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1.0 Introduction

In 2010, the Ontario Geological Survey (OGS) initiated a 3-D mapping project of Quaternary deposits in the southern part of the County of Simcoe. This was one of several projects underway as part of the OGS' groundwater mapping initiative. The project was established to provide information on the geometry and properties of surficial sediments and bedrock for geoscience-based groundwater resource management (Bajc et al., 2012). OGS field work in south Simcoe County has included surficial mapping, coring of sediments to bedrock, ground gravity surveying, borehole geophysical logging, and an airborne time domain electromagnetic (TDEM) survey (Figure 1).

To support these surveys, the Geological Survey of Canada (GSC) acquired 21.2 line-kilometers of high-resolution seismic reflection profile data in October 2013 within the OGS' airborne electromagnetic survey area using an IVI Minivib source and a 48-sled (144 channel) landstreamer array (Bajc et al., 2014, Pugin et al., 2015). The system and processing techniques are described in three papers by Pugin et al. (2009, 2009b, and 2013). Figure 1 identifies the locations of the seismic lines, and one interpreted seismic profile is presented in Bajc et al. (2014).

In October 2014, the GSC subsequently conducted downhole geophysical logging in two unconsolidated sediment boreholes drilled by the OGS within the south Simcoe study area (Table 1). The primary objective of this logging was to measure downhole compressional (Vp) and shear wave (Vs) velocities in boreholes drilled near seismic reflection profiles collected by the GSC. This borehole dataset was used by the GSC to verify the conversion of the seismic reflection time sections into depth sections. A secondary objective was to measure the range of *in situ* chemical and physical properties of the subsurface materials and borehole fluid. Induction (magnetic susceptibility and apparent conductivity) and natural gamma logs were used to identify variations in the sedimentary units intersected by the deep boreholes, and downhole temperature logs were collected to identify changes in temperature gradients within the borehole fluids. This report contains the results of the downhole logging, which are presented on Figures 2 and 3, and as digital data in Appendix A.

1.1 Boreholes Geophysically Logged as Part of the GSC Study

Between 2011 and 2013, the OGS drilled 25 boreholes within the south Simcoe study area (Bajc and Rainsford, 2011; Bajc et al., 2012, 2014; Rainsford, 2013). Twenty four of the boreholes were cored to bedrock with 3- 6 m of bedrock retrieved at each site. Fifteen boreholes were cased with 63.5 mm ID PVC and geophysically logged using natural gamma and apparent conductivity tools (Rainsford, 2013). These wells are currently utilized as deep groundwater monitors.

Boreholes SS-12-02 (ID 024925) and SS-13-08 (ID 024939) were jointly selected by the GSC and the OGS for logging, as SS-13-08 was located on seismic Line 11, and SS-12-02, although not directly on a seismic line, intersected a thick package of both Newmarket Till and older stratigraphy which has been traversed by other GSC seismic lines in the Oak Ridges Moraine. (e.g. Pugin et al, 2001; Pullan et al., 2002; Sharpe et al., 2003). SS-12-02 also has only a few metres of metal surface casing which allowed for the use of electromagnetic induction logs in the upper portion of the borehole.

Boreholes were advanced using PQ mud-rotary coring, and continuous cores were geologically logged, photographed, and sampled by the OGS. PVC screens were placed at depths of 150.75 – 152.25 m in SS-12-02, and 142.10 – 145.10 m in SS-13-08. Borehole SS-12-02 was drilled in an upland setting and intersected Newmarket Till overlying a thick (85m) package of glaciolacustrine silt

and clay rhythmites (correlative with the Thorncliffe Formation) that are underlain by a sequence of older tills (Bajc et al, 2012). Borehole SS-13-08 intersected a sequence of valley-fill glaciolacustrine deposits, overlying diamicton interpreted to be Newmarket Till, then older deposits belonging to the Thorncliffe Formation, followed by older tills interbedded with glaciolacustrine deposits (Bajc et al., 2014). An unconformity occurs at the contact between the Thorncliffe Formation deposits and the older tills. A graphical representation of each well and interpreted stratigraphy is shown alongside the geophysical logs in Figures 2 and 3.

Table 1. Summary of borehole geophysical logs collected during the 2014 GSC field work campaign. UTM coordinates are in zone 17 (WGS84). Gam=Natural gamma, Cond=Apparent conductivity, MagSusc=Magnetic susceptibility, Fl.Temp=Fluid temperature, Vp=Compressional wave velocity, Vs=Shear wave velocity.

Borehole (Original ID)	OGS Borehole ID	GSC Geophysical Logging	Easting (m)	Northing (m)	Collar Elevation (m)	Maximum Depth Logged (m)	GSC Geophysical Log Suite
SS-12-02	024925	Oct 23-24, 2014	602 163	4 902 748	291	155.00	Gam, Cond, MagSusc, Fl.Temp, Vp, Vs
SS-13-08	024939	Oct 21-22, 2014	597 757	4 874 254	259	147.92	Gam, Cond, MagSusc, Fl.Temp, Vp, Vs

