2000), McMaster (Gerber et al, 2001)). The 8 “high quality” survey holes used in this study are identified with asterisks (*).

Hole Identification	Hole Length (m)	Casing Type	Logged by QLS 2002	Logged by GSC	Logged by McMaster
CVC-ORM-01b *	180.62	PVC	√		
EE11-1F	71.78	PVC	√		√
Grasshopper1 *	59.54	PVC	√		
Grasshopper2 *	140.59	PVC	√		
GSC-NOB-01 *	190.00	PVC	√	√	
GSC-VSR-01 *	127.00	PVC	√	√	
King Valley	90.83	PVC	√		
OGS-PJB-15 *	85.00	PVC	√	√	
OGS-PJB-19 *	90.00	PVC	√	√	
Pontypool	169.14	PVC	√		
Uxbridge *	84.73	PVC	√		
Angus Glen OW1	152.40	Steel	√		
EE11-1W	40.67	Steel	√		√
Hillcrest	68.00	Steel	√		
Hillcrest2	111.56	Steel	√		
Ram Forest	62.51	Steel	√		

Quality control on the data involved 2 runs per tool (down and up) with both runs compared for repeatability. Tool calibrations were tested on a regular basis. Experiments were conducted with repeat logs of all parameters at a variety of logging speeds and sampling rates to determine the most cost effective production rates for each tool without sacrificing data quality.

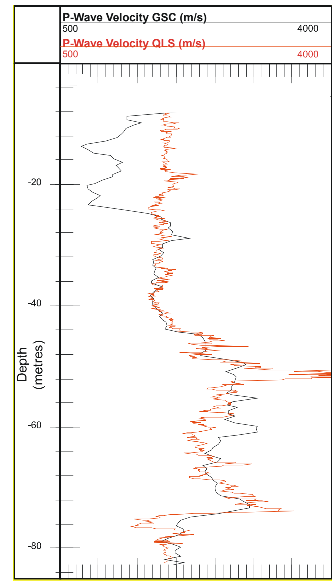

Figure 2: GSC and QLS P-Wave Velocity (m/s) Data for OGS-PJB-15 (Existing data from Pullan, et al., 2000)

4.2 Data Processing and Interpretation

4.2.1 Preliminary Processing and Presentation

LAS (log ASCII standard) files of the data were created from the raw data files while surveying each hole. The sonic data required additional analyses of P-wave 1ST-arrival behaviour, before a LAS file of the P-wave velocity was created. The LAS data from each drill-hole were then imported, screened, edited and shown as composite physical property logs. Geological lithology information from core logs and sample information, such as moisture content, were also imported into the composite plots. All of the log data from the composite plots were then uploaded into a project database.

4.2.2 Geophysical Lithology Classification

Initial visual comparison between the down-hole logs and core lithology information confirmed general correlations between the two independent data sets. A very good correlation was also achieved with down-hole logs previously surveyed by the GSC in which detailed sediment descriptions were linked to the geophysical logging (Sharpe et al., 2003).

Further examination of the composite plots for each hole indicated significant geophysical variation within the major lithology divisions, thus suggesting that geophysical logging can reveal subdivisions within larger units.

For statistical characterization purposes some major lithologic classes were refined into sub-lithologies based upon their geophysical character. For example, in Figure 3, the thick Newmarket till unit in OGS-PJB-19 is subdivided in two tills because of the distinct geophysical contrast between the top and bottom of the unit. Sub-classes of the till are also revealed in Figures 5, and 6 and are further discussed in sections 4.3.2 and 5.1.

4.2.3 Statistical Characterization

The process of quantitatively describing each lithology based on its physical properties, or “physical property fingerprinting” can be utilized to predict lithologies in non-cored holes. This analysis allows for the unique identification of each lithology subset based upon its physical properties, provided sufficient contrasts exist among the lithologies studied (see Fullagar, et al., 1999).

This type of analysis requires a lithological interpretation that is independent of the geophysical logs (i.e. core lithology). Typically a group of geologically constrained (cored) holes intersecting a representative suite of lithologies are required to develop the petrophysical characterizations for each lithology/sub-lithology. The geologically constrained petrophysical characterizations provide the foundation for applying geophysical logs to predict lithology.

