Geological and Geochemical Analysis of Quaternary Aquifers and Aquitards, Clarington Ontario

This page left blank intentionally

Assessing Aquifer Vulnerability of Private Wells through Geological and Geochemical Analysis near the Clarington Transformer Station

By KELLY WHELAN, B.Sc.

A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree of Master of Science

McMaster University

McMaster University Master of Science (2017) Hamilton, Ontario

Department of Geography and Earth Science

TITLE: Assessing Aquifer Vulnerability of Private Wells Through Geological and Geochemical Analysis at the Clarington Transformer Station.

Pages: ii,194

LAY ABSTRACT

A groundwater study was conducted in an eight square kilometre area at the southeast edge of the Oak Ridges Moraine near Oshawa, ON. It included: geology from a 130m hole through overburden (including Newmarket Till) to bedrock, groundwater age determinations and water chemistry obtained by Hydro One from 16 monitoring wells on HydroOne property (11 hectares) and 25 nearby homeowner wells, most less than 22m deep. Wells above 22m show salt and other constituents from roads, septics or agriculture and show young groundwater age. Two deep wells (100m) in the Thorncliffe Aquifer beneath the Newmarket Till also show these chemicals; one of them sampled for tritium-helium showed young age, as do some intermediate -depth wells. The pathways for young water migrating so deep are undetermined.

ABSTRACT

Groundwater conditions beneath 11 hectares property owned by HydroOne near the southeastern edge of the Oak Ridges Moraine were assessed for contamination susceptibility using groundwater and geological information from HydroOne monitoring on-site and within one kilometre. Geological information was obtained from preexisting well records and a deep cored hole through dense glacial deposits (Newmarket Till) and through two deep regional sand aquifers (Thorncliffe and Scarborough Aquifers) into shale at 130 mbgs. The multiple data types included water levels, Tritium-Helium groundwater dating, oxygen-18 and deuterium, and major and minor ions. The water table is close to surface (<3m) and wells above 22 m depth in the highly active shallow zone show chemicals and Coliform Bacteria from human activities including roads, septics and agriculture. Shallow groundwater flows downward towards the Thorncliffe aquifer; the bottom of this most active zone is unknown due to insufficient data from deeper wells. Two private wells (100 mbgs) thought to be in the Thorncliffe aquifer contain constituents indicative of human influence. Seven of eight homeowner wells show tritium from nuclear power stations, one at detection limit. Three hypotheses are proposed to explain the susceptibility of wells in the Thorncliffe Aquifer to contamination: 1) the Newmarket aquitard is contains preferential pathways due to fractures connected to sand layers allowing deep penetration of contamination, 2) recharge can occur directly into the Thorncliffe aquifer in areas where Newmarket Till is non-existent, and 3) wells have faulty construction allowing short-circuiting to depth of contaminated shallow water down and along well casings. Based on the current data preferential pathways through the Newmarket is the most plausible hypothesis. However, additional work to define groundwater flow paths both on and off-site as well as additional geochemical and isotopic analyses from existing and new deep wells is needed to better determine risk to residential wells.

ACKNOWLEDGMENTS

I would like to thank Dr. James E. Smith, McMaster University for providing supervision during the completion of this thesis. Additional information and guidance was provided by Drs. Ian Clark, Ottawa University, John Cherry, and Beth Parker, School of Engineering at the University of Guelph and Emmanuelle Arnaud, School of Environmental Sciences, University of Guelph.

Some of the data used in this thesis was collected on Hydro One property; Hydro One paid for the drilling of the high-resolution borehole, along with the installation of the monitoring wells. Jeff Cridland (Hydro One) was instrumental in coordinating site logistics and field work during the recovery of the high-resolution borehole. In addition to Hydro One consultants from Stantec, the Municipality of Clarington was represented on site during data collection by Steve Usher from SLR Consulting. The Municipality of Clarington funded triaxial permeability testing within the high-resolution borehole and geochemical analyses of private wells used in this study. Data collection from the borehole was completed by a field crew from McMaster University, the University of Guelph, and Stantec Consulting Ltd. The field personnel from McMaster and Guelph University, under the supervision of Dr. Emmanuelle Arnaud (University of Guelph) included Kelly Whelan and Sydney Duggan (McMaster University) as well as Tara Harvey (University of Guelph). Stantec consultants (Brant Gill and Natalie Spina) worked with the McMaster and Guelph University crew during the duration of drilling and data collection. Additional information and guidance during drilling was provided by Dr. Rick Gerber (Oak Ridges Moraine Groundwater Program, CLOCA). Assistance on sampling procedures and transportation of some samples to labs was provided by Steve Usher from SLR Consulting. Grain size data used in this thesis was completed by Dr. Hazen Russell and Ross Knight (Geological Survey of Canada). Geochemical data collection, diffusion sampler installation, and analysis were carried out under the supervision of Dr. Ian Clark (Ottawa University) and the team at A.E Lalonde AMS laboratory including Monika Wilk (Noble Gas/Tritium Laboratory) and Paul Middlestead (G.G. Hatch Stable Isotope Lab). The installation/removal of diffusion samplers and collection of water samples was carried out by the author with field assistance provided by Alicja Jazwiec (McMaster University) and Sydney Duggan (McMaster University). Additional help and coordination of field logistics for the geochemical study was provided by the Enniskillen Environmental Association. Field assistance and resident property access was provided by Mr. Doug Taylor and Mr. Jim Sullivan. Special thanks to all local resident who allowed installation of diffusion samplers in their wells and collection of water samples, including Mr. Doug Taylor, Mr. Jim Sullivan, Mr. Stan Kuzma, Mr. Clint Cole, Ms. Ingrid Zersch, and the Reagan family.

Financial support for field personnel costs were covered by research funds from Dr. James E. Smith (Natural Sciences and Engineering Research Council), Dr. Beth Parker and

Dr. John Cherry (University Consortium for Field-Focused Groundwater Contamination Research) and Dr. Emmanuelle Arnaud. Financial, field and laboratory assistance from all collaborators on this project is greatly appreciated.

Declaration of Academic Achievement

Contributions of this thesis include an improved understanding of the groundwater flow system at the site scale along with assessing and improving the site conceptual models (SCM) through detailed logging of 130 m of core; geochemical data collection including tritium-helium for groundwater dating as well as Oxygen-18 and Deuterium to assess groundwater residence times and aquifer connectivity at the site; and a compilation of 2 years of groundwater quality data from the HydroOne monitoring program not previously utilized to asses major ion signatures and associated groundwater flow paths. The conceptual model includes three potential pathways for younger water to reach residential well, including evidence that the aquitard may not be providing the previously assumed level of protection to aquifers below the site.

TABLE OF CONTENTS

List of Tables

List of figures

Appendix

List of Abbreviations

Bicarbonate (HCO_3^-),

Calcium (Ca^{2+})

Carbonate (CO_3^{2-})

Chloride (Cl^-)

Continuous Core (PQ)

Dissolved Organic carbon (DOC)

Deuterium (^2H or D)

Electrical Conductivity (EC)

Greater Toronto Area (GTA)

Greenland Ice Sheet Precipitation (GISP)

Helium-3 (^3He)

Integrated Cavity Output Spectroscopy (ICOS)

Los Gatos Research (LGR)

Magnesium (Mg^{2+}),

Meters Above Sea level (masl)

Meter Below Ground Surface (mbgs)

Meteoric Water Line (MWL)

Monitoring Well (MW)

Multi-level System (MLS)

Ontario Geological Survery (OGS)

Ontario Power Generation (OPG)

Oxgen-18 (^{18}O)

Potassium (K^+),

Private Well (PW)

Quality Assurance and Quality Control (QA/QC)

Site Conceptual Model (SCM)

Sodium (Na^+)

Split Spoon Sample (SS)

Standard Light Antarctic Precipitation (SLAP)

Sulfate (SO_4^{2-})

Total Dissolve Solids (TDS)

Transformer Staition (TS)

Triple Isotope Water Analyzer (TIWA-45EP)

Tritium (^3H)

Tritium Units (TU)

Vienna Standard Mean Ocean Water (VSMOW)

1 Introduction

The Oak Ridges Moraine (ORM) is called the “rain barrel” of southern Ontario because it not only supplies water to many people; it also contributes base flow to over 30 major streams (Howard et al. 1995). The ORM is a high relief landscape feature located north of the Greater Toronto area and extending from the Niagara Escarpment through Peel, York, and Durham regions. It consists of an unconfined aquifer at its core with confined aquifer conditions where surficial till deposits are found along its flanks. In 2001, the government passed the Oak Ridges Moraine (ORM) Conservation Act to protect the hydrological integrity of the ORM aquifer, which provides drinking water to over 200,000 people (Oak 2001).

In 2012, a location near Clarington, Ontario was proposed for a new Hydro One Transformer station (TS), to take over the pending loss of 3,000 MW of generation from the scheduled Pickering Nuclear Power Plant retirement in 2024. The transformer station is being constructed on Hydro One property and will consist of two (2) 500/230 kV transformers, a 500 kV switchyard, two relay buildings, one (1) electrical panel building, and the associated buswork and equipment (Stantec Consulting Ltd. 2015a).

The primary concerns of local residents, pertaining to the TS construction include regrading of the site and the potential impacts of mineral oil used for transformer insulation on drinking water quality (Cherry et al. 2013). The 11 hectares TS will include a drainage system that will collect any precipitation that falls on site, along with oil water separator tanks connected to spill containment pits to reduce the risk of any potential mineral oil spill (Stantec Consulting Ltd. 2015a). The mineral oil itself is not a contaminant; however, if it is mixed into the groundwater it can alter the redox conditions, which in turn allows for the release of metals such as iron and manganese and potentially other constituents to render the water unpotable (Cherry et al. 2013). The proposed location of the TS is at the edge and within the protection area covered under the Oak Ridges Moraine Conservation Act (Fig. 1.1); as a result, there are concerns that ORM sediments could be present below the site and that the TS represents a risk for the ORM aquifer, and to local residential water supply. These concerns and the site's location and geological setting suggest a need for a comprehensive assessment (Cherry et al. 2013).

The Clarington transformer station's near-surface geology and hydrogeology can be characterized as dominated by diamicton in the first 50 m, with shallow and deep sand zones or layers located at various depths below the surface. At depth, the diamicton is most likely the Newmarket Till, a regionally extensive aquitard referred to as the Newmarket aquitard in this thesis. The Newmarket Till was originally believed to be an aquitard that provided adequate protection to shallow and deep aquifer systems within

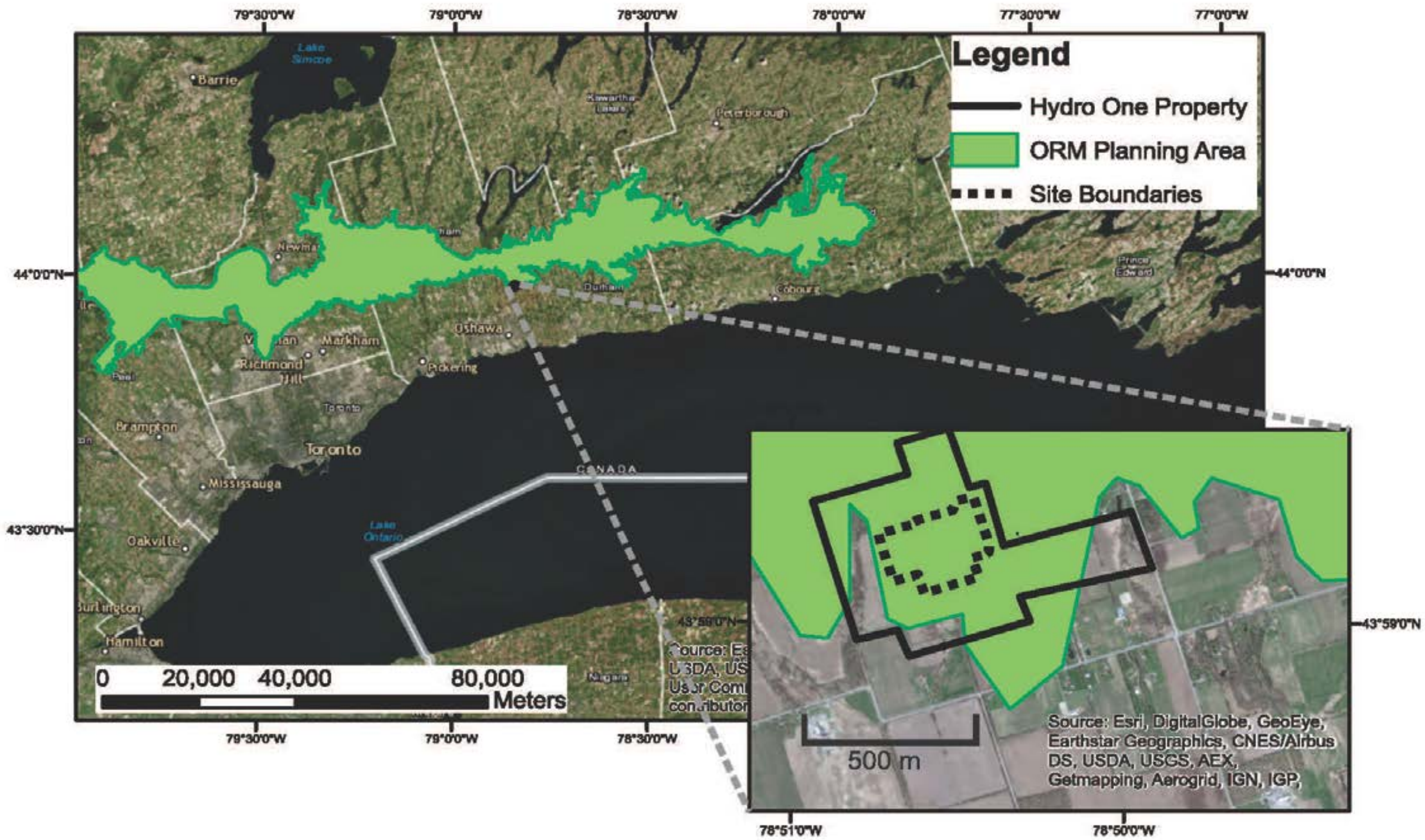


Fig. 1.1: *Land use planning boundary in relation to transformer station location. Boundary data from Ontario Ministry of Natural Resources 2001*

the unconsolidated glacial sediments. However recent studies have provided evidence that in some local areas, rapid groundwater leakage through the Newmarket Till should be of concern, whereas in other areas the Newmarket Till has proven to provide adequate protection (Gerber et. al 2001), creating the need of site specific aquitard integrity studies across the region. The Thorncliffe aquifer is one of the regionally extensive sand units that underlie the Newmarket aquitard, creating the potential for widespread contamination if the aquitard integrity is low.

Sand within a glacial till deposit encompasses a broad spectrum of high hydraulic conductivity features such as sand layers, sand bodies, sand pockets, and sand stringers and the connectivity of these features is based on geometry and configuration of each sand unit. The highest quality data for determining the geometry, orientation, and connectivity in space is best derived from outcrop or excavated areas (Kessler 2012). In this thesis, outcrop and test pits were not available for determining geometry of relatively higher conductivity zones within the till, therefore the sand found in borehole data will be referred to as “sand zones” due to the unknown lateral/vertical variability and connectivity of these features.

Currently, proposed conceptual geological models for the site differ in their hypotheses of what till unit is located at surface, which in turn has implications for the connectivity and lateral extent of the sand zones located below the ground surface.

Many local residents around the perimeter of the site have water wells completed in these sand zones. Thus, a better understanding of the stratigraphy, recharge and leakage locations, aquitard integrity, and the connectivity of these sand zones is needed to evaluate the aquifer's vulnerability.

One focus of this study is to determine if surface or below surface sand zones have the potential to be associated with ORM sediments (Mackinaw-age), thus posing a risk to the regional ORM aquifer system. This determination starts with identifying which till unit is located at the surface, specifically focusing on the discrepancies of current site conceptual models (SCM) within the first 15 mbgs. If the Newmarket Till is found at surface, the sand zones at depth are not likely to be associated with ORM sediments, and aquifer susceptibility should be assessed for local residences. If the younger Halton Till is found at surface, sand zones below ground surface could be deposited during the Mackinaw time period and could potentially be connected to the ORM regional aquifer system. The geological data collected for this study, which includes a detailed log of a 130 m core, grain size analyses, and cross sections of existing borehole records, will help to inform the current site conceptual model.

In addition to providing a geological framework for the site, the second objective of this study sets out to analyze geochemical data collected from thirty one (31) private wells and monitoring wells on and off the site to achieve a better understanding of the local hydrogeology. Many of the local residents in the area are using relatively shallow sand zones associated with diamicton or deep sand zones associated with the Thorncliffe Formation as a source of water. In a 1 km radius around the site, there are approximately 40 residential wells. Many are completed at a depth very close to the boundary of Newmarket aquitard and Thorncliffe aquifer, making it difficult to know whether a well's water supply is from a sand zone within the Newmarket aquitard or from the Thorncliffe aquifer. The use of Tritium and Helium-3 will provide estimates of groundwater age, water residence and travel times and help to assess groundwater pathways on, around, and off the site.

Oxygen-18 and Deuterium data collected for the purpose of this study in combination with pre-existing geochemical data including, major ion concentrations, and anthropogenic indicators such as concentrations of chloride, nitrate, bacteria, and sulfate can aid in determining if recharge is from surface, with leakage through the aquitard or a part of a more regional 3-dimensional flow system. The geochemical data collected and analyzed on this site together with the environmental isotope data will also aid in assessing sand connectivity, recharge and leakage variability, aquitard integrity, and local well vulnerability over an approximately 3 km distance along the east and south border of the study site.

This study's main objectives are:

1. Improving the geological framework below the site with the aid of a high-resolution borehole to bedrock (130 mbgs) and pre-existing borehole data in order to assess whether or not ORM sediments are likely located below the site, allowing for potential contamination to the ORM aquifer system.
2. Achieving a better understanding of the site's hydrogeology using Tritium-helium data to determine groundwater residence time, and estimation of recharge and leakage zones.
3. Assessing aquitard integrity and assessing the intrinsic vulnerability of private well located around the perimeter of the TS through the analysis of aquifer groundwater geochemical signatures.
4. Comparing unequally-distributed anthropogenic indicators to concentrations of equally-distributed source of Tritium and Helium data in the context of an intrinsic well vulnerability assessment.

1.1 Terminology

1.1.1 Vulnerability

It should be noted that the term "vulnerability" in literatures seems to vary in its use and at many times lacks a clear definition on how the term is being used. The general use of the term aquifer or well vulnerability should encompass groundwater travel times and flow paths, while including all the attenuation processes of the specific contaminant of concern (Cherry et al. 2006 and Frind et al. 2006). This means the study would need to include the time it takes for a contaminant to reach levels above drinking water standards by including dispersion, fracture flow/transport, matrix diffusion, biodegradation, etc. (Frind et al. 2006).

In this thesis, geochemical data is used to assess groundwater residence times and flow paths to aquifer systems in order to further our understanding of the hydrogeology of the TS. In that context, the term “intrinsic aquifer vulnerability” as presented by Frind et al. (2006) will be used in this thesis and is defined as “the protective characteristic of the pathway medium, independent of the characteristics of the contaminant”; this protective characteristic is based on physical parameters such as hydraulic conductivity, porosity, gradients, and path lengths (Frind et al. 20006). The prefix “aquifer” in this context is used to specify that only the times it takes for leakage to reach the top of an aquifer in a vertical direction and the time it takes for recharge to reach the general location of the site in the horizontal direction were considered. Specific travel times to wells could include both vertical and horizontal flow paths, and wells within the same aquifer can have varying water quality (Frind et al. 2006). Importantly, specific pathways to wells are not considered in this study. This term (intrinsic aquifer vulnerability) best suits the objective of this thesis and the currently available datasets. Future work in assessing retardation factors and hydrodynamic dispersion effects on specific contaminants as well as consideration of specific groundwater flow pathways on site and upgradient is needed to complete the vulnerability assessment of wells in this area. As the attenuation processes may be strong enough or contaminant behaviors in water may allow enough protection to local wells.

1.1.2 Recharge vs. Leakage

In this thesis the term Recharge will be used to describe groundwater moving from surface to the water table and directly into an aquifer. Specifically where the aquifer outcrops, is unconfined or is exposed at surface (Fig. 1.2). Leakage is to describe groundwater flow through an aquitard, where groundwater flux moves through the bottom of the confining unit (Fig. 1.2)

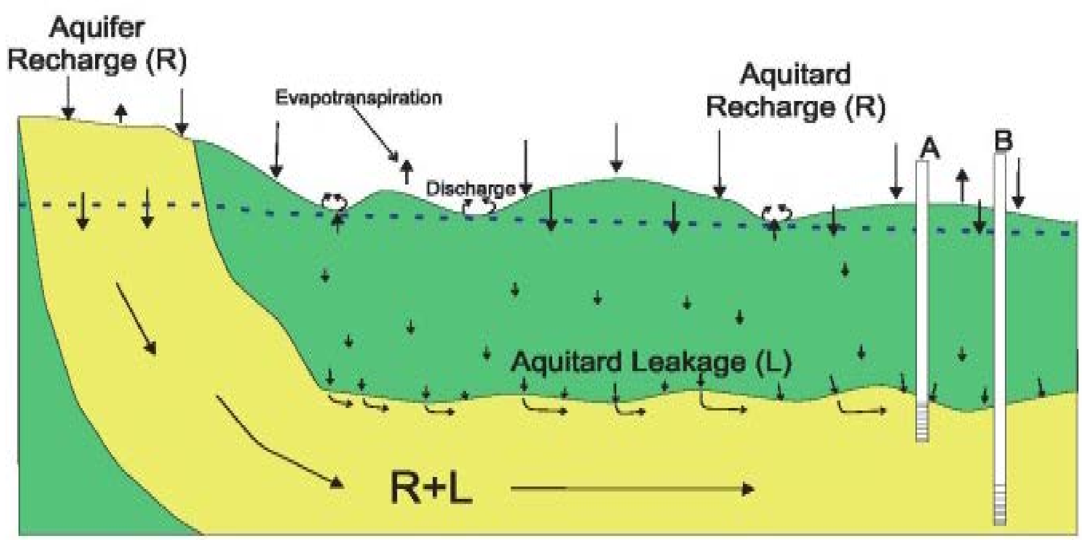


Fig. 1.2: *Rate of water entering the water table or an area where an aquifer is exposed at surface is considered recharge, whereas leakage is groundwater moving through the bottom of the aquitard. Wells screened within the aquifer can have varying water quality or have a combination of groundwater from recharged and leakage. Well A would be predominantly leakage water, whereas well B would be composed primarily of recharged water.*

1.2 Thesis Organization

In Chapter 2, an extensive literature review on the ORM region is followed by the presentation of all previous work done on the Clarington TS site pertaining to site conceptual model development (SCM). The existing models to date include two models created by Stantec Consulting Ltd. and one model created by Steve Usher from SLR Consulting. Following the overview of the data known to date, this thesis presents geological and geochemical datasets to refine the SCM. Chapter 3 focuses on the high resolution data collected from cores MW5-14D and MW5-14D(2) combined with thirty (30) preexisting boreholes and monitoring wells that are used to create three cross sections on site. Analysis of these geological data leads to the development of a stratigraphic framework for the site. The remaining chapters 4-6 focus on both new and pre-existing geochemical data and includes the analysis of Tritium, Helium-3, anthropogenic constituents, Oxygen-18, Deuterium, and major ion concentrations to assess the local hydrogeology and aquitard integrity below and around the perimeter of the site.

There were two thesis projects based on data collected at or next to the Clarington Transformer Station. The primary focus of this study is to determine the geology and hydrogeology at a site scale using new and existing geological data across the site as well as geochemical data collected from adjacent monitoring wells and private wells. In contrast, the other thesis (Duggan 2016) focuses on using a high-resolution well-cluster located on the southwest corner of the TS and makes design recommendations for a future multilevel groundwater monitoring well next to the cluster. Duggan (2016) makes use of multiple data sets from the well-cluster including geophysics, portable x-ray fluorescence, and moisture content to assess small-scale hydrogeological properties and to identify key stratigraphic units at that location.

2 Literature Review

2.1 Introduction

The Quaternary unconsolidated sediments in and around the Oak Ridges Moraine area (Fig. 2.1) are underlain by the Paleozoic bedrock surface (Howard et al. 1995), which is typically a flat-laying formation dissected by the Laurentian Valley and its tributaries (Sharpe et al. 1999). The bedrock found under the unconsolidated sediments

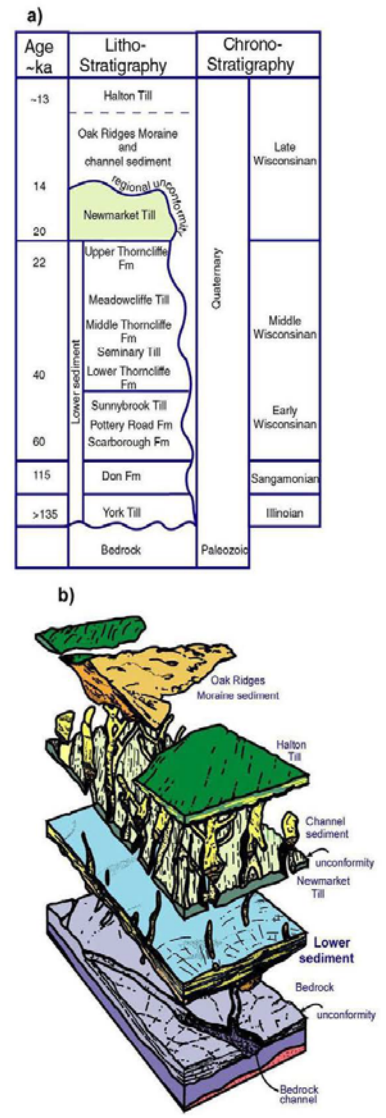


Fig. 2.1: Conceptual geological model of ORM and associated sediments. A. stratigraphic framework showing the timing of all geological units during the Wisconsinan glaciation. B schematic diagram showing the stratigraphic units in succession and typical properties associated with them, such as carved channels and unconformities (Sharpe et al. 2002b).

consists of limestone, shale, and sandstone that are estimated to be of Ordovician age (Sharpe et al 1999). From Lake Ontario northward to the City of Oshawa (Fig. 2.2), the bedrock changes from Lindsay Limestone Formation to the Whitby Shale Formation. Near Oshawa, Ontario it is reported that the Paleozoic bedrock gradually slopes southeastward toward Lake Ontario (Brennand 1998).

The bedrock is cut by valleys (Logan et al. 2006) that form a regional unconformity that overlies the Ordovician Bedrock (Sharpe et al. 1999) and is covered by unconsolidated sediments (Brennand 1998) (Fig. 2.1.). The unconsolidated sediments generally increase in thickness towards the north from Lake Ontario to the Oak Ridges Moraine (Brennand 1998) (Fig. 2.2) and can be divided into 5 major stratigraphic units from the bottom up including, Lower sediments, Newmarket Till, Channel sediments, ORM, and Halton Till (Fig. 2.1; Sharpe et al. 2003).

The unconsolidated sediment succession is made up of a three-part aquifer system defined by Gerber and Howard (2002). Lower sediments are comprised of aquifers and aquitards and include the lower and middle aquifer system called the Scarborough and Thorncliffe formations, respectively (Gerber and Howard 2002). These aquifers provide municipal and residential water supply within the region.

The Newmarket Till is a regionally extensive aquitard that protects the Lower sediments. It is composed of diamicton with sand zones, which provide water supply for private wells within the region. Generally speaking, deeper wells are often used for

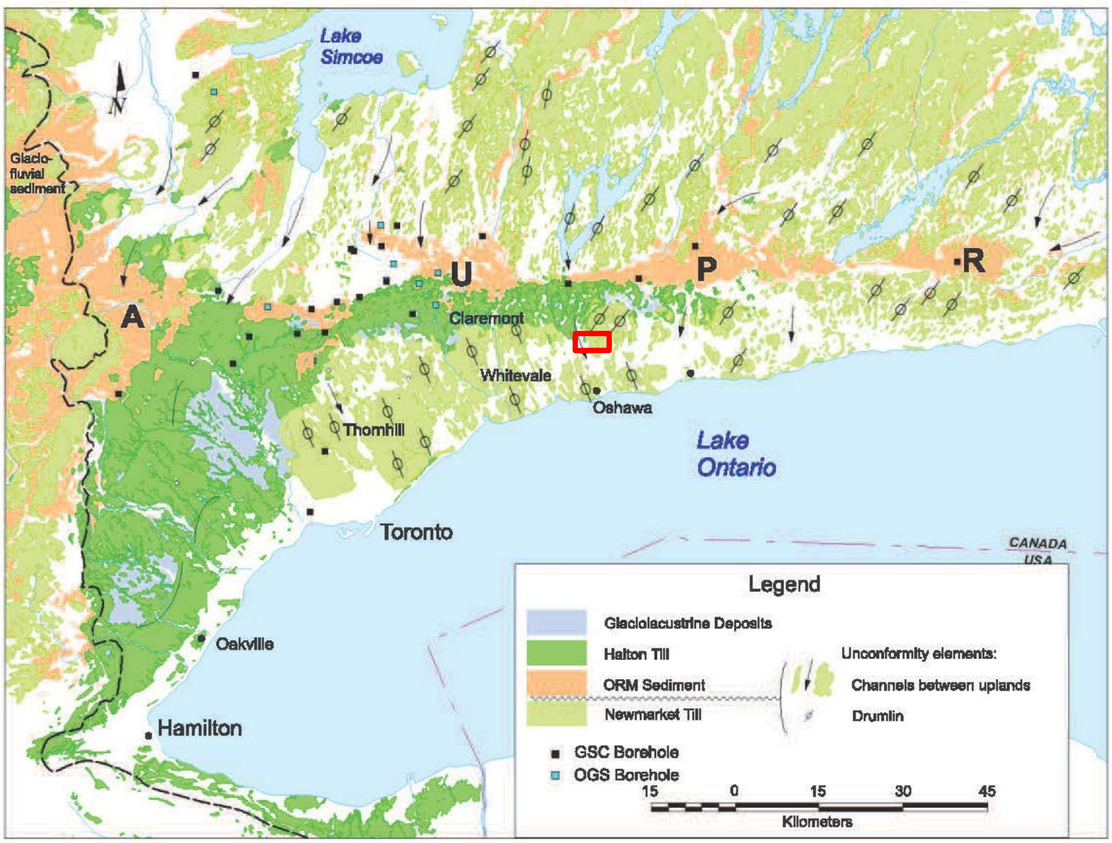


Fig. 2.2: Map showing general location of the Oak RidgesMoraine as well as the distribution of the associated Halton Till, relative to the study site (red box). Locations of Albion Hills wedge (A), Uxbridge wedge (U), Pontypool wedge(P), and Rice Lake wedge (R) of the ORM (Barnett et al. 1998) are also shown. Northwest southeast drumlin orientation is marked south of the moraine. Figure is modified from Sharpe and Russell (2016).

municipal supply while shallower wells are used for private residential supply (Sharpe et al. 2003). The Oak Ridges Moraine (ORM) is located in southern-central Ontario (Fig. 2.2) and its relatively coarse-grained sediments overly the Newmarket Till or the Lower sediment package where the Newmarket Till is nonexistent. The 1400 km^2 west-east trending sandy belt (Russell et al. 2004) forms the upper aquifer in the three aquifer systems defined by Gerber and Howard (2002). The ORM is one of the last deposits in the stratigraphic succession providing significant recharge to lower aquifers (Russell et al. 2004) and contributing to the base flow of over thirty major streams (Howard et al. 1995). The interlobate moraine is up to 20 km wide (Sharpe et al. 2002a), extends over 140 km eastward from the Niagara Escarpment, and is deposited over the Peel, York, and Durham regions (Howard et al. 1995) (Fig. 2.2).

As large population centers within the Greater Toronto Area continue to grow, the use of the ORM area is making a transition from agriculture to residential and commercial development. This land use change may impact the quality of important groundwater recharge to the ORM and underlying aquifer systems (Wexler et al. A &B 2003) that provide water for many communities throughout southern Ontario making it necessary to achieve a better understanding of the highly variable system (Howard and Beck 1986).

2.2 Regional Geological Framework

2.2.1 Lower Sediments

The oldest unconsolidated sediments located on top of the Paleozoic bedrock unconformity are usually lumped into one unit called “lower sediments”. The Scarborough Formation, Sunnybrook Till, and Thorncliffe Formation all make up the lower sediments (Sharpe et al. 1999) and are composed of sand, silt, clay, and till (Sharpe et al. 1999). The Scarborough and Thorncliffe formations and the Sunnybrook Till can be identified at the Scarborough bluffs, SW of the study site, and are thought to extend north, past the ORM (Sharpe et al. 1996).

Originally, it was believed that the lowermost unit, the Scarborough Formation, was of Sangamonian age (Fulton et al. 1986). The Sangamonian is considered to consist of predominantly non-glacial sediments, right before the Wisconsinan Glaciation began. Later studies including the Sharpe et al. 2002b (Fig. 2.1) conceptual model, indicated that Scarborough Formation and above units were deposited during the Wisconsinan Glaciation and that most of the “lower sediments” were deposited in proglacial lake environments (Sharpe et al. 1999). The Scarborough Formation sand units are usually preserved in bedrock valleys (Wexler et al. B 2003) and consist of sand and silt-sand rhythmites (Sharpe et al. 1999).

The Sunnybrook Till was deposited over the Scarborough Formation during the Early Wisconsinan (Fig. 2.1) (Sharpe et al. 2002b). It is a fine grained silty-clay diamicton aquitard that varies in thickness (6-10 m) (Barnett 1992). The unit is described as a diamicton with a clayey silt matrix, with a highly variable sand and clast content (Eyles and Elyes 1983). Eyles and Eyles (1983) and Eyles et al. (2005) have stressed a glaciolacustrine origin for the Sunnybrook diamicton with evidence of iceberg grounding. In contrast, Hicock and Dreimanis (1989) have interpreted the variable facies of the Sunnybrook as recording deposition of both deformation and subglacial till. In their model, the sediment was mostly likely deposited by ice moving west-northwest as the ice lobe moved out of the Ontario basin deforming pre-existing proglacial lacustrine sediment, whereas clast fabrics and deformation within the till points to a change to west-southwest ice flow during the deposit of a subglacial till (Hicock and Dreimanis 1989). Brennand (1998) agrees that the Sunnybrook Till may represent an ice advance, but also suggests it may be an ice-marginal deposit in a glacial lake during the beginning of an ice retreat.

Above the Sunnybrook Till is the Thorncliffe Formation. The Thorncliffe Formation is a complex predominately sandy glaciolacustrine sequence that closer to Lake Ontario can also be described as alternating aquifers and aquitards. Aquifers consist of coarsening upward sandy sequences and the aquitards are very compact, clast poor, and clay-silt diamictons (Brennand 1998). This formation marks the start of the middle Wisconsinan (Fig. 2.1) (Sharpe et al 2002b). In the Toronto Area, the Thorncliffe Formation is the main deposit representing this time period. The sand units within the Thorncliffe Formation represent high lake levels (Fulton et al. 1986). An Ice sheet was believed to be blocking a drainage outlet in the eastern end of the Lake Erie basin, which allowed for the formation of lakes greater in size than the current extent of the Great Lakes (Barnett 1992), and the deposition of these glaciolacustrine sequences associated with the Thorncliffe formation. The predominantly sandy Thorncliffe Formation can be interbedded with diamicton units known as Seminary Till and Meadowcliffe Till closer to Lake Ontario (Fulton et al. 1986), which suggests that ice repeatedly, advanced and retreated locally into the Ontario Basin (Fulton et al. 1986).

2.2.2 Newmarket Till

During the Late Wisconsinan stage, multiple retreat and re-advances of the Laurentide Ice Sheet contributed to the deposition of an extensive and thick sandy till, the Newmarket Till, in the GTA area (Barnett 1992). The major ice lobes surrounding the ORM area at the time were the Simcoe Lobe and the Ontario Lobe (Howard et al 1995). This set up an environment where the lobes were able to advance and retreat rapidly. The Newmarket Till is of late Wisconsinan age (Sharpe et al. 2002b) and was deposited subglacially by a regionally extensive ice sheet (Sharpe et al. 2002b) with the ice lobes in this area retreating and advancing in independent cycles (Fulton et al. 1986). The till is estimated to range between 5-30 m in thickness but can be as thick as 50 m (Sharpe et al. 1996) (Sharpe et al. 2002a). The highly variable thickness of the Newmarket Till makes the till nonexistent in some locations (Desbarats et al. 2001). Sharpe et al. 2002b suggests that the Newmarket Till was formed by till accumulation that may have been periodically interrupted by erosion and localized deposition as evidenced by thin discontinuous sand and silt stringers. The Newmarket Till is an extensive sheet that was subjected to high energy meltwater erosion and scouring after deposition. On the upper surface of the till, this resulted in drumlins and tunnel channels that form another regional unconformity in the unconsolidated sediments (Fig. 2.1), the first located on top of the bedrock. This unconformity cuts all the way to bedrock in some places forming a highly irregular surface (Sharpe et al. 2002b). The meltwater and scouring produced tunnel channels approximately 10 km long and 5 km wide (Russell et al. 2004). Sharpe et al. 2002b estimates the tunnel channels to be up to 40 km long with depths greater than 100m.

The Newmarket Till has an abrupt or gradational contact with the underlying lower sediments. Sediments below the Newmark Till, such as the Thorncliffe Formation, show signs of deformation by glaciotectonic compression in the southward direction, resulting in the incorporation of angular rafts of sandy lacustrine sediment during the deposition of the Newmarket Till. Deformation in sediments below the till, clast fabric analyses, and incorporated rafts associated with the Newmarket Till all provide evidence of southward-flowing ice (Boyce et al. 1995)

The till is composed of 10-15 percent pebbles and cobbles with a dense massive silty sand matrix (Sharpe et al 2002a). The Newmarket Till can be divided into two subunits, an upper and lower section (Boyce et al. 1995). The lower till is a heterogeneous mixture of silty sand and sandy diamicton and lenses and rafts of lacustrine silt and sand are common features. The till is a mixture of boulders and pebbles with glaciotectonically disturbed sediment that gradually becomes more homogenous as you move upward. The upper till has granitic and carbonate boulders and contains a small amount of sand stringers of <5cm - 0.5 m in thickness (Boyce et al. 1995). Brennand (1998) also mentioned a possible upper and lower section of the Newmarket Till, and suggested it may be separated by a lenticular sand and silt unit. Brennand (1998) and Boyce et al (1995) both agree that the lower unit is a silty sand to sandy silt diamicton, and the upper till is a massive silty sand to sandy silt diamicton with boulder deposition.

The sand and gravel stringers mentioned above separate tabular till beds into sections that average up to 6 meters thick (Boyce et al. 1995). These bed separations have been observed in outcrop in the upper Newmarket Till (Boyce et al. 1995), and can be laterally continuous or discontinuous (Boyce and Eyles 2000). Other typical architecture found within the till are silt, sand, and gravel units that are typically less than 5 meters thick, vertical sand dikes, and fractures (Gerber et al. 2001). Sheet-like sand and gravel bodies are estimated to be approximately <1 m thick and can be continuous over distances greater than 100 m (Boyce and Eyles 2000). Laterally discontinuous sand and gravel bodies are also typical architecture within the till, and are typically <10 m in length (Boyce and Eyles 2000).

The Newmarket Till can be easily identified by it high velocities associated with downhole and surface seismic logging (Pugin et al. 1999). The high velocity is uncommon for unconsolidated material, which gives evidence of overcompaction (Pugin et al. 1999). The Newmarket Till is an important marker bed (Gerrie et al. 2003) that can be used to correlate between boreholes (Pullan et al. 2002). The seismic velocities range anywhere from 2,200-3,000 m/s, easily differentiated from surrounding stratigraphic units (Pullan et al. 2002). Pugin et al. (1999) and Boyce et al. (1995) both indicate different seismic properties throughout the Newmarket Till, providing evidence that the till is not uniform.

2.2.3 Channel Fill Sediments

There are two main types of channels eroded into the Newmarket Till. Some are steep-sided and deep, whereas others are shallow and broad channels (Pugin et al. 1999). The eroded channels in the Newmarket Till that form the regional unconformity contain thick channel sediments that appear to be related to the ORM (Sharpe et al. 1999). Evidence from seismic reflection and drill core data suggest the tunnel channels continue under the ORM. The formation of drumlins, which can be seen north of the

ORM (Barnett et al. 1998), played a role in the channelization of meltwater erosion (Russell et al. 2003). These channels follow a northeast-southwest trend and can be seen north of the ORM (Sharpe et al. 1996). The channel sediments were deposited during waning flow of regional meltwater floods (Sharpe et al. 1999) meaning they were first deposited under high energy flow events, and then make a transition into the waning flow events indicated by Sharpe et al. (1999).