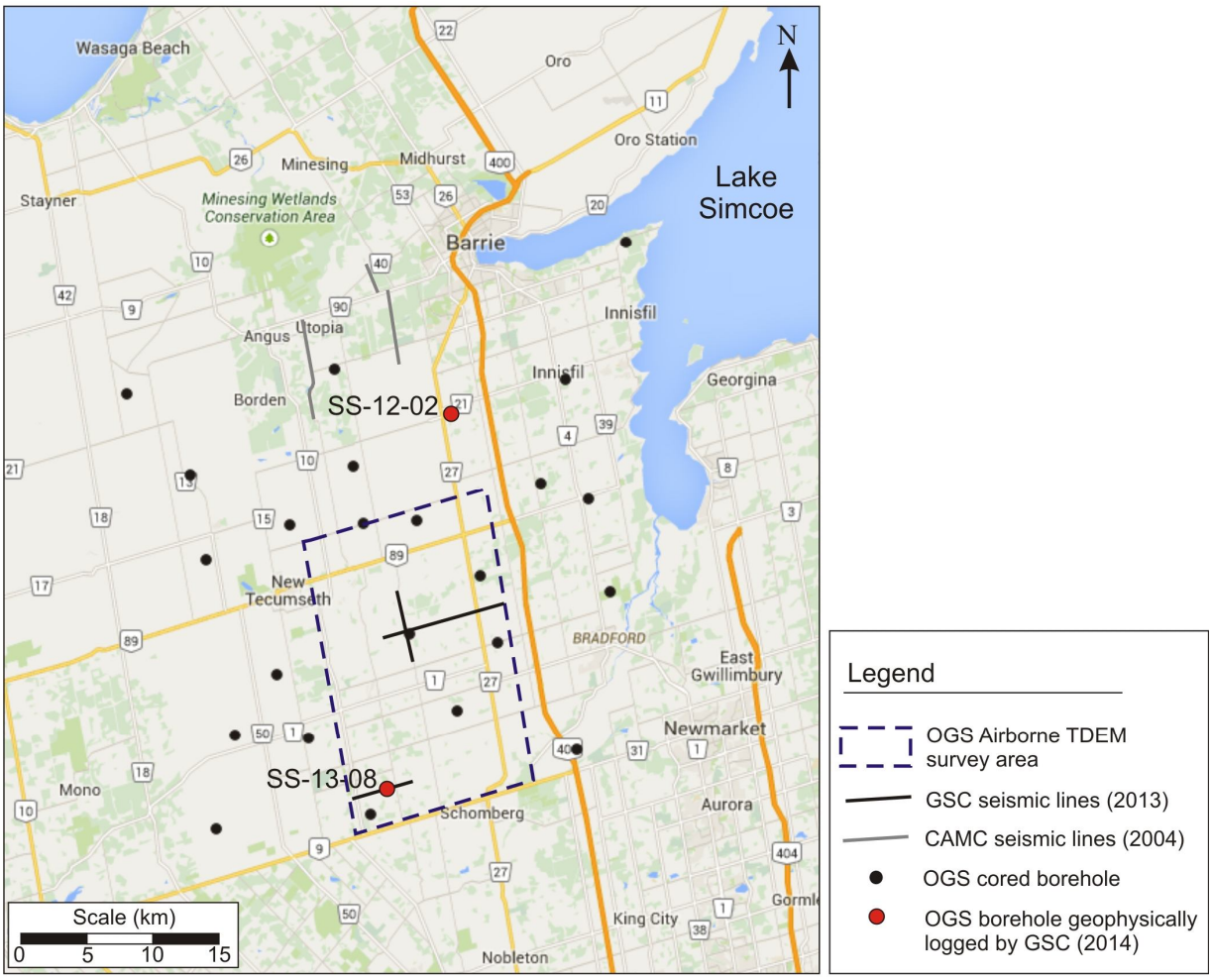


Figure 1. Location map of the south Simcoe study area showing locations of OGS cored boreholes drilled between 2011-2013, Conservation Authorities Moraine Coalition (CAMC) seismic lines (collected by GAPS in 2004), GSC seismic lines, and the locations of the two boreholes geophysically logged by the GSC in 2014 (© Google Maps 2015).

2.0 Field Work – Geophysical Logging

Downhole geophysical logs provide a means of identifying and characterizing lithological units based on variations in their chemical and physical properties. Geophysical logs also augment geological logging by providing information on changes in sedimentary properties that may not be visible in the core, across intervals of missing core, and where boundaries are uncertain due to the logging of cuttings. Downhole logs collected as part of this study included natural gamma, induction (apparent conductivity and magnetic susceptibility), downhole seismic (compression (P) and shear (S) wave traveltimes), and fluid temperature. A summary of the logging methods used and the data collection parameters are listed in Table 2. Additional detail on these and other logging techniques used by the GSC in unconsolidated deposits is available in Crow et al. (2015).

Upon arrival at each site, water level loggers were removed from the wells and the piezometric fluid level was measured. The fluid temperature tool was lowered into the borehole to collect data on a down run in the undisturbed fluid. A minimum period of 20 minutes was allowed for the tool to thermally equilibrate in the top of the water column before the fluid logging began. The fluid temperature logs were collected using a tool developed at the GSC for high sensitivity gradient measurements, and recorded using in-house software. Following fluid logging, the gamma and induction logs were collected in up and down runs, followed by the seismic logs. The geophysical logs did not reach the total drilled depth of the borehole due to the accumulation of fines in the bottom few metres of the PVC casing.

Gamma and induction logs were acquired using a Mount Sopris logging system with a Matrix console and interchangeable downhole probes. A laptop computer recorded the data using the Matrix LoggerSuite software (V10.5). On-site calibrations were carried out with the conductivity and magnetic susceptibility tools prior to each run using known calibration points (low point: 0, and a user selected high point for conductivity logging (95 mS/m) using calibration coils). Tools were allowed to thermally equilibrate in the borehole fluid for at least 10 minutes, and were generally recorded on down and up runs. All logs were corrected for sensor offsets and casing stick ups, and recorded relative to ground surface.

The P- and S-wave seismic surveys were carried out in the cased boreholes using a downhole receiver array and an energy source on the surface positioned 3 m from the borehole collar. The cables supporting the receivers were lowered by hand to the bottom of the hole, and pulled uphole at one metre intervals where stationary measurements were recorded. Data were obtained for the P-wave surveys using a multi-channel hydrophone array (12 hydrophones at 1 m spacings) in the water-filled portion of the borehole. S-wave logs were obtained using a clamped 3-component downhole receiver with 15 Hz geophones. In both cases, the source was a small metal hammer striking a metal plate vertically (P-wave) or at a 45° angle (S-wave) from the ground surface. The plate was coupled with the ground by removing the top few centimetres of soil, leveling the plate, and then driving the vehicle onto it to seat it in place. A Geometrics 24-channel Geode seismograph was used and data were recorded on a laptop computer after reviewing each record on screen. The systems and field procedures developed for downhole P- and S-wave logging are described in detail in Hunter et al. (1998).

Table 2. Details of the downhole geophysical logs acquired in two boreholes.

Downhole Geophysical Log *[Manufacturer]*	**Logging Unit**	**Radius of Investigation** ***[Vertical resolution]***	**Logging Speed**	**Logging Interval**	**Practical interpretations**
Spectral Gamma *[Mount Sopris]*	Counts per second (cps)	0.3 m *[centimetres, function of logging speed]*	1 m/min	0.01 m	Relative grain-size, lithological boundaries
Apparent Conductivity (Inductive) *[Geonics/Mount Sopris]*	milliSiemens/ metre (mS/m)	0.3 m *[submetre]*	3 m/min	0.02 m	Formation conductivity (grain and/or porewater conductivity), lithological boundaries
Magnetic Susceptibility (Inductive) *[Geonics/Mount Sopris]*	parts per thousand SI (ppt SI)	0.3 m *[submetre]*	3 m/min	0.02 m	Magnetite (heavy mineral) concentration, lithological boundaries
Fluid Temperature *[GSC]*	Frequency, converted to degrees Celsius (°C)	Influenced by surrounding materials [logging interval]	1 m/min	0.01 m	Anomalies due to groundwater flow; lithology (as related to thermal conductivity)
Compressional (P) Wave *[Pro-Seismic Services Ltd.]*	Metres/second (m/s)	Wavelength-dependent (metre scale) *[metre scale]*	n/a stationary recordings	1 m	variation in lithology, compaction, identification of reflecting horizons
Shear (S) Wave *[Geostuff Ltd.]*					

3.0 Data Processing

Geophysical log data were imported into WellCAD software (V5.0) for processing and interpretation. As logs were recorded relative to ground surface, depth adjustments were not required during post processing. Induction logs were truncated inside metal surface casings, but were otherwise unaltered. Upward and downward runs were overlaid to check for tool-induced temperature drift and ensure repeatability. Up runs were generally chosen for display, as they have constant upward tension on the wireline and are thermally adjusted to downhole temperatures for the longest period of time.