Petrophysical data for each hole were exported for statistical analysis to extend the interpretation. The statistical characterization included calculating centroids (means or medians) and spreads for each of the physical properties based upon lithology (e.g. determining the median value and standard deviation for P-wave velocity within the Newmarket Till). Statistical results for each parameter were outlined graphically, by lithology, in “Box and Whisker” plots (Figure 4). The box represents the centroid (median parameter value) for each sub-lithology and the whiskers indicate the upper and lower spreads. The yellow bars beneath each lithology value represent the number of data points for each lithology used to calculate the statistics. Figure 4, graphically illustrates the range of P-wave velocities by lithology for hole OGS-PJB-19. The significant P-wave velocity contrast is evident between Newmarket Till units (circled in red) and other ORM lithologies. Units suffixed with “Lw” or “Up” represent the Lower and Upper (ORM) sediment sequences, respectively. The sand and silt units followed immediately by a ‘U’ in these plots are unsaturated units.

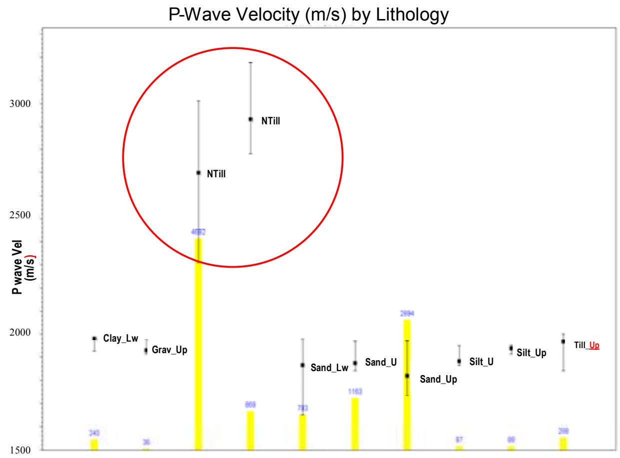

Figure 4: Box-and-Whisker Plot showing P-wave Velocity Contrast between Newmarket Till and other ORM Lithologies

4.3 Statistical Characterization Results

4.3.1 Physical Property Analysis and Differences In Hole Construction

The multi-hole statistical analyses completed for the YPD study looked at a comparison of similarly constructed “high quality” holes, i.e. 3 inch PVC and 3.5 inch PVC. Differences in hole construction can include: casing type, inside casing diameter, outside hole diameter, amount and type of grouting used, and the presence of screens and sand pack. Grouping the wells based on construction avoids the ambiguities associated with varying hole geometry and foreign backfill material (e.g. it is not valid to quantitatively compare data from various hole diameters without normalization, and it was determined that normalizing the data would introduce significant error).

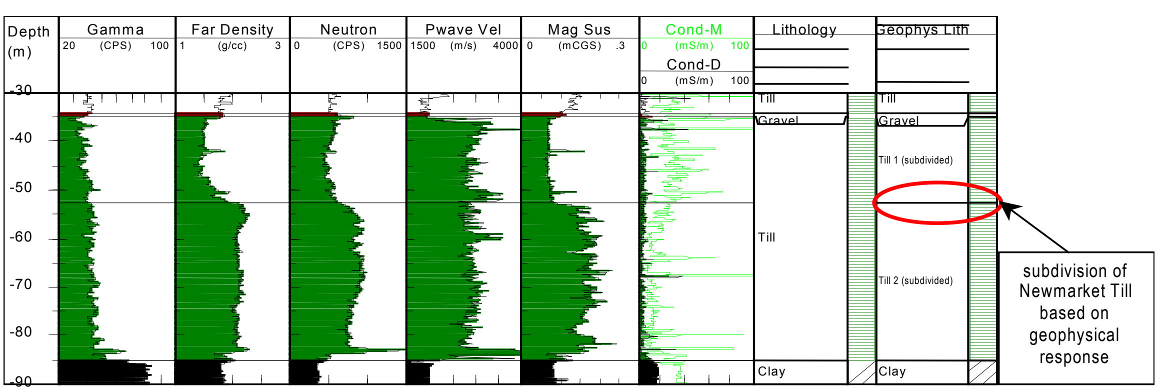

Figure 3: OGS-PJB-19 – Close up of Newmarket Till Showing Till Unit Divided into two Geophysical Interpretation Units

4.3.2 Multi-hole Composite Statistical Characterization of Regional Lithologies

A multi-hole, multi-parameter statistical characterization was completed for each sub-lithology, defining its upper and lower geophysical limits in the YPD survey area. The "high-quality" survey holes (see section 4.1) were divided into two statistical categories based on hole construction: i) the two OGS holes which were constructed with 3.5 inch PVC pipe; and ii) Uxbridge, Nobleton, CVC-ORM-01b, Grasshopper and Vandorf which were constructed with 3 inch PVC casing. For illustration purposes, this section discusses statistics from the 3.5" PVC cased holes only. Results from all multi-hole statistical analyses are integrated and summarized for each regional geologic model unit below in section 5.0 Discussion.