The erosion and filling of channels can be considered part of the first stage in the deposition of the ORM (Russell et al. 2004). Barnett et al. (1998) also considered subglacial sedimentation in the channels, the first stage in the ORM formation. The erosional processes that produced the channels created a sediment delivery system directly to the ORM (Barnett et al. 1998). The flow in the channels decreased leading to sedimentation (Barnett et al. 1998), which began the transition into the channel filling and ORM development.

2.2.4 The Oak Ridges Moraine

The Oak Ridges Moraine (ORM) is an outwash and fan-delta deposit in a glaciolacustrine setting, specifically in an interlobate lake (Barnett et al. 1998). The Interlobate lake was dammed between the Ontario and Simcoe Lobe creating the most extensive deposit of the late Wisconsinan period (Howard et al 1995). In the

Wisconsinan period, during the Mackinaw interstade, an ice retreat was accompanied by climate warming creating the converging flow of meltwater between both the Ontario and Simcoe Lobe (Russell et al. 2004). Each stage during the development of the ORM marks a change in meltwater discharge, ice cover, and location of subglacial/proglacial basins (Barnett et al. 1998). Stage I was a result of waning flow through tunnel channels as discussed above (Russell et al. 2004 and Barnett et al. 1998). In stage II of the ORM formation, the subglacial cavity began to expand and subaqueous fan sedimentation and low energy environments followed. Eskers from tunnel fills lead into fan sediments that extend southwesterly. Stage III of the ORM formation is the transition of subaqueous fan deposits to delta deposits. This delta deposit occurred in a large ice controlled lake and the distribution of sediments was controlled by the topography of the basin and the locations of sediment sources (Barnett et al. 1998).

The Oak Ridges Moraine is composed of 4 wedge-like bodies that widen to the west (Fig. 2.2). Textural trends within the sediments indicate paleoflow came from the northeast (Sharpe et al. 1996). The four sections of the ORM from west to east are Albion Hills, Uxbridge, Pontypool, and Rice Lake wedge (Fig. 2.2). Each of these wedges are connected by east-west trending ridges (Wexler et al. B 2003) and each wedge has evidence of one of the 4 stages in the ORM development (Barnett et al. 1998). Albion Hills shows sequences of fan to delta sedimentation, corresponding to stage III of the ORM formation. Uxbridge show evidence of stage II under subaqueous deposition and is composed of sand and gravel bodies that have a southwest trending pattern, and thick clast supported units composed of pebbles, boulders, and gravel. The Pontypool wedge, near Clarington Ontario, also show evidence of stage II development and contains evidence for westward paleoflow as well as coarse clast supported units with gravelly sediments arranged in a tabular sheet. Evidence of stage I development in the Rice Lake wedge includes coarsening upward sequences, large ripples, and high energy scours. All wedges exhibit areas of hummocky topography, plains, and ridges at surface (Barnett et al. 1998) and ORM sediments in general have a finning and expanding westward trend (Sharpe et al. 2016).

The ORM aquifer is mostly unconfined except along the southern edge where Halton Till onlaps the ORM sediments (Russell et al. 2005). If contaminants are released into the unconfined aquifer system, and if downward gradients are present, there is potential for contaminants to migrate through tunnel channels that cut into the Newmarket, and into the lower regional aquifers (Sharpe et al. 2002b).

2.2.5 Halton Till

The last stage of deposition was believed to be during the last major ice re-advance in southern Ontario (Fulton et al. 1986; Howard and Beck 1986), resulting in the deposition of the Halton Till, marking the end of the ORM development (Sharpe et al. 1999). The Halton Till is mainly made up of clayey silt to silt diamicton with the presence of interbedded sand, silt, and clay (Sharpe and Russell 2016). The till covers approximately 150-200 km^2 and overlaps the ORM on the southern flank, forming the highest stratigraphic unit (Sharpe et al. 1996) (Fig. 2.1) and is discontinuous south of the ORM and east of Toronto (Sharpe and Russell 2016) (Fig. 2.2).

Barnett et al. (1998) suggested that evidence for northwest ice advance lies in the orientation of shear planes within the diamicton, along with unidirectional overturned strata beneath the diamicton within the ORM region. In contrast to an ice re-advance model, Sharpe and Russell (2016) recently suggested the till was deposited during the waning flow of meltwater after the formation of the ORM, meaning it was not deposited subglacially. In this reinterpretation, Sharpe and Russell (2016) argue that if the Halton Till was deposited solely from a re-advance of ice, the sediments associated with the ORM would have been truncated leaving an abrupt contact between the units; however, this is not observed in areas where Halton Till overlies the ORM. Halton Till follows the characteristic features of the ORM, such as ridges and kettles and a gradational contact where Halton Till overlies the ORM is common, whereas an abrupt contact is common where the Halton Till is underlain by the Newmarket Till (Sharpe and Russell 2016), providing evidence that a late ice re-advance was unlikely.

Russell et al. 1998 suggested that the glaciolacustrine character of the Halton drift and evidence of small ice fluctuations and high ponded water levels suggests the drift may have been deposited from a transition from ORM development, observed near the Uxbridge wedge (Fig. 2.2). Observations of gradational contacts were not observed by Howard and Beck (1986), and in contrast to Russell et al. (1998) and Sharpe and Russel (2016), there is evidenced at the Scarbourgh Bluffs, that this till truncates underlying sediment providing evidence of an ice advance. Howard and Beck (1986) also note that evidence of a change in orientation of drumlin ridges from north-south to north-west-southeast near Pickering and Whitevale, Ontario (Fig. 2.2) is evidence of erosion during the ice-readvance associated with the deposit of the Halton till.

In this most recent depositional model of Sharpe and Russell (2016), fine grained sediments suspended in the pooled lakes began to settle after the formation of the ORM, leaving behind a slow transition into Halton Till. Paleoflow within the stratified sediments associated with Halton Till matches that of the ORM sediments, by a general trend of finning and expanding westward (Sharpe and Russell 2016). The Halton sediments also show finning upward facies from sand to mud, providing evidence of waning flow (Sharpe and Russell 2016). Areas where no Halton Till is present, indicates an area where the ice sheet that once constrained and the southern boundary of the ORM sediments was securely grounded.

In this model, the sand in the near surface is attributed to post ORM depositional conditions rather than with the ORM and the Mackinaw interstadial. Sandy interbeds and interbedded diamictons are common in glaciolacustrine basins. They can be created by seasonal changes, floods, and changing ice-marginal events and should not be automatically assumed to be climate-forced Mackinaw interstadial deposits (Sharpe and Russell 2016).

Sparse subsurface data and isolated outcrops have led to some confusion in the mapping of the Newmarket Till and Halton Till. Sharpe and Russell (2016) argue that the Halton Till has been incorrectly mapped in many locations, creating confusion of typical sediment grain size distribution and the lateral extent of the formation. However, according to their study the Newmarket Till will have a much higher sand and stone content when directly compared to sediments associated with Halton deposition. As such, where the Halton Till overlies the Newmarket Till, grain size analysis, stone content and gamma and conductivity readings provide a distinct way to differentiate each deposit (Sharpe and Russell 2016).

2.3 Hydrogeology/Sediments

The unconsolidated sediments can be simplified into three aquifer systems: lower, middle, and upper. The aquifer systems correspond to the Scarborough Formation, Thorncliffe Formation, and Mackinaw Interstadial/Oak Ridges Complex respectively (Sibul et al. 1977 in Gerber and Howard 2002). The groundwater within the three aquifer systems mainly flows towards the south with horizontal groundwater gradients ranging from .001 to .01 (Gerber and Howard 2002). The middle and lower aquifers are separated from the upper aquifer by the Newmarket Till, a regionally extensive aquitard.

One of the first extensive hydrochemical investigations to evaluate aquifer interaction was carried out by Howard and Beck (1986). The evidence presented, provided insight into hydraulic connections between the surface and the middle and lower aquifer systems, bringing the Newmarket aquitard integrity into question. Before this study, it was also believed the Halton Till covered most of the ORM, but high recharge areas suggested otherwise (Howard and Beck 1986).

The integrity of the Newmarket Till as a regional aquitard is in part controlled by the variable thickness from the unconformity on the upper surface of the unit (Debarats et al. 2001). In some areas the unconformity, made up of tunnel channels and drumlins, may extend to lower sediments or to bedrock (Russell et al. 2004). Eroded areas of the Newmarket aquitard are considered breached channels and have a big impact on regional groundwater flow. The channel fills are typically sand and gravel aquifers, potentially creating windows into the confined aquifers below for potential contamination should local hydrogeological conditions permit downward groundwater flux.

Even in areas where the Newmarket aquitard is not eroded, hydraulic conductivities vary over several orders of magnitude, and may have the ability to allow water to leak into the middle and lower aquifers (Gerber et al. 2001). Vertical and horizontal hydraulic conductivity within the matrix of the Newmarket Till ranges from 10^{-11}-10^{-10} m/s (Gerber et al. 2001 and Sharpe et al. 2002a). Flow through the aquitard is thought to primarily occur through interconnected heterogeneities such as silt and sand laminae and thin silt, sand, and gravel lenses (Gerber et al. 2001) as well as sandy interbeds, sheets, bodies, or fractures that allow groundwater leakage through the aquitard (Sharpe et al. 2002a). Typical horizontal hydraulic conductivity is up to 10^{-5} m/s in the sand zones (Sharpe 2002a). Gerber and Howard (2002) estimated 35-40 mm/year for leakage through the aquitard and with bulk K values ranging from $5x10^{-10}$-$5x10^{-9}$ m/s, two orders in magnitude faster than the tills matrix K mentioned above. Indeed, it is typical to see a range in hydraulic conductivity over 4-7 orders of magnitude within the Newmarket Till when carrying out slug tests in the field (Gerber and Howard 1996; Gerber et al. 2001). This wide range of values is in part related to the approach used in measuring conductivity. However, the wide range also speaks to the internal heterogeneities that have been documented in the sediment characteristics (Gerber et al. 2001 and Sharpe et al. 2002a).

Gerber (1999) used FRACTRAN to estimate fracture spacing and aperture size within the till based on ^{18}O, Deuterium, and hydraulic head profiles resulting in an average 3-4 m spacing and apertures ranging from 25-30 µm. The analysis of sediment heterogeneity and architecture by Gerber et al. (2001) used two angled boreholes 70 mbgs (meters below ground surface), and test pits and determined fracture spacing within the till was, at a minimum, 0.02 m apart within the first 2 m of the till. Observed vertical and horizontal joints reaching 2 mbgs began to dissipate. However, 1-2 hours after excavation of the tests pits were complete, fractures began to widen rapidly. The maximum fracture spacing appeared to be 50 m but limited outcrop data made it difficult to get an accurate representation of the Newmarket aquitard fracture network for deeper depths. The inability to distinguish between machine breaks and fractures in the core, also made determining a fracture network from core difficult. The upper portions of the aquitard showed that fracture spacing is more variable and more closely spaced in field test pits. Sand and silt laminae of less than 5 cm and sand zones of less than 5 meters were noted to be the most common heterogeneities within the aquitard. Sand dikes, inclusions, and more extensive and laterally connected interbeds are also a part of the tills heterogeneities (Fig. 2.3). Also, a steeply dipping sand dyke, 80 mm wide has also been noted in a test pit 8-9 m below the top of the till (Gerber 1999), providing additional evidence that vertical and horizontal heterogeneities can play a major role in groundwater movement through an aquitard. Irregular joints and fractures and steeply dipping vertical sand intersect horizontal features creating preferential pathways for groundwater migration through the Newmarket Till (Gerber 1999). The site-specific combinations of these features contribute to the local architecture of the Newmarket aquitard and to the vertical groundwater flux (Gerber et al. 2001) (Fig. 2.3) creating a need to assess the aquitard's integrity at each site specifically. The highly variable nature of the Newmarket aquitard makes it essential that reports completed in areas where the integrity is high, should not be used to determine the integrity of other sites and vice-versa. Due to the variable thickness and variable vertical hydraulic conductivity present in the Newmarket aquitard, it is essential to evaluate aquifer susceptibility by evaluating the integrity of this aquitard (Desbarats et al. 2001).

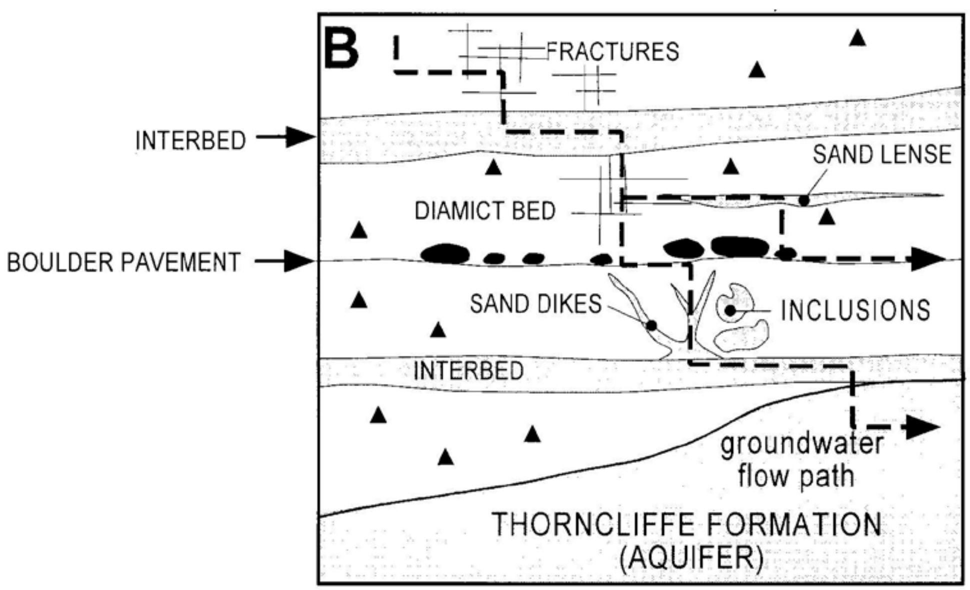


Fig. 2.3: Newmarket aquitard heterogeneities contributing to vertical groundwater movement(Gerber et al. 2001). Dashed line indicates potential groundwater flow paths through vertical fractured diamict beds and vertical and horizontal heterogeneities. Diamict beds are marked with black triangles.

3 Geology and Glacial History of Site

The hydrogeology of the site at Clarington will be determined in part by the distribution of aquitard and aquifer materials, the distribution of sediment heterogeneity within the thick Newmarket aquitard, and the connectivity of aquifer materials. It is therefore critical to better understand the subsurface geology at the site and to refine the site's geological framework. This chapter focuses on the geology and glacial history of the site, reviewing geological conceptual models that have been proposed to date and revisiting these models in light of new data.

3.1 Site Background

The study is located in the Greater Toronto Area and sits within and at the edge of an area of protection associated with the Oak Ridges Moraine Conservation Act of 2001 (Fig. 1.1). The study area encompasses a Hydro One construction site near Clarington Ontario at the corner of Concession Road 7 and Langmaid Road and the surrounding lands (Fig. 3.1). It is currently undergoing construction of a transformer station to accommodate the closure of the Pickering Nuclear Plant before 2024. This construction is creating a significant land use change from an area with predominantly agricultural land use to an area with predominantly industrial purpose.

The site topography slopes downward to the southwest corner of the transformer location. Topographic highs are located at the northeast corner, the eastern, and on the western side of the Hydro one property line (Fig. 3.1).

The site currently has a total of twenty-nine (29) geotechnical boreholes, drilled by Exp (2012) and Inspec Sole (2013), and twelve (12) monitoring wells that are all 25 meters below ground surface (mbgs) or less; there is one (1) additional monitoring well at a depth of 40 mbgs (MW5-14I) that was installed by Stantec as part of the groundwater monitoring program for the proposed transformer site. Additionally, the site has three high-resolution boreholes that are located on the southwest corner of the site (Fig. 3.1; MW5-14S(2), MW5-14D, and MW5-14D(2)) that form a well cluster with previously drilled wells MW5-14I and MW5-14S. The depths, location, drilling and core type, and drilling or installation date of the high-resolution boreholes and monitoring wells are summarized in Table 3.1 and Fig. 3.2.

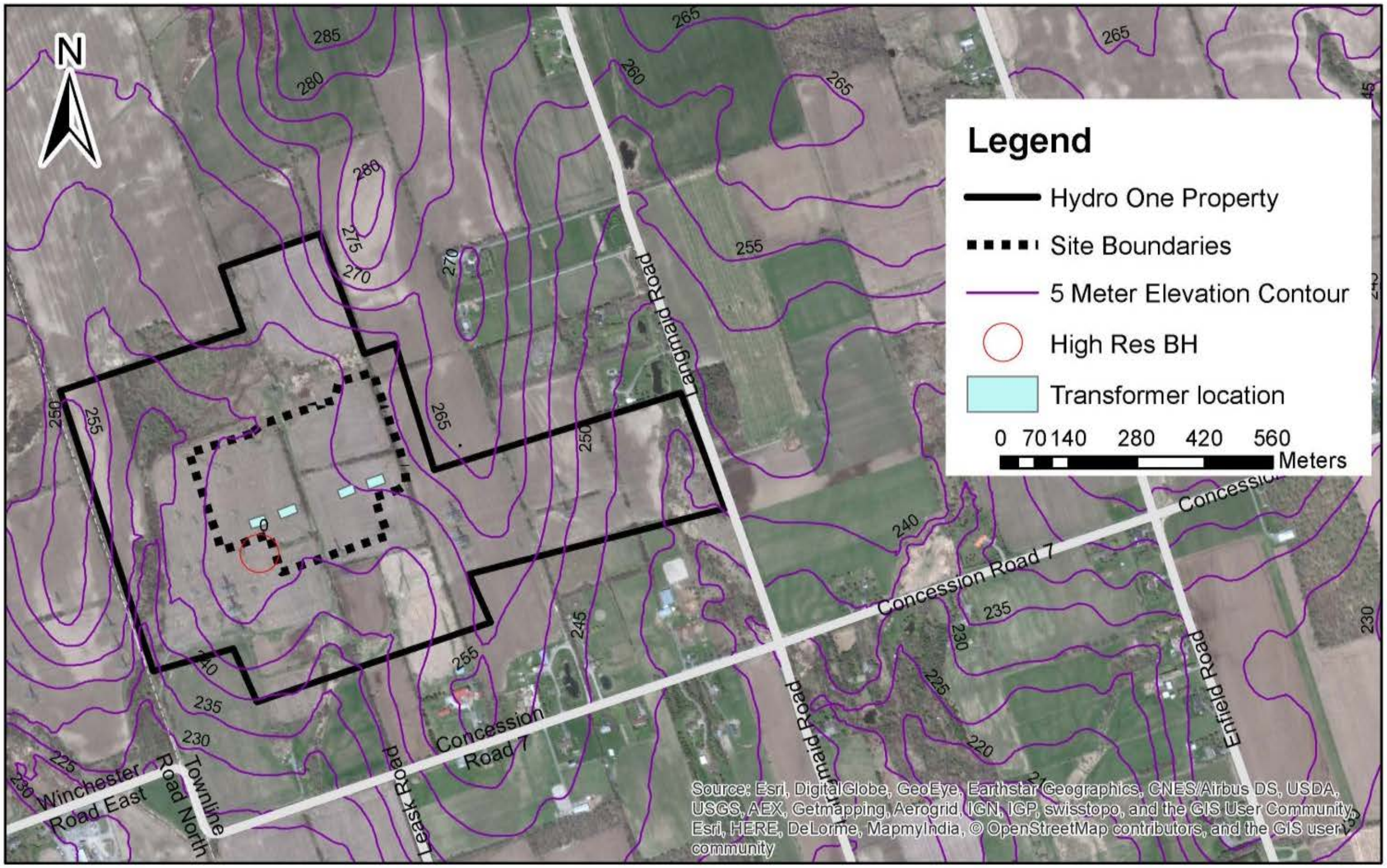


Fig. 3.1: *Location and topography of the Hydro One Transformer Station and high-resolution borehole/well cluster location, produced with ArcGIS (Stantec 2014). Transformer Location* from Hydro One "*CLARINGTON TRANSFORMER STATION MAPS & DIAGRAMS" on the project website.*

High Resolution Wells	Date Installed	Depth (mbgs)	Drilling Type	Core Type
MW5-14D	Dec 2014	54.99	Track Mount CME 75 108 mm ID Hollow Stem Auger	PQ
MW5-14D(2)	Dec 2014	129.54	Track Mount CME 75 101.6 mm ID Hollow Stem Auger	PQ
MW5-14S(2)	Dec 2014	4.14	Track Mount CME 75 108 mm ID Hollow Stem Auger	PQ
Stantec Wells	**Date Installed**	**Depth (mbgs)**	**Drilling Type**	**Core Type**
BH9-15	Mar 2015	10.11	Track Mount ME 75 158.8mm ID Hollow Stem Auger	PQ
MW8-15 (BH8-15)	Jan 2015	16.9	Track Mount CME 75 108mm ID Hollow Stem Auger	PQ
MW4-15D	Jan 2015	25.1	Track Mount CME 75 108mm ID Hollow Stem Auger	PQ
MW7-14	Oct 2014	7.6	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW6-14	Oct 2014	7.6	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW5-14S	Oct 2014	6.1	Track Mount CME 75 108mm ID Hollow Stem Auger	PQ
MW5-14I	Oct 2014	40.1	Track Mount CME 75 108mm ID Hollow Stem Auger	PQ
MW4-13S	Dec 2013	4.57	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW4-13D	Dec 2013	15.24	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW3-13S	Dec 2013	6.71	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW3-13D	Dec 2013	15.24	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW2-13S	Dec 2013	4.57	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW2-13D	Dec 2013	15.24	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW1-13S	Dec 2013	6.1	Track Mount CME 75 108mm ID Hollow Stem Auger	SS
MW1-13D	Dec 2013	15.24	Track Mount CME 75 108mm ID Hollow Stem Auger	SS

Table 3.1: *Summary of new high-resolution boreholes and Stantec monitoring wells/boreholes located on site. PQ= continuous core SS= Split spoon sample. Data from Stantec 2015b report.*

3.2 Existing Site Conceptual Models (SCM)

3.2.1 Geology SCM

In a 2014 Pre-Station construction report, Stantec (2014) included a regional scale cross section and two local cross-sections (B-B’ and C-C’; Fig. 3.3) with geological interpretations (Figs. 3.4 and 3.5). The local scale cross sections B-B’ and C-C’ from the Stantec (2014) report were relevant to the current study and included the use of eight (8) geotechnical boreholes, two (2) private wells, eight (8) monitoring wells, and twelve

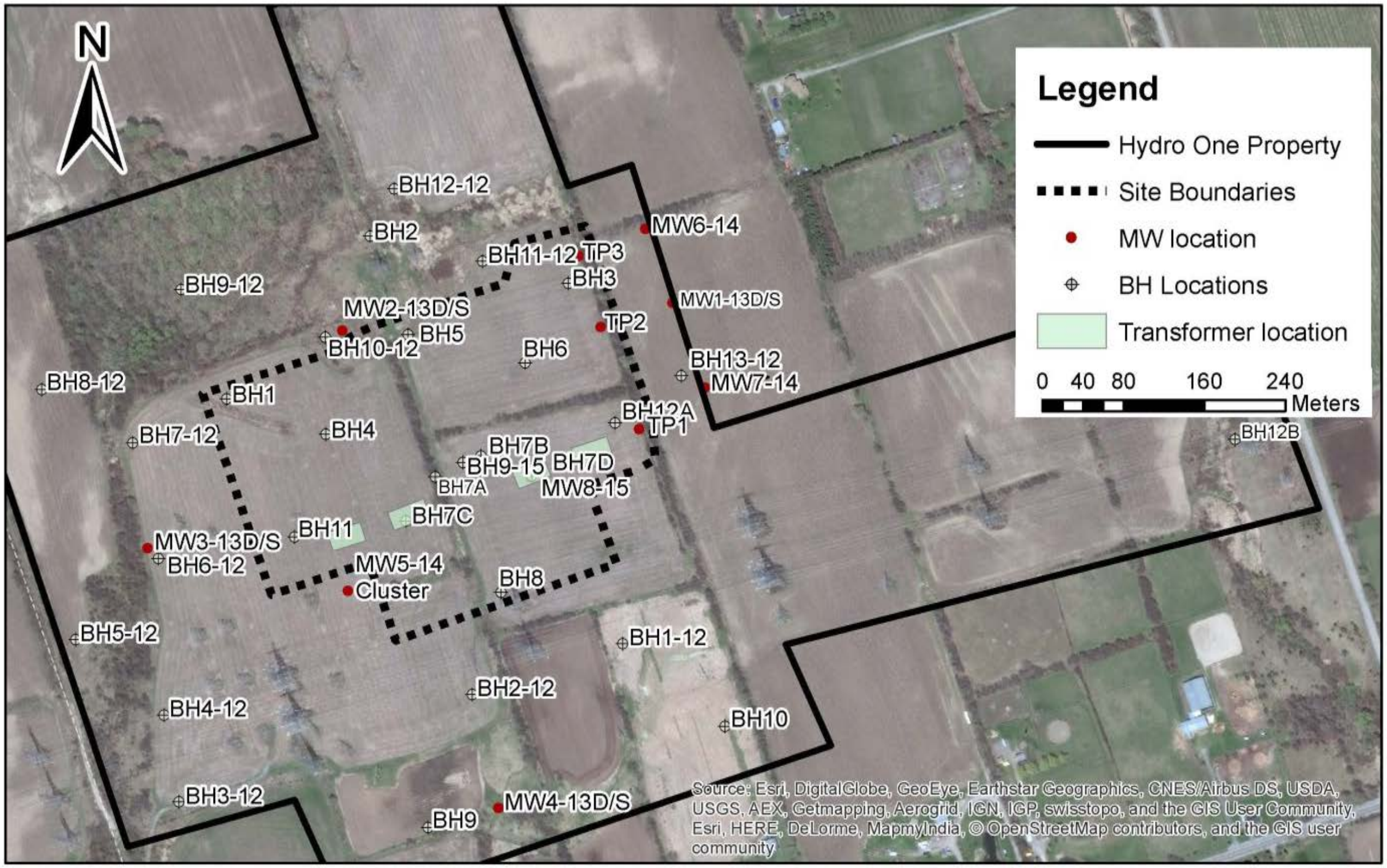


Fig. 3.2: *Location of Monitoring Wells (MW) and Boreholes (BH) on the Hydro One Transformer Station site and high-resolution borehole/well cluster location, produced with ArcGIS (Stantec 2015b).Transformer Location* from Hydro One "*CLARINGTON TRANSFORMER STATION MAPS & DIAGRAMS" on the project website.*

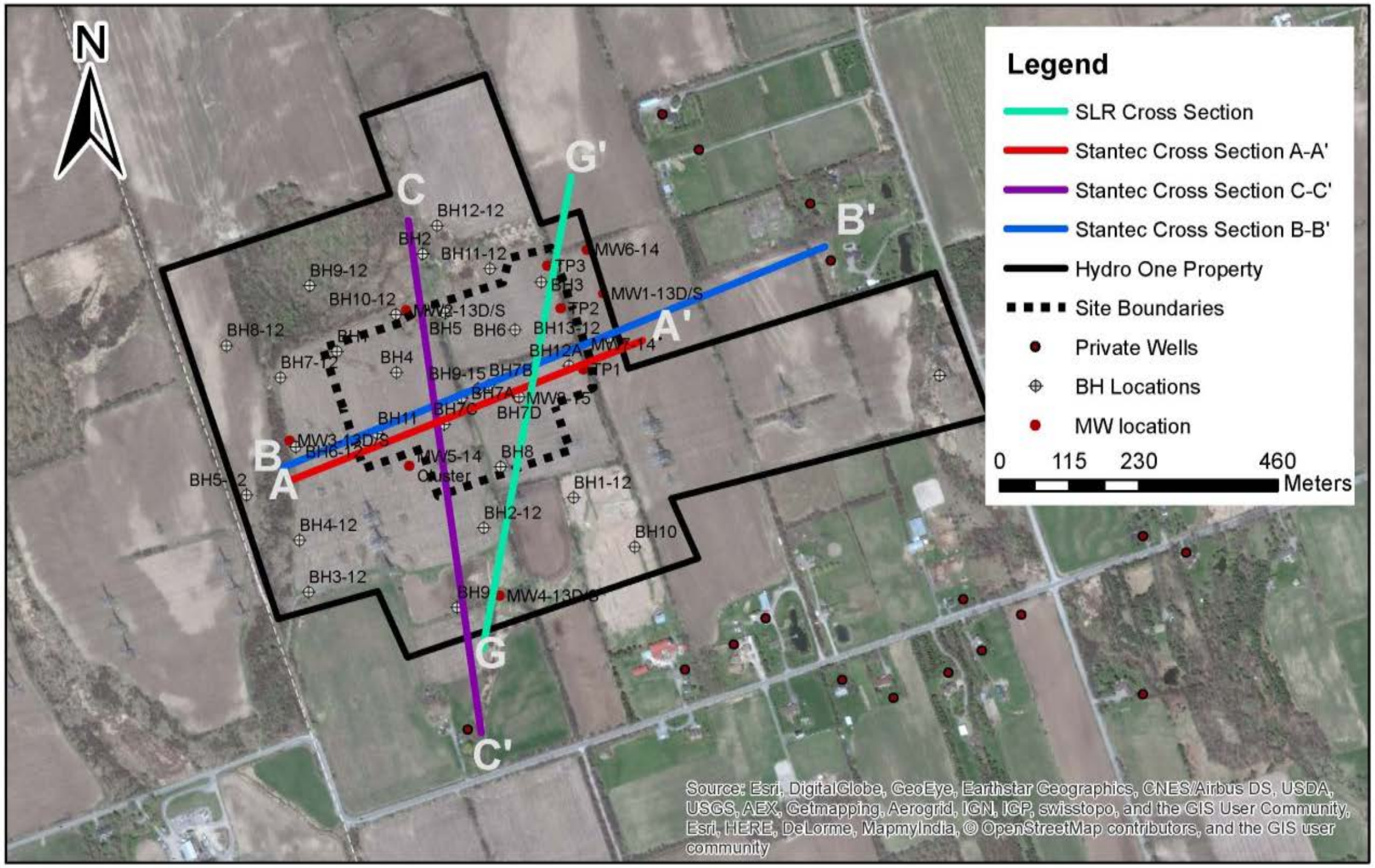


Fig. 3.3: *Hydro One Transformer Station with Stantec and SLR Cross Section locations, produced with ArcGIS. (Stantec 2015b and SLR 2015)*

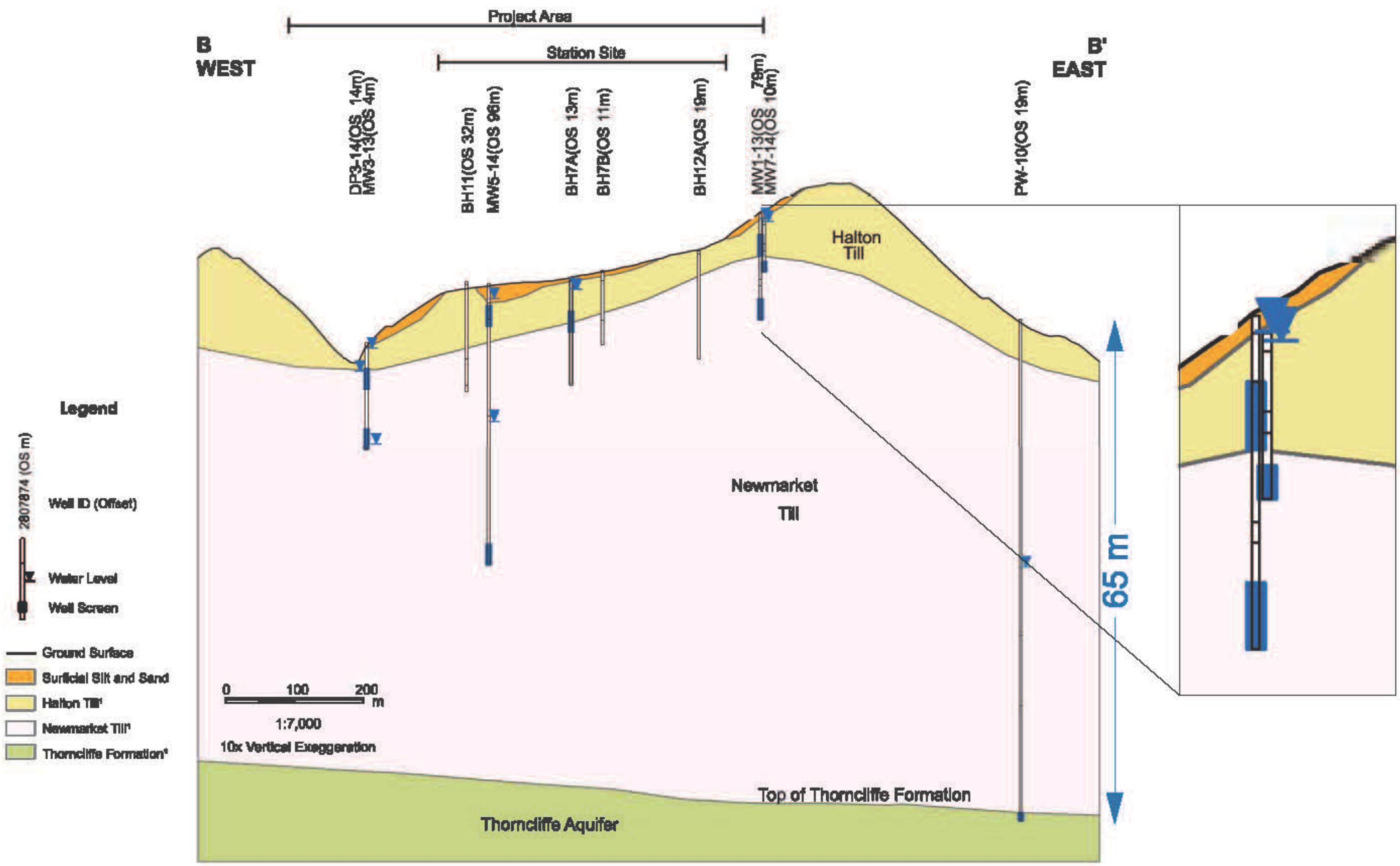


Fig. 3.4: *Stantec (2014) Cross Section B-B' and geological interpretation, edited from Stantec (2014) . Location of geological cross section can be viewed in Figure 3.3.*

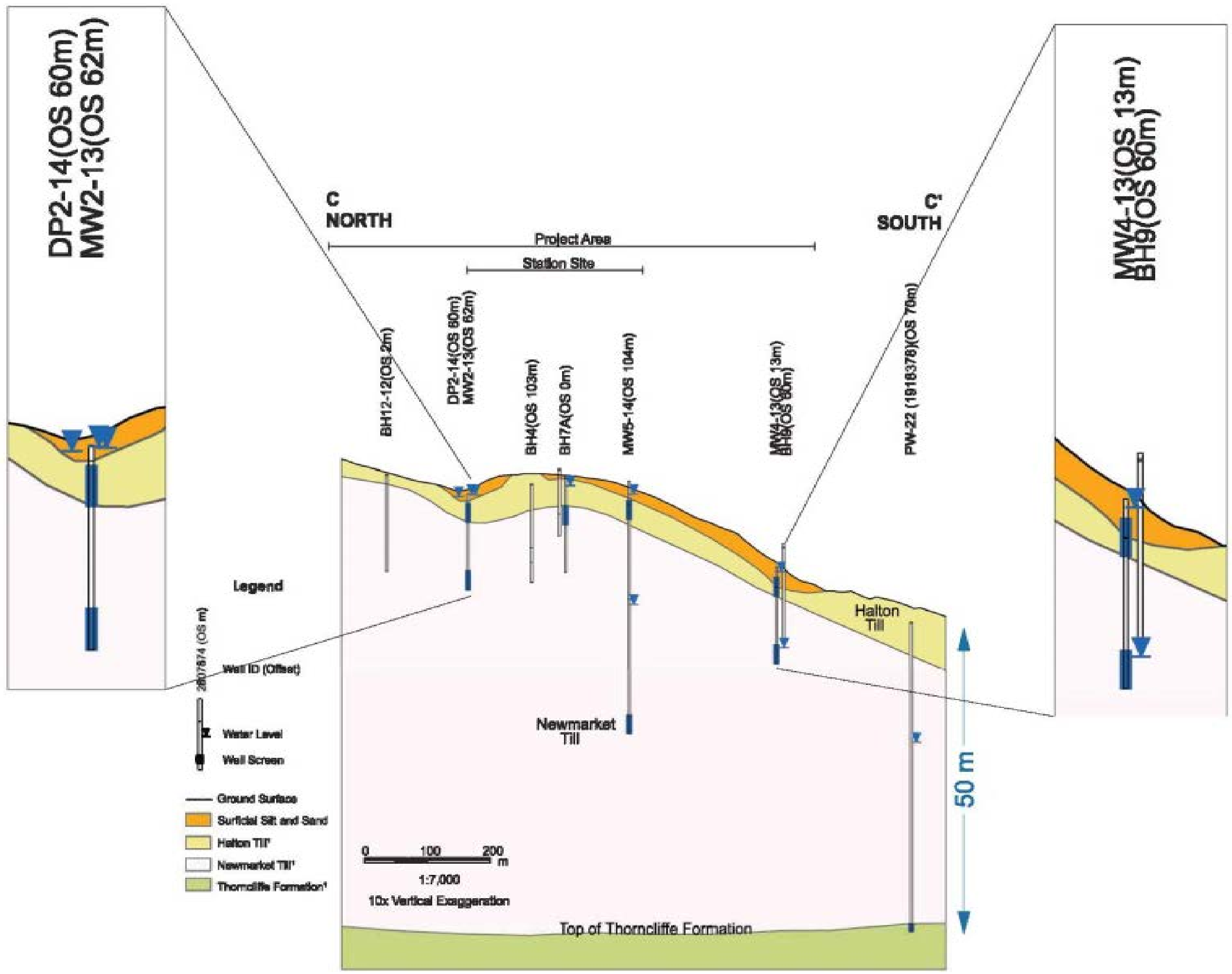


Fig. 3.5: *Stantec (2014) Cross Section C-C' and geological interpretation, edited from Stantec (2014). Location of geological cross section can be viewed in Figure 3.3.*

(12) grain size samples collected at various depths from six different boreholes or test pits (Table 3.2).The nature of the sediments were determined during installation of the monitoring wells where split spoon samples or continuous core was collected (Table 3.1).

The interpretations made from these cross sections suggests that the Stantec (2014) conceptual model has a continuous Halton Till at surface overlying the Newmarket Till directly under the site location. The interpretation mentions the textural compositions of the two tills were very similar in grain size and the top of the Newmarket Till appears to be determined by color change, sediment description, and density alone. The report states the characteristic over-consolidated nature of the till made it simple to determine where the Newmarket Till began. Stantec also states that the upper portions of the Newmarket Till in these two cross sections may be weathered Newmarket, which potentially makes determining the boundary between the two tills more difficult. Based on these cross-sections, Stantec (2014) concluded that no potential Oak Ridges Moraine or Mackinaw sediments were present below the site as the wells used in the cross sections presented (Figs. 3.4 and 3.5) did not contain any sand

Stantec Report 2014						
Well ID	**Depth (mbgs)**	**Grain Size Depths (m)**	**Gravel %**	**Sand %**	**Silt %**	**Clay %**
MW5-14I/S	40.1	4.7	1.5	51	25	10
		12.9	26	31	25	18
		24.1	7	37	34	21
		27.4	10	43	29	18
		38.1	12	38	34	16
MW6-14	7.6	6.2	18	38	30	14
		7.0	8	41	34	16
MW7-14	7.6	6.3	8	42	40	10
		7.1	9	43	34	14
TP-1	4.88	4.9	16	39	32	13
TP-2	4.88	4.6	43	25	23	9
TP-3	4.88	3.7	37	29	25	9
MW1-13D/S	15.24					
MW2-13D/S	15.24					
MW3-13	15.24					
MW4-13	15.24					
BH4	15.71					
BH7A	15.3					
BH7B	10.65					
BH9	15.89					
BH11	15.71					
BH12A	15.4					
BH12-12	15.02					
PW-10	65.8					
PW-22	*MOE Well record States 161 meters; most likely in feet					
Stantec Report 2015						
Well ID	**Depth (mbgs)**	**Grain Size Depths (m)**	**Gravel %**	**Sand %**	**Silt %**	**Clay %**
MW5-14D	54.99	3.8	21	46	24	9
		4.6	11	52	24	13
		8.4	16	38	29	17
		13.4	12	39	28	21
		25.0	18	37	28	17
		38.9	9	38	34	19
		49.6	1	60	23	16
		52.6	0	63	22	15
BH9-15	10.11	3.9	15	34	33	18
		7.2	24	35	26	15
		10.5	9	35	33	20
			Gravel %	**Sand %**	**Silt % and Clay %**	
MW8-15	16.92	4.0	6	52	44	
		8.6	15	47	38	
		16.4	12	45	43	
MW5-14D(2)	129.54					
MW5-14S(2)	14.14					
MW4-15D	25.2					

Table 3.2: *Summary of all geotechnical boreholes (BH), monitoring wells (MW), test pits (TP), and private wells (PW) used in the 2014 geological interpretation in the Stantec 2014 report, and the additional wells used for the geological interpretation revision associated with the Stantec 2015b report.*

between the two tills. The report did mention that potential ORM could be present further to the east of the site in discrete finger-like deposits.