Multi-fold P-wave and single-fold S-wave travel times were picked using a semi-automatic picking program with a pick-to-pick cross-correlation (Ivanov and Miller, 2004). Interval velocities were computed using a derivative requiring two consecutive first arrival time picks. This method selects

arrival times through cross-correlation using spline interpolation and requires highly accurate arrival times. A three-point weighted-average filter was applied to these travel times. Interval velocities were then computed using the difference in travel time (dT) between successive readings divided into the difference between station depths (dZ). The distance between the source and the downhole tool was computed using the hypotenuse of the tool depth downhole and the source-borehole collar distance (3 m).

4.0 Results

Lithological Observations

The primary geophysical responses to textural and mineralogical variations were identified from the induction logs (magnetic susceptibility and apparent conductivity). Magnetic susceptibility values were more elevated in the sands and sandy diamictons than in the fine-grained units (silts, clays and silty/clayey tills). These logs were therefore better able to resolve lithological variation based on changes in the coarser grain sizes (fine sand to gravel), and are a more useful indicator of change in material provenance than natural gamma or apparent conductivity (Figure 4). For example, the very fine sands in the screened interval of SS-13-08 (142.65 – 143.65 m depth) display lower magnetic susceptibility levels (6.4 ± 0.6 ppt) than sands of the same texture in the upper 80 m of the borehole (16 ± 1 ppt). Similarly, the silts in the lower 80 m of the borehole recorded much lower magnetic susceptibility levels (8.0 ± 1.0 ppt) than the silts in the upper 80 m (14.7 ± 1.6).

Figure 5 shows that changes in the finer grain size fraction (clays, silts) are more readily identified using the apparent conductivity tool, but cannot as easily identify the variation between sand and silt. Therefore, the use of both induction logs together improves the ability to identify variation in grainsize across the clay to gravel grainsize range, and also to indicate the presence of upward fining or coarsening sequences, as seen in the Thorncliffe Formation in SS-12-02.

The natural gamma log also identified upward fining and coarsening sequences, but lithological variations were not consistently evident in the gamma log alone due to the relatively limited dynamic range in gamma counts measured (15 – 35 cps).

Ranges in velocities (mean ± one standard deviation) in the various material types are displayed in Figure 6. In SS-13-08, the uppermost 64 m (silts, silty fine sands, and sands) display lower velocities than the underlying diamictons and silts. In this upper interval, the Vp:Vs ratios range between 3.3 and 4.3, whereas, in the lower interval this ratio ranges between 2.4 and 2.8. This ratio change between glaciolacustrine deposits and the underlying diamictons is interpreted to reflect the change in compaction through glacial loading, an effect also noted by Hunter (2003) in a comparison of water-saturated unconsolidated Holocene and Pleistocene materials. In SS-12-02, where the entire sequence has been glacially loaded, the velocity ranges can be quite large, but the Vp:Vs ratios consistently range between 2.7 - 3.3. Due to the absence of borehole fluid in the upper 35 m of SS-12-02, the P-wave velocities in the Newmarket Till could not be measured; however, Pullan et al. (2002) indicate that a Vp exceeding 2500 m/s is typical of Newmarket Till, leading to a Vp:Vs ratio of ~3.

Interpretation

The relatively elevated magnetic susceptibilities measured in the Newmarket Till and the glaciolacustrine valley-fill sediments indicates a greater magnetic mineral content is present in these sediments, suggesting a change occurred in the provenance of the source material at a later time in the depositional sequence. The elevated magnetic susceptibility and Vp values (2400 m/s) in the silty/sandy diamicton at the base of the valley-fill sequence in SS-13-08 also supports the interpretation that this unit is Newmarket Till, as suggested by Bajc et al. (2014). However, logs collected in Newmarket Till in other OGS boreholes east of the south Simcoe area (eg. OGS-93-15, -17, -18, -19) do not indicate similar elevated magnetic susceptibilities (Pullan et al., 2002) which could provide interesting information about the variability of sediment sources. The very low magnetic susceptibility values measured in the Paleozoic bedrock (4.0 ± 0.2 ppt) indicates that the source of Newmarket Till is dominated by Precambrian (granitic) bedrock rather than Paleozoic (carbonate) bedrock.

The velocity logs in SS-12-02 and SS-13-08 (and interpreted unit velocities, Figure 6) indicate highly variable P- and S-wave velocities, which reflect the chaotic nature of the glacial sediments. This was also observed in the GSC's high-resolution seismic reflection profiles (Bajc et al., 2014), and suggests a complex and highly variable vertical and lateral velocity character in the deposits. While the ranges of Vp and Vs velocities were quite large within the lithological units, the ratio of Vp:Vs may be a useful indicator of depositional setting (i.e. glacially-loaded sediments versus deglacial valley-fill and glaciolacustrine environments) even without sedimentary core logging. This relationship will be explored further in a review of the GSC's southern Ontario borehole dataset.