Petrophysical statistics were calculated based on both lithology (Clays to Cobbles) and the regional geological model unit for each lithology (e.g. Newmarket till, Lower Sediments etc.). This allowed for quantitative multi-hole comparisons between general lithologies (e.g. sands, silt, till, clay etc.) and also between similar lithologies from various geologic model units (e.g. lower sediment sands vs. ORM sediment sands).

The 3.5 inch PVC hole composite analysis includes OGS holes 15 and 19, located in the York and Durham regions of greater Toronto, respectively. The holes were logged previously by the Geological Survey of Canada with a different suite of logging tools (Pullan et al., 2002). Figure 5 is an example of the composite statistics plot for density from the 3.5-inch holes (OGS-PJB-15, and 19)

Note the significant density contrast between the two Newmarket Till (Ntill) sub-classes. The lower density NTill corresponds to the "Till 1" sub-lithology identified in Figure 3 from approximately 35m to 52m depth. The same sub-lithology is also identified in Figure 6 as the smaller of the two Newmarket Till clusters in the 3-D cross plot.

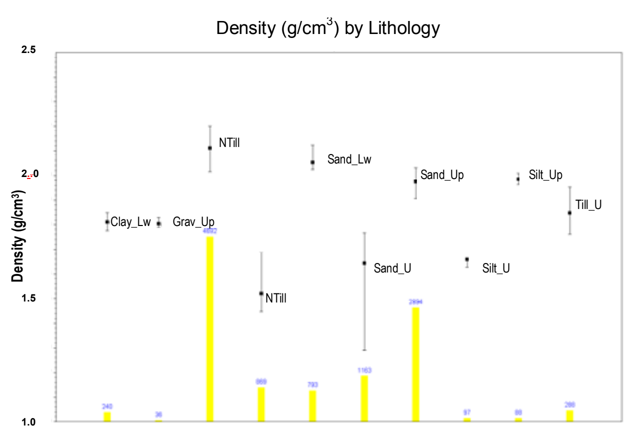

Figure 5: Density Box-and-Whisker Plot based on General Lithologies from 3.5" PVC Cased Boreholes

The unsaturated sand and silt units (suffixed with "U") in Figure 5 likely have lower density values because the pore space is filled with air instead of water. The same unsaturated units exhibited anomalously high neutron responses confirming the lack of hydrogen or more specifically H_2O. Several till units in the OGS holes were identified in core as Newmarket Till, and have a comparatively higher density than the other units. The same till units also exhibited relatively high P-wave velocity ranges (e.g. Figure 3).

The survey parameters for the 3.5-inch holes were cross-plotted to better represent the statistical segregation of each lithology class. Figure 6 is a 3-D cross plot of P-wave velocity, neutron, and density for the two OGS holes. The two classes identified as Newmarket Till are indicated within the red circles. Both groups have a higher P-Wave Velocity, but their densities vary (also refer to Figures 3,5). The clustering of the data points allows for identification of the two classes of Newmarket Till in the OGS holes.

5 DISCUSSION

5.1 Geophysical Characterization of the Newmarket Till

The Newmarket Till is an important marker bed within the ORM hydrostratigraphy, as it acts as a regional aquitard separating upper and lower confined aquifer systems (Desbarats, et al., 2001). Earlier work by Pullan et al. (2000, 2002) demonstrated that: i) the Newmarket Till is characterized by relatively high sonic velocity (>2500 m/s), and ii) natural gamma, inductive conductivity, and magnetic susceptibility logs, by themselves cannot be used to differentiate the Newmarket Till.

Data from the present study provide additional evidence to support earlier work and supplements previous findings with results from additional parameters such as neutron and dual detector calibrated density. Statistical analysis of the geophysical logs from this study indicate that the Newmarket Till is usually identified with a combination of acoustic velocity, neutron, and density parameters logged within PVC cased wells (see Figure 6).

Magnetic susceptibility measurements highlighted variations within the Newmarket Till but were not particularly useful at distinguishing the till from other lithologies. Inductive conductivity and natural gamma both demonstrated a consistent uniform response through the Newmarket Till but lacked sufficient contrasts to identify the till. The till was geophysically and geologically distinguished in wells OGS-PJB-15, OGS-PJB-19, and GSC-BH-VSR-01.

Differences in bed accumulation and mineralogy are noted within the Newmarket Till (Barnett et al., 1998), however further work is required to correlate geophysical results to this data. Results from the current study indicate that geophysical logging reveals subdivisions within the till (Figures 3,5,6) and that the petrophysical properties could eventually help improve correlation of Newmarket till on a sub-lithology scale.