Very shallow and near surface grain size samples were also not collected or analyzed in either of the Stantec (2014, 2015b) reports. This makes it difficult to assess their interpretation on the basis of grain size differences that are expected between these two tills. The statement in the report that says the textural composition of both tills were very similar, suggesting that there may not be Halton Till at the site (see chapter 2).

Following the Stantec (2014) study, Stantec added an additional 5 monitoring wells and one (1) additional BH towards the end of 2014 (Table 3.2). Based on the installation of these additional monitoring wells and boreholes, Stantec (2015b) created an additional cross section A-A' and a revised geological model (Fig. 3.6). The revised conceptual model based on this additional cross section, which is very close to the 2014 cross section B-B', now displays Newmarket Till at surface, with a surficial sand layer on top (Stantec 2015b). The upper portion of the succession is now identified as weathered till instead of Halton Till, with the apparent change in the till's density at surface due to depressurization and weathering (Stantec 2015b).

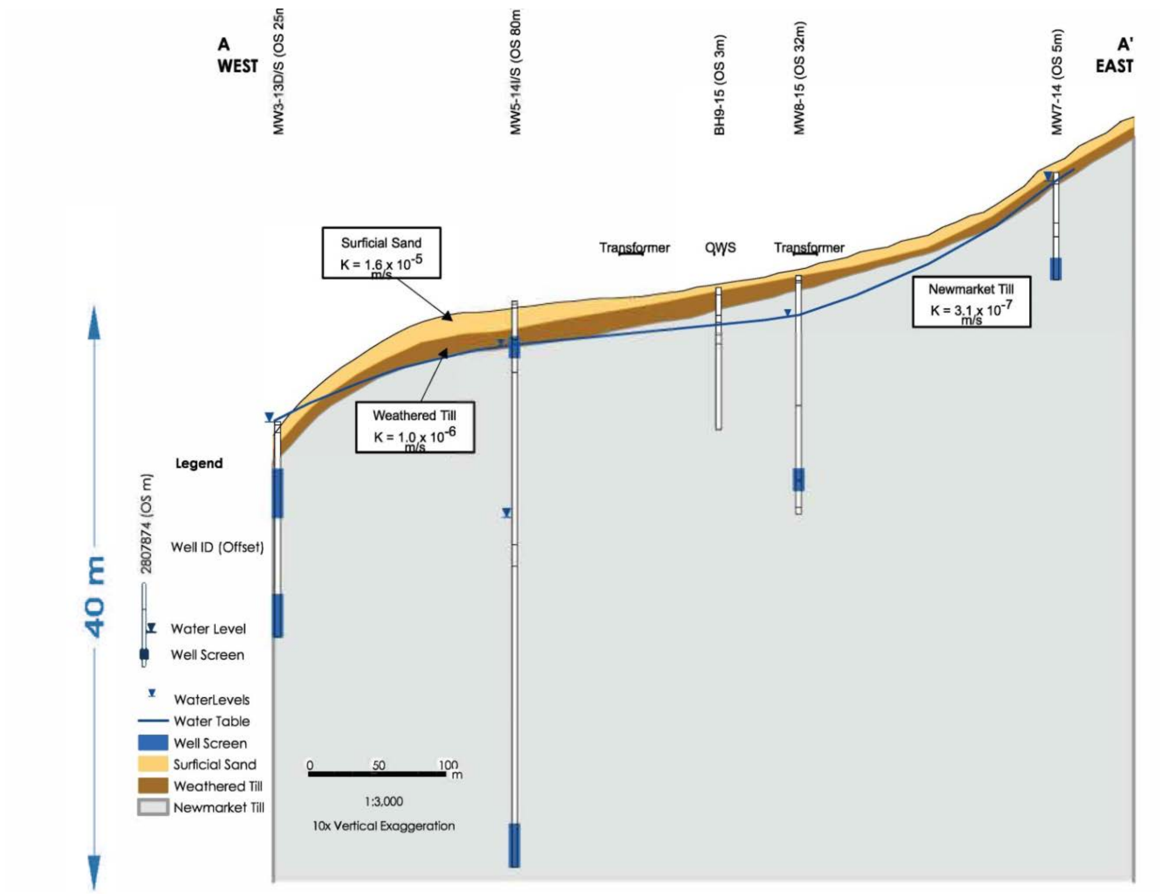


Fig. 3.6: *Stantec (2015) Cross Section A-A' with geological interpretation, edited diagram modified from Stantec (2015). Location of geological cross section can be viewed in Figure 3.3.*

Another conceptual model of the site (Fig. 3.7) was presented by Steve Usher in 2015 (SLR Consulting) on behalf of the Municipality of Clarington based on all available data presented in the technical review by Cherry et al. 2013 and the Stantec (2014) baseline condition report. This interpretation is based on a northeast to southwest cross section through the site (Fig. 3.3, cross section G-G'). In the conceptual model presented, a continuous layer of Halton Till is shown at the surface. Shallow sand zones are also depicted below the site from 6-9mbgs and 11-15mbgs. The report states these shallow sand zones are not connected to the ORM but were still deposited in the Mackinaw time period, meaning they were deposited at the same time as the ORM (SLR 2015). This entails a possible of lateral connection to other Mackinaw age aquifers, downgradient from the major ORM aquifer system.

Underneath the shallow sand is the thick continuous Newmarket Till unit underlain by the Thorncliffe and Scarborough formations, as is expected from the

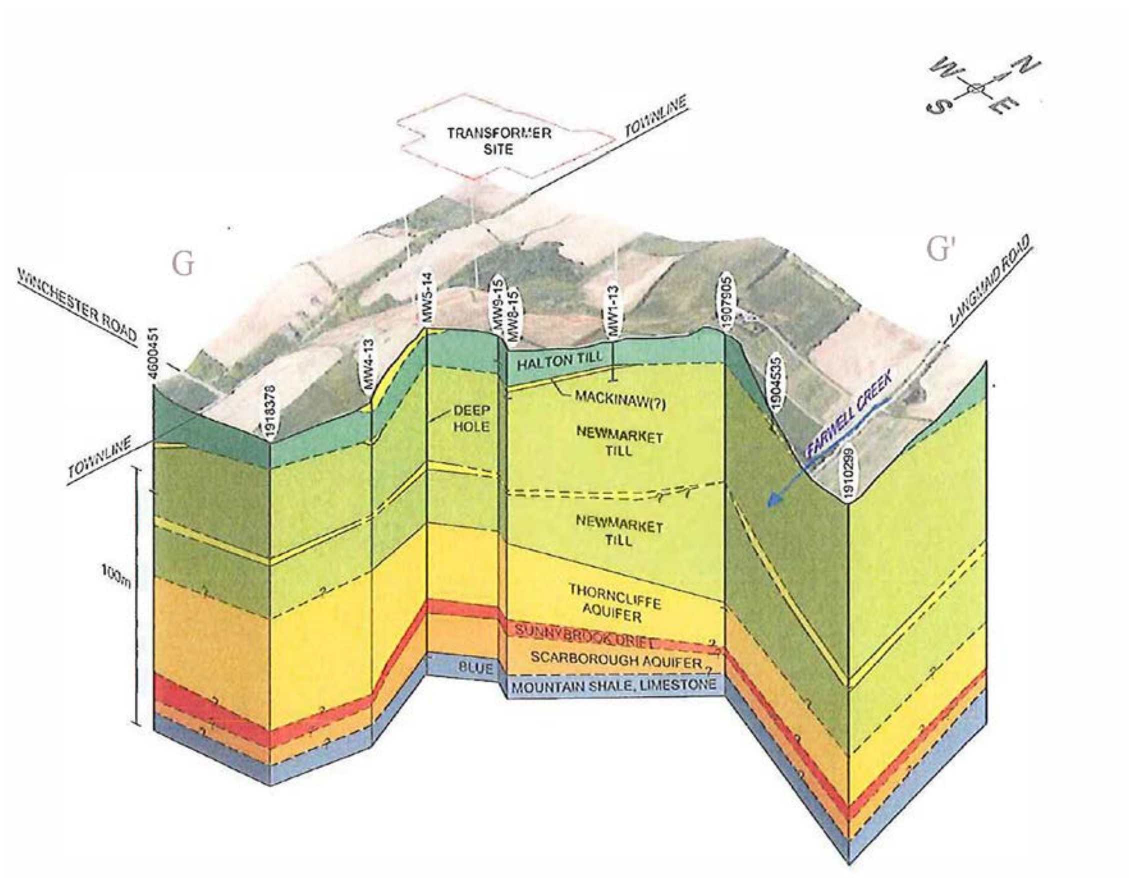


Fig. 3.7: *Steve Usher's (SLR Consulting) conceptual model. Figure edited from SLR 2015. Location of geological cross section can be viewed in Figure 3.3.*

regional stratigraphic framework (see chapter 2).

The main discrepancy between the conceptual models presented to date appears to be in the top 15m, and relates to the origin of the near surface till and the surface and shallow sand zones. This discrepancy creates the need to improve the geological understanding to try and discriminate between these competing hypotheses.

3.2.2 Discussion of Geological SCM

One aspect of the 2015 Stantec conceptual model that has not changed from the 2014 model is that there are no shallow sand layers or sand zones within the thick Newmarket Till under the transformer station. The 2015 report also suggests that Mackinaw and Halton Till deposits cannot be present. The latter is problematic because the Newmarket Till at surface would only rule out the potential of sand zones within the till to be of Mackinaw age. Based on this conceptual model, it is still possible that small pockets of Halton till could be present in thin deposits at surface. There is also potential for the surficial sand to be of Mackinaw or Halton age, as its higher stratigraphic position relative to the Newmarket Till indicates it is younger in age.

The shallowest grain size sample was 3.7 mbgs (Table 3.2), thus potentially missing a textural composition change within the surface till/tills. Based on the location of this site, regional mapping suggests the Halton Till would be relatively thin and patchy (Fig. 2.2; Sharpe and Russell 2016; Ontario Geological Survey 2010) and detailed grain size analysis may improve the geological understanding across the site. When the Newmarket Till and Halton Till overlie each other directly, they could potential be distinguishable based on the stone and sand content (Sharpe and Russell 2016) in combination with geophysics and p-XRF data analyzed by Duggan (2016). It is also possible that grain size differences may not be diagnostic as Halton ice would have incorporated Newmarket sediments before depositing it as Halton till. In that case orientation of drumlins near the study area may also help determine the diamicton's origin since Halton ice came from the SE whereas drumlins in this area suggest a NE to SW flow consistent with Newmarket ice flow lines (Fig 2.2).

The discrepancy in the interpretation of the near surface geology creates a scenario where multiple conceptual models are possible. If the Halton Till is at surface and continuous as suggested in Stantec 2014 and SLR 2015, it creates a potential for sand zones around 12 mbgs to surface that sit above the Newmarket and below the Halton to be of Mackinaw age (Fig. 3.8 diagram A). If this is the case, the need to determine the thickness and extent of the Halton Till and the connectivity of the shallow zones is crucial to determine if the till protects these shallow sand zones and if the sand zones are connected to other correlative aquifer. These deposits are used for water supply in private wells and determining their level of protection against a land use change is essential. If Newmarket Till is found underlying some surface sand as proposed in the 2015 Stantec conceptual model, shallow sand zones found between 5-12m would not be of Mackinaw age (Fig. 3.8 diagram B), and would instead represent sediment

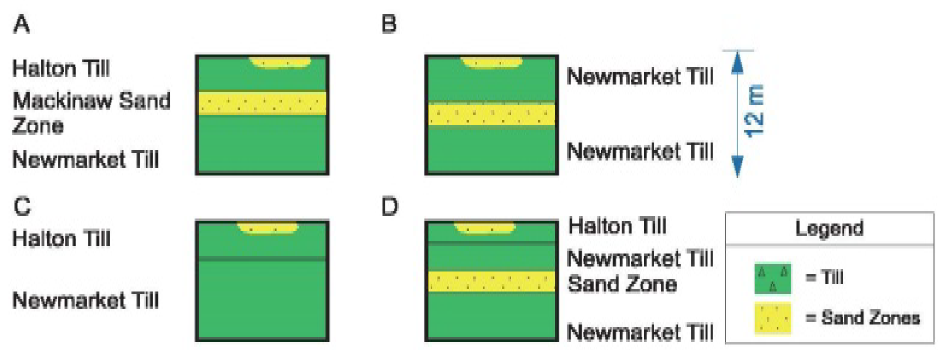


Fig. 3.8: Four conceptual model diagrams representing possible stratigraphy found on site based on regional stratigraphic framework. Surface sands sitting on top of Halton Till cannot be of Mackinaw age, however sands at surface above the Newmarket Till have potential to be of Mackinaw age. See text for details.

heterogeneities within the till. If this is the case, there would still be a need to assess the level of connectivity through fractures and other sediment heterogeneities between sand zones within the Newmarket Till and between the sand zones and the surface. A third and fourth option is that Halton Till lies directly over Nemmarket Till with no potential Mackinaw or ORM age sediments present under the site (Fig. 3.8 diagram C and D). If Newmarket Till is found above the sand zones from 5-12 m and the Halton Till deposit is discovered to be much thinner than some of the conceptual models indicate, it would not be possible for the sand zones to be of Mackinaw age (Fig. 3.8 diagram D)

If Halton Till is found at surface (Fig. 3.8 diagram A,C&D), surface sands sitting on top of the Halton Till cannot be of Mackinaw age. Instead, they would likely be either associated with the Halton formation, which includes many facies including silt and sand

(Sharpe and Russell 2016), or associated with lake Iroquois glaciolacustrine deposits, which are common within the area. Iroquois deposits are relatively thin (<2m) and consist of well sorted sands (CLOCA 2011). If on the other hand, there is Newmarket Till at surface (Fig. 3.8 diagram B), the origin of the surface sands would need to be investigated as they would have potential to be of Mackinaw age, Halton age or associated with Lake Iroquois deposits.

One of the key objectives of this study was to better constrain the stratigraphy at this site, in order to provide a robust geological framework for future hydrogeological investigations. We present the new data in the context of existing borehole data using multiple cross sections in order to address this objective. For the purpose of this study the term diamicton, is a descriptive term commonly used in the description of glacial sediments that are a poorly sorted mixture of sand, silt, clay and gravel (Hambrey and Glasser 2003). Although this is a well-accepted term in geology, it is not often used by drillers. Instead the interpretive term till, present in some of the original borehole logs presented below, is used to describe various combinations of sand, silt and gravel without necessarily having obtained clear evidence of its subglacial (till) origin. Some engineers when describing sediments encountered will not use the term till, to avoid implying origin, and will instead describe just the matrix material and associated geotechnical properties.

3.3 Methods/Data Collection

University of Guelph and McMaster University were on site for the drilling of MW5-14S(2), MW5-14D, and MW5-14D(2) led by Stantec in December 2014. All three boreholes were completed by Ardvark drilling from November 24th 2015 to December 18th 2015. It was originally planned to have one continuous borehole to bedrock (130m) and one shallow borehole, however during the drilling of MW5-14D, a sand zone was hit at 52.5 mbgs. This sand was originally believed to be the Thorncliffe Formation, and the drillers opted to drill another hole to reach bedrock in anticipation of difficult drilling conditions. A well was installed and screened within the sand zone and the drill rig was moved over a meter to start a new hole to bedrock. Continuous core was not collected in MW5-14D(2) for the first 50mbgs; PQ coring continued after 50mbgs in MW5-14D(2). Due to their proximity, these two boreholes are referred to as the deep high-resolution borehole and are treated as a single borehole in the analysis of site geology.

The December 2014 high resolution boreholes in the cluster were continuously cored (PQ coring) in 5 foot runs, logged, and photographed in the field. Due to the drilling technique used, core was retrieved with a coating of drilling mud. The core was cleaned with a knife to remove excess drilling mud, measured for recovery length, and brought inside to be photographed. Photographs were taken in 5 foot sections along with more detailed 1 foot sections of each run (Fig. A1). Original photos were taken at a lower exposure to avoid losing detail in overexposure situations. The final photographs were processed in Adobe Lightroom 5 and color corrected using ColorChecker Passport extension.

After the cores were photographed, the core was moved to the logging station (Fig. A2). The cores were logged to the cm scale using a detailed logging sheet (Fig. A3). Grain size classification was made using the Wentworth size classification chart and the classification of diamicton of Hambrey and Glasser (2003).

Once core photographing and logging was complete, grain size samples were collected at various depths throughout the entire core to quantify grain size distribution, along with duplicate grain size samples to ensure repeatable results (Fig. A4). Grain size samples were collected in 6 inch segments and placed in plastic bags to be labeled. At greater depths, the till became very dense and hammer and chisel was used to remove the grain size samples (Appendix Fig. 4). A total of ninety-six (96) grain size samples were collected and the grain size analysis was completed by the Geological Survey of Canada-Northern Canada Division Sedimentology Lab, using the camsizer and Lecotrac LTIDO.

Out of the newly collected ninety-six (96) grain size samples associated with the high-resolution borehole, forty three (43) of the analyzed samples were used with the well logs to better determine lithology changes in this study. To address this study's objective, only the first 10 mbgs and 50-70 mbgs of the high-resolution borehole log was used to determine what till unit is at surface and where the basal contact of the

Newmarket Till is located. The reader is referred to Duggan (2016) for detailed analysis of the entire high-resolution borehole.

Preexisting and new data was compiled to create three (3) geological cross sections located on site (Fig. 3.9) and a site conceptual model. Preexisting data included the use of twenty-three (23) geotechnical boreholes, seven (7) monitoring wells associated with the Hydro One monitoring program, and fifteen (15) grain size samples analyzed by Stantec (Stantec Consulting Ltd. 2014, 2015b). Well-logs from Stantec (2014) and (2015b) associated with geotechnical boreholes and monitoring wells were used for cross sections located on site and comparing the grain size distribution curves of the grain size samples and their depths relative to the sand zones is an important step in determining whether the diamicton can be interpreted as the Halton or Newmarket Till.

3.4 Results

New cross section locations that differ from Stantec (2014) and (2015B) and SLR (2015) were chosen for this study to allow for additional boreholes and monitoring wells to be examined (c.f. Fig. 3.3 and 3.9). The new location were selected to incorporate as many boreholes as possible, allowing for a multiple angled view along transects to achieve an accurate representation of the site.

Cross section D-D' (Figs. 3.9, 3.10) runs perpendicular to the reported shallow groundwater flow direction (Stantec 2014) and displays surface and shallow sands and

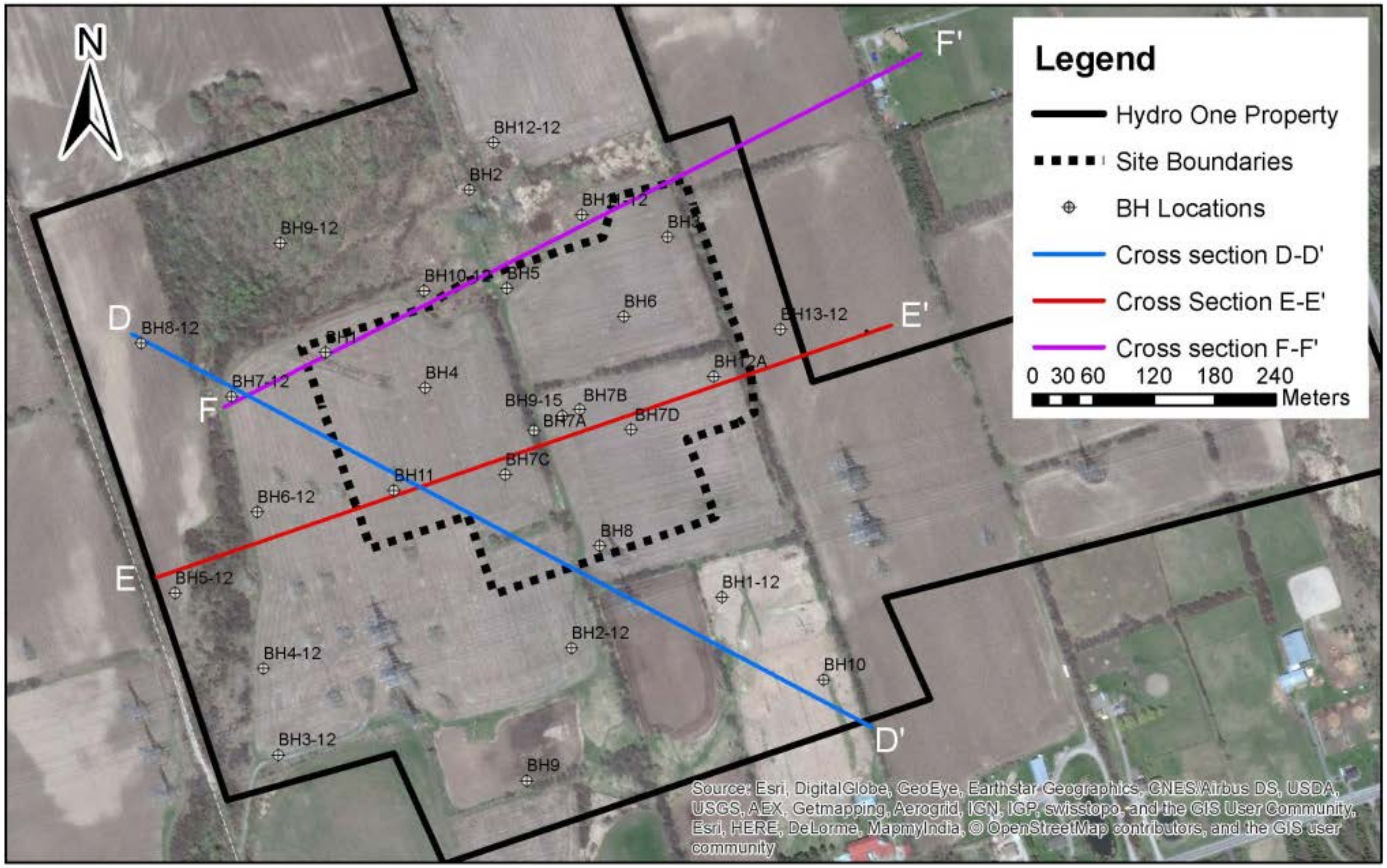


Fig. 3.9: *Hydro One Transformer Station with locations of cross section created as part of this study. Base map and property boundaries produced with ArGIS and data from Stantec (2014, 2015b)*

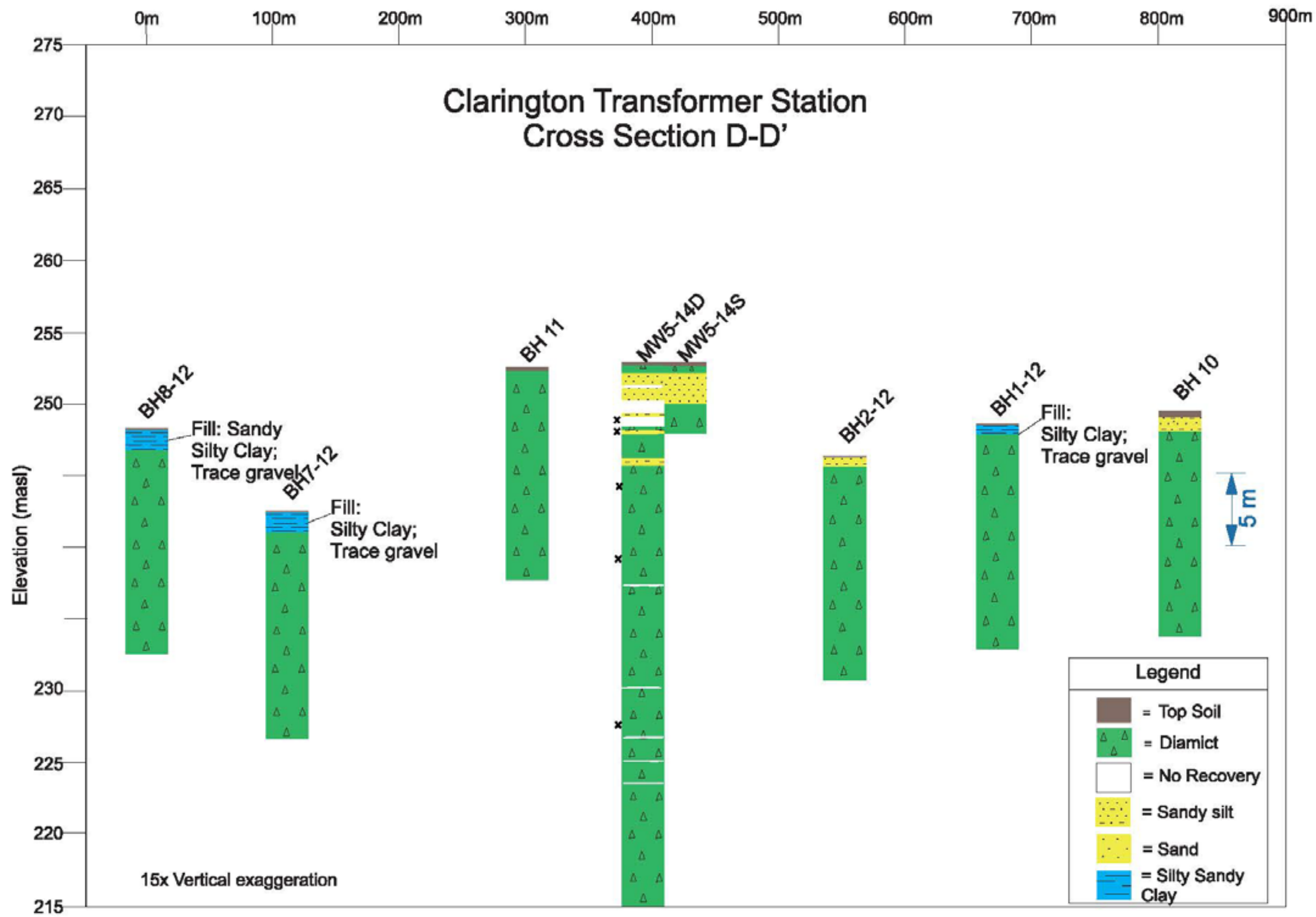


Fig. 3.10: Original borehole logs described by Stantec, Exp, and Inspect Sole (Stantect 2014 and 2015) with sediment descriptions. Locations of Stantec grain size samples used in Fig 3.14B are shown with an(X)

silty sands above and below diamicton units. Fill material was reported in three of the geotechnical boreholes BH8-12, BH7-12 and BH 11-12, and described as silty clay with trace gravel. Grain size samples from Stantec (2014) are located at various depths within the MW5-14D high resolution borehole. Intervals of no recovery documented throughout MW5-14D. The diamict behaved as solid rock during sampling, and therefore in deeper depths fully recovered cores was a normal occurrence. The small no recovery zones at depth may be evidence of small interbeds that were lost during core recovery, speaking to internal horizontal heterogeneities (pers comm. Boyce, 2017).

Cross Section E-E’ (Figs. 3.9 and 3.11) runs west to east along the middle of the site and is again dominated by diamicton, with sand both at surface and at shallow depths. Sand, sandy silt, silty sand, and silty sand with gravel zones are also depicted in borehole logs. Fill material was reported in three of the geotechnical boreholes BH5-12, BH6-12 and borehole 13-12, and described as silty clay with trace gravel.

Cross Section F-F’ (Figs. 3.9 and 3.12) also runs west to east however it is located on the Northern edge of the site property. Diamicton again dominates the succession with sandy and sandy silt zones observed below ground surface and at surface along the transect. Lithology descriptions are noted in areas where sandy zones at depth are located to get a general sense of the till above and below these sand zones. Sparse grain

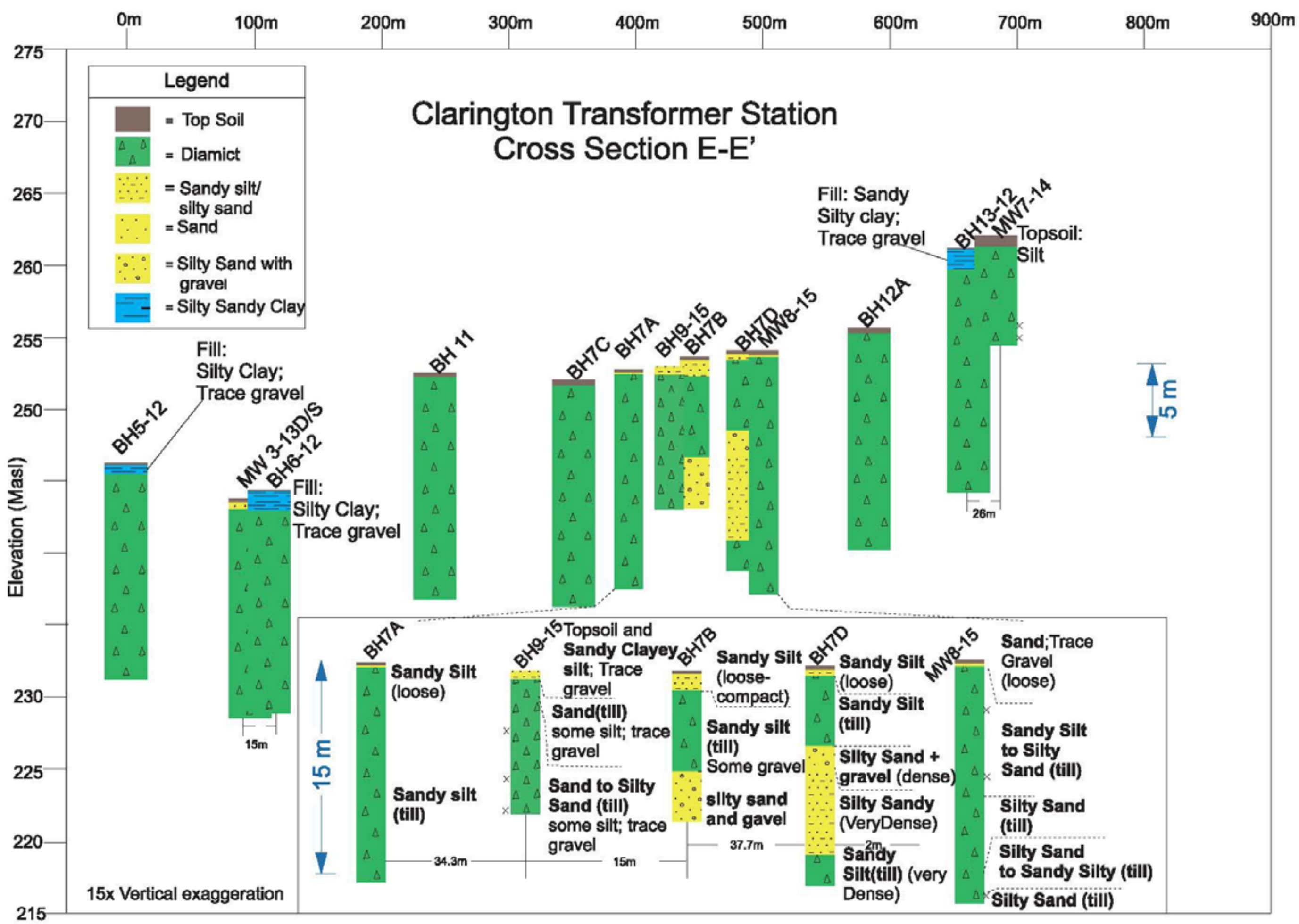


Fig. 3.11: Original borehole logs described by Stantec, Exp, and Inspect Sole (Stantect 2014 and 2015). Stantec grain size sample locations used in Fig 3.14B are shown with an (X) on MW7-14, BH9-15 and MW8-15

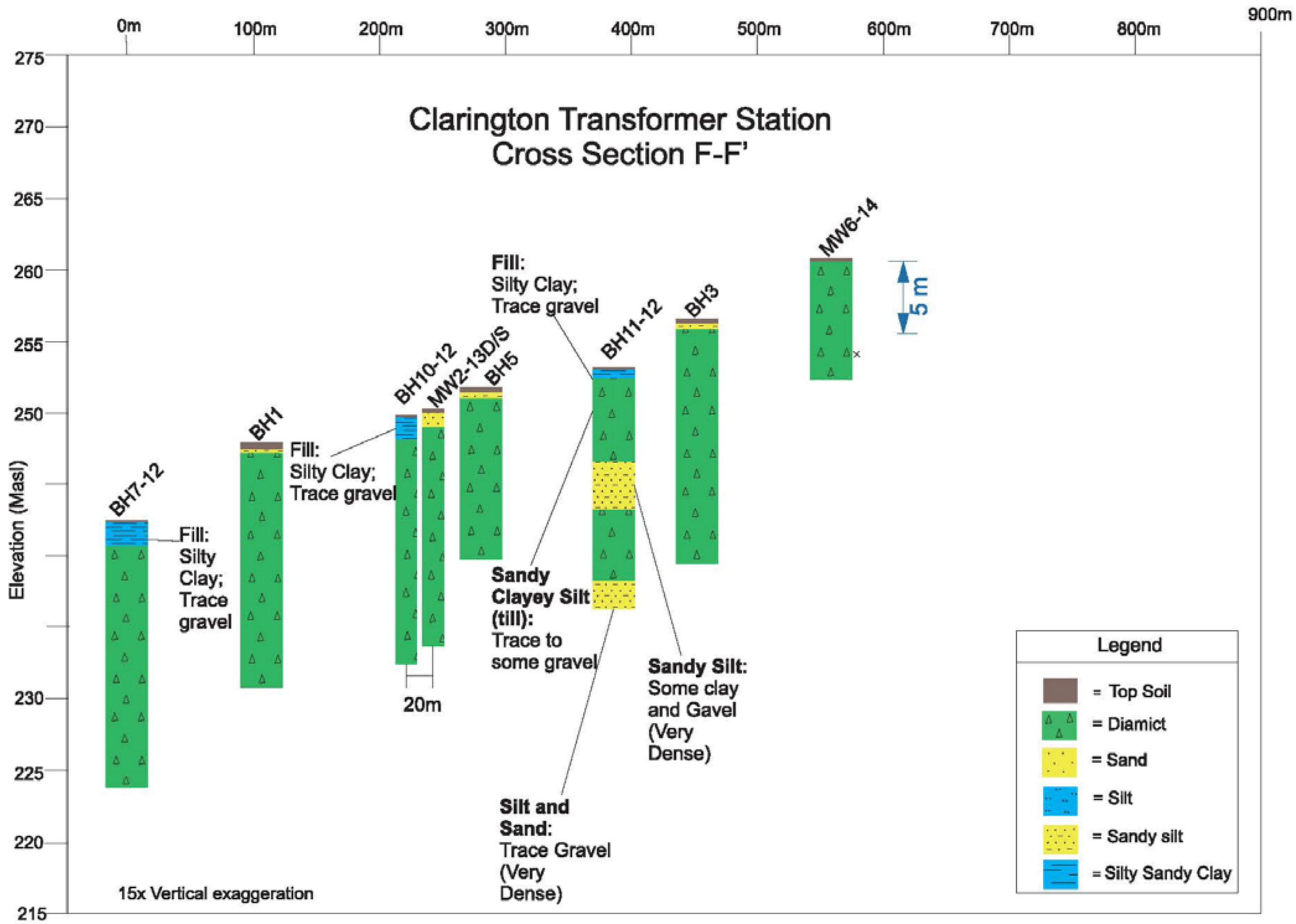


Fig. 3.12: Original Borehole logs described by Stantec, Exp, and Inspect Sole (Stantect 2014 and 2015). Location of Stantec grain size sample used in Fig 3.14B are shown with an (X).

size data is available along this transect, but is located at higher elevations than the sandy and sandy silt zones. Fill material was reported in three of the geotechnical boreholes BH7-12, BH10-12 and Borehole 11-12, and described as silty clay with trace gravel as discussed below.

Detailed lithology logs of MW5-14D and MW5-14D(2) are consistent with the finding in cross section D-D’, E-E’, and F-F’, shallow sand zones are within the first 10mbgs (Fig. 3.10-3.12; 3.13 A) and are also shown at depths deeper than the analyzed crossed sections providing visual evidence of heterogeneities with the Newmarket Till (Fig. 3.13 B). Grain size samples from Stantec (2014) and (2015B) and grain size samples collected for this study are plotted in ternary diagrams (Fig. 3.14). Grain size samples from the high-resolution borehole (Fig. 3.14A), stay well above typical sand content associated with Halton Till (i.e. close to 20%). In Fig. 3.14B, the Stantec (2014) and (2015B) grain size samples scattered around the site are also well within the range of sand content associated with the Newmarket Till documented by Sharpe and Russell (2016)

3.5 Geological Analysis

3.5.1 Origin of Till

The major discrepancy observed in conceptual models presented for the site to date is related to the origin and stratigraphic interpretation of the tills and sand zones in

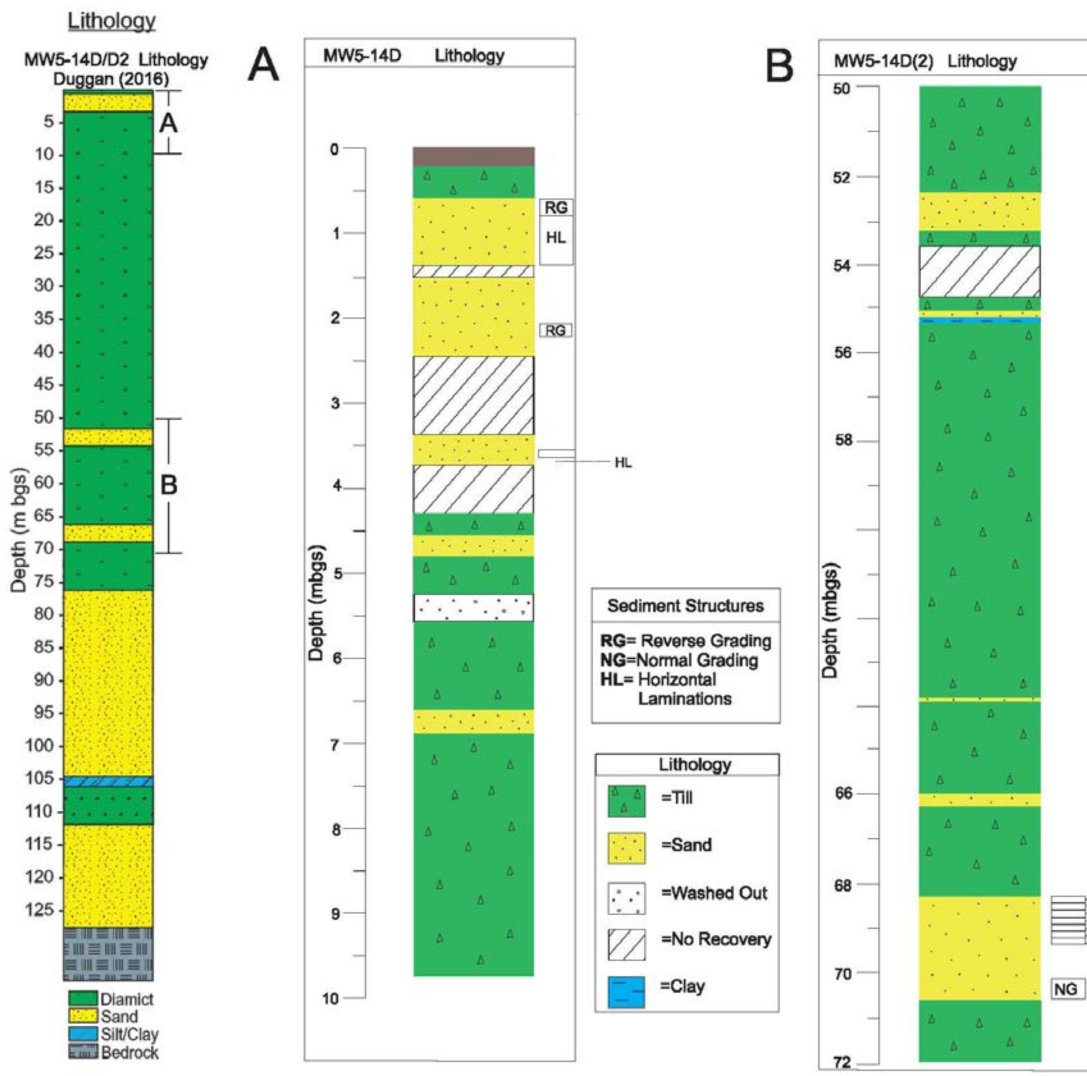


Fig. 3.13: Detailed lithology log of MW5-14D and MW5-14D(2) from 0-10 m (A) and from 51.8-71.8 m (B), showing distribution, thickness and structures of sand zones associated with diamicton. Locations of A and B are marked on Duggan (2016) lithology log to bedrock (far left).