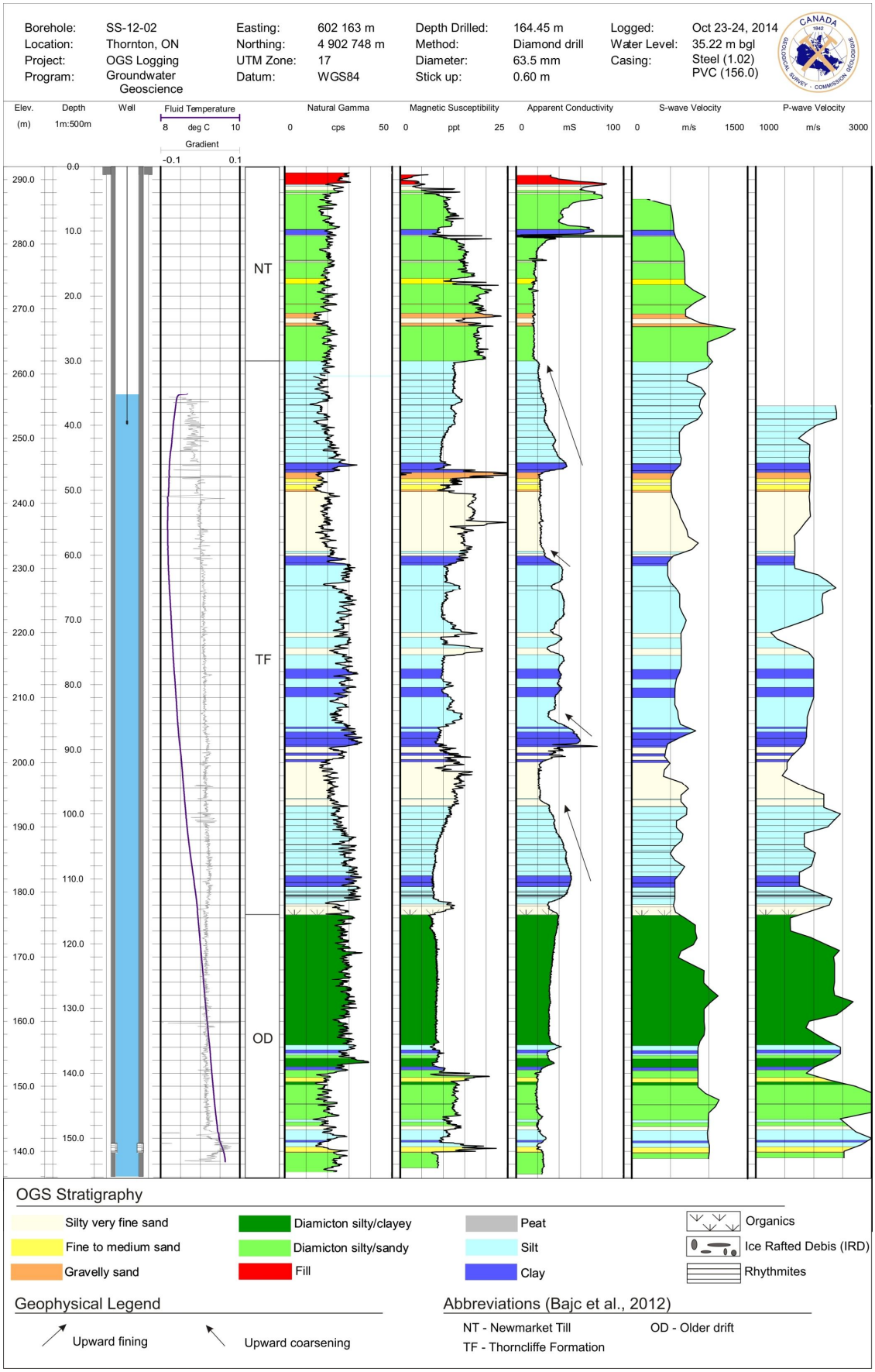


Figure 2 – Borehole geophysical logs collected in OGS borehole SS-12-02 in Thornton, ON. A large format figure is available in Appendix A.

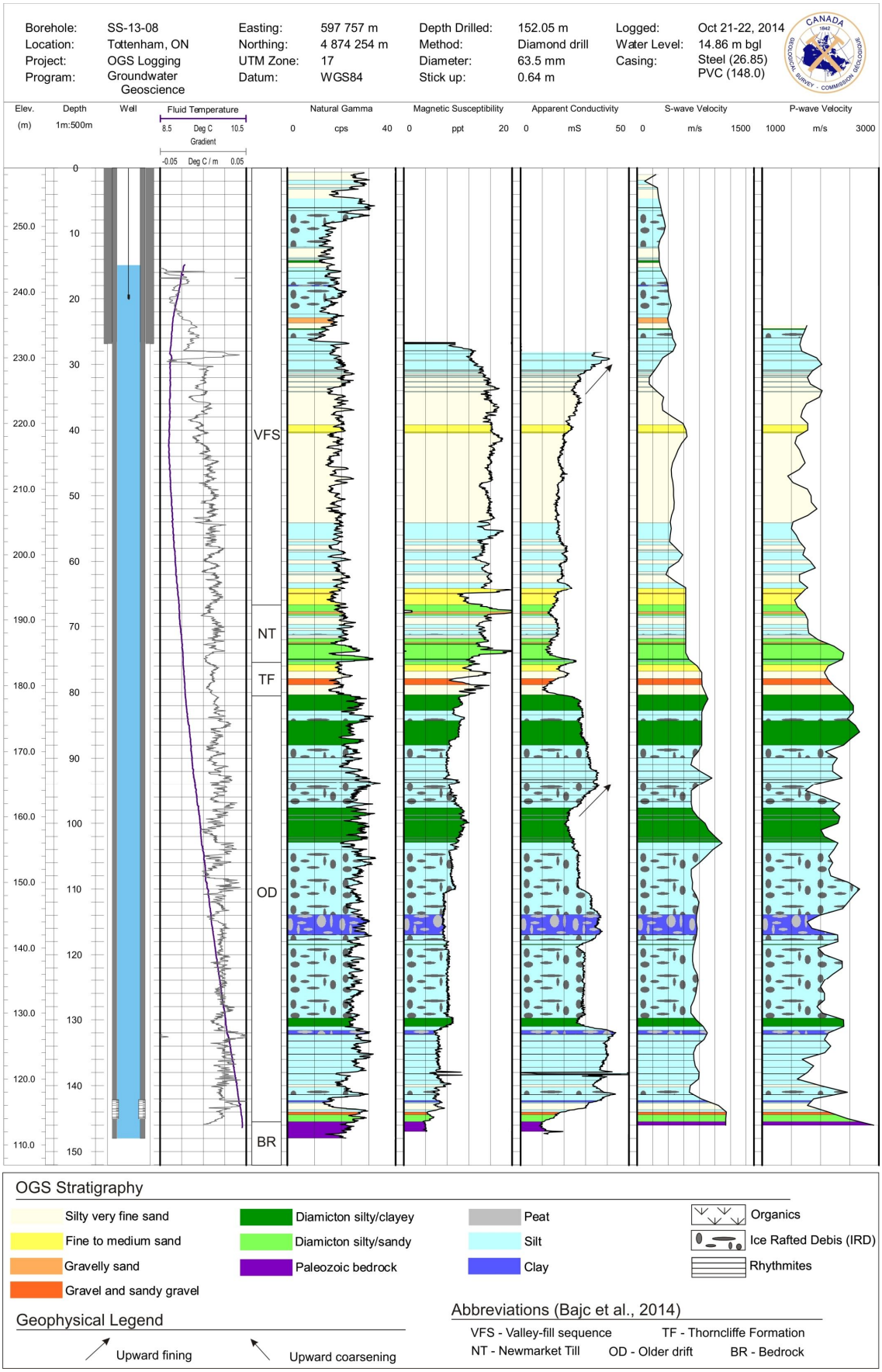


Figure 3 – Borehole geophysical logs collected in OGS borehole SS-13-08 near Tottenham, ON. A large format figure is available in Appendix A.