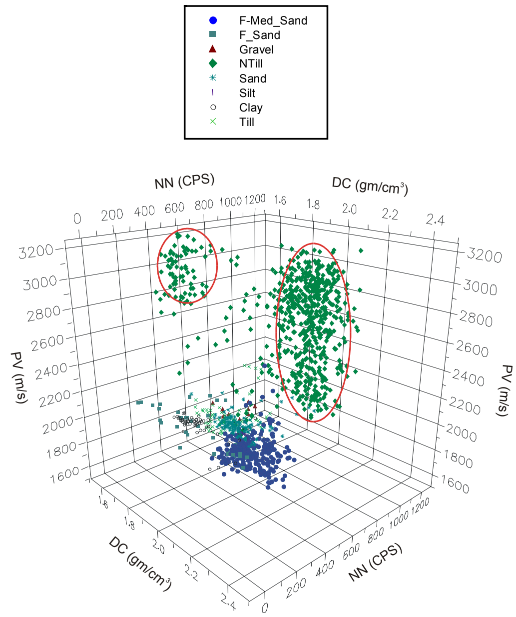

Figure 6: Neutron (NN)/Density (DC)/P-wave Velocity (PV) Multihole 3-D Cross-Plot showing Two Distinct Clusters of Newmarket Till.

5.2 Mapping of the Lower Sediments

The geophysical response to grain size patterns is a key diagnostic feature of the lower sediments; however not all Lower Sediments exhibit this signal because several formations comprise this grouped package. Keith Fligg (Ontario Ministry of the Environment) initially identified these sequences by their geophysical response (Fligg, et al., 1983). The pattern is seen in the natural gamma, inductive conductivity, and neutron logs (to a lesser degree) in Figure 7 (GSC-BH-NOB-01) and was also present in Grasshopper road, and Pontypool holes. The Pontypool and Nobleton holes are approximately 80 km apart and exhibit a very similar general pattern indicating there is potential for borehole geophysics to provide regional hole-to-hole correlations. The upper part of the sequence is missing in the Grasshopper hole because of channel erosion and deposition of channel sediments.

The temperature gradient log (DT) in Figure 7, responds to grain size in a similar fashion as the inductive conductivity and gamma logs. The DT response may be an indication of thermal conductivity variations among lithologies and warrants further study.

5.3 ORM Sediments

Of the holes logged in this study, no obvious grain size patterns are apparent in the ORM Sediments, as was found in the case of the Lower Sediments. This suggests the potential of exploiting the presence (or absence) of the grain size patterns to distinguish the ORM Sediments from the Lower Sediments where the Newmarket Till has been eroded.

Much of the ORM Sediments lie within the upper casing in the holes, which is typically steel and many of these sediments are unsaturated, both of which affect the geophysical log responses. There is therefore, more limited statistical information about the upper sediments. Within the two OGS holes, the sands comprising ORM Sediments have a lower density than the sands from the Lower Sediments as illustrated in Figure 5. This is likely due to higher compaction at deeper burial depths and is probably consistent across most holes in the region.

5.4 Tunnel Channels

Channel fill sediments are apparent in holes: CVC-ORM-01b, GSC-BH-NOB-01, Pontypool, Grasshopper, Uxbridge, and GSC-BH-VSR-01, as indicated by the core

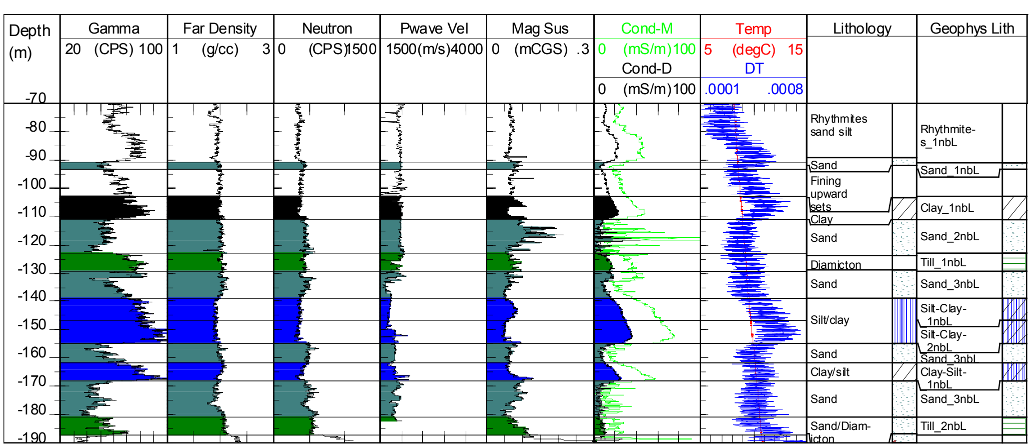

Figure 7: Physical Property Logs for GSC-BH-NOB-01 - Responses to Grain Size Sequences in Lower Sediments