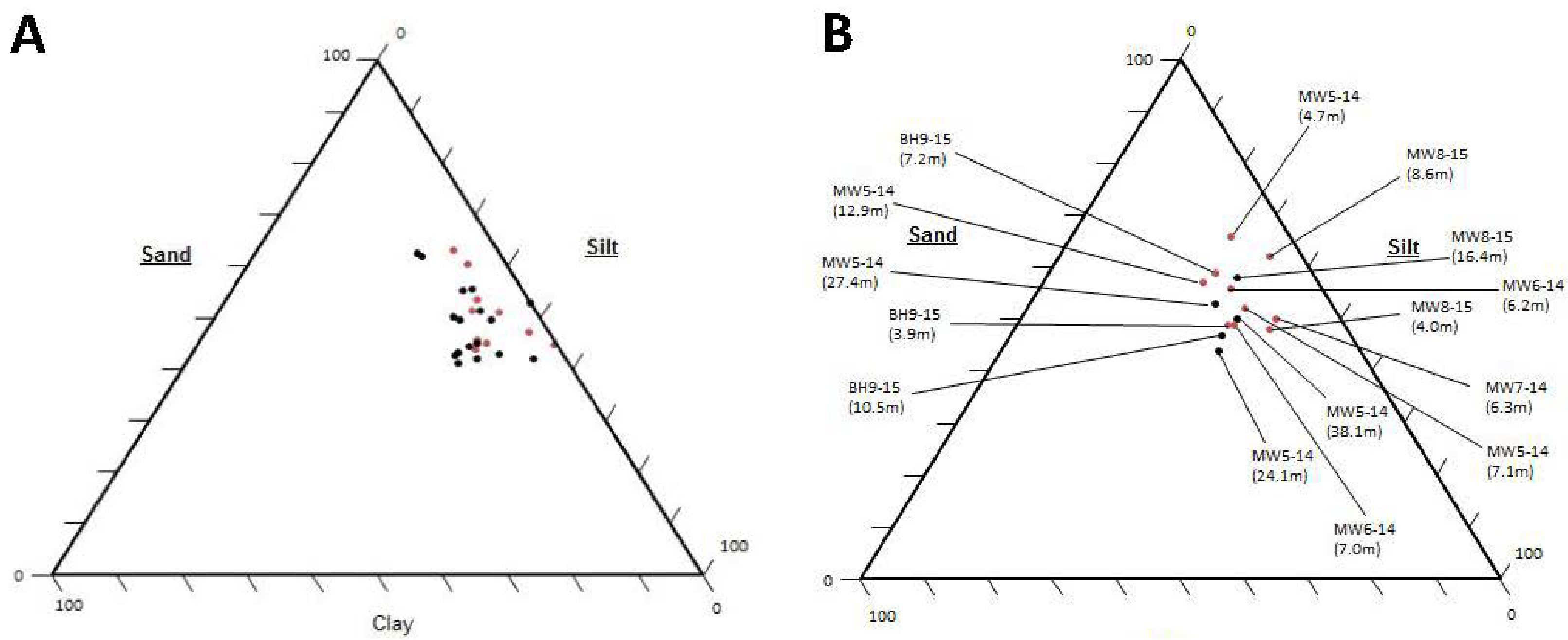


Fig. 3.14: *Comparison of grain size distribution of diamicton at various depths within the first 40 mbgs.* ***A****: Grain Size samples from MW5-14D (Clay; <.002mm, Silt; .002-.063mm, Sand; >.063) collected from above and below the shallowest sand zone (Fig. 3.13 diagram A; 0.6m-50mbgs) and* ***B****: grain size distributions from various wells around the site (Stantec Consulting Ltd. 2015b). (Clay; <.002mm, Silt; .002-.065mm, Sand: >.065mm). Shallow sand zones are located from approximately 6-9mbgs and 11-15mbgs. Grain size distribution from above sand zones are marked with a* ***red dot*** *and below sand zones are marked with a* ***black dot****. Grain size data shows no change in textural composition with depth, Ternary diagram from Graham and Midgley (2000).*

the top 15 m of the subsurface on site (Fig. 3.8). Many boreholes on site displayed the presence of sand and/or silt within diamicton units at various depth such as MW5-14D, MW5-14S, BH11-12, BH12B, BH7B, and BH7D (Figs. 3.10, 3.11, and 3.12) as well as sand at surface.

There is an apparent lack of grain size data at shallow depths to determine if Halton Till or Newmarket is at surface and unfortunately, no single well has grain size samples locations above and below a sand zone within the same borehole. However, grain size data was available sporadically around the site in MW5-14D (Fig. 3.10), MW6-14 (Fig. 3.12), BH9-15, MW8-15, and MW7-14 (Fig. 3. 11). Some wells have grain size data above and some have grain size below sand zones, to allow for comparison of till textural composition above and below from wells within the same vicinity. If the sand zones are of Mackinaw age and thus related to the ORM, there may be a visible grain size distribution change in the till, as the Halton Till is said to be finer grained than the Newmarket Till (Russell and Sharpe 2016). BH7D has a sand zone at 5.63 mbgs and is located 2m away from MW8-15 (Fig. 3.11), which has several grain size samples, thus allowing for the best comparison of grain size changes relative to a sand zone.

Assuming lateral continuity of till units across the 2m interval, and if the sand located in BH7D is of Mackinaw age, MW8-15 should have Halton Till directly on top of Newmarket Till and the a potential change in grain size distribution. Figure 3.14 shows that there is 48 % sand at 4.0 mbgs above the adjacent sand zone and 62% sand at 8.6 mbgs below the adjacent sand zone in BHD7. Considering the typical sand content in the Halton Till near Oshawa, ON is closer to 20% (Sharpe and Russell 2016), these data suggest there is little difference between the tills above and below the sand zone.

Furthermore, there are no major grain size distribution changes with depth anywhere across the site based on the grain size samples of other pre-existing boreholes and of the high-resolution borehole until depths closer to 68 mbgs (Figs. 3.14, 3.15). The surface diamicton above the shallow sand zone does not have a major textural composition change from samples taken at greater depth. The diamicton grain size samples collected from the high-resolution boreholes also appear to be very similar to the diamicton grain size distribution found around the site.

To determine the stratigraphic context of the sand zones located below the site based on current available data is to first determine what till unit is present above and below. This can be done using a number of distinguishing characteristics, namely grain size, stone content descriptors used by drillers, geophysics, density, and geomorphology. It should be noted that while Sharpe and Russell (2016) suggest distinct grain size differences between the two tills, other depositional models. Barnett et al. (1998) and Howard and Beck (1986) suggest an ice re-advance would create the potential for an incorporation of Newmarket Till sediments during Halton ice re-advance and therefore create very similar grain size (Dillon 1990). The Halton Till has increased sand content towards the east (Fig. 2.2) following the same decreasing in grain size trend to the west as the ORM which lead to the Sharpe and Russell (2016) waning flow model. Consequently, sand content in this study area may also make differentiating the till difficult at our site.

Grain size samples GS-002, and GS-003 (Fig. 3.16) have 6%, and 8 % stone content; this is also consistent with the Newmarket Till being at surface as Halton Till typically has a 1-2% stone content, whereas the Nemwarket Till ranges from 5-10% stone content according to the Sharpe and Russell (2016) model. GS-001 was collected from the top soil (Fig. 3.16), which may explain why this unit has a lower stone content of 3%.

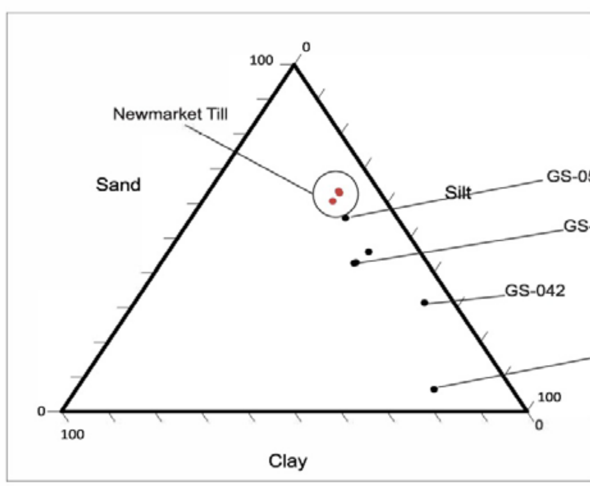


Fig. 3.15: Grain size analysis of MW5-14D(2) . Grain size sample locations (Fig. 3.20) between 50-70 mbgs collected from diamicton. Newmarket grain sizes are GS-035 and GS-039. (Grainsize distribution does not appear to change until GS-042 at approximately 68 mbgs, suggesting a change in diamicton by displaying an increase of silt, typical of the Thorncliffe diamicton (Brennand 1998). Ternary diagram from Graham and Midgley (2000).

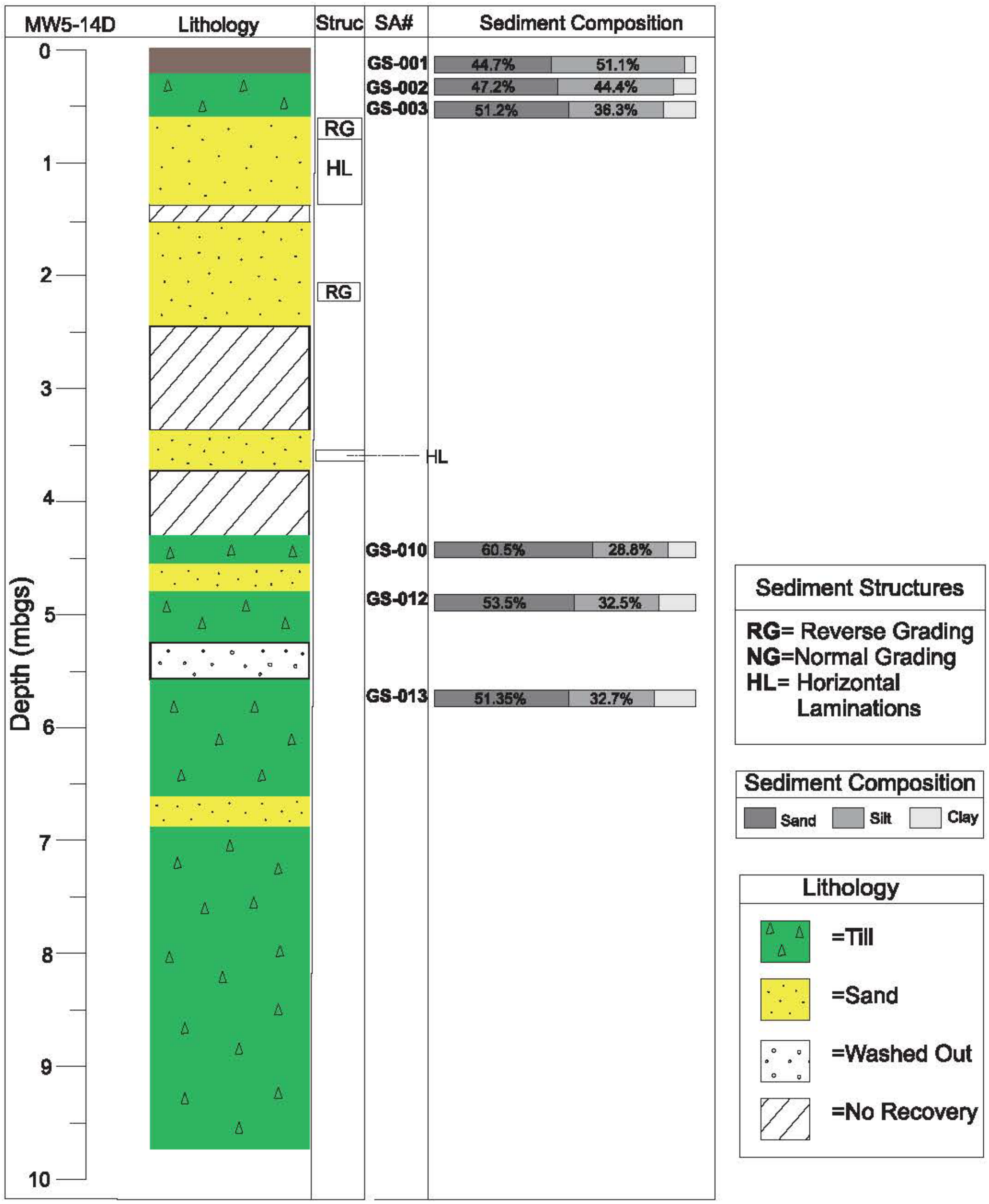


Fig. 3.16: MW5-14D geology with grain size distribution and sediment structures with depth.

The sediment descriptions from continuous core and split spoon sampled boreholes also suggest the Newmarket Till is at surface as descriptions in boreholes from all the cross sections (Figs. 3.10-3.12) range from a silty sand to sandy silt till, a similar range to what is reported for the Newmarket Till (Boyce et al. 1995 and Brennand 1998).

One of the defining characteristics of the Newmarket Till is its overconsolidated nature or density differences. At shallow depths, mostly 5 mbgs and shallower, the diamicton is reported as less dense in most boreholes. This is most likely due to weathering of near surface till (OGS 2013 in Stantec 2014), though this change of density has also been used elsewhere to delineate the Halton/Newmarket Till contact

Typical architecture within the Newmarket Till includes sand and gravel zones that are not laterally extensive, are typically smaller than 5 meters thick (Gerber et al. 2001), and have a silty sand to sandy matrix (Boyce et al. 1995). Most of the shallow sand zones encountered in the cross sections are consistent with these regional observations. In contrast, BH7D has a sand zone 7.6 m thick (Fig. 3.11), that is thicker than the typical sand zones reported within the Newmarket Till.

In BH7D (see inset of Fig. 3.11), the much thicker zone (7 m thick) is described as consisting of an upper unit of dense silty sand and gravel (1.5 m thick) and a lower thicker unit of very dense silty sand (6.1m). It is likely that the upper 1.5 m is actually till considering the descriptors silty sand and gravel technically amount to the upper unit being a diamicton using the textural classification of Hambrey and Glasser (2003) and that the terms “dense” is more typically associated with descriptions of Newmarket Till. In this context, it should be noted that MW8-15, located two (2) meters away, has no sand zone present. It is also evident that slight grain size distribution changes like those described in geotechnical borehole BH7D, are common within the Newmarket Till (Fig. 3.11). As a result, the sand zone within BH7D is likely within the range of other sand zones in the Newmarket Till.

In assessing whether or not there is Halton Till on site, there are several other points to consider. First, if the Halton Till is suggested to be deposited by waning flow from the ORM development by Sharpe and Russell (2016), reverse grading observed at the top of the shallow sand zone in MW5-14D (Fig. 3.16) would not be expected as waning flow would produce normal grading from sand into the overlying finer grained diamicton of the Halton Till. As mentioned previously, it is also believed that the Halton till was deposited by an ice advance as evidence by changes in the orientation of drumlin ridges (Fig 2.2) (Howard and Beck 1986). Just north of the site drumlin orientation is northeast southwest (Fig. 2.2), and the evidence of an ice advance resulting in the deposition of Halton Till can be seen in this map with the drumlin orientation changes to northwest southeast near the Lake Ontario shoreline. Topographic highs northeast and west of the site are drumlin orientated in a northeast southwest direction, suggesting no evidence of a Halton ice re-advance at this study site (Fig. 3.1). This provides an additional line of evidence, rather than relying on grain size data alone, that Newmarket Till may be at surface at this site.

Second and in contrast, geophysics data presented in Duggan (2016) show and increase in gamma from approximately 6 mbgs and shallower, potentially suggesting that Halton Till sediments are present near and at surface at that location as these sediment produced higher gamma readings than the Newmarket Till (Pullan et al. 2002).

There are also small pockets of silty clay at surface in some locations around the site. The pockets of silty clay are found in BH8-12, BH7-12, and BH1-12 (Fig. 3.10); BH5-12, BH6-12, and BH13-12 (Fig. 3.11); and BH7-12, BH10-12, and BH11-12 (Fig. 3.12). These were interpreted as fill material in the Stantec (2014) report but may be discontinuous Halton Till deposits. The boreholes where this clay was not described are reported by a different consultant to have till at the surface, suggesting the different descriptions may be related to the different logging techniques of each consultant (e.g. BH13-12 and MW7-14; Figure 3.11). There are no grain size samples or borehole geophysics available in areas where the silty clay layers were observed to potentially confirm or deny the possibility of small patches of Halton till. While the sediment descriptions suggest the possibility of discontinuous Halton Till at surface, the site is located well below the southern extent of the Halton Till as suggested by Sharpe and

Russell (2016) (Fig. 2.2). This should be explored further with future sampling and mapping of surface sediments on site in order to refine the existing regional maps.

In sum, based on this discussion and the interpreted shallow geological cross sections that are based on currently available data (Fig. 3.17, 3.18, and 3.19). The exact origin of the near surface till is unknown at this time due to conflicting evidence from grain size, geomorphology, density, and geophysics.

The geological framework (Fig. 3.17, 3.18, 3.19) identifies till with discontinuous sand at surface and discontinuous sand zones at depth. The key question that should be addressed with future work concerns the hydraulic connectivity of these sand zones. This will best be addressed through hydraulic testing (slug/pump tests) in the shallow sand zones, which has not been feasible to date due to onsite access issues.

3.5.2 Newmarket-Thorncliffe Contact

Other than the high-resolution borehole to bedrock (130m), most holes on this site did not go deep enough to comment on the lateral variability of the lower contact of the Newmarket Till or the underlying stratigraphic units. Detailed analysis of the high-resolution borehole, along with stratigraphic interpretation to bedrock is discussed in (Duggan 2016).

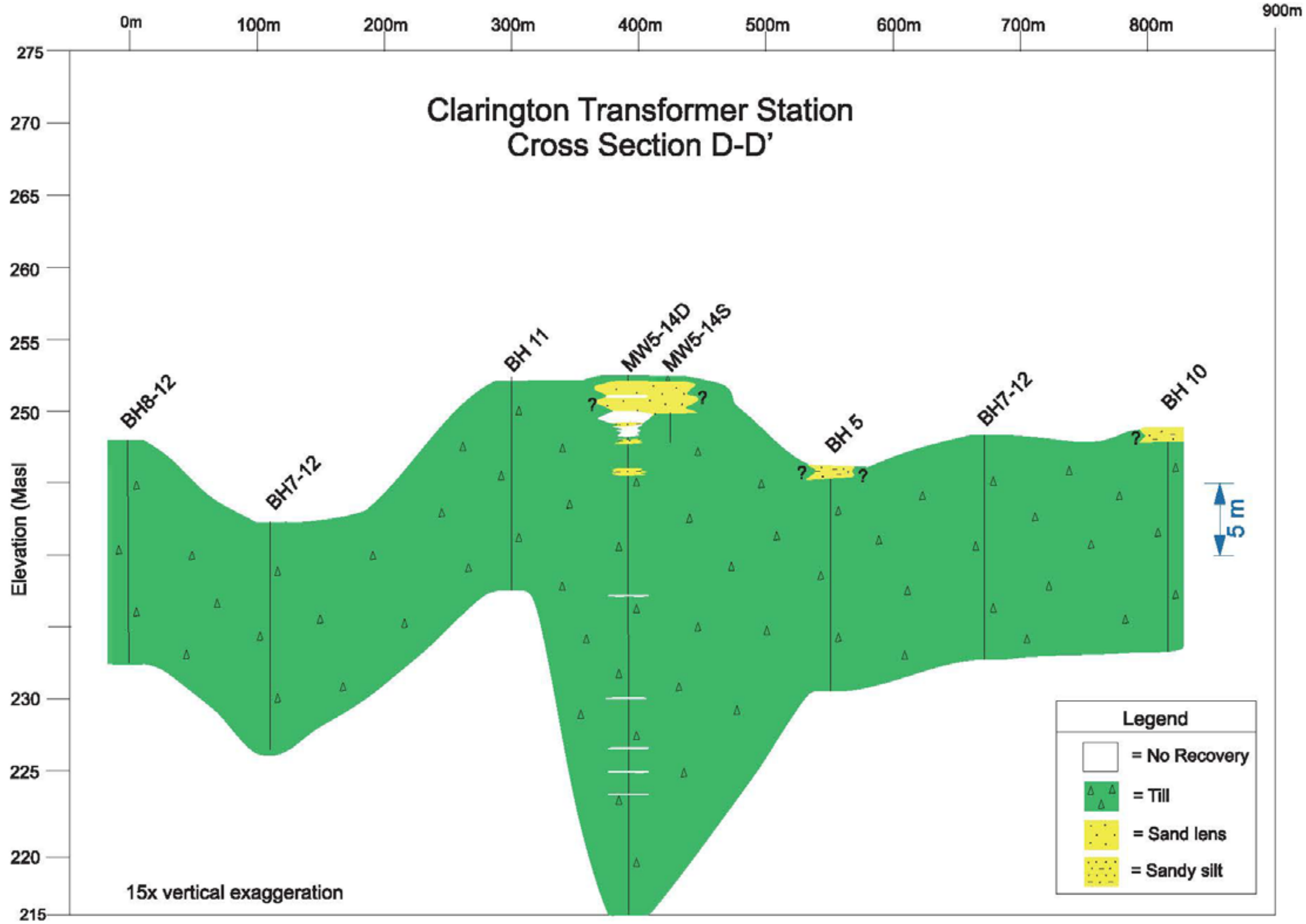


Fig. 3.17: Interpreted geological cross section D-D'

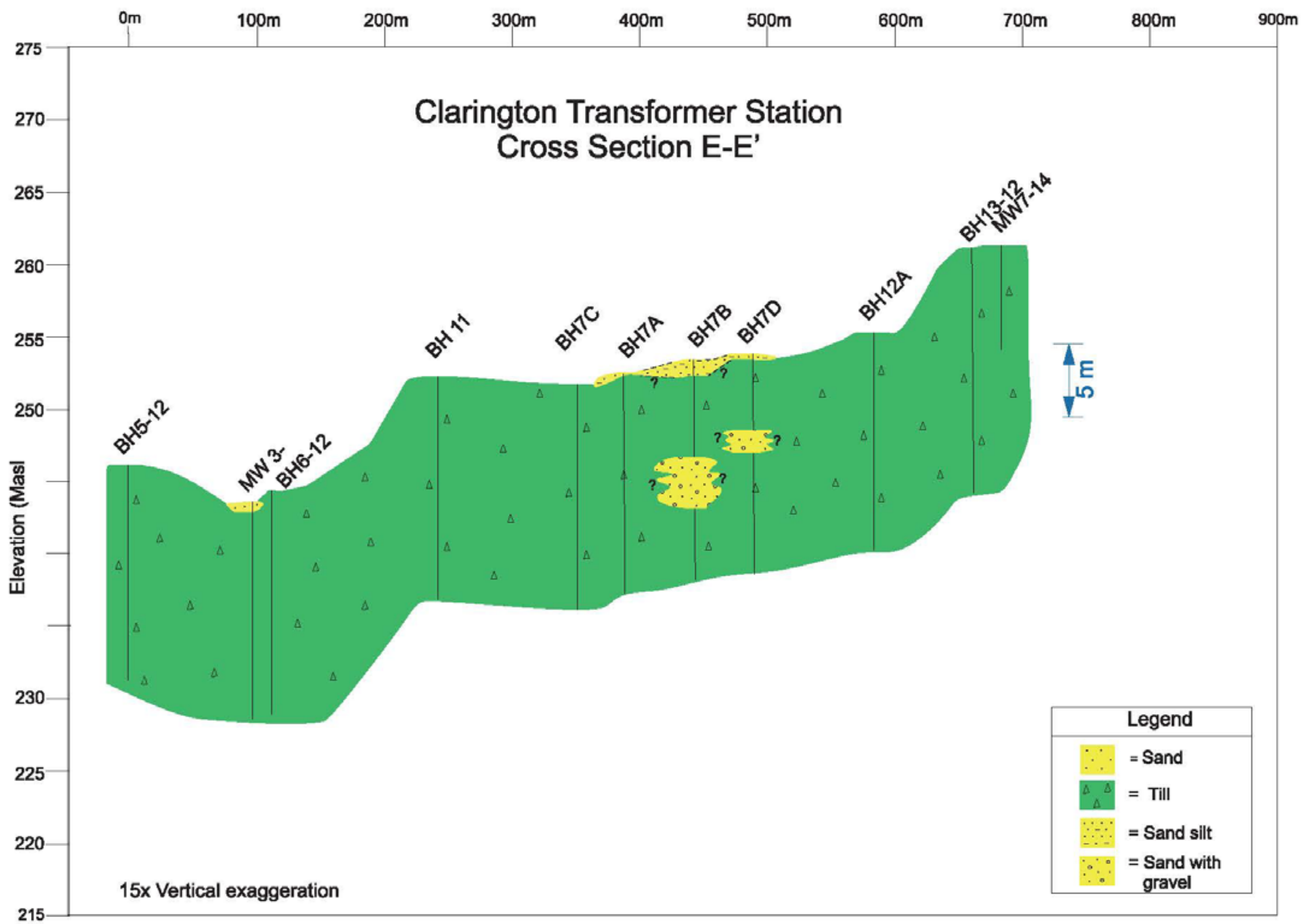


Fig. 3.18: Interpreted geological cross section E-E'

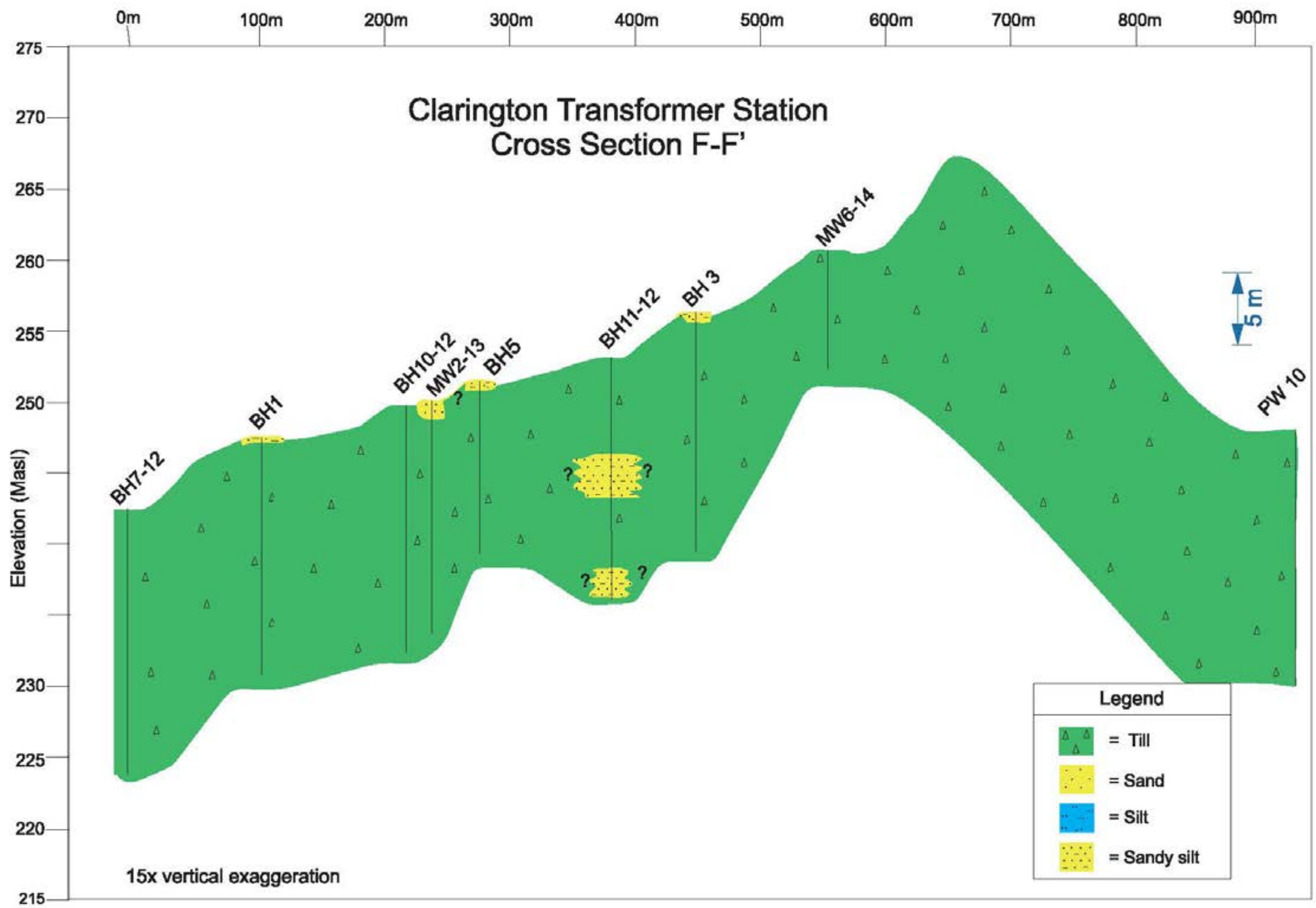


Fig. 3.19: Interpreted geological cross section F-F. PW10 is only depicted to the first 30 mbgs for the analysis of shallow geology.

Duggan (2016) reported the start of the Thorncliffe Formation is approximately 75 mbgs with 1-8 m thick beds of alternating normal and reverse graded sandy sediments. Regionally, the Thorncliffe Formation underlies the Newmarket Till and is a complex glaciolacustrine sandy sequence that could be composed of alternating aquifers and aquitards (Brennand 1998). Aquifers within the Thorncliffe Formation have coarsening upward sequences and interbedded aquitards that consist of a clast poor, clay silt diamicton (Brennand 1998). Here, we discuss the nature of the sediments (grain size distributions and sedimentary structures) between 50 and 70 mbgs and the depth of the basal contact of the Newmarket (Fig. 3.20).

The first major sand deposit at depth in MW5-14D/D(2) was found about 50-55mbgs (Fig. 3.20). The analysis of the diamicton above and below this sand deposit includes sample numbers GS-035, GS-039, and GS-040 (Fig. 3.20). The grain size distributions of these samples seem to be very close to other samples that are higher up in the succession and have been identified as Newmarket Till (Fig. 3.14), suggesting the first sand zone at 50-55mbgs is likely still a part of the Newmarket Till.

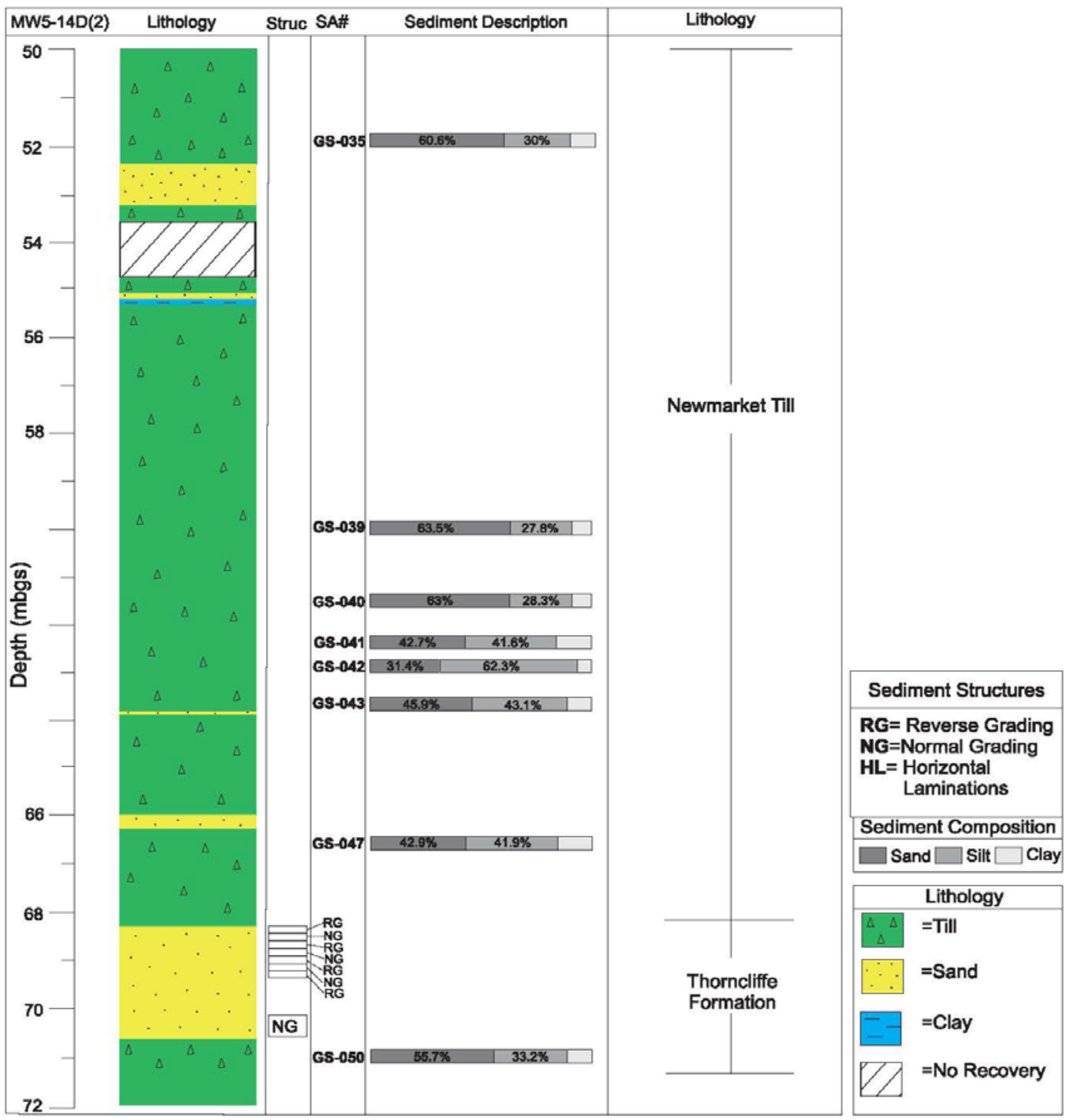


Fig. 3.20: Concluded geological interpretation based on MW5-14D(2) lithology, sediment structures, and grain size data.

Moving deeper below ground surface, the grain size distribution changes before reaching the sand zone at 63mbgs, from having sand content in the 60% range to having sand content in the 30-45% range. The sand content is consistently lower below 60 m depth, with larger silt and clay content indicating a possible change in the diamicton. However, the sand units at this depth do not appear to have any type of grading within them suggesting it may still be the Newmarket Till (Fig. 3.20). The contact appears to be more gradual than Duggan (2016) suggests, as sands with grading characteristics of the Thorncliffe sands occur at 68 m depth and the diamicton shows a gradual change to a finer grained diamicton at about 60m depth (Fig. 3.20). Since the Thorncliffe Formation is described as interbedded with finer grained diamicton, it is possible that the Thorncliffe contact is shallower than previously reported (Duggan 2016). The bottom of the Newmarket Till is considered to be a deformation zone and can be <10 m thick including Thorncliffe sediments that are incorporated into the Newmark Till during deposition (Gerber 1999). This mixture of sediments may also explain an apparent grain size distribution change in the diamicton near the determined boundary. Based on the data presented above, this study is suggesting the boundary between the Thorncliffe Formation and Newmarket Till is 75 mbgs as suggested by Duggan (2016) but the deformation zone and sediment incorporation has the potential to range from 68 -75 mbgs.

Due to lack of high quality wells 20 mbgs or greater, cross sections of offsite private wells (Fig. 3.21) were created from information available from Ministry of Environment (MOE) water well records (Figs. 3.22 and 3.23). The private well cross-sections were produced from lower quality MOE water well data, but interpretations were made using the site's current geological framework achieved by using higher quality borehole data (Fig. 3.20). Many of the local residential wells are close to the determined potential boundary (68-75 mbgs) between the Newmarket Till and Thorncliffe Formation (Figs. 3.22 and 3. 23), making it difficult to know whether these wells are completed in a Newmarket sand zone or the Thorncliffe aquifer. For this reason, the range of 68-75mbgs for the Newmarket/Thorncliffe is suggested when evaluating the stratigraphy of private wells off site that terminate in deep sand zones. Based on current available data from the high-resolution core MW5-14D(2) at the southwest corner of the site and proximity to private wells (Figs. 3.1 and 3.21) it is likely any residential wells below 68mbgs is either completed in the Thorncliffe Formation or is in a sand zone that is likely hydraulically connected to the Thorncliffe through deformation structures at the base of the Newmarket Till.

Isopach data from Sharpe et al. (2005a) suggests the Lower Sediments (Thorncliffe Formation to bedrock) thickness within the TS area is 75-160 meters thick, but can become < 50 m thick in the east and west direction away from the site. At our site the

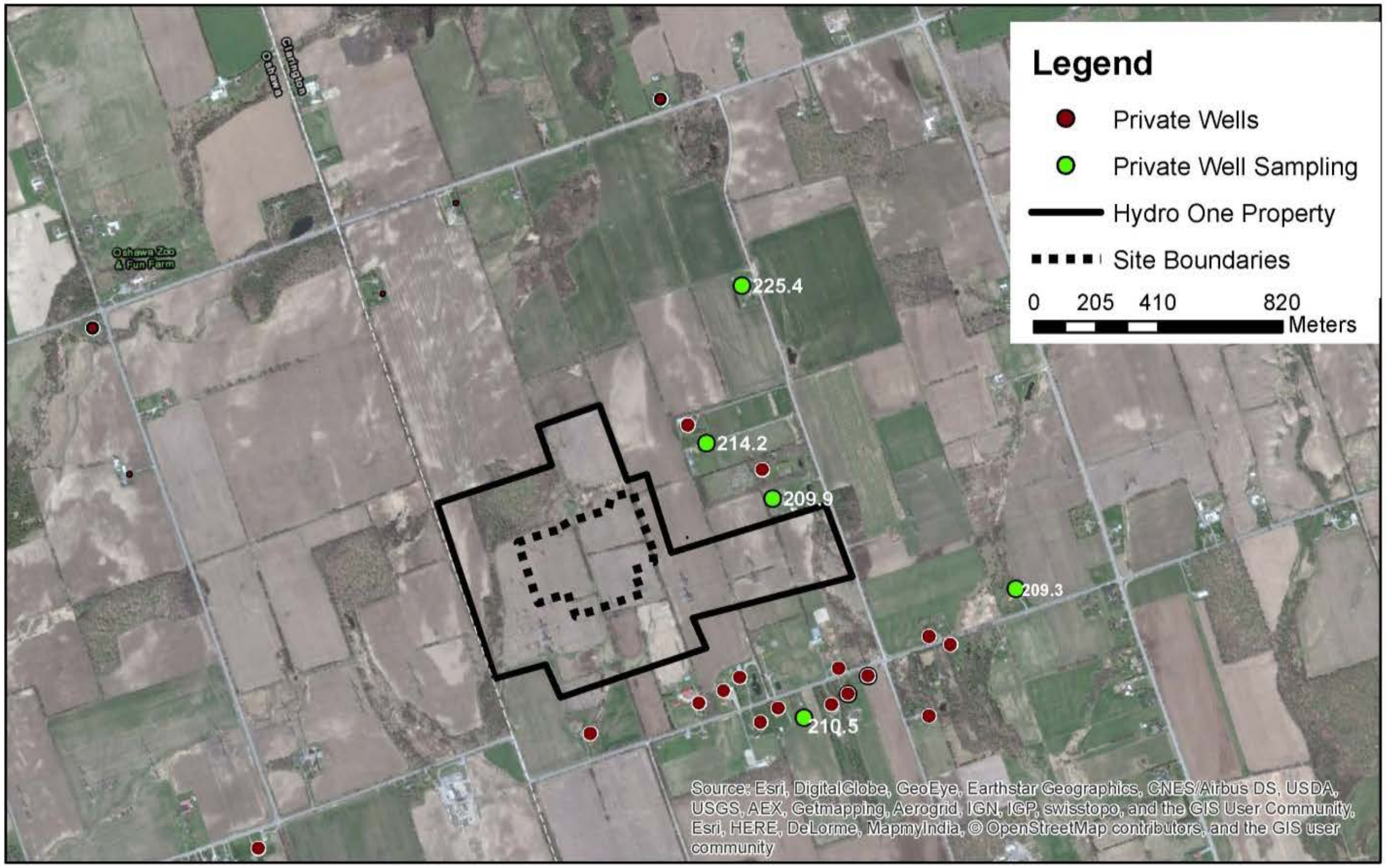


Fig. 3.21: Private Well locations (Stantec 2015a). Private well cross section locations not shown to respect the privacy of the private property owners. Private well groundwater elevation in meters above sea level, of sporadically pumped supply wells. Water levels were collected on 8/17/2016.