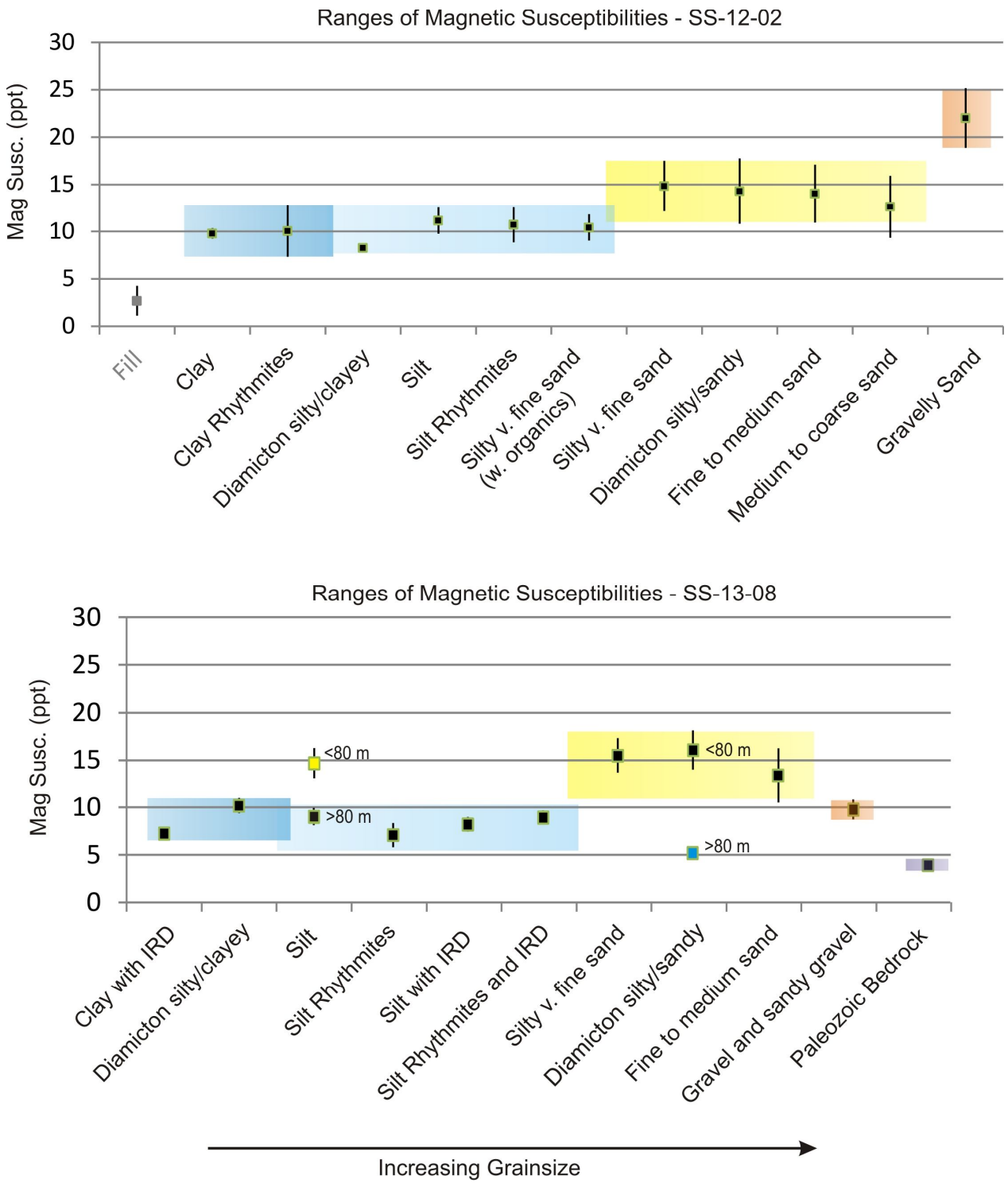


Figure 4 – Ranges in magnetic susceptibilities measured in the two logged boreholes. The mean value of each stratigraphic unit type is shown by the box, and the whiskers represent one standard deviation. Twenty five centimetres above/below each boundary are removed from the calculations to take into account the averaging effect of the coils in the induction tool over a lithological contact.

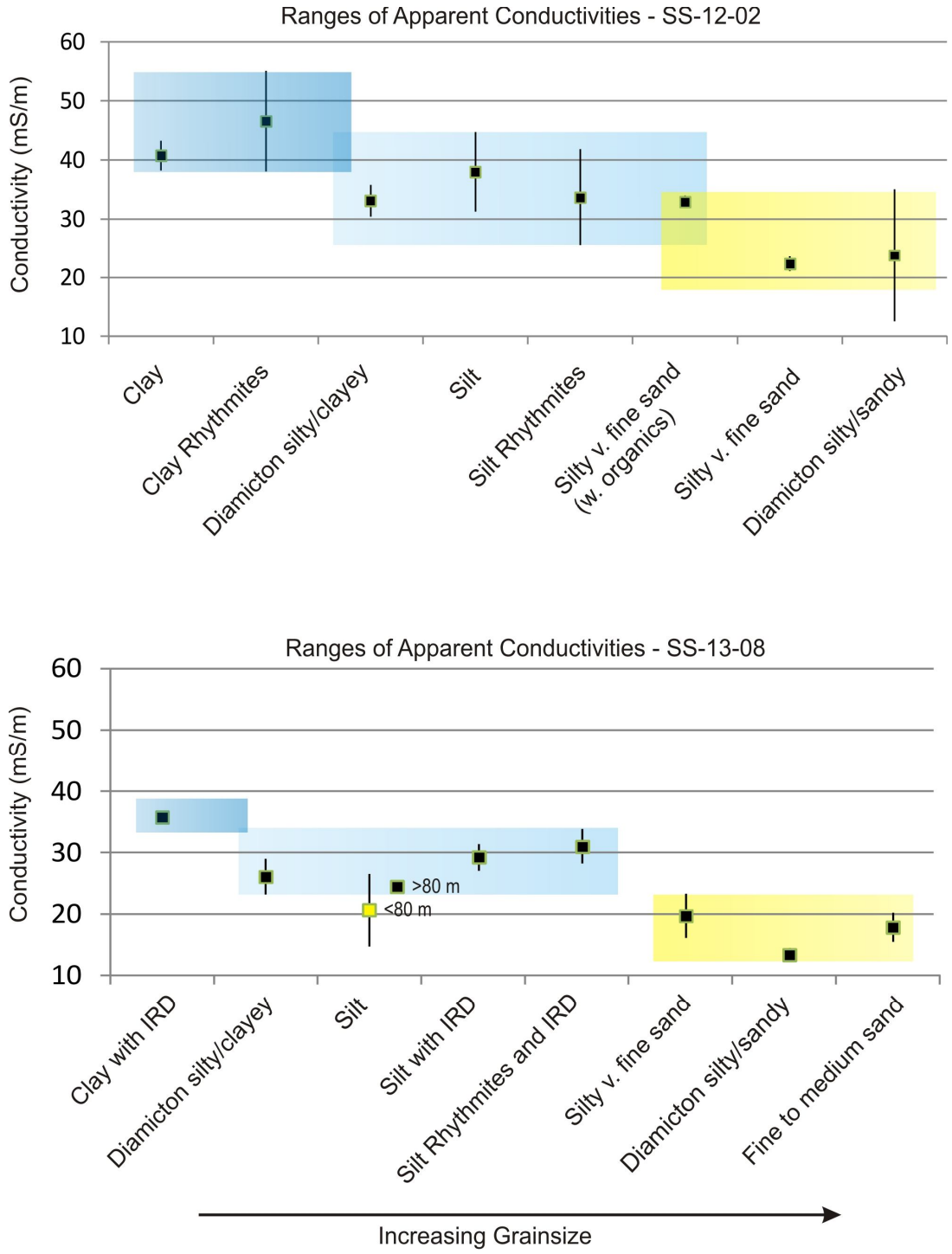


Figure 5 – Ranges in apparent conductivities measured in the two logged boreholes. The mean value of each stratigraphic unit type is shown by the box, and the whiskers represent one standard deviation. Fifty centimetres above/below each boundary are removed from the calculations to take into account the averaging effect of the coils in the induction tool over a lithological contact.