logging completed to date. The channel bottom is represented by a layer of gravel in most holes, forming part of a regional unconformity (Russell et al., 2002). Gravel has a distinct geophysical signature, including a high density and a high P-wave velocity, which can "stand out" on log traces. Inductive conductivity logs through the channel sediments have a distinct erratic character, especially when contrasted with the relatively smooth character of the lower sediments.

5.5 Aquifer Considerations

Variations in the neutron log in the upper part of hole OGS-PJB-19 indicate the presence of perched water above the regional water table. The unsaturated conditions result in anomalous measurements for logs such as density and neutron. Moisture content samples were obtained from core and lab analyzed for Grasshopper and CVC-ORM-01b, (samples acquired by Central Lake Ontario and Credit Valley Conservation Authorities respectively) the results of which correspond inversely to the neutron logs. This inverse relationship between neutron logs (shown in black) and moisture content (shown in red) demonstrated in Figure 8 indicates there is potential to estimate porosity from neutron logs. The fluid property logs, i.e. temperature, and temperature gradient, can give some indication about relative groundwater flow velocities (Taylor et al, 1999).

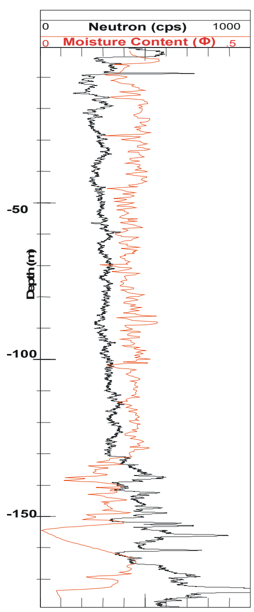

Figure 8: Neutron and Moisture Content Correlation for hole CVC-ORM-01b

6 CONCLUSIONS

The project successfully built on results from previous mutli-parameter surveys (Pullan et al 2000, 2002), by supplementing this previous work with additional parameters and data acquired from new boreholes. Specifically, this study verified that: i) although natural gamma and conductivity logs are useful in distinguishing grain size (clays from sands etc) these two parameters alone can not reliably identify the Newmarket Till, ii) P-wave velocity logs clearly identify the Newmarket Till from most underlying and overlying sediments. The newly acquired parameters such as dual detector calibrated density and neutron identified sub-units within major lithologies such as the Newmarket Till, when used in combination with other parameters. P-wave velocity data were acquired using a full-waveform sonic (FWS) tool instead of vertical seismic profiles (VSP) in previous studies yielding very similar results.

Results indicate that specific combinations of parameters are best suited to identifying key units and the best suite of parameters vary depending on the application. The best parameters for mapping various hydrostratigraphic units and aquifer properties are briefly summarized below.

The Newmarket Till is best characterized by acoustic velocity, neutron, and density parameters, likely responding to the unique dense, low porosity, compact nature of the till. Lower Sediments are best mapped with natural gamma, conductivity, and neutron responding to repetitive grain size sequences exhibited by some formations making up this grouped package. For Channel Fill Deposits, acoustic velocity, density, and neutron logs best identify gravels that typically mark the base of the channel, where as the fill sediments typically exhibit an erratic conductivity response and in general have lower density values. The ORM Sediments are best distinguished from the Lower Sediments by identifying the Newmarket Till which, when present, lies between the two. Neutron logs correlated well with moisture content samples taken from core indicating the potential of estimating porosity or moisture content from neutron data. The neutron data have also indicated zones of perched water above the regional water table. Temperature gradient logs can highlight areas of significant water flow through zones of high hydraulic conductivity, such as coarse sand and gravel.

The project sets the stage for a more extensive, routine, long-term geophysical acquisition program to improve the overall understanding of the complex geology and hydrogeology of the Oak Ridges Moraine. Building a library of borehole geophysical results from across the Oak Ridges Moraine area will greatly improve regional to more local scale stratigraphic correlation and ultimately provide improved geologic input to numerical groundwater models. The initial geophysical logging program in the York-Peel-Durham region was very successful in terms of characterizing the various stratigraphic packages in the area, correlating sediment patterns regionally, and determining which parameters are best suited for mapping specific lithologic sequences.

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