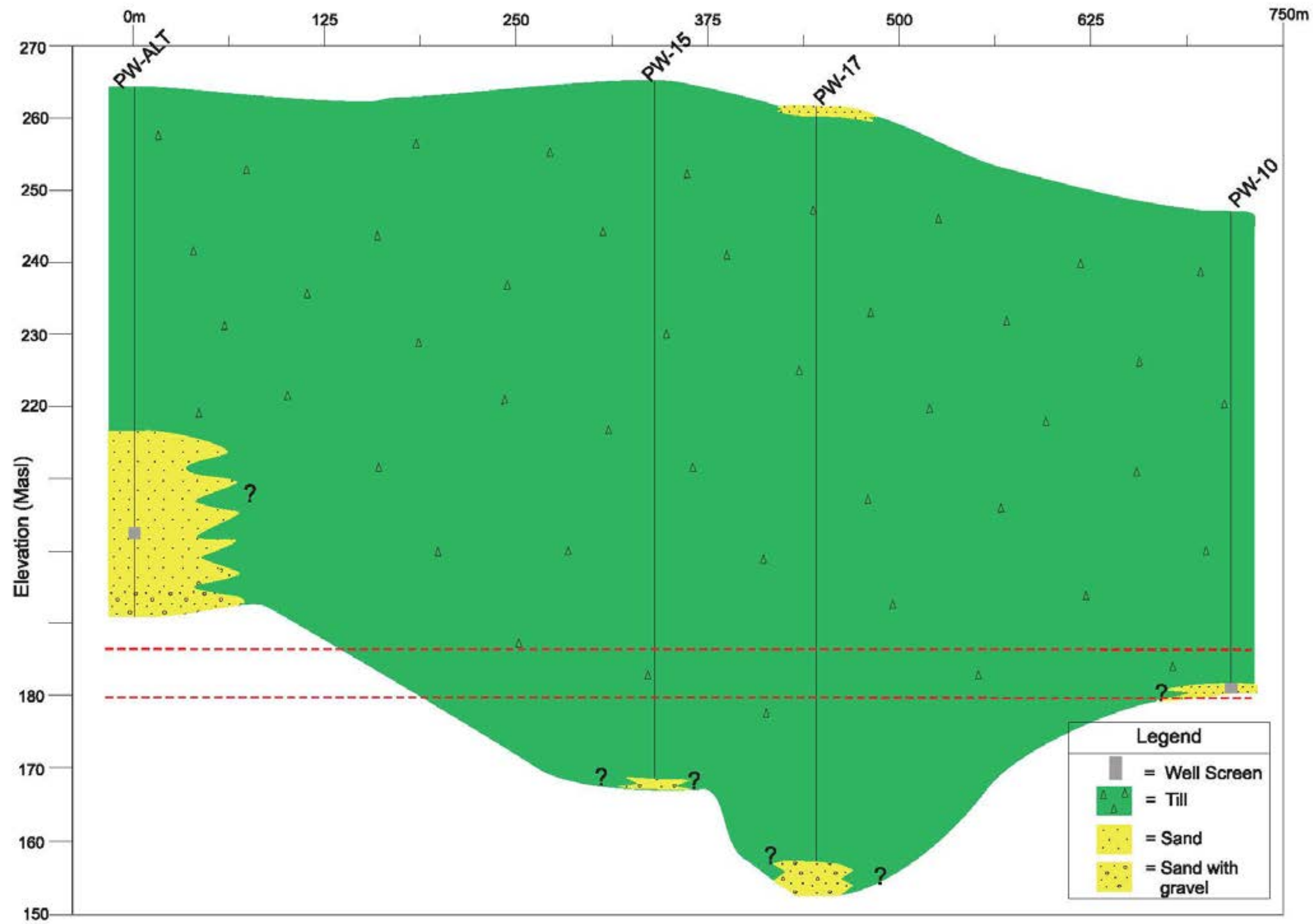


*Fig. 3.22: Private Well Cross-Section, exact orientation is not shown to respect privacy concerns. The Thornncliffe/ Newmarket Till transition zone where Thorncliffe sediments may have been entrained into the base of the Newmarket Till (**Red dotted line)** is located from 184 masl to 177 masl or 68 mbgs to 75 mbgs, determined from high-resolution. Private Wells without a screen indicate water intake is from bottom of the open well only. PW15, PW17, and PW10 are cable tool wells and PW ALT is drilled.*

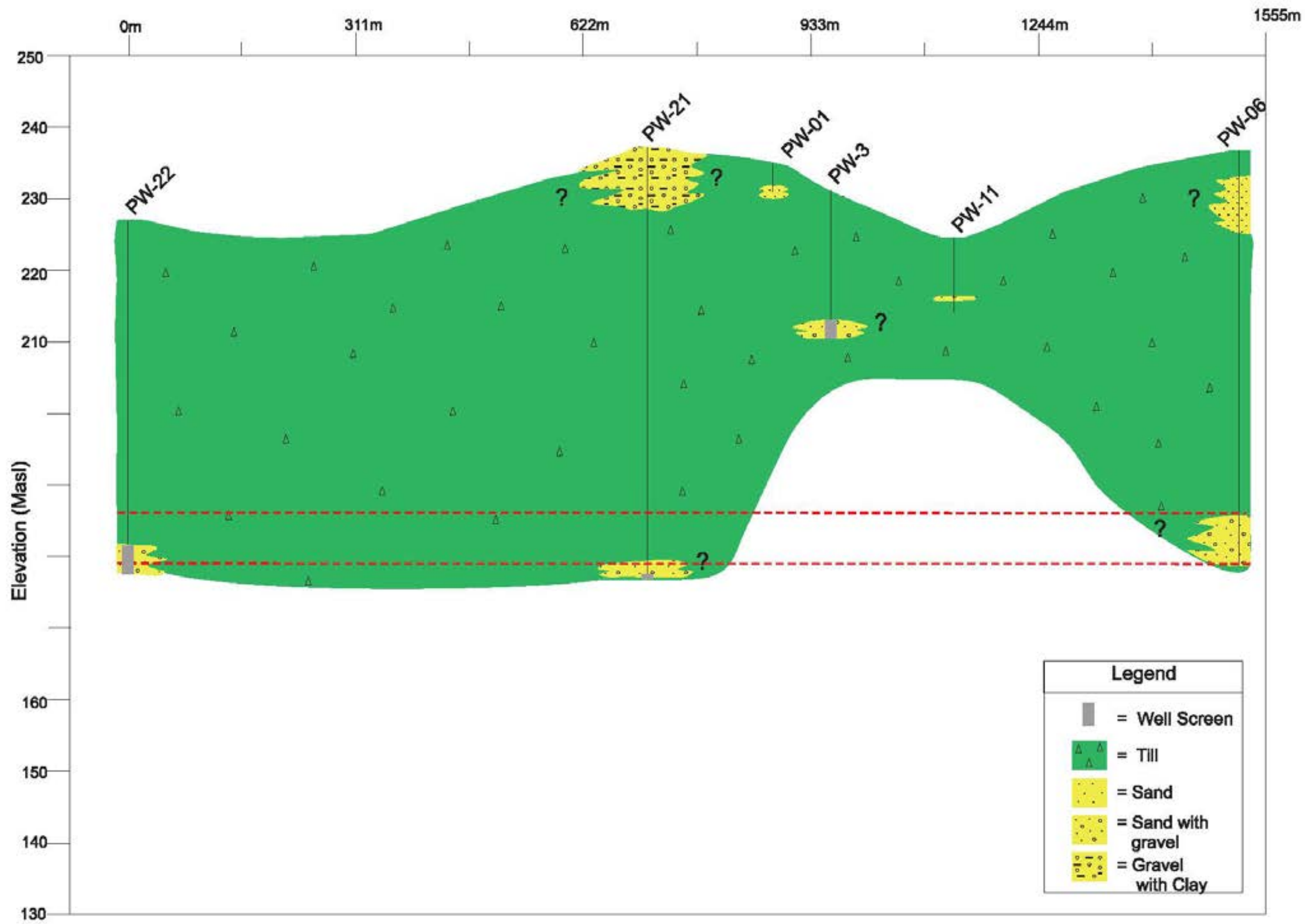


*Fig. 3.23: Private Well Cross-Section, exact orientation is not shown to respect privacy concerns. The Thorncliffe/ Newmarket Till transition zone (**Red dotted line)*** where Thorncliffe sediments may have been incorporated into the base of the Newmarket Till, *is located from 184 masl to 177 masl or 68 mbgs- 77mbgs , determined from high-resolution. Private Wells without a screen indicate water intake is from bottom of the open well only. PW21, PW03, and PW06 are cable tool wells; PW01 and PW11 are dug wells; and PW22 is drilled.*

lower sediments are approximately 65 m thick and additional data is needed to understand thickness variability of each formation at the local scale.

The Thorncliffe Formation is believed to be up to 50 m thick between Toronto and Pickering and thins to 20 m thick to the east (Chapter 4, Fig 4.5 displays Toronto and Pickering location). It also appears to have a planar upper surface near Scarborough, but more data is needed to know how planar these sediments are regionally (Sharpe et al. 2005a) as well as locally before the geometry of the Thorncliffe Formation can be defined across the site. Though many residential wells are believed to be within the Thorncliffe, it is unclear if the formation has high relief, and a 25-40 m difference between well PW ALT and PW15 (Fig. 3.22) sands provides evidence of this, or if many of these wells are actually screened within sand zones within the Newmarket Till above.

3.6 Site Conceptual Model

A conceptual model to bedrock, using the geological data of the present study and the geological interpretation to bedrock of Duggan (2016) is presented in Fig. 3.24 using transect D-D'. Unknown origin of till is at identified at surface with a shallow hydraulically active fractured/ weathered zone that will be discussed in the following chapters. The origin of sandy and clayey sediments and sand zones found at surface is also undetermined at this time.

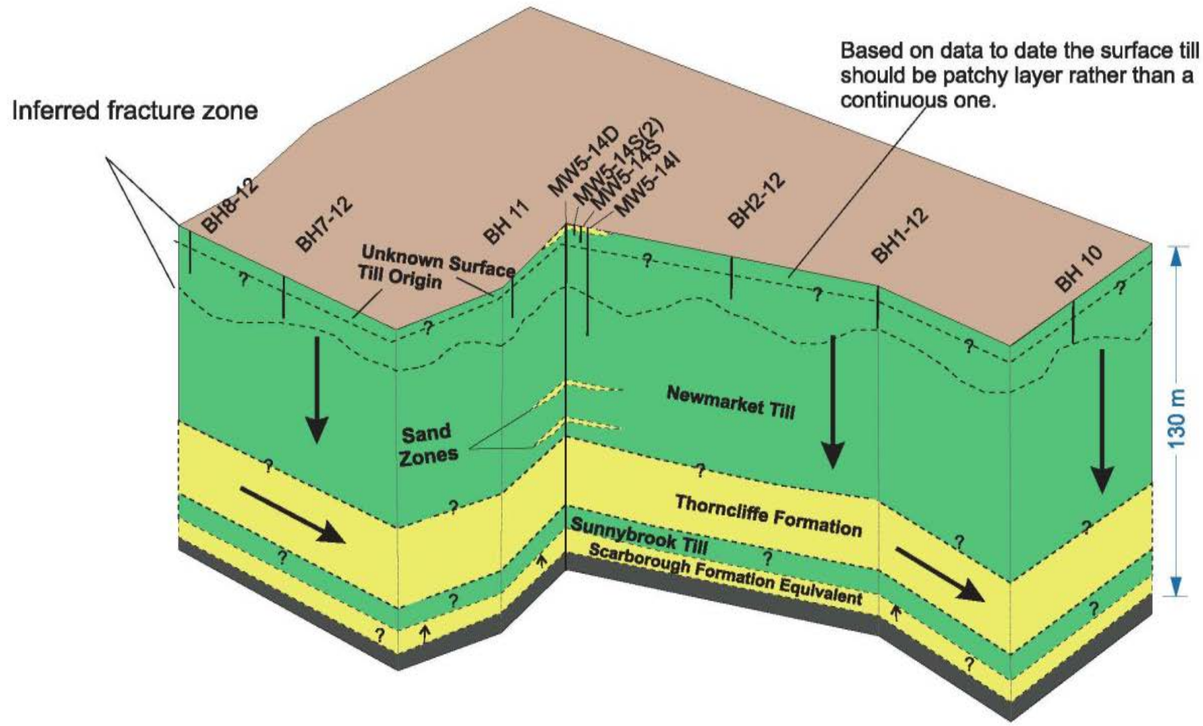


Fig. 3.24: Cross section D-D' depicted in a 3D conceptual model to bedrock. Geological interpretation below the Newmarket Till and Thorncliffe Formation based on Duggan (2016). Sand zones within the till are isolated, but may be connected by fractures and sand stringers within the till.distribution of sand zones are constrained only at the deep borehole, though they are expected throughout the Newmarket Till based on additional no recovery zones in the deep borehole and based on previous studies of the Newmarket Till (Gerber et al. 2001 and Boyce et a. 1995) The till aquitard integrity will be further informed by an extensive geochemical study in the later sections of this thesis. Thornclilffe formation thickness and depth variation at the site scale is not well constrained as most boreholes terminate at < 20 m depth. The Thorncliffe formation should be found at similar depths at large scales based on regionally available data (Sharpe et al. 2005a). Inferred fracture zone is discussed in later chapters. Arrows are groundwater flow directions based on water levels in MW5-14 cluster and existing literature on Thorncliffe aquifer (Gerber and Howard 2002).

This SCM model does not determine the origin of the surface till, and the competing hypotheses of Halton Till or Newmarket Till at surface from Stantec (2014 and 2015) and SLR (2015) (Fig. 3.5-3.7) highlights the fact the determining the surface origin of the Till is difficult at best. The lateral variability of lower sediments is unknown because low quality MOE data off site and relatively shallow depths of most of the boreholes on site does not allow for the determination of the contact between Newmarket Till and the Thorncliffe Formation.

The site conceptual model depicts sand zones found at depth that appear to be protected by a thick unit of till. The sand zones shape and lateral extent is unknown with current available borehole data, and hydraulic connections between the zones can only be inferred at this time with geochemical evidence discussed in chapters 4-7.

3.7 Conclusion

Based on high-resolution borehole data and wells on and off site it is determined that the Newmarket Till is present below the site however the origin of shallow till is still unknown, resulting in the scenario where shallow sands zones near 5 mbgs could be of Mackinaw age. The Transition to the lower sediment package is 75 mbgs and the zone of incorporated sediments is from lower package to the Newmarket Tills is estimated to be 68-75 mbgs, based on evidence of a change in the grain size of the diamicton and the presence of graded sands in sand zones above 75 m. Due to lack of high quality data on the site and unknown variability in lower aquifer systems, most residential wells near this transition are considered to be potentially connected with the Thorncliffe Formation.

3.8 Future work

To further confirm or deny the presence of Newmarket Till at surface, future work would involve very shallow grain size sampling and surface and downhole geophysics. Geophysically, the Newmarket Till can be used as a marker bed in the area due to the till's over consolidated nature. During our sampling on site, a hammer and chisel had to be used to collect sediment samples, as the unconsolidated material behaved almost like solid rock. This creates a signature seismic velocity of 2,200-3,000 m/s for unconsolidated sediment (Pugin et al. 1999) making the identification of the Newmarket Till relatively easy compared to other units. The weathered and less dense portions of the Newmarket Till has potential to create different seismic velocity measurements, which could make it difficult to determine near surface geology on seismic geophysics alone. To differentiate between the two tills, Halton sediments will produce higher gamma and conductivity readings than the Newmarket (Pullan et al. 2002) in downhole geophysical surveys. Assuming the grain size data between the two tills is different, the grain size analyses would also help to distinguish the Halton and Newmarket tills at surface. Combining downhole, surface geophysics, and grain size data has the potential to reduce the uncertainty of naming units in this glacial depositional environment.

More importantly in the context of understanding the groundwater flow system future work should include pumping tests within surface sands to determine their lateral extent and connectivity. The inability to name the till essentially does not affect the investigations of hydrogeological properties of sand zones at this site, and the vulnerability of these wells can still be determined by integrating the geological data with more high resolution hydraulic data.

Since many private wells are close to the transition from Newmarket to Thorncliffe, additional drilling of high-resolution boreholes would help to assess the thickness and variability of the Lower Sediments at this site. Additionally, large scale pumping tests could be used to determine the extent and connectivity of the sand in those wells, which may help constrain the stratigraphic context of the private wells. While previous studies have shown significant leakage through the Newmarket till (Gerber et al. 2001), the Thorncliffe aquifer should be more laterally extensive compared to a Newmarket sand zones such that the hydraulic signature obtained from pump tests may help constrain the stratigraphy on site.

4 Hydrogeology of site based on Tritium-Helium

A well informed hydrogeological model is a key component for assessing the potential contamination risk of nearby water sources. Tritium-Helium (^{3}H- ^{3}He) can be used as an environmental tracer to estimate the age of the groundwater and to improve the understanding of site-specific hydrogeology. At the Clarington TS site, tritium can be used to estimate the age of the groundwater, which in turn will inform the rate of recharge and leakage at depth. This tritium derived age is a direct result of groundwater velocity and residence times, and can aid in determining the origin of the groundwater itself (Murphy et al. 2011).

4.1 Basic Site Hydrology

Based on water level measurements in monitoring wells on site (Stantec 2015b) and in private wells offsite, the Clarington Transformer Station has shallow groundwater flow generally from the northeast to the southwest (Fig. 4.1). Limited data from wells within the same depth below ground surface, or water levels collected from around the same time of year, did not allow for the construction of a flow net. Other hydrologic characteristics of the site include a wetland to the north, surface water streams that flow towards the southwest and a watershed divide to the east of the site (Fig. 4.1). Private well flow direction, on the opposite side of the divide (Fig. 3.21) could not be determined due to continuously/periodic pumping for water supply, making it unknown if wells were recovered and at equilibrium during the collection of water levels.

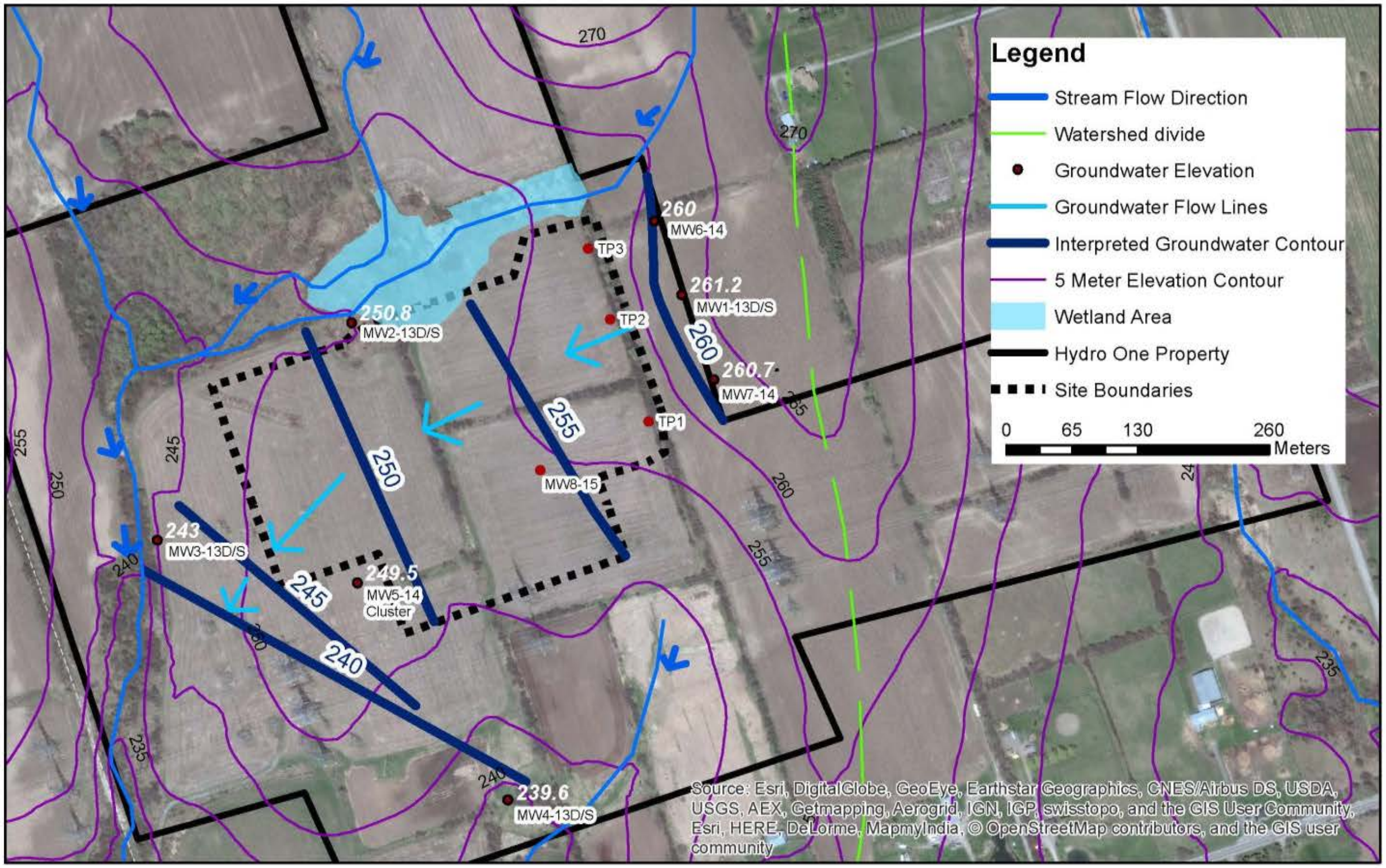


Fig.4.1 Surface water and shallow groundwater flow interpretation across the TS. Groundwater flows direction is to the southwest across the site. Water levels were collected in April 2015 by Stantec as part of the Hydro One groundwater monitoring programs (Stantec 2015b). The interpretation of groundwater flow direction is based on snap shot Stantec water levels prior to excavation at the TS.

Water levels in well 15 mbgs and above are all near or above surface in areas where wells are located near the wetland (Fig. 4.2). MW2-13D/S displays water levels above ground surface, as it is located near the wetland area marked in Fig. 4.1. Hydrographs corresponding to well nest MW1-13D/S and wells MW6-14 and MW7-14 show seasonal fluctuations in water levels greater than a meter, and MW2-13 displays fluctuations in water levels up to a meter (Fig. 4.3 and 4.4). Seasonal fluctuations of less than 50 cm are usually not considered hydraulically active and fluctuations of greater than 2 m is considered considerably active material and also provides evidence of preferential pathways in low flow material (Ruland et al. 1991). Hydrographs in wells nests MW1-13D/S and MW2-13D/S show excellent evidence of the presence of secondary permeability due to their almost identical magnitude of water level fluctuations and with almost no lag or muting between each response. Fluctuations in single wells MW6-14 and MW7-14 also displayed the same >1m fluctuation in water levels suggesting the till material is not behaving like a porous medium, and that preferential pathways must be present (Fig. 4.4). A detailed water budget of the site was not carried out as part of this thesis because the data needed is currently not well constrained. However, once additional data are collected at the site (including the multilevel monitoring well presented in Duggan 2016), a water budget would be valuable in better understanding the groundwater flow system in this area.

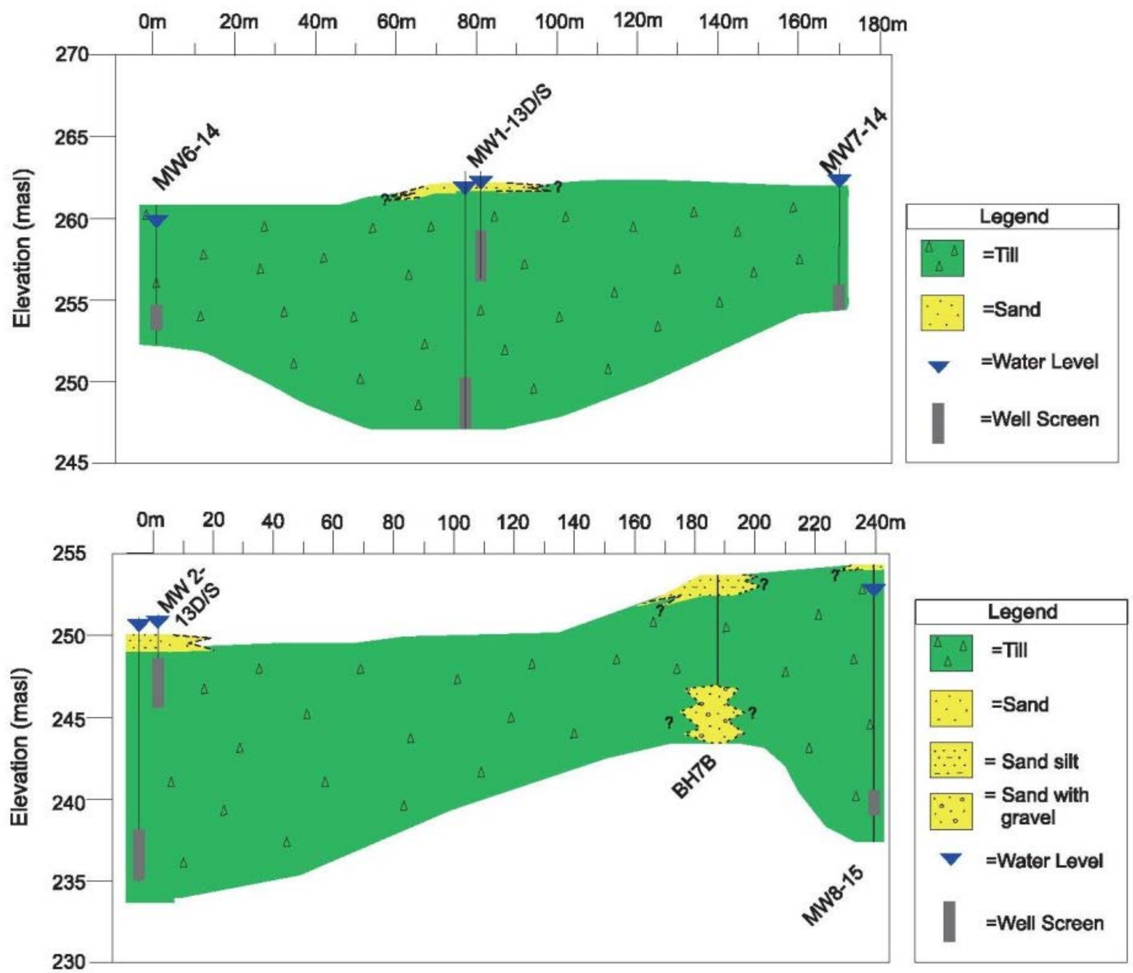


Fig. 4.2: Cross sections of water levels close to or above surface associated with MW nest and MW on site. Cross sections are perpendicular to shallow groundwater flow and well locations can be seen in Fig 4.1. Water levels are collected by Stantec in April 2015.

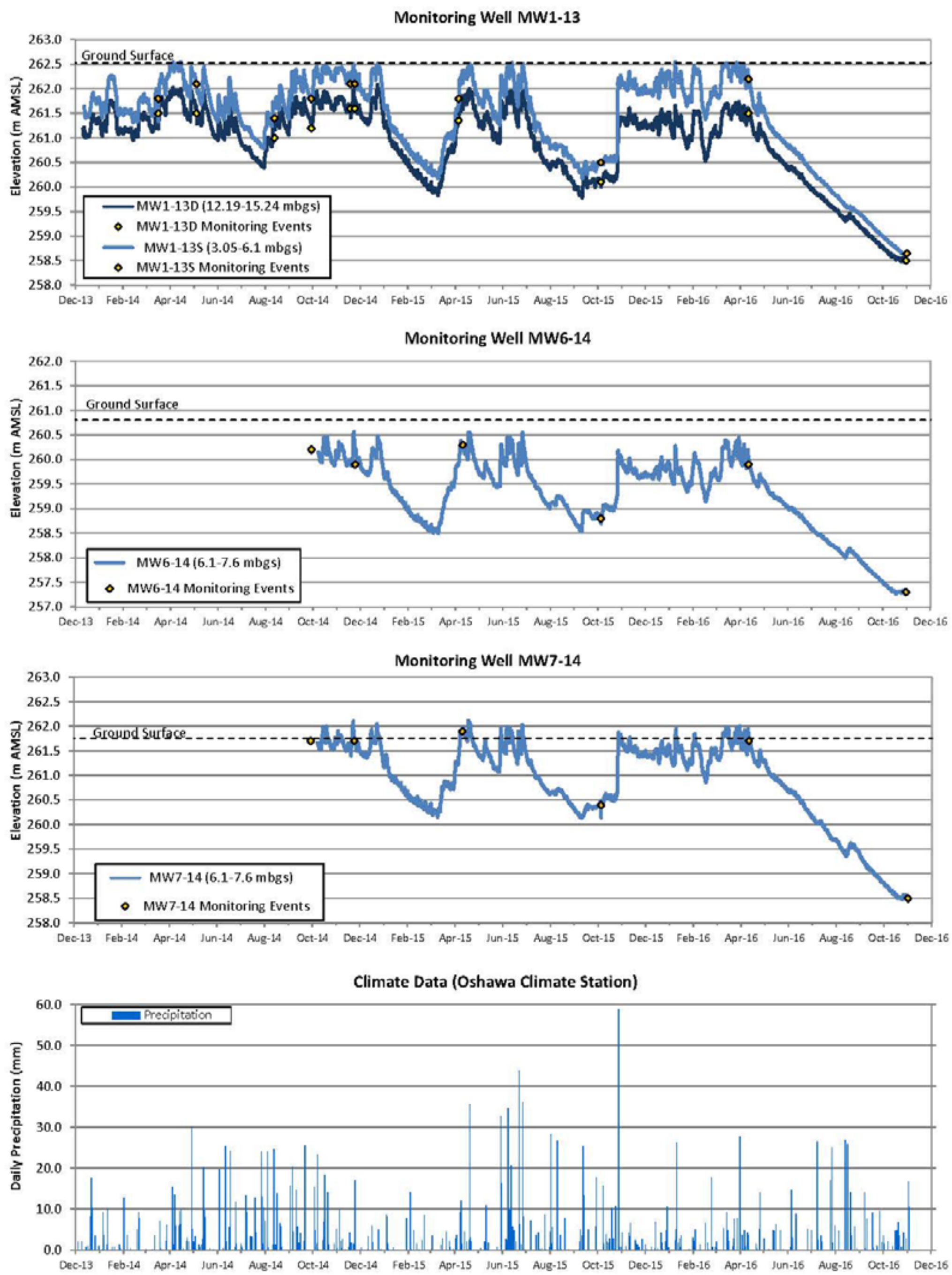


Fig. 4.3: Hydrographs of MW in Fig. 4.3 (top)cross sections. Seasonal fluctuations in water levels >1 m are large for porous medium, and response to precipitation is almost identical with almost no lag between shallow and deep wells suggesting presence of fractures. (See text for discussion)

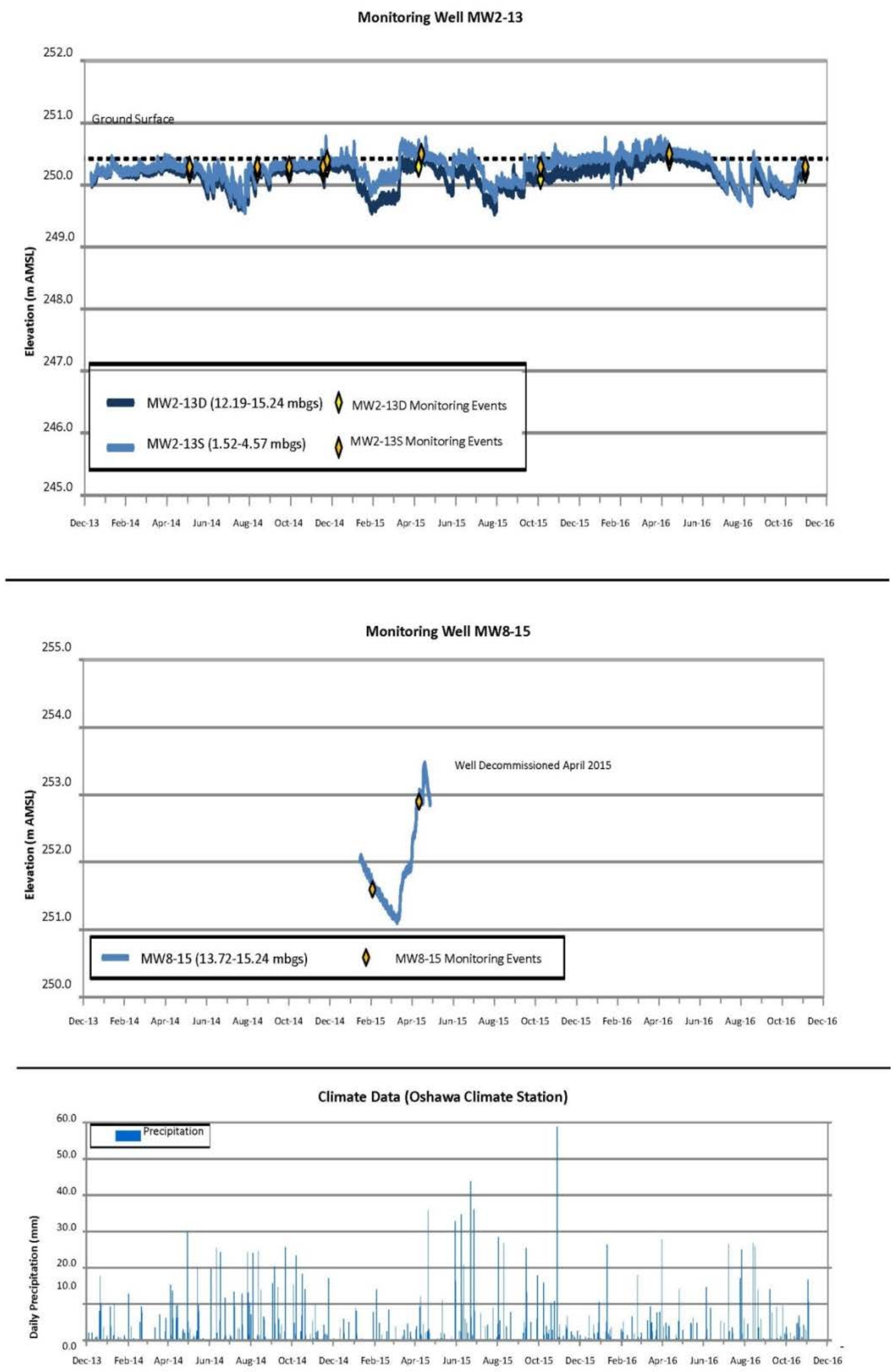


Fig. 4.4: Hydrographs of MW in Fig. 4.3 (bottom) cross sections. Seasonal fluctuations in water levels up to 1 m are large for porous medium, and response to precipitation is almost identical with almost no lag between shallow and deep wells suggesting presence of fractures. MW2-13 is located near a wetland and can be seen in fig. 4.1. (See text for discussion)

4.1.1 Existing Hydrogeological SCM

Existing Hydrogeological models summarized in this section, were completed prior to this study. These SCMs will be assessed in future sections, as both imply that vertical leakage is very slow at this site. Stantec's (2014) hydrogeology model included the use of twelve (12) monitoring wells and twenty-three (23) private wells. The estimated hydraulic conductivity of the upper aquitard ranged from $2x10^{-7}$ to $7x10^{-9}$ m/s and the hydraulic conductivity from the lower portion of the aquitard in well MW5-14I (40 mbgs) was estimated at $1x10^{-9}$m/s based on slug test results. Groundwater levels were measured from fall 2013 to fall 2014 and a downward vertical gradient of 0.6m/m was calculated from MW5-14S and private wells within the Thorncliffe aquifer. Based on these data, the estimated rate of leakage is 18mm/yr, giving a vertical travel time of over 700 years (Stantec 2014). Stantec (2015b) reports the downward hydraulic gradients within the shallow or upper aquifer are consistent with the ones reported in the Stantec (2014) report, and no change in travel times or hydraulic conductivity times were reported.

SLR (2015) estimated that recharge to the Thorncliffe aquifer is from an area 6,000m north of the site and typical travel times within the aquifer are reported to be 105 m/yr estimated from tritium concentrations collected prior to this study. SLR (2015) suggested that vertical leakage within the till is approximately 0.05m/yr, which would make the groundwater 1,500 years old. Due to these travel estimates, vertical leakage was ruled not plausible due to the estimated groundwater age of 57 years old based on tritium concentrations from within the aquifer sampled in 2015. Tritium samples from 2015 are further discussed below together with those collected for this study.

The strong vertical gradients at this site were interpreted to be an indication that the aquitard was providing adequate protection to the lower aquifers systems. Duggan (2016) calculated the largest drop in hydraulic head toward the bottom of the till from 51.7 mbgs to 55 mbgs with a vertical gradient of 2m/m. Larger vertical gradients do not automatically exclude the possibility of a preferential pathways (Cherry et al. 2006), and should not automatically imply that the aquitard is providing adequate protection.

4.2 Tritium-Helium Background

Before the ^{3}H- ^{3}He technique was developed, analysis of tritium concentrations alone was used to date groundwater. The tritium peak of 1963 was very useful for tracing groundwater, but has since been flushed out from most groundwater systems or is highly attenuated by dispersion/decay. Using the tritium exponential decay equation (4.2.1) requires the knowledge of initial tritium (T_0) concentration and assumes no effect from hydrodynamic dispersion and the more time has passed since the 1963 tritium peak, the less useful dating groundwater from a decay equation becomes (Clark 2015).

$$t = -17.77 ln \frac{T_t}{T_0} \qquad (4.2.1)$$

where t = Time T_0= Initial concentration T_t=Tritium Concentration

Tritium-helium analysis is completed by measuring concentrations of daughter product, helium-3 (^3He), produced from the β decay of Tritium (Gudkov et al. 2014). Testing for tritium and helium simultaneously allows for this type of groundwater dating to continue as the tritium signal decays further. Spring peaks and seasonal fluctuations of tritium can make estimating T_0 difficult, unless seasonal changes are observed over long periods. Using tritium and He^3 combined allows for the age of groundwater to be measured down to a scale of months, with greater accuracy than estimations from tritium values alone. Substituting in He^3 and rearranging equation 4.2.1 removes T_0 (equation 4.2.2) allowing time (t) to be calculated with less error than the simple decay equation (Clark 2015).

$$He^3 = T_t\,(e^{\lambda t} - 1) \tag{4.2.2}$$

Where He^3 = Helium Concentration; T_t=Tritium Concentration; λ=Decay Constant; and t=Time.

All the tritium and helium calculation should be used as a mean age, meaning groundwater can be a mixture of very old and very young water. The use of tritium, tritium-helium and other isotopes used for groundwater age dating has a major complicating factor when the flow occurs in fractured porous media where flow in the fractures dominates all flow and the porous matrix blocks between the fractures have low permeability but substantial porosity. The interpretation of the age dating isotopes requires a different conceptual model than is the case for granular porous media on which almost all of the literature on isotope age dating is based.

This complication is relevant to the Clarington site because bulk flow in the Newmarket Till may be governed by fractures in some parts or perhaps all parts of this geologic unit. The complication in fractured porous media arises because of diffusion-driven mass transfer of isotopes from the fractures, where they are being transported, into the low permeability matrix that has relatively large volume of pore water, which is immobile or nearly so. This effect known as the ‘matrix diffusion effect’ (Foster 1979) causes loss of the isotope such as tritium from the active flown system. This loss caused by diffusion results in the apparent age of the groundwater, as sampled from wells, to be artificially older than the “age” based on the calculated travel time of the bulk flow of the groundwater (Freeze and Cherry 1979). Farah et al. (2012) shows the effects on tritium used for aquitard integrity assessments.

It should also be noted that if leakage through fractures or secondary permeability features is occurring, diffusion into the matrix may have a compounding effect on the tritium-helium groundwater age equation used in this thesis. This is because helium has a higher diffusion coefficient or is more strongly retarded by matrix diffusion than tritium, which could lead to incorrect ratios of tritium to helium in the groundwater age equation leading to an underestimation of age (Aeschbach-Hertig et al. 1998).

4.3 Previous work

The Clarington TS is located between the Pickering Nuclear Power Plant to the SW and the Darlington Nuclear Power Plant to the SE (Fig. 4.5). Both of these power plants report annual monitoring information, specifically tritium concentrations in precipitation and groundwater, collected from the Ontario Power Generation (OPG) (OPG 2015) (Fig. A5). Tritium concentration in precipitation data from 2-3km south of the TS site at monitoring station DF12 (Fig. 4.5) contains tritium with values ranging from 59 - 93 TU (2009 to 2012; n=4) whereas groundwater values ranged from 36 – 51 TU (2009 to 2015; n=7). The city of Oshawa water supply has tritium values that range from 47 - 78 TU (2005 to 2015; n=11) (Fig. A5) (OPG monitoring reports). Precipitation data from the DF12 site may provide a good approximation of the equally distributed source tritium concentration during recharge at the TS.

Previous tritium analyses have been carried out in the vicinity of the Clarington TS. These analyses were completed on water samples from private wells at various locations around the site in 2015. Due to privacy laws, exact locations of the sampled wells are not displayed (Fig. 3.21). Six (6) total wells were sampled for tritium including PW10, PW21, PW01, PW03, PW06, PW18 (Figs. 3.22 and 3.23). The results from this study showed both low and elevated concentration levels of tritium (TU) ranging from 0.8 to 47.1 TU at depth (Table 4.1).