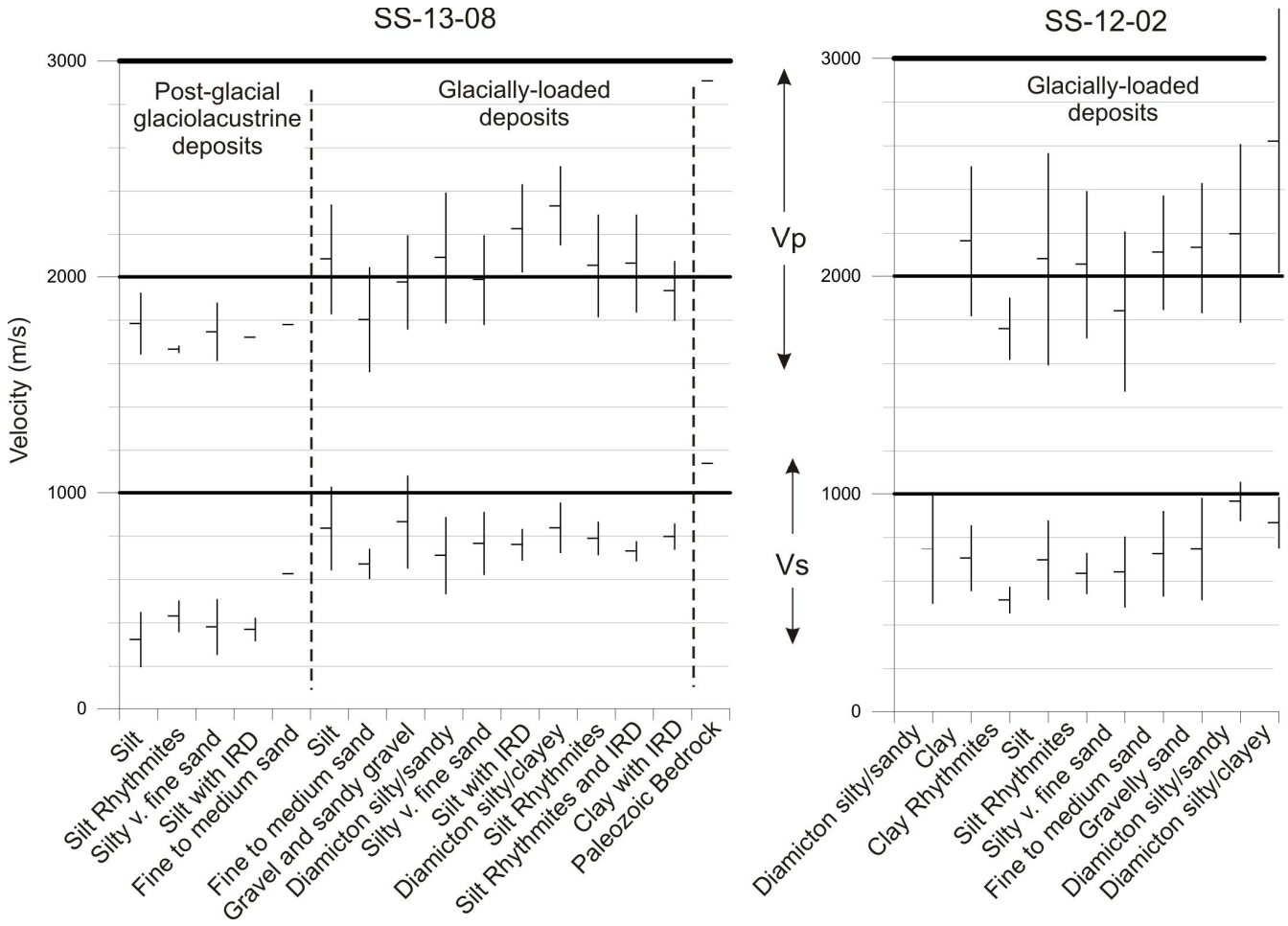
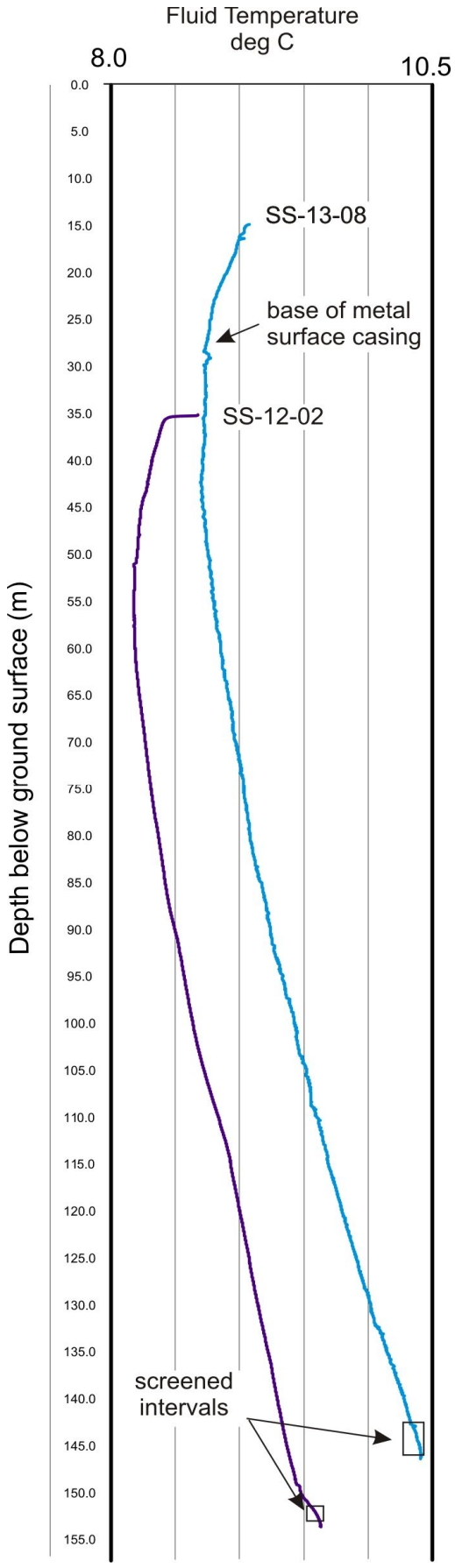


Figure 6 – Ranges of velocities (mean ± one standard deviation) encountered in various lithological materials. Despite the wide ranges in velocities within the sediment types, relatively low shear wave velocities measured in the glaciolacustrine deposits in SS-13-08 result in a higher Vp:Vs ratio than in the glacially loaded sediments.