The tritium peak, once used for groundwater dating, has been attenuated by decay, meaning residence times cannot be calculated with these tritium values alone. In this case, a qualitative analysis can be done using the relationship of higher TU values corresponding to younger or recent groundwater recharge, and lower TU values corresponding to older more protected aquifer systems.

4.4 Sampling/Methods

Sampling of dissolved He^3 was completed by installing diffusion samplers (Fig. A6) in six (6) wells, including PW03, PW06, PW10, PW17, PW-ALT, and PW-21 for the duration of a week. The wells were chosen based on the criteria that wells were constructed with steel casing and had sufficient data from the MOE water well record including geology and well construction details. Steel casing wells were preferred over concrete wells to help reduce the possibility of poorly sealed wells, creating a connection directly from surface.

4.4.1 Diffusion Samplers- Helium measurement

The diffusion samplers were made of gas-permeable silicon tubing attached to sealed copper tubes that allows for gas to diffuse into the sampler while keeping the polar water molecules out (Clark 2015) (Fig. A6). Two diffusion samplers were suspended in

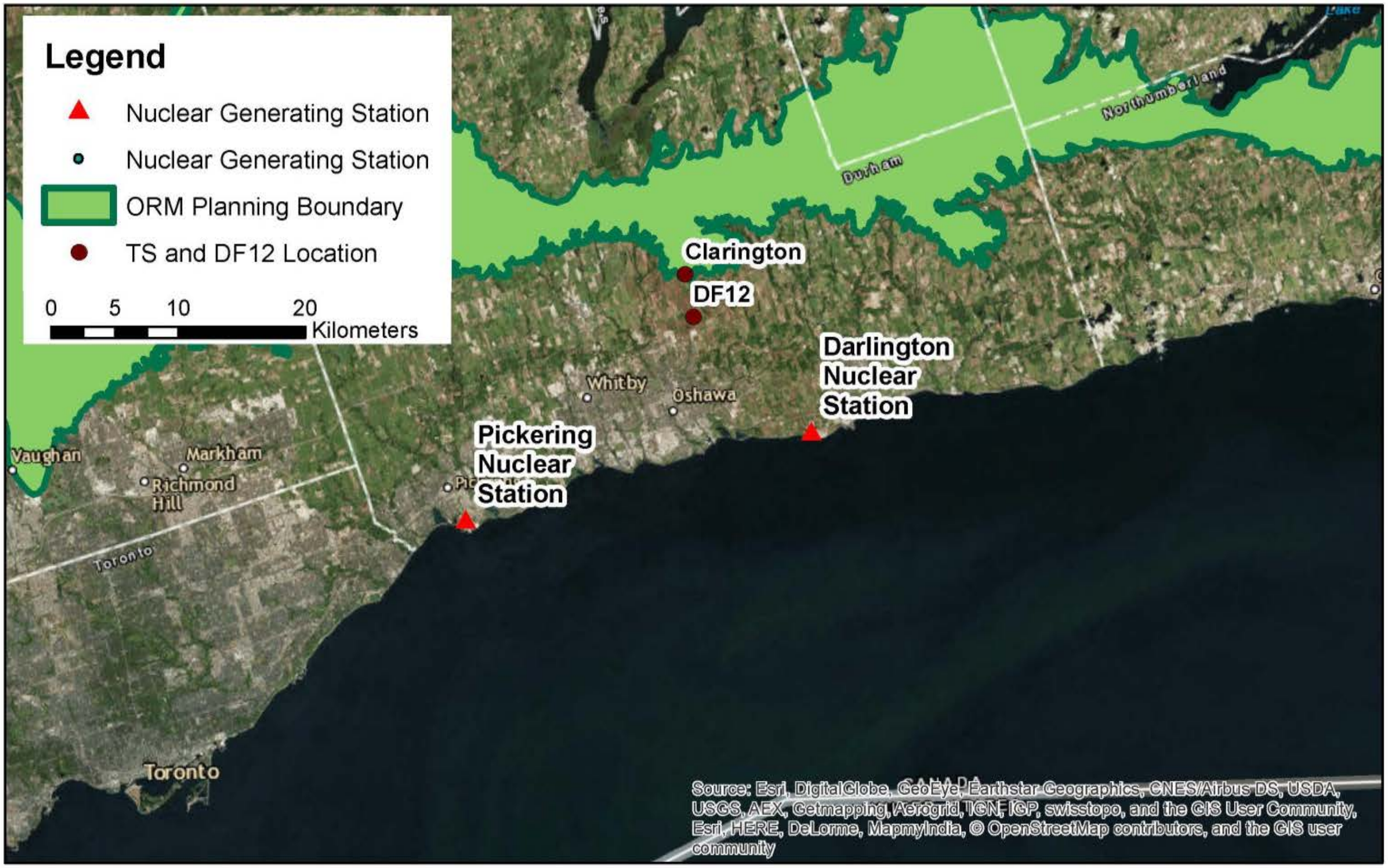


Fig.4.5 Map showing location of the DF12 tritium monitoring station associated with the Pickering and Darlington Nuclear Power Plants (OGS 2015). The monitoring station is located 15 km NW of the Darlington Nuclear Power Plant and approximately 2-3 km south of the TS. TU values reported in Fig. A7

Private Well ID	Depth (mbgs)	TU	TU ±	Stratigraphic unit
PW10	65.8	21.2	1.8	Newmark/Thorn Transition
PW21	61.0	1.5	0.7	Newmark/Thorn Transition
PW01	3.66	47.1	1.8	Surface Till/ Newmarket
PW06	57.9	2.1	0.5	Newmarket
PW03	18.9	38.3	2.2	Newmarket
PW18	76.2	0.8	0.8	Newmark/Thorn Transition

Table 4.1: Tritium (TU) concentration in private wells located in cross section figs. 3.22 and 3.23, from the original tritium study from August 2015 by local residents. Newmark/Thorn Transition refers to the interval between 68-75 mbgs where sand zones within the Newmarket Till are thought to be Thorncliffe sediments entrained by ice during deposition of the Newmarket Till.

each well for duplicate analysis. The diffusion samplers were suspended below the lowest water level recorded from the supply wells to ensure the samplers were submerged during the sampling duration. The samplers were installed using fishing line and metal anchor outside of the well casing (Fig. A7). After a week, the samplers were removed and the copper tubing was crimped and protected with silicon ends to ensure a proper seal during shipping (Figs. A8 and A9).

The analysis is completed by separating the noble gases from reactive gases using cryogenic traps getter pumps (Ian Clark, Pers. Comm. 2017). The separated gases are then analyzed for Helium-3, Helium-4, Neon-20, and Neon-22 concentrations using a Helix split flight tube (SFT) noble gas spectrometer at the A.E Lalonde AMS Laboratory located at the University of Ottawa.

4.4.2 Tritium

Tritium levels were determined by collecting two 500ml Nalgene bottles of water from each private well. The water samples were analyzed using an electrolytic enrichment method to establish tritium levels. Electrolytic enrichment reduces the detection to 0.8 ± .8 TU or better (Clark 2015) improving the detection limit, from other direct count methods by an order of magnitude. The sample was analyzed by the Quantulus liquid scintillation counter at the A.E Lalonde AMS Laboratory located at the University of Ottawa.

4.4.3 Hydraulic Gradients and Triaxial permeability

Hydraulic gradients and triaxial permeability values allow for groundwater age calculations to be compared directly to hydraulic properties on site. The values will later be used for the calculations of vertical fluxes associated with the aquitard to see if the calculated travel times agree with the geochemical analysis on site. Five (5) monitoring well nests installed by Stantec Consulting Ltd, allow for vertical gradients within the Newmarket aquitard to be calculated. Calculations are completed by using water levels of monitoring wells that were collected by Stantec Consulting Ltd. In April 2015.

Triaxial permeability samples were collected from the high-resolution borehole recovered core to allow for the analysis of the matrix hydraulic conductivity and were analyzed by Golder Associated Ltd. Twelve (12) inch cores were collected at various depths, wrapped in plastic wrap, and put into a Ziploc bags removing as much air as possible.

Combining the calculated hydraulic gradients, with the average value of triaxial hydraulic conductivity ($4.7x10^{-10}$m/s), allows for the vertical component of Darcy flux to be calculated (equation 4.4.3.1) through the Newmarket aquitard.

$$q = -K \frac{dh}{dl} \qquad (4.4.3.1)$$

q= Darcy Flux (m/s); *K*= Hydraulic Conductivity; and *dh/dl* = Hydraulic Gradient

Where clay content is from 10-15%, it is expected the triaxial permeability results will provided very low hydraulic conductivity values, meaning the effective bulk hydraulic conductivity should behave as clayey aquitard unless preferential pathways are presents such as fractures (Cherry et al. 2006). Triaxial permeability samples provide small scale matrix properties of the aquitard, meaning the effective bulk vertical hydraulic conductivity may not be represented in the lab derived hydraulic conductivity numbers. The probability of the core samples including vertical fractures or heterogeneities is low, and comparison to slug tests can provide evidence of missed horizontal fractures and heterogeneities if hydraulic conductivity values differ (Cherry et al. 2006). Though slug test are controlled mostly by horizontal features within the till, which make for direct comparison to core sample difficult, the slug test can still provide evidence of internal heterogeneities that are not represented in a small scale core sample (Cherry et al. 2006).

4.4.4 Groundwater age calculation

Groundwater age is calculated after the analysis of the diffusion samplers is complete, and values of total He-3, He-4, Ne-20, and Ne-22 within the copper tube are produced ($^{3}He_{in\ cu}$,$^{4}He_{in\ cu}$.,$^{20}Ne_{in\ cu}$, $^{22}Ne_{in\ cu}$). For the purposes of this study, concentration of He-3 and Ne-20 within the diffusion samplers and within a standard air sample will be used to date the groundwater.

The first step in calculating the amount of tritiogenic ^{3}He in groundwater, is to correct for dissolved atmospheric He and Ne using the temperature–solubility equation (equation 4.4.4.1 and 4.4.4.2). Where He_{diss} , Ne_{diss}, and $^{20}Ne_{diss}$ is equal to the helium/neon/neon-20 solubility in water at a recharge temperature (T).

$$He_{diss} = 4.07x10^{-12}T^2 - 2.58x10^{-10}T + 4.89x10^{-8}cc/cc_{H_2O} \quad (4.4.4.1)$$

$$Ne_{diss} = 2.50x10^{-11}T^2 - 2.31x10^{-9}T + 2.28x10^{-7}cc/cc_{H_2O} \quad (4.4.4.2\ A)$$

$$Ne^{20}{}_{diss} = (2.50x10^{-11}T^2 - 2.31x10^{-9}T + 2.28x10^{-7}) * Ne^{20}{}_{air}$$

$$cc/cc_{H_2O} \quad (4.4.4.2\ B)$$

Where He_{diss}= Helium solubility; Ne_{diss}=Neon solubility; $Ne^{20}{}_{diss}$=Neon-20 solubility; $Ne^{20}{}_{air}$=Neon-20 in air; and T= Recharge temperature

Henry's law is used to determine dissolved concentration of helium in water. By assuming an ideal gas, He_{diss} and Ne_{diss} are normalized to a Bunsen Coefficient (∝) and divided by atmospheric Helium or Neon, then multiplied by the He and Ne concentrations measured within the diffusion samplers ($He_{in\ Cu}$ and $NE_{in\ cu}$). These calculations are completed for isotopes helium-3, and Neon-20 separately.

$$(He^3, Ne^{20})_{H_2O} = \frac{(He,Ne)_{diss}}{(He,Ne)_{Total\ in\ air}}\ x\ (He^3, Ne^{20})_{in\ Cu} \quad (4.4.4.3)$$

Where He^3_{H2O}, Ne^{20}_{H2O}=Helium/Neon Concentration in Water; $He_{total\ in\ air}$= Atmoshperic concentration of Helium; $He^3_{in\ Cu}$,$Ne^{20}_{in\ Cu}$= Neon and Helium concentration in diffusion samplers; and $(He,Ne)_{diss}$ is calculated from results of Equations 4.4.4.1 and 4.4.4.2 A.

Equation 4.4.4.4 and 4.4.4.5 are used to calculate He_{excess} acquired from atmospheric air.

$$Ne_{excess\ in\ air} = \frac{\left[\frac{(Ne^{20}{}_{H_2O} - Ne^{20}{}_{diss})}{Ne^{20}{}_{air}}\right]}{Ne_{total\ in\ air} * Ne^{20}{}_{air}} \qquad (4.4.4.4)$$

$$He_{excess} = Ne_{excess\ in\ air}\ x\ He_{total\ in\ air} \qquad (4.4.4.5)$$

Where $Ne_{excess\ in\ air}$=Ne acquired from excess air; Ne^{20}_{H2O} is from Equation 4.4.4.3 Ne^{20}_{diss} is from Equation 4.4.4.3 B; Ne^{20}_{air}= Neon-20 Concentration from standard air sample; and Ne $_{total\ in\ air}$=Total neon concentration from standard air sample

Tritiogenic He^3, meaning the concentration of Helium-3 in groundwater from β decay only, is calculated using equation 4.4.4.6.

$$He^3{}_{trit} = He^3{}_{H_2O} - (He_{diss} x\ He^3{}_{air}) - (He_{excess}\ x\ He^3{}_{air}) \qquad (4.4.4.6)$$

Where He^3_{trit}=Helium from β Decay; $^3He_{H2O}$ is from equation 4.4.4.3; He_{diss} is from equation 4.4.4.1; He^3_{air}=Helium concentration in standard air sample; and He_{excess} is from equation 4.4.4.5

The measured tritiogenic He^3 in equation 4.4.4.6, represents the amount of He^3 produced from the decay of tritium. He_{trit}^3 and measured tritium concentration can then be used to calculate time (t) by rearranging the decay equation (4.2.2).

$$t = 17.77xln\left(1 + \left[\frac{He^3{}_{trit}}{T_t}\right]\right) \quad (4.4.4.7)$$

Where t=Time; He^3_{trit}= Tritigenic He^3; and T_t=Tritium Concentration

The ratio He_t^3/T_t is the concentration ratio expressed in tritium units, requiring the conversion of Helium units, cc at STP per cc to tritium units (TU). The conversion is completed using the ideal gas law and the moles of H in a cubic centimeter of water.

To allow for comparison of the age of groundwater to hydrogeological properties found around the site, a velocity and a Darcy flux must be calculated. A simple calculation using distance, velocity, and porosity provides an estimate of the average pore water velocity needed to allow for ≤20 year old groundwater at these depths. Rearranging the equation for travel time, produces the average linear pore water velocity ($\overline{V}$) in m/s by using the age of the ground water, time (t) in seconds, and the depth of the well (D) in meters.

$$\overline{V} = \frac{D}{t} \quad (4.4.4.8)$$

Using the average linear pore water velocity from equation 4.4.4.8 and estimated porosity (n), an estimation of Darcy flux (q) can be calculated.

$$q = \bar{v} * n \qquad (4.4.4.9)$$

This estimate allows for direct comparison to the Darcy Flux calculated from hydraulic gradients and triaxial permeability samples from equation 4.4.3.1 to the Darcy Flux calculated from the average vertical velocity calculated from equation 4.4.4.8 by using the groundwater age estimates, and intrinsic properties of the till in equations 4.4.4.9.

The estimated porosity of the Newmarket aquitard on our site is 0.26 as determined by Duggan (2016), based solely on data collection from the continuously cored high resolution borehole and calculated using an average of diamicton on grain size samples within the till. Porosity of Newmarket Till can be as low as 0.11 in some areas, which would slightly affect the Darcy flux velocities and future work should be completed to further asses the best porosity value to use in these calculations.

4.5 Results

Water levels from five (5) monitoring well nests (Fig. 4.6) summarized in Table 4.2 produced vertical hydraulic gradients that ranged from 0-1.6 and previously reported slug test values, with shallow wells ranging from $1.3x10^{-5}$ to $8.6x10^{-8}$ m/s and deeper wells ranging from $8.7x10^{-6}$ m/s to $1.3x10^{-7}$ m/s (Table 4.3)(Fig 4.6). Triaxial permeability samples at various depths ranged from $1.05x10^{-9}$ to $1.88x10^{-10}$ m/s and averaged $4.74x10^{-10}$ m/s (Table 4.4) (Fig. 4.7), producing vertical Darcy Flux values ranging from $1.67x10^{-10}$ to $2.67x10^{-11}$ and average $3.88x10^{-10}$ m/s (Table 4.3). Table 4.4 and Figure 4.7

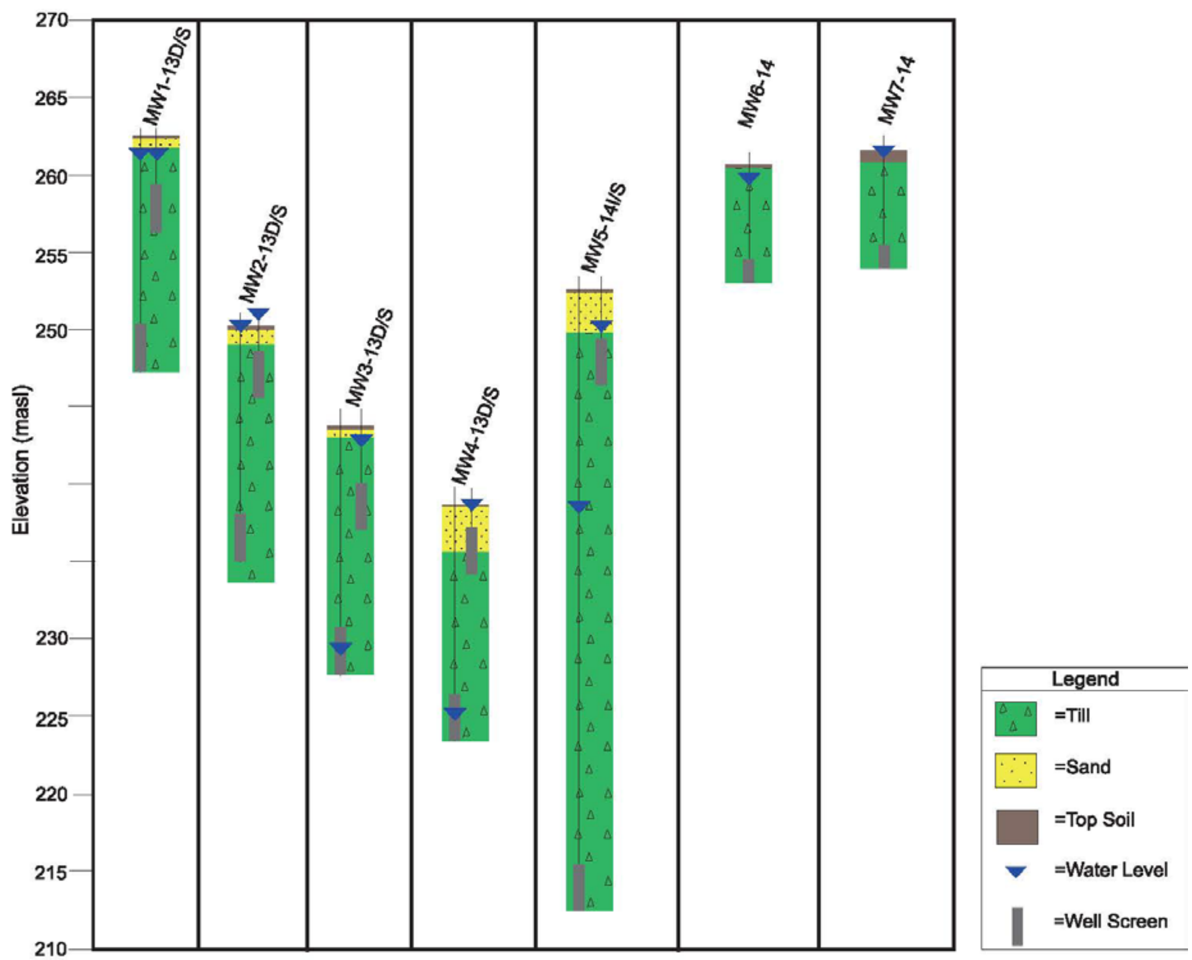


Fig. 4.6: Well nest water levels used for calculations of hydraulic gradients. Monitoring wells are displayed in meters above sea level and do not indicate location. The static water levels of the deep high resolution borehole are presented in fig. 4.7 as reported by Duggan (2016). Locations of well nests can be seen in Fig. 3.2.

Well ID	Depth (mbgs)	Water Level (mbgs)	Depth (masl)	Ground Surface (masl)	water level (masl)
MW1-13D	15.24	1.3	247.3	262.5	261.2
MW1-13S	6.1	1.3	256.4	262.5	261.2
MW2-13D	15.24	0.2	235.2	250.4	250.2
MW2-13S	1.57	-0.4	245.8	250.4	250.8
MW3-13D	15.24	14.73	228.7	244.0	229.3
MW3-13S	6.71	0.87	237.3	243.9	243
MW4-13D	15.24	13.7	223.5	238.7	225
MW4-13S	4.57	0.3	234.2	238.9	238.6
MW5-14I	40.1	14.6	212.5	252.6	238
MW5-14S	6.1	2.6	246.5	252.6	250

Table 4.2: Summary of pre-existing well nest (locations in figure 4.1) depths and water levels collected by Stantec consulting, to be used in calculation of vertical gradients around the site.

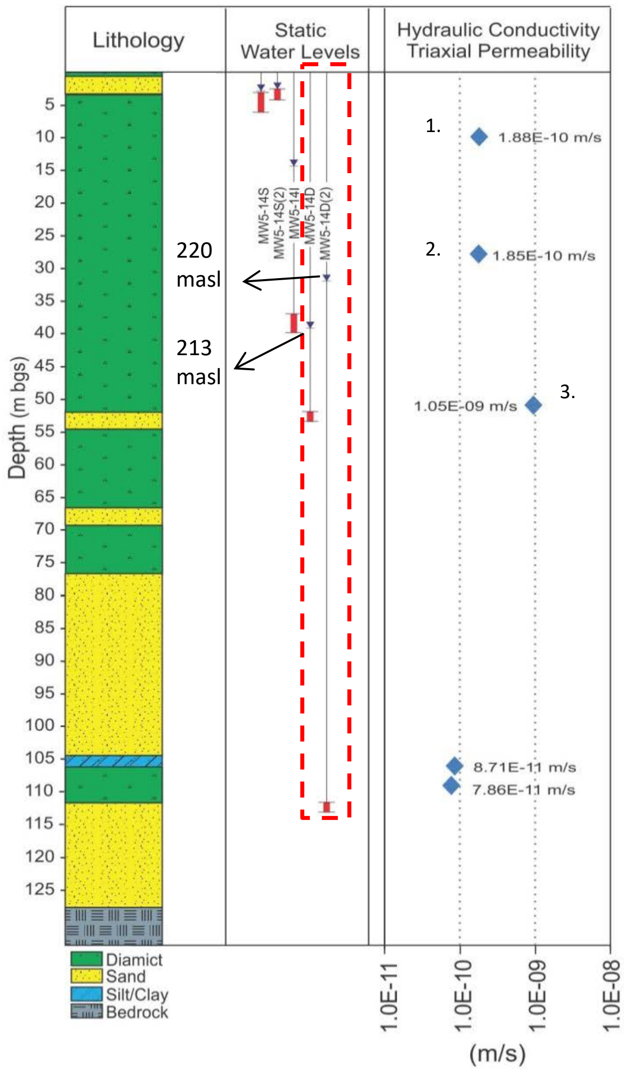
Well ID	Stantec (2014) Slug Test (m/s)	Well ID	Gradient	Triaxial Permeability Vertical Darcy Flux (m/s)
MW1-13D	8.70E-06	MW1-13D		
MW1-13S	8.60E-08	MW1-13S	0	-
MW2-13D	9.90E-08	MW2-13D		
MW2-13S	1.50E-07	MW2-13S	0.06	2.67E-11
MW3-13D	-	MW3-13D		
MW3-13S	7.20E-09	MW3-13S	1.6	7.54E-10
MW4-13D	-	MW4-13D		
MW4-13S	1.30E-05	MW4-13S	1.3	6.05E-10
MW5-14I	1.30E-09	MW5-14I		
MW5-14S	1.60E-05	MW5-14S	1.4	1.67E-10

Table 4.3: Slug test values are from Stantec (2014). Calculated Gradients for the purpose of this thesis with data summarized in table 4.2 and calculated vertical Darcy Flux from vertical gradients and triaxial permeability data in table 4.4.

Location of Triaxial Permeability Samples				
Sample ID	Top Depth (masl)	Bottom Depth (masl)	Sediment Description	Hydraulic Conductivity (m/s)
CLA-MW5-14D-TP-001	242.8	242.49	Diamicton	1.88E-10
CLA-MW5-14D-TP-002	224.76	224.45	Diamicton	1.85E-10
CLA-MW5-14D(2)- TP-004	201.69	201.39	Diamicton	1.05E-09

Sample ID	Top Depth (mbgs)	Bottom Depth (mbgs)	Triaxial Data from Upper Newmarket (m/s)	Closest Grain Size Sample Midpoint (mbgs)	clay content < 2 um (%)
CLA_MW5-14D-TP-001	10.06	10.37	1.88E-10	8.59	13.21
CLA-MW5-14D-TP-002	28.1	28.41	1.85E-10	31.44	13.27
CLA-MW5-14D(2)-TP-004	51.17	51.47	1.05E-09	49.74	12.64

Table 4.4: Triaxial permeability sample locations and corresponding hydraulic conductivity (m/s) and grain size results collected in December 2014 collected by the University of Guelph and McMaster team.



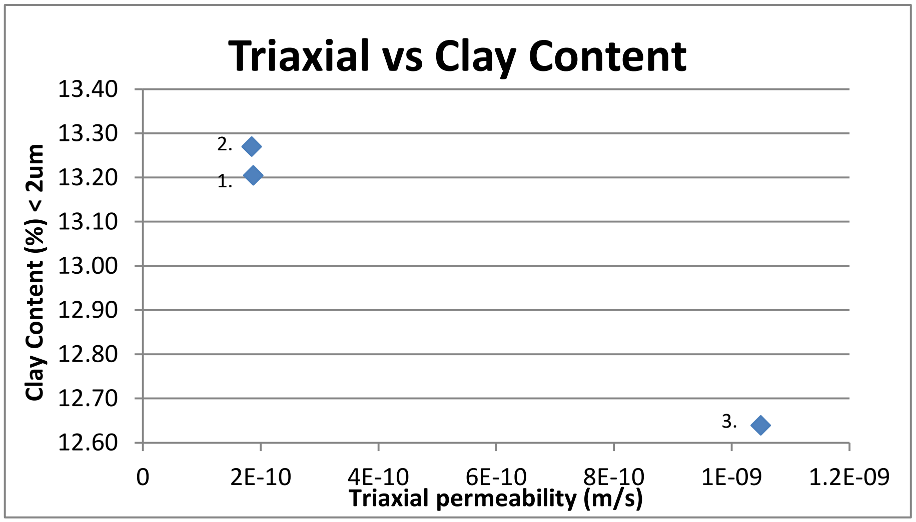


Fig. 4.7: Figure modified from Duggan (2016) displaying static water levels and triaxial permeability sample locations. Hydraulic conductivity values used in this study are from 5 mbgs and 55 mbgs. Triaxial vs Clay Content graph displays that clay content is high enough within the core samples to control the till's hydraulic conductivity in the vertical direction.

displays clay content ranging from 12.64-13.27% from similar sampling depths from the triaxial permeability samples.

TU levels are elevated at depth in 7 out of 8 wells sampled; indicating that newly recharged water is present and the remaining well showed a concentration right at the detection limit of 0.8 TU (Fig. 4.8). Tritium groundwater concentration at the TS with

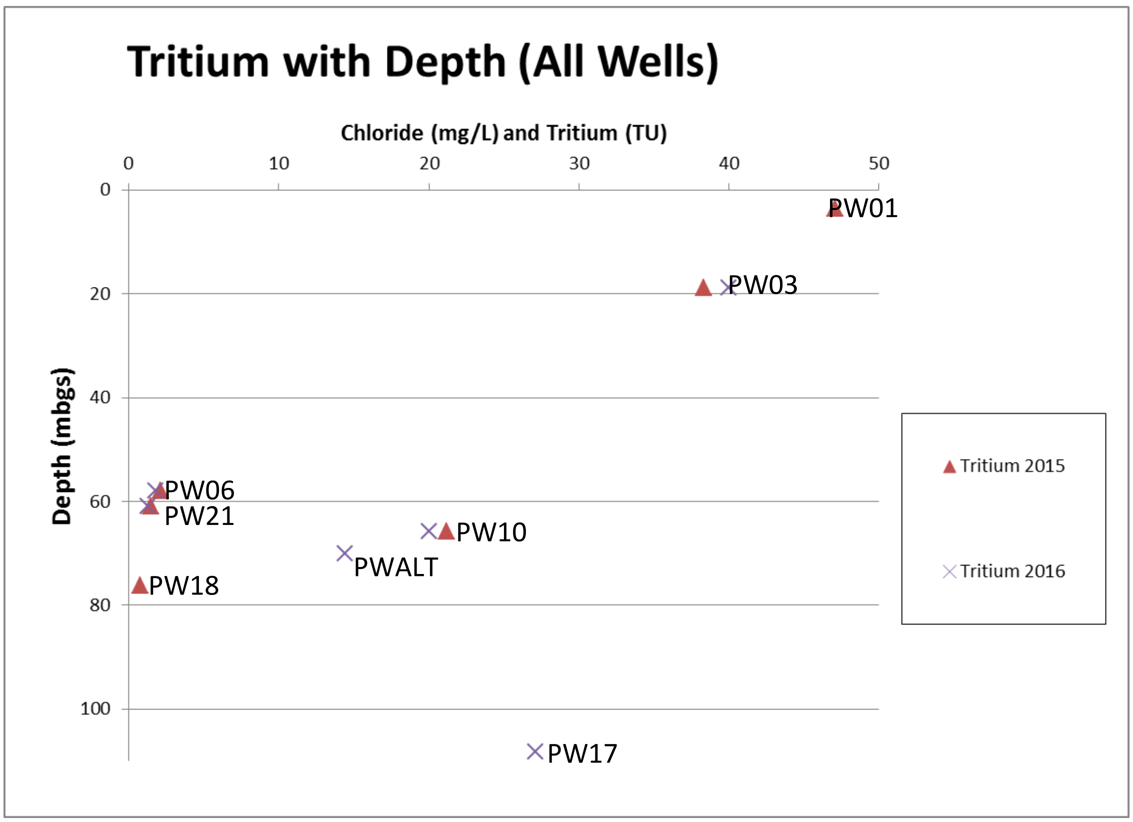


Fig. 4.8: Tritium (TU) concentration in private wells with depth; Original Tritium study was completed in August 2015, and the current tritium study was completed in August 2016.

depth ranged from 0.8-47TU (Fig. 4.8), however tritium concentration in local precipitation concentration ranged from 59 - 93 TU between 2009 and 2012 at the DF12 monitoring station 2-3km to the south of the TS site suggesting all wells tested near the TS have some level of protection.

Table 4.5 displays the concentrations of dissolved gasses within the copper tube diffusion sampler used in the groundwater age calculation completed by the A.E Lalonde AMS Laboratory. Columns are labeled and correspond to values determined from each equation step presented in section 4.4.4. Groundwater age ranged from 5.1-23.5 years old in wells that ranged in depth from 18.9-108.2mbgs, where the T-He age represents a mean of a range of ages within the groundwater and assumes a simple plug flow model (Table 4.6). This groundwater might include an age range of a decade or more, but fracture flow or leaking well casing could provide the means to mix decades old groundwater with very young (few years of less) groundwater.

The mean age in groundwater increase with depth to 60 mbgs and then becomes younger around 65mbgs to 100 mbgs. The age depth plot associated with sand zones within the Newmarket aquitard and into the Thorncliffe aquifer should increase with depth all the way through the succession if the preferential pathways had limited influence on the aquitard (Ruland et al. 1991). The shallowest well, PW03, is close to 19 mbgs and has the highest TU concentration of 40 TU. The most interesting concentrations to note are those from wells PW18, PW06, and PW21. All three of these wells have tritium values less than 2 TU, and have significantly lower tritium

			Equation 4.4.4.2	Equation 4.4.4.1	
Well ID	20Ne in Cu (cc/cc)	3He in Cu (cc/cc)	diss 20Ne (cc/cc)	Diss He (cc/cc)	Groundwater Temp C
PW03	3.66E-05	2.30E-11	1.76E-07	4.64E-08	18
PW10	2.31E-05	1.92E-11	1.84E-07	4.73E-08	12
PWALT	2.95E-05	1.85E-11	1.86E-07	4.74E-08	11
PW17	2.35E-05	2.08E-11	1.86E-07	4.75E-08	11
PW06	2.95E-05	1.62E-11	1.86E-07	4.74E-08	11
PW21	2.75E-05	1.50E-11	1.78E-07	4.67E-08	16

	Equation 4.4.4.3	Equation 4.4.4.3	Equation 4.4.4.4	Equation 4.4.4.5	Equation 4.4.4.7		
Well ID	20Ne H2O (cc/cc)	3He H2O (cc/cc)	excess air 20Ne (cc/cc)	excess He	Tritiogenic 3He (cc/cc)	Tritiogenic 3He (TU)	+/-
PW03	3.91E-07	2.04E-13	2.38E-07	7.57E-08	3.32E-14	13.4	2.4
PW10	2.58E-07	1.73E-13	8.19E-08	2.61E-08	7.08E-14	28.5	1.1
PWALT	3.33E-07	1.67E-13	1.63E-07	5.19E-08	2.81E-14	11.3	0.9
PW17	2.66E-07	1.89E-13	8.83E-08	2.81E-08	8.30E-14	33.4	1.2
PW06	3.33E-07	1.47E-13	1.63E-07	5.18E-08	7.78E-15	3.1	0.6
PW21	2.99E-07	1.33E-13	1.33E-07	4.23E-08	8.89E-15	3.6	0.5

Table 4.5: Ne^{20} and He^{3} values used in the calculation of Titriogenic He^{3}. Helium diffusion samplers were installed in the wells from Aug 2nd2016- to Aug 9th 2016 and data collected by the University of Guelph and McMaster team

Well ID	Depth (mbgs)	Screen (mbgs)	TU value	+/-	Age (year)	+/-
PW03	18.9	17.7-18.9	40	2.4	5.1	0.3
PW10	65.8	64.6-65.8	20	1.1	15.7	0.6
PWALT	70.1	60.9-62.4	14.4	0.9	10.3	0.6
PW17	108.2	107-108.2	27.1	1.2	14.3	0.5
PW06	57.9	-	1.8	0.6	17.9	5.0
PW21	61.0	59.7-61	1.3	0.5	23.5	6.8

Table 4.6: Summarized results of age and TU concentrations from private well sampled in August 2016 by the University of Guelph and McMaster Team

concentrations than the deeper wells located at 70 mbgs and 100 mbgs. Tritium concentration increases from 2 TU, in wells PW06 to PW21, to 14.4 TU at 70 mbgs and then increases further to 27.1 TU near 100 mbgs (Table 4.6).

If the aquifers are being replenished by vertical leakage, the average pore water velocity needed to bring groundwater with the mean age ranging from 5.1-23.5 years to depths of ≤108.2 mbgs, ranged from 1.03×10^{-7} to 8.23×10^{-8} m/s (Table 4.7) (Equation 4.4.4.8). The average vertical Darcy flux using equation 4.4.4.9 needed to reach private well depths within a timeframe equivalent to the groundwater age calculated (Table 4.6), ranged from 1.03×10^{-7} to 8.23×10^{-7} m/s (3.25 m/yr -2.6 m/yr), two orders of

Well ID	Depth (mbgs)	TU value	Age (year)	V (m/s)	Darcy flux (m/s)
PW03	18.9	40	5.1	1.18E-07	3.06E-08
PW10	65.8	20	15.7	1.33E-07	3.46E-08
PWALT	70.1	14.4	10.3	2.16E-07	5.61E-08
PW17	108.2	27.1	14.3	2.40E-07	6.24E-08
PW06	57.9	1.8	17.9	1.03E-07	2.67E-08
PW21	61.0	1.3	23.5	8.23E-08	2.14E-08

Table 4.7: Calculated average pore water velocity (V) and Darcy flux based on calculated age of groundwater and depth in table 4.6. This calculation is based on the assumption of intergranular flow using an equivalent porous medium approach.

magnitude faster than the ones calculated from well nests based on onsite hydraulic gradients and triaxial permeability hydraulic conductivity data (Tables 4.3 and 4.4). The rates calculated on this site are also faster than the leakage rates calculated from Gerber et al. 2001 at 1 m/yr, highlighting the regional variability within the Newmarket Till.

4.6 Discussion

The results show groundwater ages of less than 24 years old from 108 mbgs and above. If the average vertical Darcy flux (3.88 x10-10 m/s) (Table 4.3) calculated from onsite gradients and triaxial permeability samples is a good representation of vertical leakage through the till, the average porewater velocity of groundwater can be used to calculate how deep newly recharge water would move. Using the average porewater velocity of 1.49×10^{-10} m/s, calculated from triaxial data, and the equivalent time of the reported ages of groundwater produced from tritium-helium data (5.1-23.5 years), the average water would reach depths ranging from 0.24 to 1.1 mbgs (Table 4.8). These

Well ID	Depth (mbgs)	Age (years)	Age (s)	V (m/s)	Darcy flux (q)
PW03	0.24	5.1	160833600	1.492E-09	3.88E-10
PW10	0.74	15.7	495115200	1.492E-09	3.88E-10
PWALT	0.48	10.3	324820800	1.492E-09	3.88E-10
PW17	0.67	14.3	450964800	1.492E-09	3.88E-10
PW06	0.84	17.9	564494400	1.492E-09	3.88E-10
PW21	1.11	23.5	741096000	1.492E-09	3.88E-10

Table 4.8 Depths the average groundwater molecule would reach calculated using triaxial permeability and average Darcy flux calculated from well nests. This calculation is based on the assumption of intergranular flow using an equivalent porous medium approach

depths are much shallower than the groundwater depths associated with private wells, suggesting that preferential pathways may be contributing to vertical leakage.

Triaxial permeability results agree with grain size samples near the same depth (Table 4.4) that suggest that clay content is high enough for the till to behave like a clay layer (Fig. 4.7). However, another line of evidence that suggests small core samples may not accurately represent the till hydraulic conductivity properties is the results from the Stantec (2014) slug tests (Table 4.3). The slug tests are displaying the quickest hydraulic conductivity values up to 6 mbgs ranging from 10^{-5} to 10^{-8} m/s, which are typical values for silt, and silty sand, and glacial till (Freeze and Cherry 1979). The quickest shallow hydraulic conductivities were in MW2-13S and MW5-14S, and both screens are closer to surficial sand layers than other shallow screens, suggesting that this till might be more weathered and less consolidated (Fig. 4.6). The remaining shallow wells that are screened within the till unit (MW1-13D/S and MW3-13D/S) have lower hydraulic conductivity and may be deep enough to be below the weathered portion of the till, or may also be within an area where heterogeneities are nonexistent (Fig. 4.6). At 15 mbgs the wells slug test values decrease to as low as 10^{-9} m/s and are as high as 10^{-6}m/s (Table 4.3), providing evidence that heterogeneities within the till occur at various depths, and may not have been captured in the small-scale core samples used in triaxial permeability analyses. Vertical Darcy Fluxes calculated from the average triaxial permeability provided and well cluster gradients are approximately one to two orders of magnitude slower than the lowest values produced from slug tests. These discrepancies between hydraulic conductivity measurements may be due to differences in horizontal and vertical flow within the till, but may also suggest the presences of preferential flow paths (Cherry et al. 2006).

This study and the Gerber et al. (2001) study both suggest that small scale tests for determining permeability within the till may not give an accurate representation of the till's hydrogeological properties on a site or at a regional scale. The vertical Darcy flux calculated from triaxial data and on site gradients may not be an accurate representation on the effective bulk hydraulic conductivity of the Newmarket aquitard. Instead, the estimated vertical Darcy flux calculated with private wells depths and groundwater age may be a better representation of the till's hydraulic conductivity properties if heterogeneities not captured in these samples are playing a role in groundwater movement.

Typical travel times within the Thorncliffe aquifer were reported to be approximately 105 m/yr in the SLR (2015) report. The groundwater age reported from wells potentially within the Thorncliffe aquifer ranged from 14-15 year olds, and the closest area of recharge is estimated to be 6,000 m north of the site (SLR 2015), making the need for the average groundwater velocity to be closer to 300 m/yr. Hydraulic conductivity ranges of a few orders of magnitude are not uncommon, however additional data is needed to determine if these flow rates are plausible within this unit.

4.7 Conclusion

Tritium and helium concentrations provided an age for the groundwater within the private wells, and in turn an estimated average linear pore water velocity ranging from 1.18×10^{-7} to 8.23×10^{-8} m/s. Lab derived Vertical Darcy flux within the till matrix, based on onsite hydraulic gradients, averaged 3.88×10^{-10} m/s with an estimated average linear pore water velocity of 1.49×10^{-9}m/s. These calculations are based on the assumption of intergranular flow, and no fractures or high hydraulic conductivity features are considered.