Hydrogeological Observations

Fluid temperature logs collected in both boreholes are presented relative to depth in Figure 7. Temperature ranges of the fluids are in agreement with those measured by Taylor et al. (1999) during their study of borehole fluid temperatures in the Oak Ridges Moraine. Borehole fluid temperatures were undisturbed for several months prior to logging, except for the removal of the water level logger from the top few metres of fluid. In both wells, fluid temperatures follow a bow-shaped arc ranging between 8.17 and 9.64ºC in SS-12-02, and 8.70 and 10.41ºC in SS-13-08. Despite the differences in absolute temperature ranges (0.8ºC ± 0.1ºC), trends provide useful information about the shallow geothermal properties of the subsurface. In the top 40 – 50 m below ground surface, surface climatic conditions, presence of metal surface casing, and, at sub-degree scales, material type (i.e. aquitard vs. aquifer), all influence the recorded temperatures. At 51.2 m depth (SS-12-02) and 42.3 m (SS-13-08), the temperature reaches its minimum of 8.17ºC and 8.70 ºC respectively, which falls within the predicted temperature range (8 - 10 ºC) of the shallow geothermal field at this location in Southern Ontario at 50 m depth (Grasby et al., 2009) Below this depth, a positive temperature gradient of +0.01ºC/m is measured up to 120 m.



Temperature gradient logs in SS-12-02 indicate greatest variability (+Δ0.02 ºC) within the screened interval where fluid is entering the borehole. Smaller deviations (Δ0.01 ºC) occur at depths of 47.85 m and 51.10 m within gravel and silty very fine sand units which may indicate some groundwater flow is occurring within these units behind the casing wall. In SS-13-08, a deviation in the gradient is visible at the screen depth, but its amplitude is small and no greater than other gradient deviations in the well. The greatest variation in the gradient occurs at 28.6 m (1.7 m below the base of the steel surface casing). The cause of this anomaly within a silt (aquitard) unit is unknown, and is attributed either to completion details related to the grouting of the metal/PVC casing, or perhaps to a zone of artesian flow in a gravel unit 5 m above the anomaly.

Figure 7 – Fluid temperature logs, measured in two OGS boreholes, shown relative to depth.

5.0 Conclusions

A suite of geophysical logs (electromagnetic induction, natural gamma, temperature, and velocity) was collected in two PVC-cased OGS boreholes drilled in unconsolidated sediments in the south Simcoe County area. The logs, shown in Figures 2 and 3, were collected to assist in the interpretation of seismic profile data collected by the GSC in the study area, and to develop correlations between the geophysical logs and the local stratigraphy.

Induction logs (apparent conductivity and magnetic susceptibility) were used to identify changes in the main stratigraphic units. Magnetic susceptibility logs provide greater capability for resolving coarser grained beds (fine sand to gravel) than apparent conductivity logs alone, but the response of the apparent conductivity tool was more sensitive to clay-rich beds. The combined use of both induction tools provides an enhanced ability to identify variations in grain size across the clay to gravel grain size range, and to indicate the presence of upward-fining or -coarsening sequences which are so visible in the Thorncliffe formation in SS-12-02. Magnetic susceptibility also provides a means of identifying the presence of magnetic minerals which can indicate variations in provenance between units of the same grainsize, as seen in SS-13-08. Newmarket Till and the overlying valley-fill sediments exhibited elevated magnetic susceptibilities relative to the underlying Thorncliffe Formation and older tills interbedded with glaciolacustrine deposits. This trend is not observed in all OGS boreholes in the region logged by the GSC with the same tool (e.g. Pullan et al., 2002), potentially indicating changes in provenance and/or time of deposition of these sequences.

Velocity logs in both wells revealed highly variable stiffness in the diamictons, indicating a complex structure. Ratios in Vp:Vs appear to be useful indicators of deglacial glaciolacustrine versus glacially-loaded sediment packages.

The fluid temperature logs indicated that groundwater temperatures are primarily in equilibrium with the shallow geothermal gradient, but minor deviations in material type (i.e. aquitard vs. aquifer) also influence the temperature gradients on a very fine scale ($\Delta \sim 0.01$ºC). The minimum temperatures recorded in the boreholes were measured between depths of 43 – 51 m, reflecting the depths to which surface climatic conditions are presently influencing subsurface temperatures.

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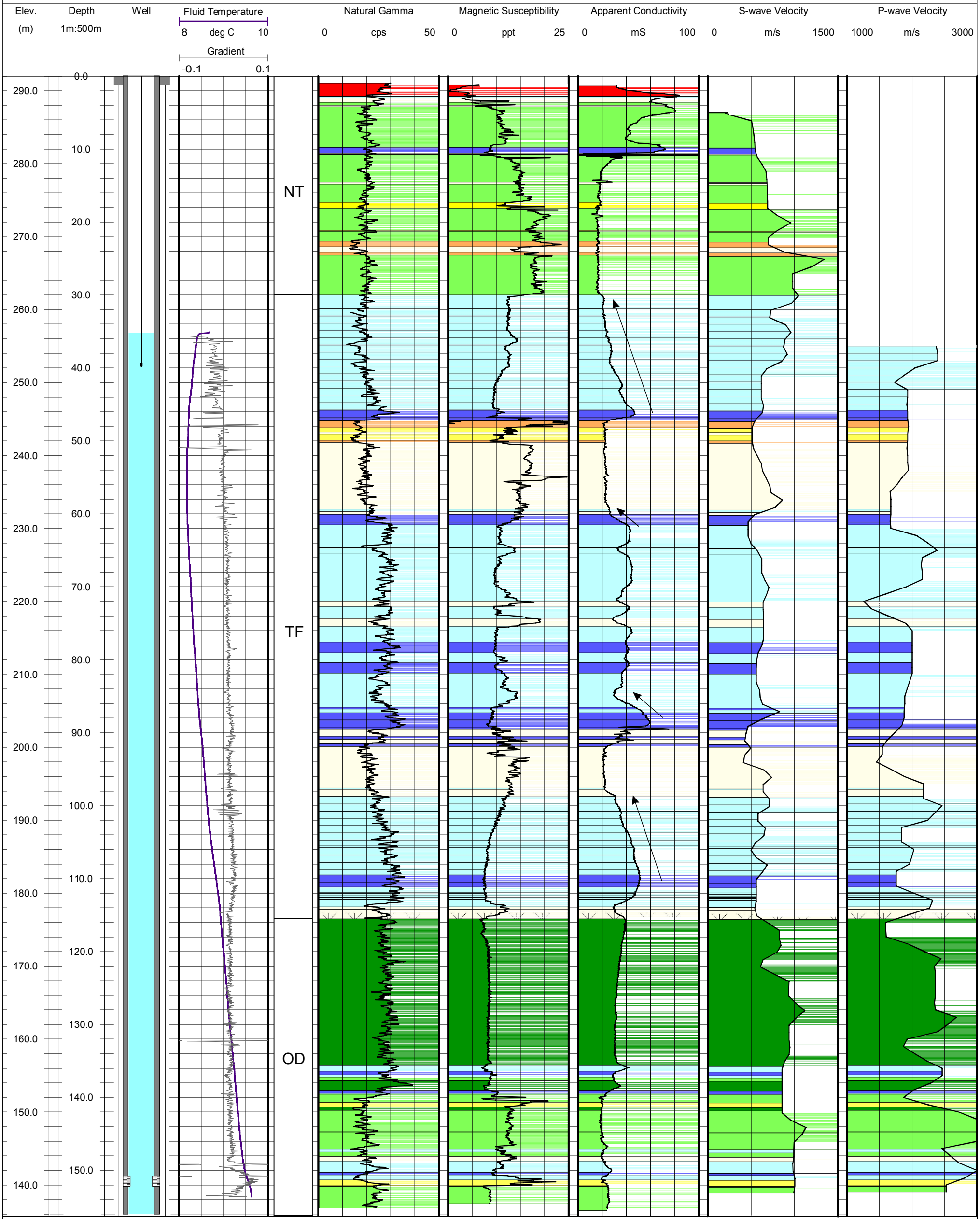
Borehole:	SS-12-02	Easting:	602 163 m	Depth Drilled:	164.45 m	Logged:	Oct 23-24, 2014
Location:	Thornton, ON	Northing:	4 902 748 m	Method:	Diamond drill	Water Level:	35.22 m bgl
Project:	OGS Logging	UTM Zone:	17	Diameter:	63.5 mm	Casing:	Steel (1.02)
Program:	Groundwater Geoscience	Datum:	WGS84	Stick up:	0.60 m		PVC (156.0)