Darcy flux calculations from the well nests located on site suggest a much slower average leakage rate compared to the vertical velocities estimated from tritium-helium data. This suggests that permeability data from collected core and darcy flux calculations does not appear to be an accurate representation of the Newmarket aquitard hydrogeological properties and that other preferentially pathways, not captured through triaxial permeability test, are significantly affecting leakage rates.

5 Anthropogenic Indicators

In glacial sediment, chemical component such as chloride and nitrate are usually from non-natural sources making them an excellent anthropogenic indicator that provides evidence of the effects of urbanization and agriculture (Dyke 1999). The presence of these two constituents in groundwater can help assess well vulnerability, however the uneven releases or distributed nature of these constituents may create complicated distributions over a large area (Dyke 1999), such that wells where chloride is not found should not be assumed to be protected. Chloride is the most common ionic constituent used in an aquitard integrity study, and concentrations can be assessed within the aquitard or within adjacent aquifer systems to determine the risk of solute transport (Cherry et al. 2006). In this context, lowest levels found in groundwater samples can indicate background levels, meaning the water is being recharged from an uncontaminated area. Chloride levels above the determined background levels may be an indication that the well is contaminated, or is susceptible to contamination from natural (e.g. bedrock) or non-natural sources (e.g. urbanization and agriculture). For example, chloride has been linked to contamination from leachate associated with septic fields or landfill sites (Dyke 1999), or most commonly from road salt. Groundwater with nitrate or chloride are also likely to have short groundwater flow pathways, as the source of these constituents is most often from surface water or very shallow groundwater flow. Both Chloride and Nitrate concentrations have the potential to be used in this case as an indicator of intrinsic aquifer vulnerability, but can be hard to interpret on larger scales due to unevenly distributed sources (Dyke 1999).

Sulfate in groundwater usually occurs from the dissolution of gypsum or weathering of pyrite, and is usually consumed along the groundwater flow paths (Dyke 1999). This chemical property can provide an indication of long flow paths where concentration is low, estimated to be < 2.0 mg/L within the ORM area (Dyke 1999). Sulfate within the ORM area becomes reduced along flowpaths ranging from 5-10 km, suggesting that groundwater with low concentrations is associated with long regional groundwater pathways. Lower concentrations of chloride and sulfate also provide additional evidence that the groundwater is part of an extensive flow system that contributes to the prevention of high chloride concentrations at depth, that are similar or equivalent to the high concentrations found within near surface wells (Dyke 1999).

The private wells located around the site (Fig. 3.21) are included in the Hydro One groundwater monitoring program. The wells were tested for a suite of groundwater parameters and constituents over the course of two years from 2014-2016. A total of twenty five (25) Private Wells and sixteen (16) Monitoring Wells on and around the site were sampled over the course of these two years. Twelve (12) of the private wells have known locations and depths and are used here in this analysis. The remaining thirteen (13) private wells with geochemistry data have no known location or specific depths are not reported and the wells are only classified as either deep or shallow. These wells are therefore not used in the analysis presented here. An additional well, PWALT was not included in the Stantec (2014) and (2015b) monitoring program and was only sampled for tritium and isotope data. Six (6) of the private wells, with available Hydro One groundwater chemistry data, were also tested for tritium concentrations by the well owners in the summer 2015. Lastly, for the purpose of this study, six (6) private wells were tested for tritium in the following 2016 summer to allow for direct comparison of contamination indicators (Table 4.1 and 4.6). Table 5.1 summarizes what PWs and MWs have tritium and isotopes, and/or groundwater quality data.

The purpose of this chapter is to compare the pre-existing and current tritium data with the Hydro One data set of anthropogenic constituents to determine if anthropogenic constituent concentrations are consistent with the active flow depths suggested by the tritium analysis. The anthropogenic indicators being compared to tritium includes chloride, nitrate, sodium, sulfate, and bacteria. Detection limits of chloride, nitrate, sodium, and sulfate are 1.0 mg/L, 0.1 mg/L, 0.1mg/L, and 1.0 mg/l, respectively.

Well ID	Method	Depth (mbgs)	Data available	Stratigraphic Unit
MW2-13S	Drilled	1.57	Water quality	Surface Till
PW1	Dug	3.66	Tritum (2015) Water quality	Surface Till
MW5-14S(2)	Drilled	4.1	Water quatlity	Surface Till
MW4-13S	Drilled	4.57	Water quality	Surface Till
MW1-13S	Drilled	6.1	Water quality	Surface Till
MW5-14S	Drilled	6.1	Water quality	Surface Till
PW25	Dug	6.4	Water quality	Surface Till
MW3-13S	Drilled	6.71	Water quality	Surface Till
MW7-14	Drilled	7.6	Water quality	Surface Till
MW6-14	Drilled	7.6	Water quality	Surface Till
PW19	Dug	9.1	Water quality	Newmarket Till
PW02	Dug	9.1	Water quality	Newmarket Till
PW20	Dug	9.1	Water quality	Newmarket Till
PW11	Dug	10.4	Water quality	Newmarket Till
PW08	Dug	15.24	Water quality	Newmarket Till
MW1-13D	Drilled	15.24	Water quality	Newmarket Till
MW2-13D	Drilled	15.24	Water quality	Newmarket Till
MW3-13D	Drilled	15.24	Water quality	Newmarket Till
MW4-13D	Drilled	15.24	Water quality	Newmarket Till
MW8-15	Drilled	16.9	Water quality	Newmarket Till
PW03	Cable	18.9	Tritium (2015 and 2016) Water quality	Newmarket Till
MW4-15D*	Drilled	25.1	Water quality	Newmarket Till
MW5-14I*	Drilled	40.1	Water quality	Newmarket Till
MW5-14D*	Drilled	55	Water quality	Newmarket Till
PW06	Cable	57.9	Tritum (2015 and 2016) Water quality	Newmark/Thorn Transition
PW21	Cable	61	Tritium (2015 and 2016) Water quality	Newmark/Thorn Transition
PW10	Cable	65.8	Tritium (2015 and 2016)	Newmark/Thorn Transition
PWALT	Drilled	70.1	Tritium (2016)	Newmark/Thorn Transition
PW18	Drilled	76.2	Tritium (2015)	Thorncliffe
PW15	Cable	100.6	Water quality	Thorncliffe
PW17	Cable	108.2	Tritium (2016) Water quality	Thorncliffe/ Scarborough

Table 5.1: Summary of drilling method and geochemical data of each well. "Newmark/Thorn Transition" refers to the interval between 68-75 mbgs where sand zones within the Newmarket Till are thought to be Thorncliffe sediments entrained by ice during deposition of the Newmarket Till. Transition zone determined from lines marked on cross sections (Fig. 3.22 and 3.23) in masl.

5.1 Results

5.1.1 Charge Balance Error

Geochemical data collected for the Hydro One groundwater monitoring program were tested for quality assurance and quality control (QA/QC) with the calculations of charge balance error, using equation 5.1.1.1 (Clark 2015). Where **∑cat** = Sum of all major cations and **∑an**= Sum of all major anions, in meq/L (milliequivalence units).

$$Charge\ balance\ error\ (\%) = \frac{\sum cat - \sum an}{\sum cat + \sum an}\ x\ 100 \qquad (5.1.1.1)$$

A charge balance greater than 5% is considered not acceptable, as this is a sign the samples were not accurately analyzed or a major contributing anion or cation has been overlooked (Clark 2015). Three monitoring wells MW5-14I, MW5-14D, and MW2-13D displayed charge balance errors that were too large during the April 2015 sampling period used in this study. The data from these wells is not removed from the study; however it is marked or discussed in areas where results may be affected. MW5-14I and MW5-14D both had an ion charge balance over 20% during April 2015. In addition to the April 2015 sampling, all three samples collected from MW5-14I, and all two samples collected from MW5-14D were well over the acceptable limit, limiting reliable geochemical data analysis in MWs on site in depths over 20 mbgs. During the April 2015 sample period MW2-13D also had a charge balance above the acceptable limit, of approximately 9%, leaving twenty eight (28) wells with acceptable charge balances and geochemical data during the April 2015 sampling period.

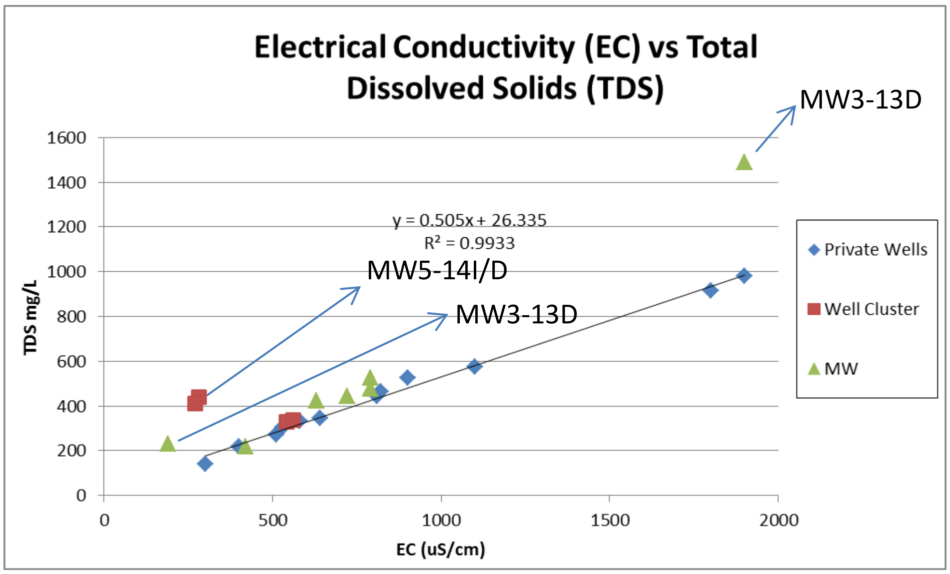
5.1.2 Electrical Conductivity (EC), Total Dissolved Solids (TDS), and pH

Total dissolved solids (TDS) is comprised of inorganic salts, which can include calcium, magnesium, potassium, sodium, bicarbonates, chloride, and sulfates (Nas and Berktay 2010) and is directly related to electrical conductivity of water. Measurement of EC can provide estimates of TDS by multiplying EC by an empirical factor (A)

$$TDS = A \; x \; EC \; \left(\frac{\mu S}{cm}\right) \qquad \text{(Equation 5.1.2.1)}$$

A ≅ 0.55 in bicarbonate waters; 0.75 in high-sulfate waters; 0.9 in high-chloride waters

Groundwater quality data at the TS comprising of EC and TDS measurements for 28 wells produced a positive linear trend between TDS vs EC. Equation 5.1.2.1 was rearranged to calculate the empirical factor with depth and they are between values used for bicarbonate and high-sulfate waters (Fig. 5.1). MW514I, MW5-14D, and MW2-13D are outside of the trends in data, which is most likely due to the high charge balance errors associated with these samples (Fig. 5.1). MW3-13D located approximately 15 mbgs produced very high EC and TDS values (1900 µS/cm and 1490) with an “A” value associated with high-sulfate waters, and a charge balance error was within the acceptable range. Based on these relationships the EC concentrations display evidence that the highest concentration of TDS should be within the first 20 mbgs, whereas lower concentrations of TDS is likely associated with depths greater that 40 mbgs (Fig. 5.2 A).



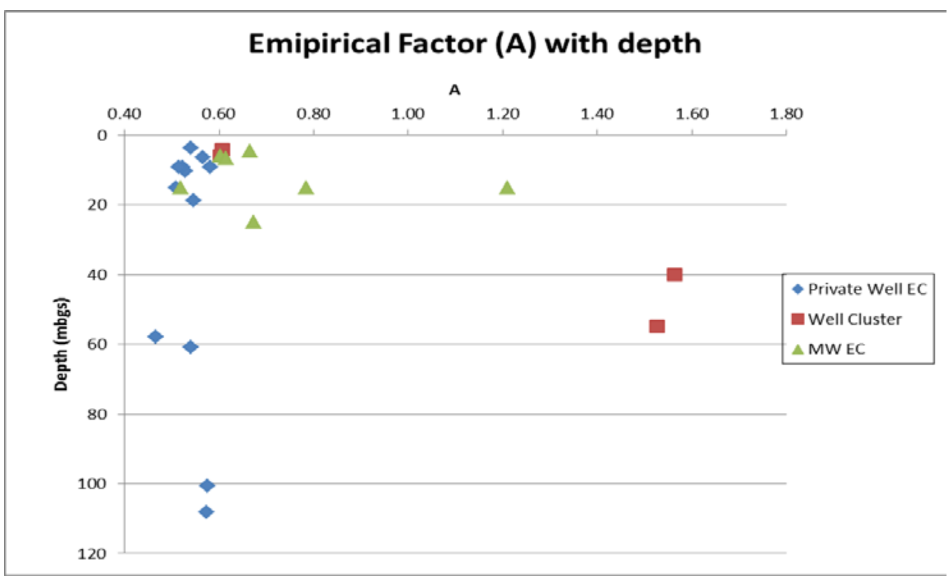


Fig. 5.1: (A) Total dissolved solids (TDS) and Electrical Conductivity (EC) display a positive linear trend. EC varies with TDS as TDS within the groundwater directly affects the conductivity of the fluid. (B) Empirical Factor produced from the ratio of TDS to EC stayed mostly within the bicarbonate water range (A= 0.55) and generally under the high-sulfate water range (A=0.75). Empirical factors above 1 are associated with wells that displayed charge balance errors > 5%.

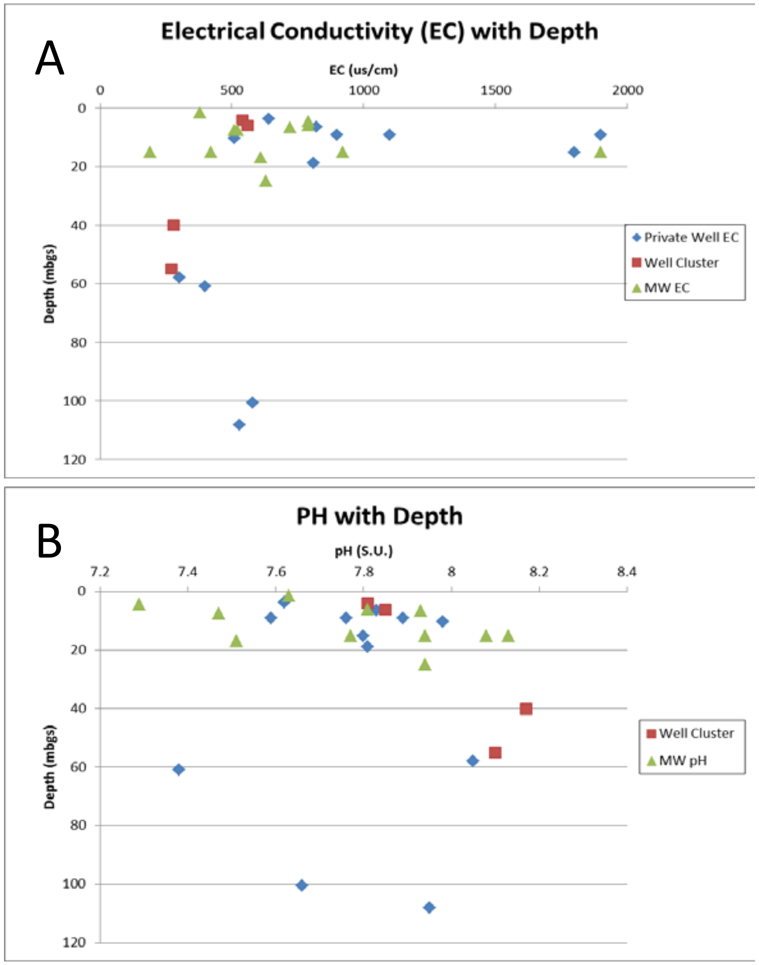


Fig. 5.2: Electrical Conductivity (EC) versus depth in all wells (A). The highest values occur within the first 20 mbgs with generally lower values at greater depth. pH in both private wells and MW (B) show no trends but ranged from 7.3-8.2.

No apparent trends were observed between pH and depth; pH approximately ranged from 7.3-8.2 (Fig. 5.2 B).

5.1.3 Chloride

Pristine groundwater concentrations are estimated to be 4 mg/L based on the lowest levels of chloride found on site (Dyke 1999). The measurement uncertainty at a 95% confidence interval and 10 times the detection limit is +/- 0.36 mg/L. The scatter plot of chloride concentration from all 28 wells with depth (Fig. 5.3) shows that high concentrations of chloride indicative of active groundwater flow appears to be within the first 20mbgs. Chloride concentrations around the site start to decline at or below these levels around 40-60 mbgs, then increases above pristine levels again around 100mbgs.

This generally follows the tritium concentration depth plot found around the site. Higher levels of tritium are matched with higher levels of Chloride within the first 20 mbgs and at 100 mbgs. However, within the 50mgs-60mbgs range, PW10 and PWALT show higher concentrations of tritium than wells PW18, PW06, and PW21. PW10 and PWALT did not have geochemical data to allow for direct comparison to better analyze how chloride concentrations correspond to tritium concentrations, and if the two both display evidence of active flow. The very large chloride concentration in some of the private wells may suggest wells construction issues, as these values are from shallow

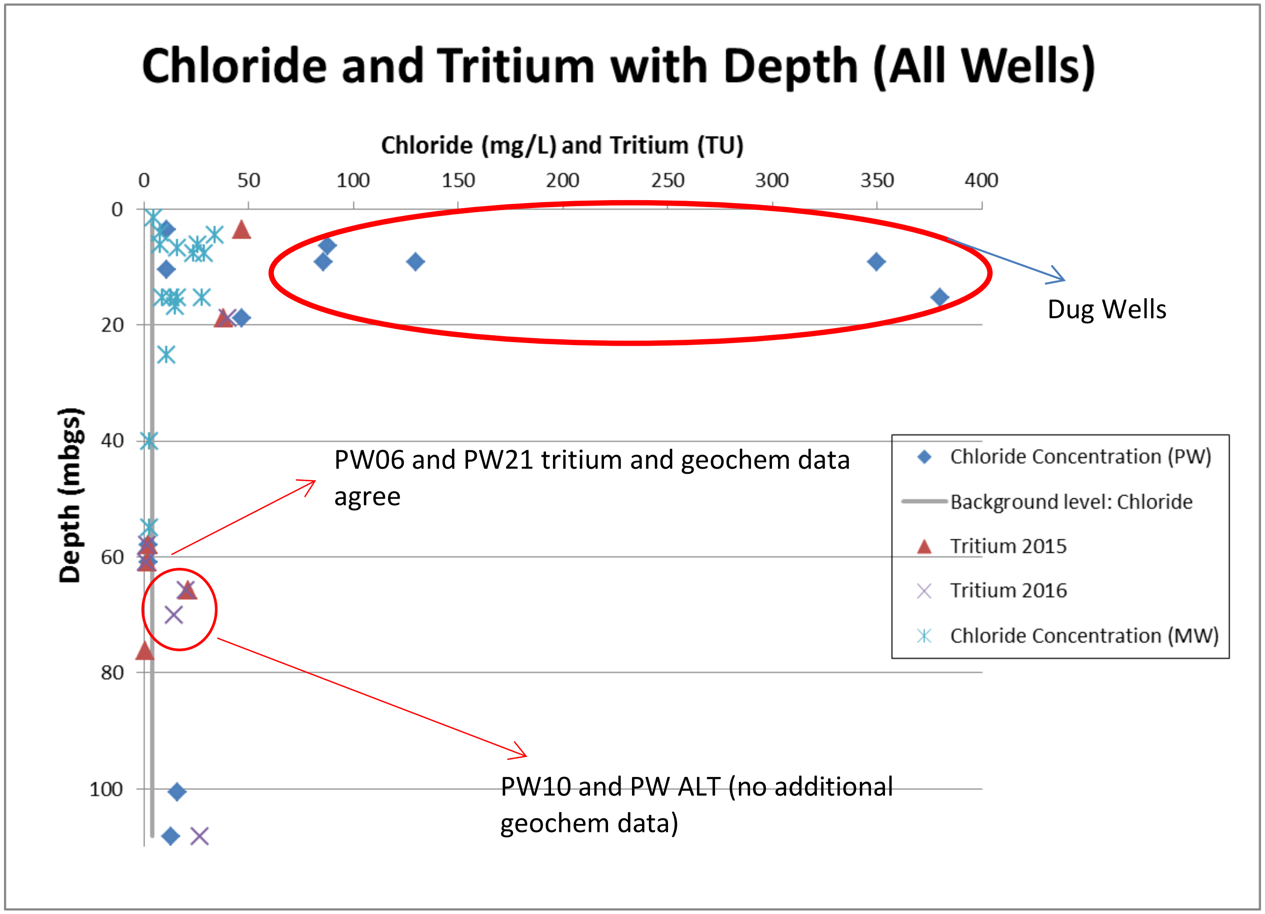


Fig. 5.3: Tritium (TU) and Chloride (mg/L) concentration with depth plot in private and monitoring wells. Geochemistry chloride samples were collected in April 2015 from various locations on and around the site. Chloride concentrations appear to follow the trends of TU concentration with depth, meaning that chloride may be a good anthropogenic indicator at this site. Background level (gray line) indicates estimated pristine concentration level at or below 4 mg/L based on the lowest levels found on site.

wells PW25, PW08, PW19, PW02, and PW20 and are all Dug wells (Table 5.1). A second scatter plot was produced to show only wells that had tritium and chloride data (Fig. 5.4 A). The comparison of chloride concentration to tritium concentration generally agrees. Where tritium levels were above 2 TU, chloride concentrations are above pristine levels. Despite some annual variability in chloride concentration, this relationship remained the same over multiple sampling periods (Fig 5.4B). Both Chloride and TU concentration levels in the wells suggest that there is increased intrinsic aquifer vulnerability within the first 20 mbgs and at 100mbgs (Dyke 1999 and Ruland et al. 1991). While Chloride from the underlying shale bedrock has been shown to influence lower aquifers (Rick Gerber, pers, comm, 2017), the wells on site are 25-30m above bedrock, making this potential source of chloride unlikely. Future study should explore the possibility of bedrock sources of Chloride at depths greater than 100m.

5.1.4 Nitrate

Pristine level of Nitrate in the groundwater at this site is estimated to be 0.5 mg/L, based on the lowest levels found (Dyke 1999) at the TS. The measurement uncertainty at a 95% confidence interval and 10 times the detection limit is +/- 0.07 mg/L. Nitrate concentrations appear to follow the same trend as chloride and tritium (Fig. 5.5), whereas higher Nitrate occurs in depths <20 mgbs and again at approximately 100 mbgs, with a decrease to pristine levels around the 60 mbgs mark. Highest Nitrate

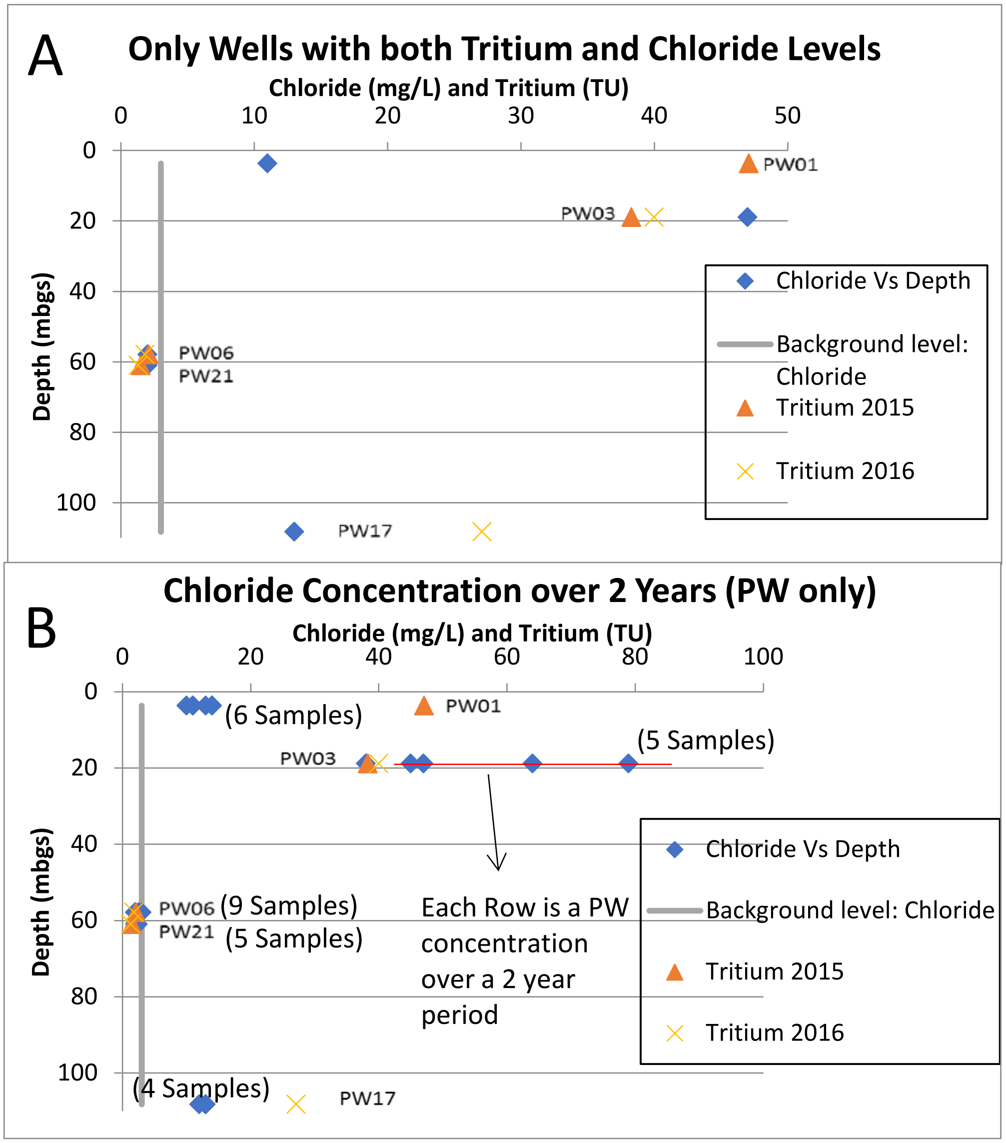


*Fig. 5.4: **A:** Tritium (TU) and Chloride (mg/L) concentration with depth plots in private wellsh. Geochemistry chloride samples were collected in April 2015 from various locations around the site. **B:** Tritium (TU) and Chloride (mg/L) concentration with depth plots in private wells over a two year period. Geochemistry chloride samples were collected in April 2015 from various locations around the site. Concentration fluctuations over 2 years provide additional evidence that apparent trends of well vulnerability are consistent. Background level (gray line) indicates estimated pristine concentration level of 4 mg/L based on the lowest levels found on site. Sample numbers in (B) indicate how many samples were collected over a 2-year period, since overlap in data points occur.*

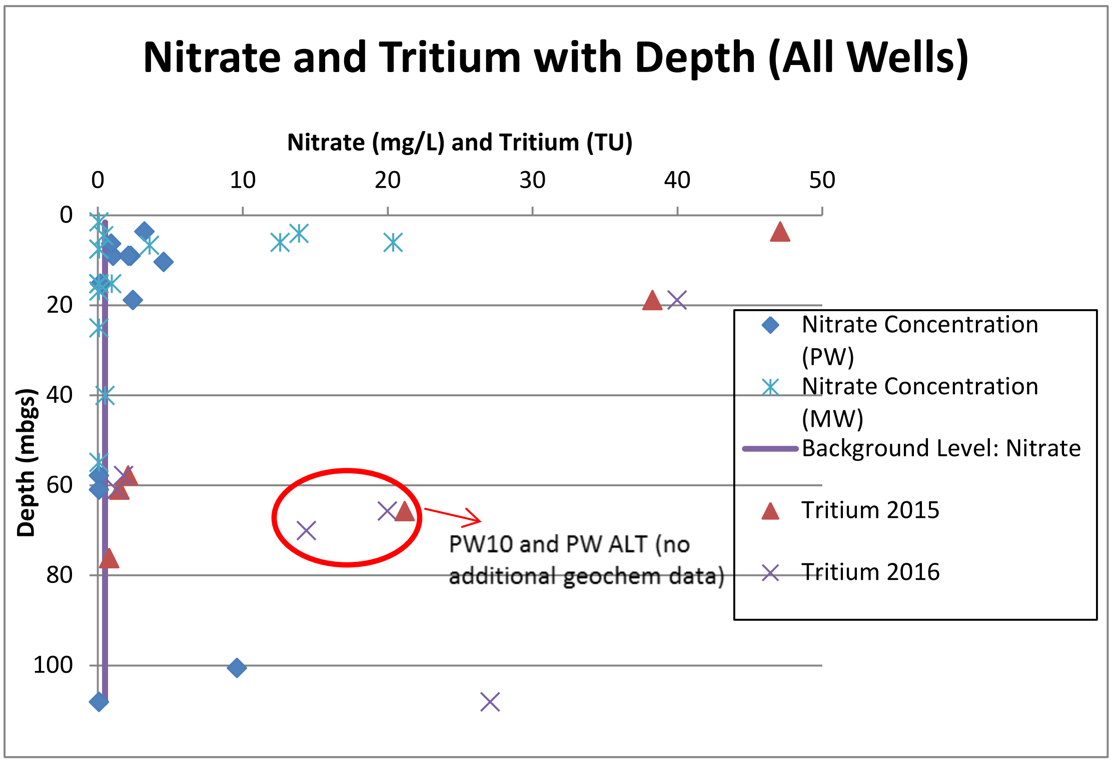


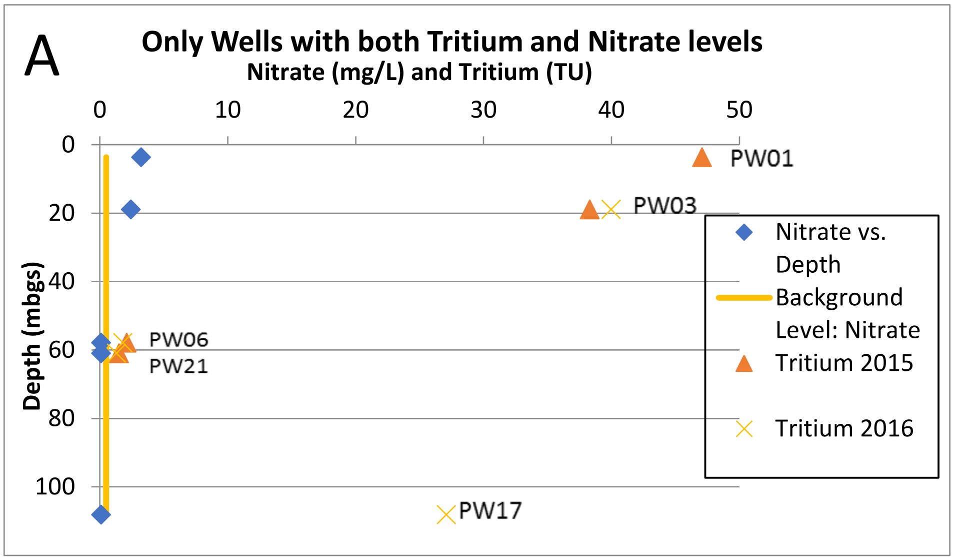
Fig. 5.5: ***A:*** *Tritium (TU) and Nitrate (mg/L) concentration with depth plots in private and monitoring wells. Geochemistry Nitrate samples were collected in April 2015 from various locations on and around the site. Nitrate appears to display the same trend as Chloride and Tritium. Background level (purple line) indicates estimated pristine concentration level of 0.5mg/L based on the lowest levels found on site.*

levels are in MW, located on site, which may be primarily due to the fact the site used to be used for agricultural purposes.

A scatter plot comparing only the wells with both nitrate and tritium values (Fig. 5.6 A) suggests nitrate values may not be good at detecting vulnerability of deeper groundwater at this site. The increase in nitrate in PW15 at 100.6 mbgs (Fig. 5.5) does not have corresponding tritium data with which to compare. However, PW17 displayed both higher tritium levels and nitrate levels below pristine levels. Nitrate concentrations over the course of two years at this site are consistent over time, and stay below pristine levels in PW17 at 108.2 mbgs, where a higher concentration of tritium was found (Fig. 5.6 B). This suggests nitrate may not have travelled as far down into the subsurface as tritium. This is mostly likely due to nitrate's retardation factor and reactive properties (Mikołajków 2010).

5.1.5 Sodium

Sodium concentration decreases with depth, and does not appear to follow the same trends that chloride, nitrate, and tritium displayed (Fig. 5.7 A). Higher concentrations do occur within the first 20 mbgs; however, the sodium concentrations in the shallowest well (PW01) are similar to the sodium concentrations observed in three deeper wells (PW06, PW21, and PW17) (Fig. 5.7 B). The lack of relationship between



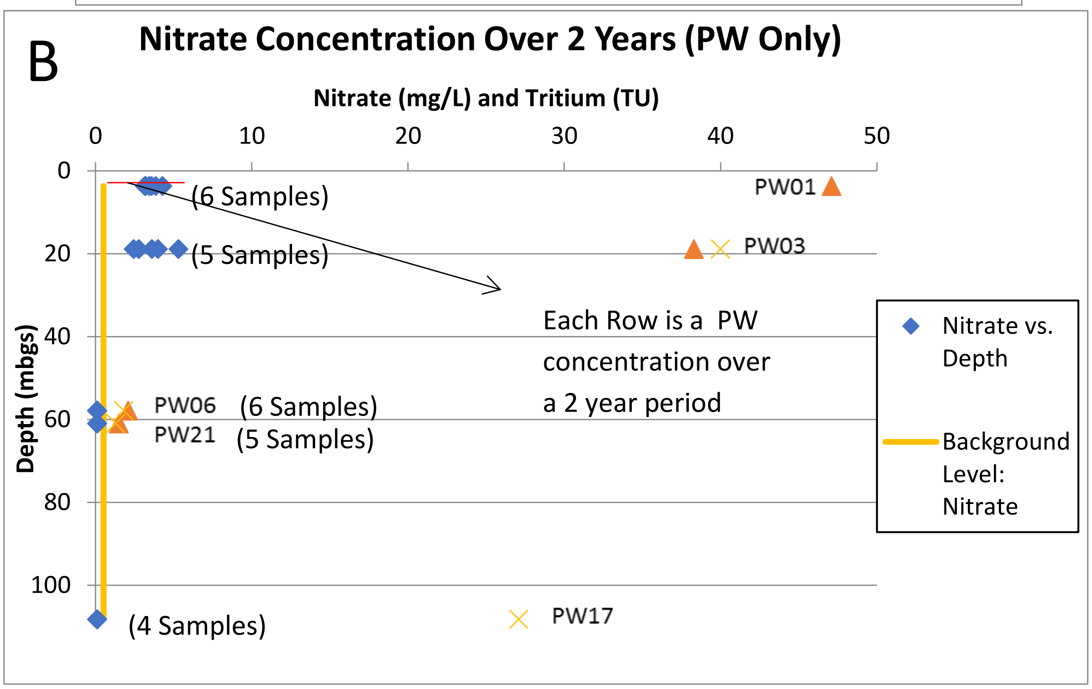
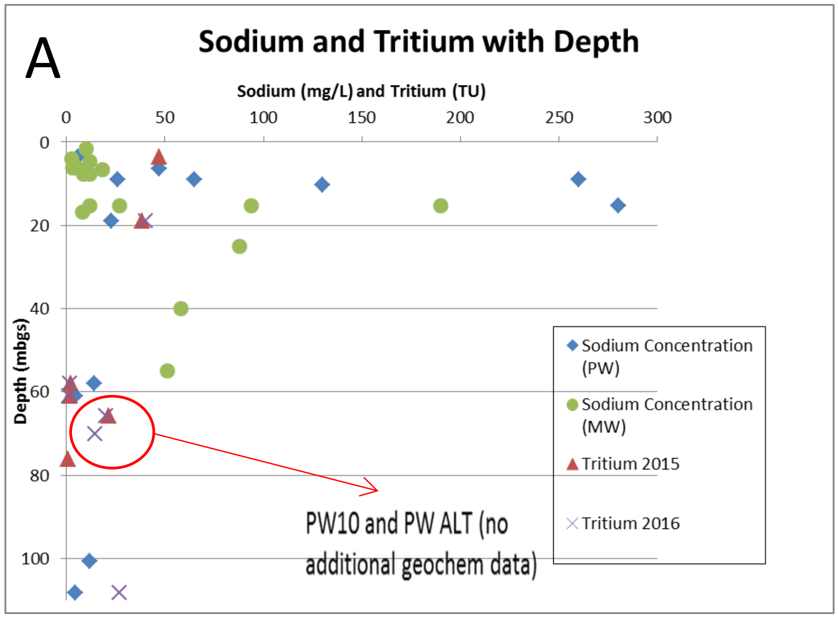


Fig. 5.6: ***A:*** *Tritium (TU) and Nitrate (mg/L) concentration with depth in private wells. Geochemistry Nitrate samples were collected in April 2015 from various locations around the site. When samples are directly compared in wells with Tritium, it appears that Nitrate is not as consistent as chloride in matching TU trends.* ***B:*** *Tritium (TU) and Nitrate (mg/L) concentration with depth in private wells from 2014-2016 at various locations around the site. Background level (Orange line) indicates estimated pristine concentration level of 0.5 mg/L based on the lowest levels found on site. Sample numbers in (B) indicate how many samples were collected over a 2-year period, since overlap in data points occur.*



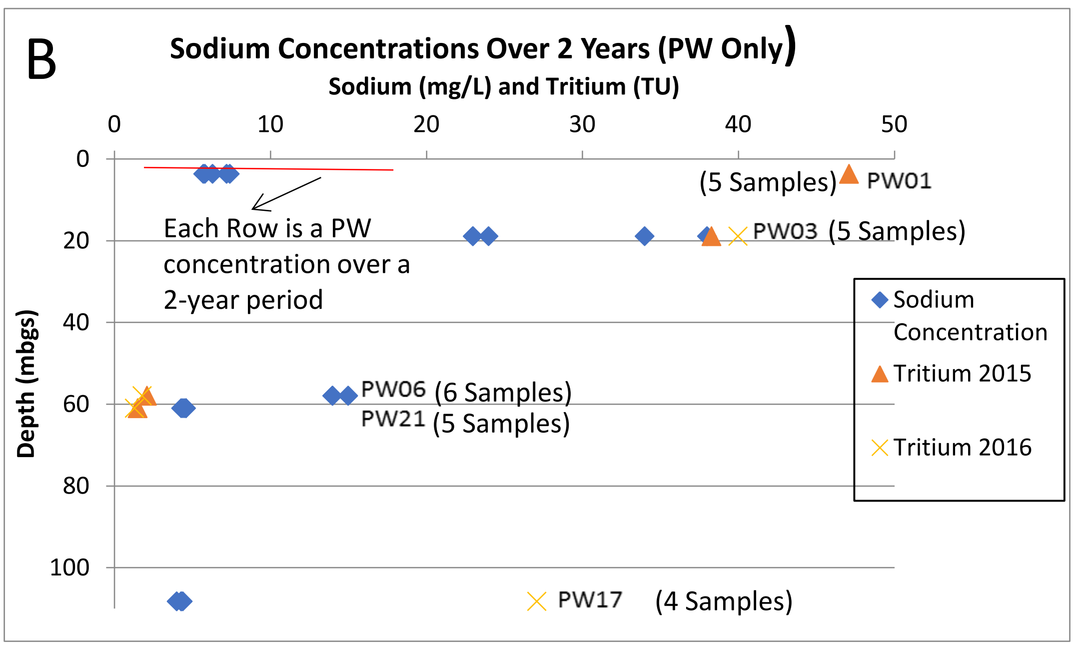


*Fig. 5.7: **A:** Tritium (TU) and sodium (mg/L) concentration with depth in private and monitoring wells. Geochemistry sodium samples were collected in April 2015 from various locations on and around the site. Sodium continuously decreases with depth, and does not appear to follow TU trend associated with depth around 100 mbgs. **B:** Tritium (TU) and sodium (mg/L) concentration with depth in private wells from 2014-2016 at various locations around the site. Concentrations of sodium fluctuate significantly over a 2 year period. There is no apparent match with TU concentrations. Sample numbers indicate how many samples were collected over a 2-year period, since overlap in data points occur.*

sodium concentrations and tritium concentration suggests sodium may not be a useful well vulnerability indicator.

5.1.6 Sulfate

Though sulfate is not an anthropogenic indicator, sulfate should have very low concentrations where groundwater is a part of a more extensive, longer flow path. Lower concentration of sulfate, accompanied by lower concentrations of chloride provides additional evidence of a more extensive flow system. Low sulfate concentration levels within the ORM area are estimated to be 2.0 mg/L (Dyke 1999). The measurement uncertainty at a 95% confidence interval and 10 times the detection limit is +/- 0.70 mg/L.