OGS Stratigraphy

- Silty very fine sand
- Fine to medium sand
- Gravelly sand
- Diamicton silty/clayey
- Diamicton silty/sandy
- Fill
- Peat
- Silt
- Clay
- Organics
- Ice Rafted Debis (IRD)
- Rhythmites

Geophysical Legend

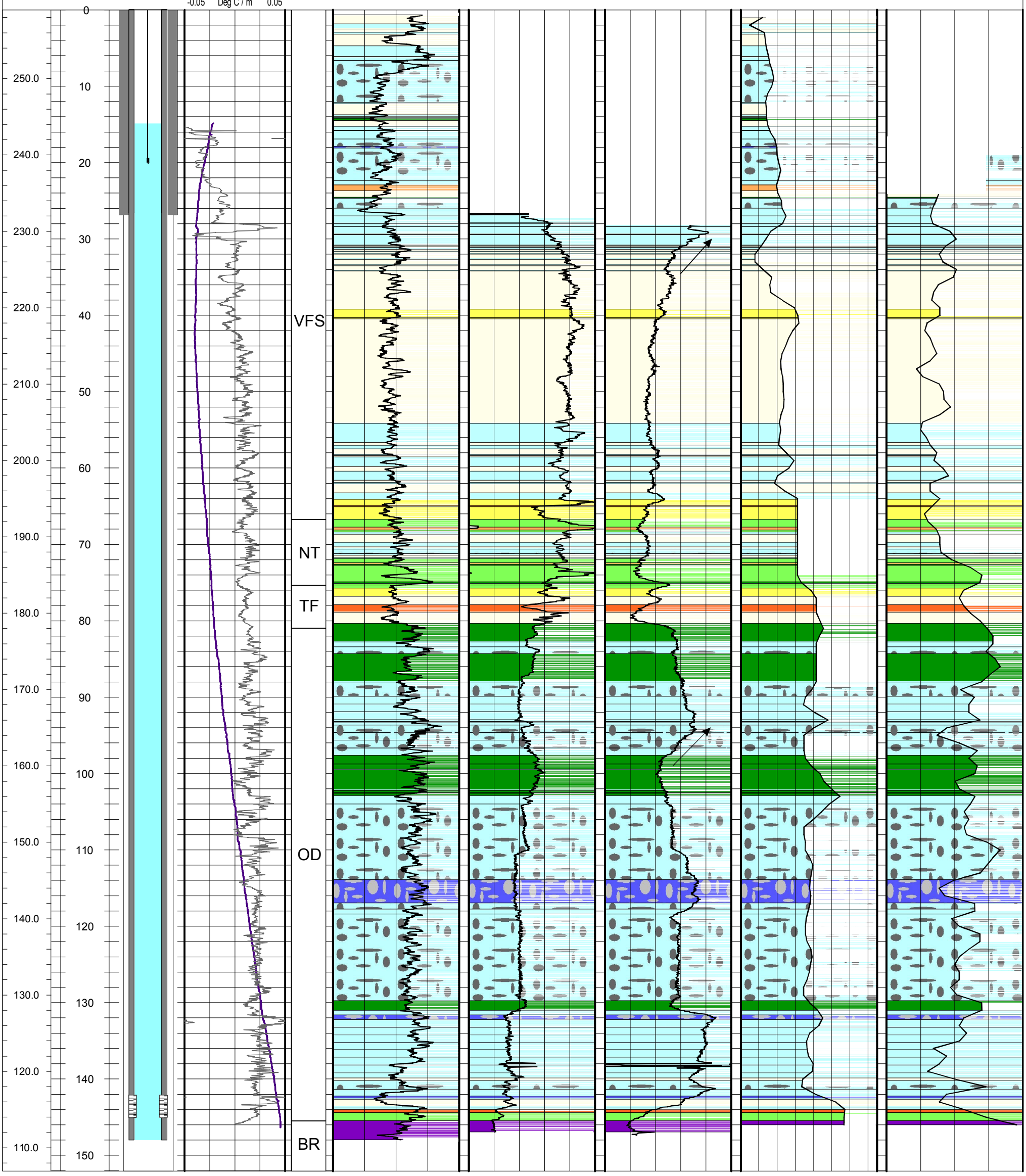
- Upward fining
- Upward coarsening

Abbreviations (Bajc et al., 2012)

NT - Newmarket Till
OD - Older drift
TF - Thorncliffe Formation

Borehole:	SS-13-08	Easting:	597 757 m	Depth Drilled:	152.05 m	Logged:	Oct 21-22, 2014
Location:	Tottenham, ON	Northing:	4 874 254 m	Method:	Diamond drill	Water Level:	14.86 m bgl
Project:	OGS Logging	UTM Zone:	17	Diameter:	63.5 mm	Casing:	Steel (26.85)
Program:	Groundwater Geoscience	Datum:	WGS84	Stick up:	0.64 m		PVC (148.0)

Elev. (m) | Depth 1m:500m | Well | Fluid Temperature 8.5 Deg C 10.5 | Gradient -0.05 Deg C / m 0.05 | Natural Gamma 0 cps 40 | Magnetic Susceptibility 0 ppt 20 | Apparent Conductivity 0 mS 50 | S-wave Velocity 0 m/s 1500 | P-wave Velocity 1000 m/s 3000



OGS Stratigraphy

- Silty very fine sand
- Fine to medium sand
- Gravelly sand
- Gravel and sandy gravel
- Diamicton silty/clayey
- Diamicton silty/sandy
- Paleozoic bedrock
- Peat
- Silt
- Clay
- Organics
- Ice Rafted Debis (IRD)
- Rhythmites

Geophysical Legend

Upward fining

Upward coarsening

Abbreviations (Bajc et al., 2014)

VFS - Valley-fill sequence
TF - Thorncliffe Formation
NT - Newmarket Till
OD - Older drift
BR - Bedrock