As discussed above, Chloride concentration with depth displays some very large concentrations within and around the first 20 mbgs, decreases around 60 mbgs to pristine levels, and then begins to increases again around the 100 mbgs. Sulfate levels when compared to Chloride values with depth, consistently remain above 2.0 mg/L all the way down to 108 mbgs, and do not decrease within the wells that exhibited pristine levels of chloride, around 60 mbgs (Fig. 5.8).

All sulfate concentrations are high compared to the background level within the ORM area of <2.0 mg/L reported by Dyke (1999). This indicates the groundwater pathways must be shorter and less extensive, suggesting recharge from an area close to the site may be likely. The pristine levels of chloride found in wells around 60 mbgs may be explained due to the unequally distributed source zones associated with chloride (Dyke 1999).

The average chloride and sulfate values around the site are highest within the first 20 mbgs and around the 100 mbgs mark (Table 5.2) and high sulfate and chloride values may provide evidence of short groundwater pathways (Dyke 1999). Though chloride level averages are lower within deeper wells than shallower wells, suggesting

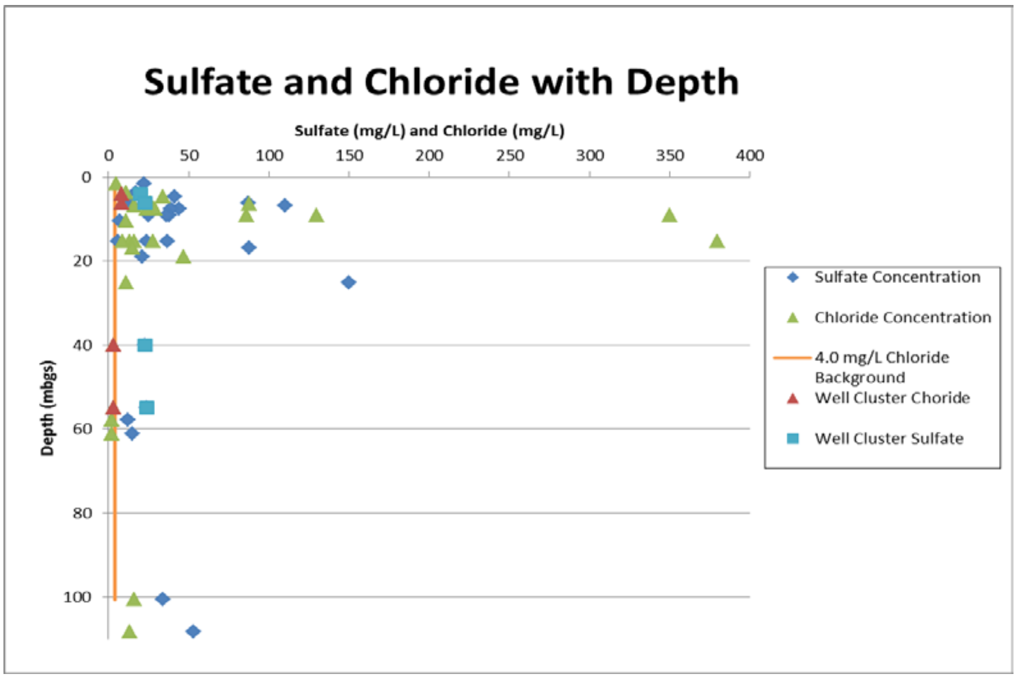


Fig. 5.8: Chloride and sulfate (mg/L) concentration with depth in private and monitoring wells. Sulfate is not an anthropogenic indicator, but should display lower concentrations for aquifers associated with regional flow systems. Sulfate concentrations show little variation with depth at this site.All sulfate values are above 2 mg/L. Background level (Orange line) indicates estimated pristine concentration levels of Sulfate based on data from the ORM area (Dyke 1999).

Well ID	Method	Depth (mbgs)	Chloride (mg/L)	Sulfate (mg/L)
MW2-13S	Drilled	1.57	5	22
PW1	Dug	3.66	11	17
MW5-14S(2)	Drilled	4.1	8	20
MW4-13S	Drilled	4.57	34	41
MW1-13S	Drilled	6.1	26	87
MW5-14S	Drilled	6.1	8	23
PW25	Dug	6.4	88	14
MW3-13S	Drilled	6.71	16	110
MW7-14	Drilled	7.6	29	44
MW6-14	Drilled	7.6	24	39
PW19	Dug	9.1	350	25
PW02	Dug	9.1	86	38
PW20	Dug	9.1	130	36
PW11	Dug	10.4	11	7
PW08	Dug	15.24	380	37
MW1-13D	Drilled	15.24	13	24
MW2-13D	Drilled	15.24	9	6
MW3-13D	Drilled	15.24	28	
MW4-13D	Drilled	15.24	16	
MW8-15	Drilled	16.9	15	88
PW03	Cable	18.9	47	21
MW4-15D*	Drilled	25.1	11	150
MW5-14I*	Drilled	40.1	3	23
MW5-14D*	Drilled	55	3	24
PW06	Cable	57.9	2	12
PW21	Cable	61	2	15
PW15	Cable	100.6	16	34
PW17	Cable	108.2	13	53
* Ion Charge Balance >5%				
Shallow 1.57-18.9 mbgs				
Average Chloride			Average Sulfate	
		64		37
Intermediate (40.1-61 mbgs)				
Average Chloride			Average Sulfate	
		3		19
Deep 100.6-108.2 mbgs				
Average Chloride			Average Sulfate	
		15		44

Table 5.2: Average chloride and sulfate concentrations for shallow (<20 mbgs), intermediate (40-61 mbgs), and deep (>55 mbgs) wells. MW4-15D, MW5-14I, and MW5-14D are included in intermediate averages, however the sample's ion charge balance of these wells are greater than the acceptable 5%. On average, there were higher concentrations of chloride and sulfate in the shallow wells, compared to the intermediate wells.

the aquitard is preventing the arrival of equivalent shallow chloride levels, the spike in sulfate concentration should not be observed if groundwater is traveling or recharging from 6,000 m away, as estimated by SLR (2015). This suggests faster groundwater velocities and shorter distances are allowing the arrival of Sulfate at great depths before it has a chance to be reduced (Dyke 1999).

5.1.7 Bacteria

Coliform contamination is most likely to begin to show up in wells during wet periods, therefore “snapshot” readings of bacteria counts must be interpreted with care when considering well vulnerability as absence of bacteria may not necessarily mean low risk of intrinsic aquifer vulnerability. Drinking water standards suggests that any detectable counts of bacteria may indicate the water is not safe to drink and bacteria that is found in wells can indicate low aquitard integrity, seepage through well-casing, or defective well seals . Many factors can contribute to bacteria counts in wells, and wells should not be automatically assumed to have higher intrinsic aquifer vulnerability where bacteria is found. Figure 5.9 shows the total coliform count in each of the PWs with tritium over a 2 year period. This scatter plot shows that the highest counts are in PW01, PW03, and PW17, with bacteria counts occurring 100 mbgs. PW06 and PW21 displayed a total coliform count of zero from 2014-2016.

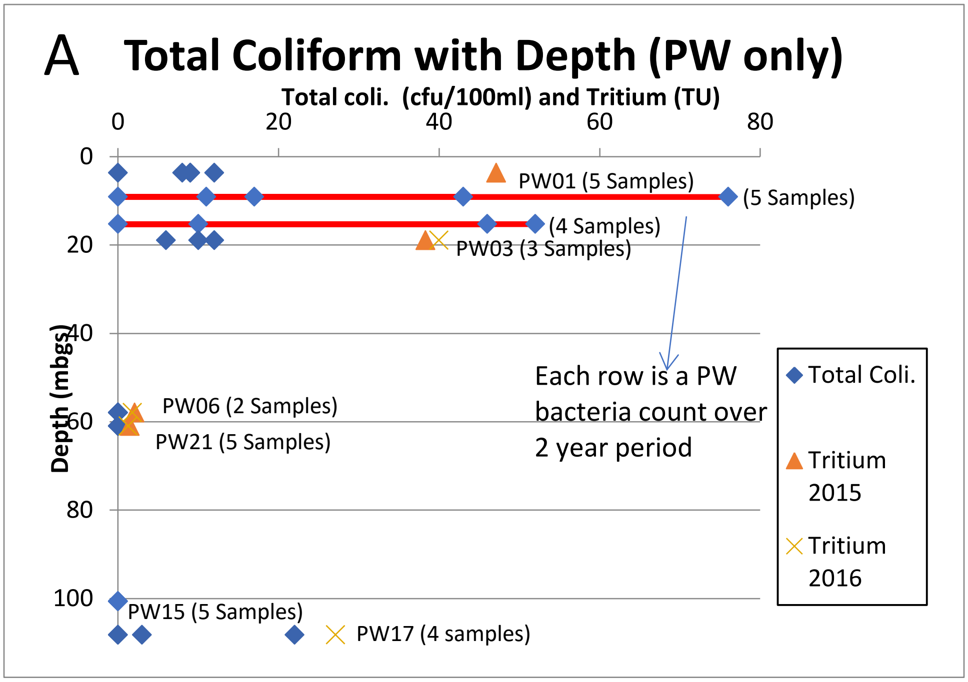


*Fig. 5.9: **A:** Tritium (TU) and Total coliform (mg/L) concentration depth plots in private wells. Microbiological coliform samples were collected from 2014-2016 from various locations around the site. Bacteria count over a 2-year period agrees with the highest vulnerable wells determined by TU sampling. Sample numbers indicate how many samples were collected over a 2-year period, since overlap in data points occur.*

Bacteria needs to be monitored over longer periods of time due to the yearly fluctuations, and therefore may not be a good parameter to use when assessing well vulnerability over short durations of time.

5.2 Discussion

The best indicator for assessing well vulnerability, when compared to tritium values is chloride. Chloride was the most consistent with tritium values around the site, whereas other indicators such as sodium, and nitrate were not as consistently related with tritium in deeper wells. These results were expected as chloride is often used as a conservative tracer in groundwater studies.

At the Clarington site, the reporting of tritium-helium ages 5-23 years, (Chapter 4) can seem inconsistent with the findings of Coliform microbes (based on the Total Coliform analyses) in the same wells considering microbes such as bacteria and even viruses live generally on the order of months in groundwater (Cherry et al. 2006). It is important to note that this tritium-helium age estimate is an average age and groundwater can be a mixture of very young and very old water.

Furthermore, the transport of bacteria and viruses, which are physical particles, is different than the transport of water isotopes such as tritium and the transport of any dissolved constituents such as chloride and nitrate. In fractures within fractured porous media, particles such as bacteria and viruses can move much faster than the water isotopes and dissolved contaminants, which will travel much slower than the bulk movement of water in the fractures (McKay et al. 1993). This is due to the strong effects of molecular diffusion on the water isotopes and dissolved constituents. In contrast, diffusion has almost no effect on particles, even small particles such as colloids. The relatively rapid transport of colloidal particles representing viruses compared to bromide and chloride tracers was demonstrated by a field tracer test in near-surface fractured till by McKay et al. (1993). This means bacteria are representative of the fastest water flowing through preferential pathways or in other words of average linear pore water velocity in a groundwater system (Cherry et al. 2006).

Wells near the surface all consistently displayed evidence of anthropogenic indicators, suggesting that this zone is vulnerable and additional data is needed to determine the extent of this zone as many wells were shallower than 20 mbgs. Wells within the Newmarket/Thorncliffe transition zone such as PW18 (Not located in cross section areas), PW10, PWALT, PW21, and PW06 (Figs. 3.22 and 3.23) that displayed increased TU are PW10 and PWALT at 65.8 and 70.1 m depth respectively, however no additional geochemical data was available from these wells. The remaining wells within this transition zone displayed pristine levels of anthropogenic indicators and lower values of TU, possibility suggesting that many of these wells may be completed in sand zones that are hydraulically isolated from other sand either in the Newmarket Till or underlying Thorncliffe Formation.

Near 100 mbgs, and likely within the Throncliffe aquifer, PW17 produced increased levels of TU (no tritium data was available from PW15), and both displayed increased values of chloride and sulfate providing evidence of anthropogenic effects within the Thorncliffe aquifer. The consistent chloride and tritium relationship suggests it is highly likely that all wells with elevated TU (such as PW10 and PWALT) would display chloride levels above pristine concentrations, and vice versa PW15 would likely display increased TU values.

On average, there were higher concentrations of chloride and sulfate in the shallow wells, compared to the intermediate wells (Table 5.2). Chloride averaged 3 mg/L in the intermediate wells, suggesting that longer flow paths or slower groundwater velocities through the Newmarket aquitard may have prevented the arrival of chloride near the bottom of the till. Sulfate concentrations are also lower, providing additional evidence of slower velocities recharging the intermediate wells within the area. There is a possibility that the deepest well PW17 at 108 mbgs is within the Scarborough formation (Table 5.1), and therefor may be getting chloride from the shale bedrock below, however no sands that could be ascribed to the Thorncliffe Formation were logged in the private water well recorded above this sand unit (Fig. 3.22).

It should be noted that not all possible evolutionary processes of these constituents were analyzed nor does the current data set allow discrimination of the multiple potential sources. Further evaluations beyond the scope of this thesis could utilize the groundwater quality data in a more extensive manner. Once a better understanding of sand connectivity below the site is achieved, chemical signatures of the groundwater may become more useful when determining exact flow pathways compared to short and long flow paths that was done in this thesis.

5.3 Conclusion

The best anthropogenic indicator for assessing well vulnerability appears to be chloride. This constituent agrees very well with elevated tritium values with depth, suggesting it might be the most useful groundwater parameter to assess. However, due to its unequally distributed nature, analysis of tritium is still the best option in the assessment of well vulnerability.

Chloride and sulfate concentration with depth aid in the determination if short or regional extensive groundwater flow pathways are contributing to groundwater flow within the aquifers. Sulfate should become reduced if associated with very slow groundwater velocities or traveling over a 5-10 km distance, ruling out potential recharge from the ORM. Sulfate data within all aquifers below the site suggest that leakage through the aquitard is associated with relatively short groundwater pathways, suggesting the wells within the vicinity of the site may have intrinsic aquifer vulnerability.

6 Stable Isotope and Geochemical Groundwater Signature

6.1 Background

Concentrations of isotopes within the water molecule of rainwater are dependent on climate factors such as air temperature and location (Craig 1961). The basis of this discovery led to the use of the spatial and temporal variability of Oxygen-18 (^{18}O) and Deuterium (^{2}H) as a naturally occurring groundwater signature that has the potential to be used as a groundwater tracer (Clark 2015). Isotopes exhibit the same behavior as atoms in hydrological reactions, but it is the different bond strengths created by heaver or lighter isotopes that cause them to preferentially accumulate on one side of the reaction. Atoms that have greater mass will form stronger bonds, meaning the heavier isotopes will tend to be in the more condensed phases such as ice, whereas lighter atoms such as ^{16}O will be easier to break apart, creating generally lower concentrations of ^{18}O in water vapor. It is also the slightly different free energies of isotopes during reactions that allow for the natural partitioning of heavy and light isotopes (Clark 2015).

Hydrological processes that contribute to preferential accumulation of isotopes include evaporation and formation of vapor, condensation and rainout, re-evaporation from soils and surface water, and mixing during recharge and groundwater flow. As groundwater enters the subsurface, the temperature dependent isotopic concentration in precipitation is highly attenuated. Seasonal effects of recharge and hydrodynamic dispersion create an environment where the ^{18}O content in precipitation can vary up to and over 8%, whereas the variation in groundwater is below 1% (Clark 2015). Clark (2015) suggests when analyzing isotopic concentrations over time, groundwater that does not demonstrate large variations is most likely a part of a more protected, deeper aquifer system. Spatial-scale monitoring allows for the analysis of the degree of variation in recharge to local aquifers. Heterogeneity of recharge should be highly attenuated by dispersion in a confined aquifer (Clark 2015). Consequently, ^{18}O and ^{2}H isotopic signature at each sampling point allows for interpretations of sand connectivity around the site. Sampling points at similar depths with similar isotopic concentrations could indicate sand zone connection between each well, or connection between the sand zones through preferential pathways. A stable Isotope ratio with depth of $\delta^{18}O$ and $\delta^{2}H$ in low permeability zones with a net vertical gradient would be expected to display an increase in depletion of $\delta^{18}O$ with depth. Irregular isotopic profiles may provide strong evidence that sedimentary enhanced permeability zones are present within the system (Gerber et al. 2001).

In the York Region, Husain et al. (2007) used isotopes ^{18}O and ^{2}H to better understand the groundwater flow, specifically focusing on residence time and the interconnection between the aquifers. Fractionation of stable isotopes change depending on climate and therefore create an isotopic signature of past climate conditions. Higher percentages of ^{18}O indicate colder climate conditions and unmodified groundwater. The isotopic signature thus provides natural occurring tracer for determining the origin of groundwater. Isotopic analysis provided evidence of rapid groundwater recharge and leakage based on isotopic profiles of titrated waters in the York Region (Husain et al. 2007). An atypical concentration with depth trend of a low permeability unit emerged: titrated water was present at various depths within the till. Additionally, Husain et al. (2007) found evidence of the mixing of older and recent groundwater in the York Region. The stable isotope ratio depth plot of $\delta^{18}O$ and $\delta^{2}H$ show little to no depletion in this till in contrast to the expected depletions with depth plot of depletion in $\delta^{18}O$ for a low permeability zone with a net vertical gradient. The irregular isotopic signature with depth presented provided strong evidence that sedimentary enhanced permeability zones are present within the Newmarket Till (Husain et al. 2007).

^{18}O and ^{2}H data can be compared to the Simcoe Meteoric Water Line (MWL) (IAEA/WMO 2017) to achieve a better understanding of aquifer residence times (Husain et al. 2007). Local meteoric water lines are slightly different depending on local climate conditions. These local lines can be very or slightly different in slope and deuterium excess from the Global Meteoric Line as originally defined by Craig (1961), because it reflects local re-evaporation/mixing and origin of water vapor (Clark and Fritz 1997). Isotopic signatures that fall close to the local meteoric water line can be assumed to be unmodified by a secondary process, such as evaporation or rock-water interactions

(Husain et al. 2007). Data that falls close to the MWL also gives extra confidence in the lab analysis. Modern day groundwater signatures began 8,000 years ago in the Holocene time period meaning ^{18}O depletions were around 12-10% (Edwards et al. 1996)making determining the age of groundwater with isotope signature alone difficult. However ^{18}O signatures closer to -10%, within the ORM area that are associated with the presences of detectable tritium levels can be considered to be composed primarily of modern day groundwater signature (Ian Clark, Pers. Comm. 2017).

In addition to ^{18}O and ^{2}H, natural water quality geochemical data collected from groundwater monitoring programs can be plotted in piper plots (Husain et al. 2007) to allow for the determination of different aquifer signatures. Major ions used to determine groundwater signatures include potassium (K^{+}), chloride (Cl^{-}), magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium (Na^{+}), Sulfate (SO_4^{2-}), bicarbonate (HCO_3^{-}), and carbonate (CO_3^{2-}) (Husain et al. 2007). Major ion concentrations are affected by the elements available in soil and rock in contact with the groundwater, thus giving insight into potential sources of groundwater and pathways the groundwater has travelled over time (Freeze and Cherry 1979). Aquifers systems that are recharged through regional pathways may possibly display different ion concentrations than aquifers that are replenished from vertical leakage on site only (Freeze and Cherry 1979, Husain et al. 2007).

6.2 Previous work

As part of the Hydro One groundwater monitoring program, twenty five (25) private wells off site and sixteen (16) monitoring wells on site (Fig. 3.2 and 3.21), were sampled for groundwater quality parameters over the course of approximately 2 years (Stantec 2015a). Only twelve (12) of the twenty five private wells with known locations and depths are used in this study (Table 5.1 and Fig. 3.21), due to privacy laws and data release restrictions. This groundwater quality data is used for the analysis of groundwater aquifer signatures on site, and for comparison to other aquifer signatures within the ORM area. The detection limits reported from the Hydro One groundwater monitoring program for potassium (K^+), chloride (Cl^-), magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium (Na^+), Sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) are 0.2 mg/L, 1.0 mgl/L, 0.05 mg/L, 0.2 mg/L, 0.1 mg/L, 1.0-mg/L,1.0 mg/L, and 1.0 mg/L respectively.

Husain et al. (2007) conducted a groundwater quality study within York region. Analysis of the various major ion concentrations listed above, was undertaken on samples within the ORM, Thorncliffe, and Scarborough aquifers. Direct comparison of the piper plots produced from deeper aquifer systems and shallow aquifer systems, displayed consistently different groundwater signatures (Fig. 6.1). ORM aquifer consistently shows elevated concentrations of chloride, sodium, and nitrate, indicators of anthropogenic stress. These results follow the trend identified in this study that the first 20 mbgs is usually the most vulnerable to contamination, especially where aquifers are unconfined.

An extensive regional groundwater geochemistry study was conducted by the Ontario Geological Survey (OGS); it covers a 96,000 Km^2 area, and includes bedrock and overburden groundwater signature data near the TS at various sampling locations (Figs. 6.2 and 6.3) (Hamilton 2015). Wells available from the Hamilton (2015) data set near the Clarington TS were 6.5 mbgs, 20 mbgs, 30 mbgs, and 66 mbgs. The three deeper wells from Hamilton (2015) shown in fig. 6.2 and 6.3 are drilled and the shallow well is bored and quality of wells is unknown like many private wells used in chapter 5; dug or bored wells have been shown to be more frequently contaminated than drilled wells (Rudolph et al. 1998). The major ion concentrations around the TS in the overburden wells (Fig. 6.2) are similar to the signatures found with the ORM area presented by Husain et al. (2007). The bedrock wells do not appear to be similar to any of the water signatures presented by Husain et al. (2007) and look to be depleted in chloride and sulfate and enriched in sodium. However groundwater that is interacting with bedrock is often considered poor quality and may not provide an accurate representation of groundwater pathways (Husain et al. 2007). This may explain why these samples do not conform to the groundwater signatures discussed in Husain et al.'s (2007) data set.

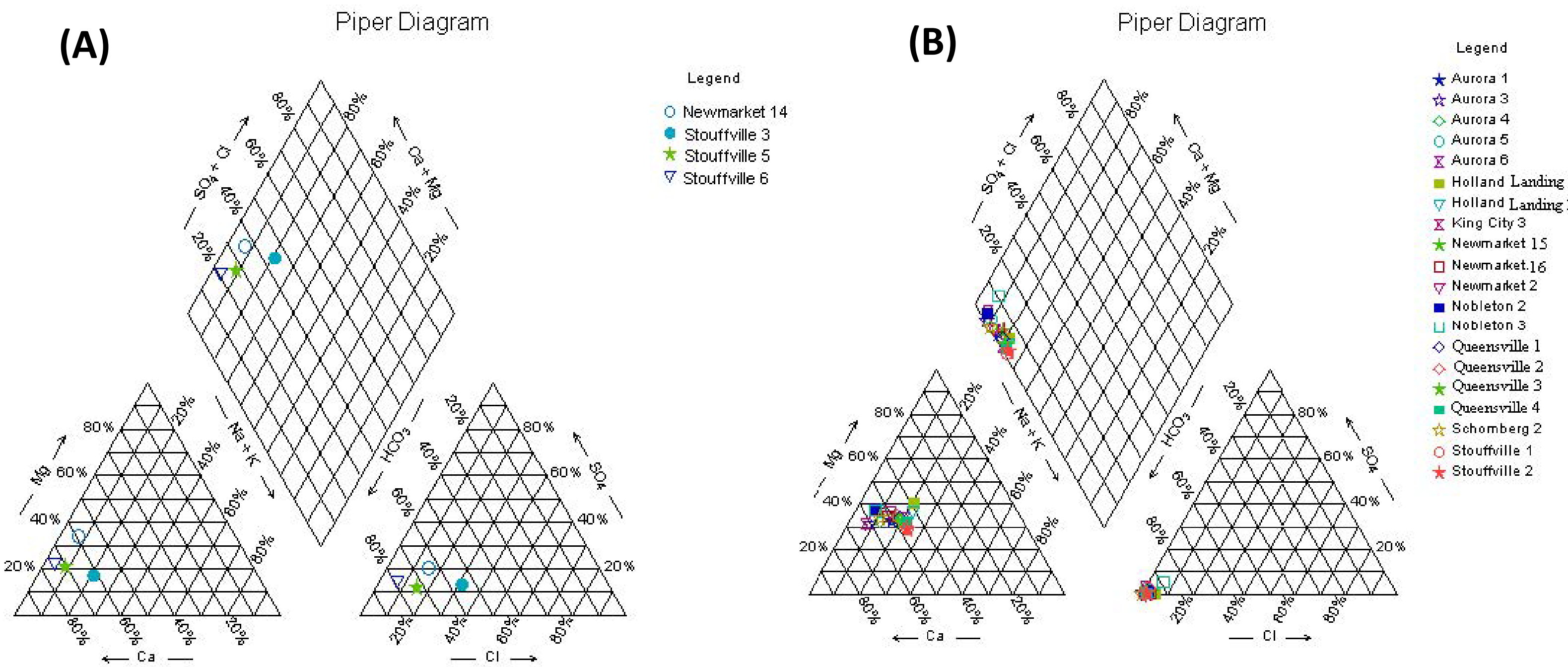


Fig. 6.1: Piper plots from shallow ORM groundwater (A) and deeper Thorncliffe or Scarborough aquifer (B) (Husian et al. 2007). Shallower groundwater shows evidence of anthropogenic effects, creating two different groundwater signatures between deeper, more protected aquifers, and shallow, unconfined aquifers.

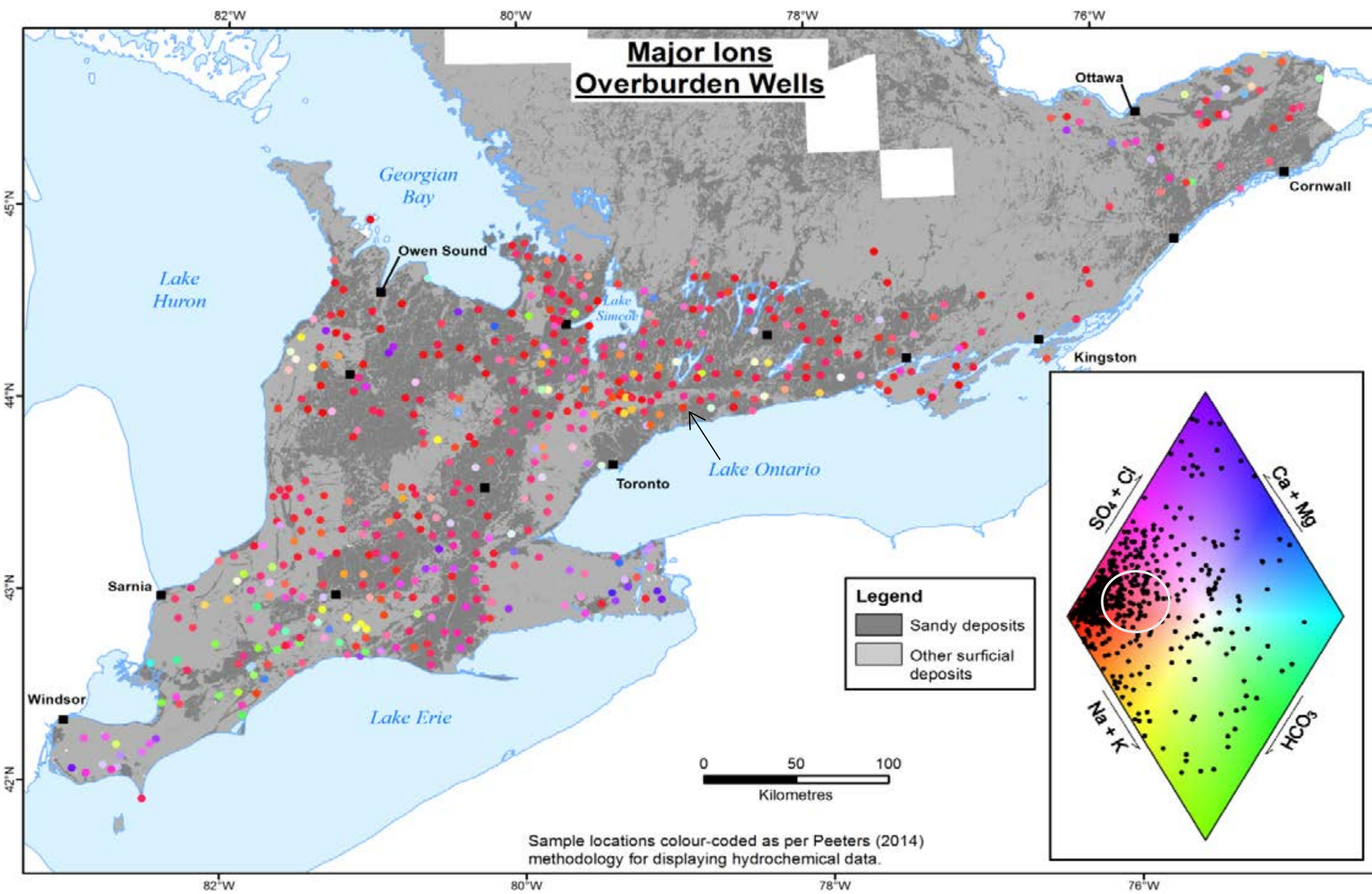


Fig. 6.2 Piper plots of overburden wells near the Clarington TS, market with a black arrow. The dots near the TS are red/pink in color. The white circle on the piper plot indicates the major ion concentration near the TS. The groundwater chemistry is very similar to the major ion concentrations found within shallow sand zones around the TS site (Hamilton 2005).This diagram offers additional comparison of major ion concentration within the ORM relative to the TS location.

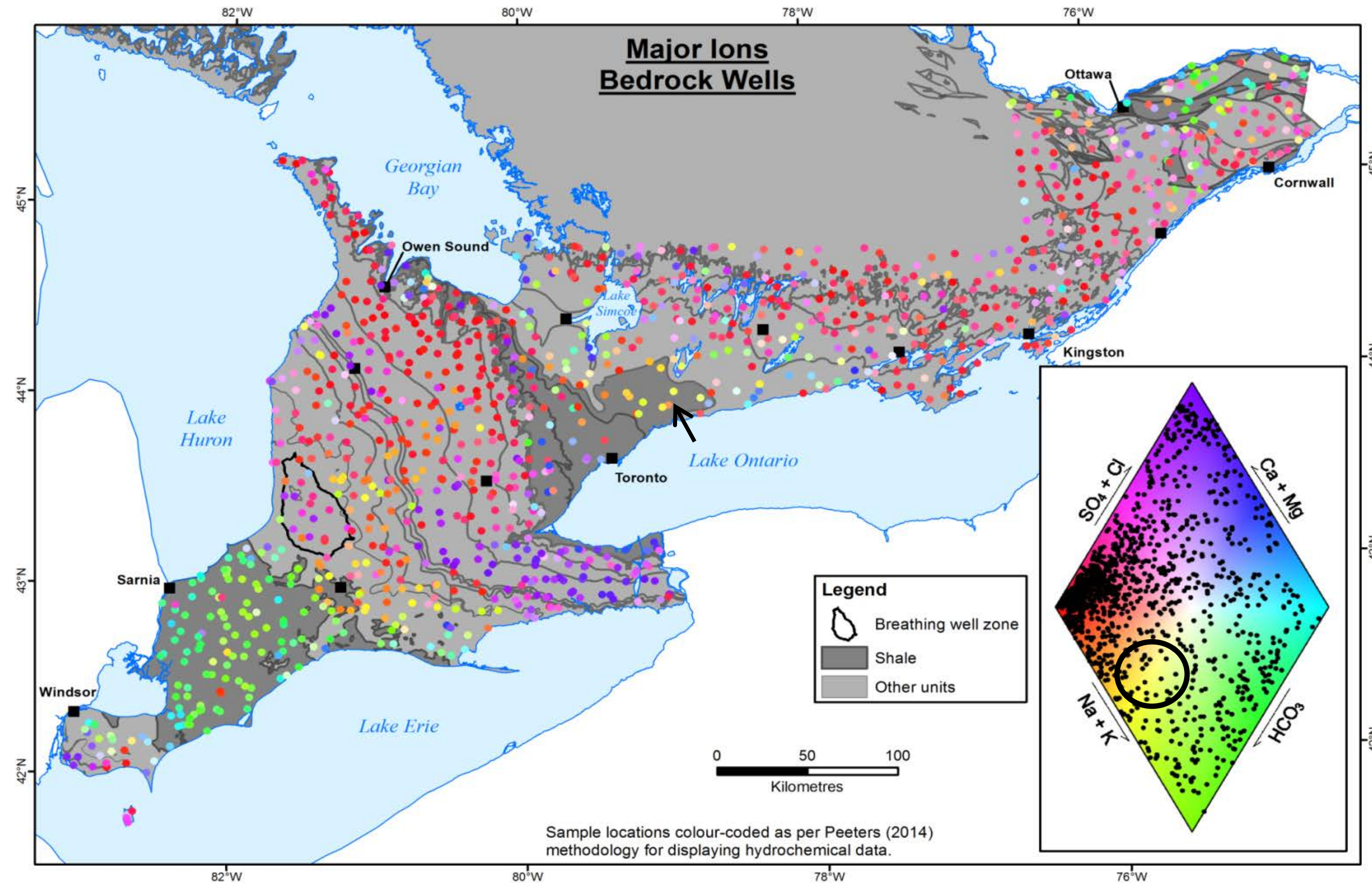


Fig. 6.3 Piper plots for bedrock Wells near the Clarington TS, marked with a black arrow. The yellow and orange dots near the TS are marked with a black circle on the Piper Plot. The location of this black circle indicates the groundwater chemistry at bedrock, is slightly different that the groundwater chemistry of aquifers within the Thorncliffe aquifer and the Newmarket aquitard found in the Husain et al 2007 study. This major ion concentration does not agree with the deep aquifer signatures found by Husain et al. 2007, however bedrock wells are typically low quality water samples when studying major ion concentrations. This diagram offers additional comparison of major ion concentration within the ORM relative to the TS location.

^{18}O depletions are also reported near the TS from this groundwater study (Hamilton 2015). Typical depletion values in overburden wells range from -10 to -10.99% and bedrock wells range from -11 to -11.99%.

6.3 Sampling/Methods

Water samples were collected for ^{18}O and deuterium from the six (6) private wells that were also sampled for Tritium and Helium at the same time (Table 5.1). The water samples were collected from residential taps in glass jars with minimal head space. The samples were shipped to G.G Hatch Stable Isotope Laboratory at the University of Ottawa, and were analyzed by direct measurement using the Triple Isotope Water Analyzer (TIWA-45EP) by Los Gatos Research (LGR). LGR's patented off-axis Integrated Cavity Output Spectroscopy (ICOS) allows for highly accurate ^{18}O and ^{2}H quantifications. ^{2}H and ^{18}O are measured with a precision of 0.5% and 0.1%, respectively and normalization of the data was completed using three internal standards that were calibrated from Vienna Standard Mean Ocean Water (VSMOW), Standard Light Antarctic Precipitation (SLAP), and Greenland Ice Sheet Precipitation (GISP) (Berman et al. 2013).

Major ion data collected for the Hydro One groundwater monitoring program were tested for quality assurance and quality control (QA/QC) using the calculations of charge balance error (equation 5.1.1.1).

Major ions used to determine groundwater signatures include potassium (K^+), chloride (Cl^-), magnesium (Mg^{2+}), calcium (Ca^{2+}), sodium (Na^+), and sulfate (SO_4^{2-}); these were collected directly from the Stantec (2015a) report. In the Stantec report, bicarbonate and carbonate were reported in mg/L of $CaCO_3$. However, the piper diagram used for determining groundwater signatures needs bicarbonate in mg/L of HCO_3^-, and carbonate mg/L of CO_3^{2-} (Husain et al. 2007).The conversions were completed using the following equations:

Bicarbonate Alkalinity as HCO_3^- (mg/L) = 1.22*Bicarbonate alkalinity as $CaCO_3$(mg/L) (Equation 6.3.1)

Carbonate Alkalinity as CO_3^{2-} (mg/L) =0.6*Carbonate alkalinity as $CaCO_3$(mg/L) (Equation 6.3.2)

Once conversions were complete, the data was plotted in piper diagrams for easy comparison of groundwater signatures around the site (Alkalinity 2009).

6.4 Results

Figure 6.4 A shows the private well ^{18}O and ^{2}H concentration compared to the Simcoe meteoric water line (MWL). All of the groundwater samples fall very close to the local isotopic ratio MWL. This means they do not appear to be altered by secondary processes such as evaporation or rock-water interactions (Husain et al. 2007). Depletion values also agreed with values published by Hamilton (2015).

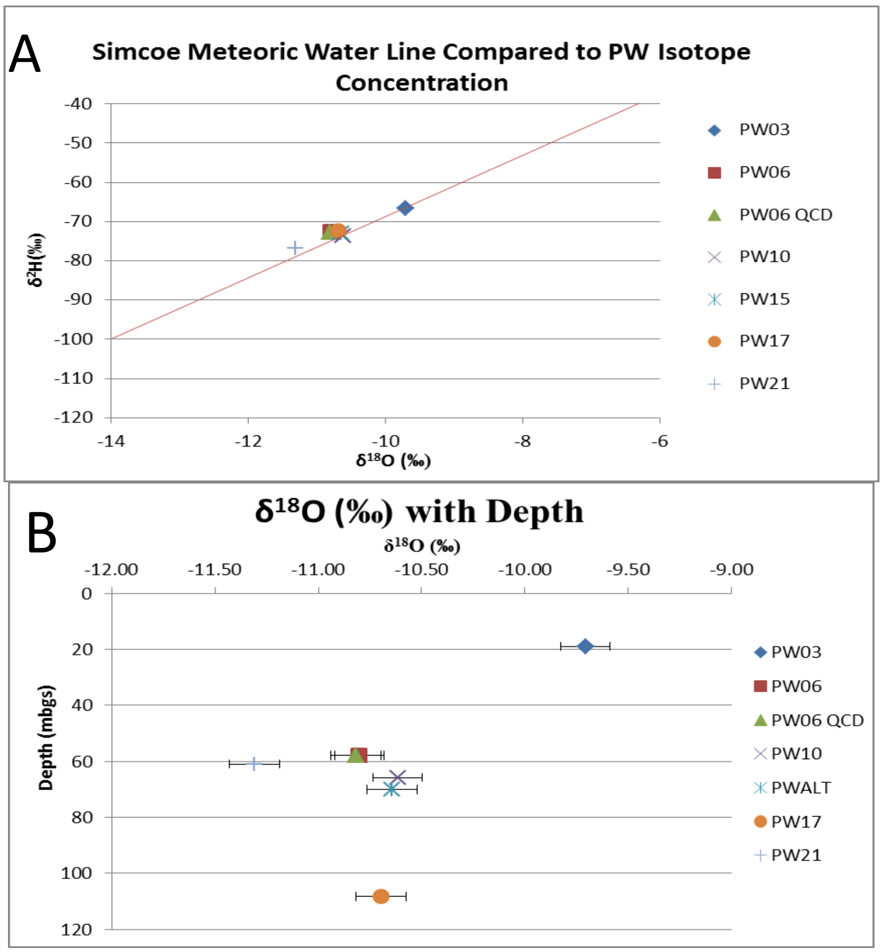


Fig. 6.4: ***A:*** *O^{18}andH^{2}groundwater signatures of private wells located off of site. Comparison to the Simcoe Meteoric Water Line* (IAEA/WMO 2017) *shows that secondary processes such as evaporation have not altered the groundwater. Groundwater samples are close to -10% depletion in O^{18}, and have detectable tritium levels providing evidence that modern groundwater is contributing to recharge. It would be expected to see a greater depletion in O^{18}, towards -16%, if the porewater within the aquifer had large concentrations of water originating from colder climatic conditions during the Wisconsinan glaciation.* ***B****: O^{18}concentratio with depth of private wells located off of site.*

Figure 6.4 B shows ^{18}O concentration with depth. The produced isotopic signature with depth is atypical of an aquitard (Clark 2015), meaning there is no consistent increase in depletion of ^{18}O with depth. This is suggesting all reported ^{18}O depleted samples within the area are largely composed of modern groundwater, due to the signatures and presence of tritium combined. PW06 and PW21 have very similar ^{18}O depletions to other wells around site, and yet had different chloride and nitrate signatures suggesting these wells were perhaps more protected. The presence of similar ^{18}O signatures and detectable tritium concentration suggests that perhaps these wells are not necessarily less vulnerable but rather the groundwater recharge may be coming from an area lacking chloride and nitrate or subsurface conditions have affected the fate of these constituents in this area.

Figs. 6.5 and 6.6 displays the major ion concentrations on and off site plotted on piper diagrams to be used for comparisons to the groundwater signatures from previous studies in the ORM region (Figs. 6.1, 6.2, and 6.3; Hussein et al. 2007 and Hamilton 2015). There are no apparent or consistent differences between the wells that are potentially located in the Thorncliffe aquifer versus wells that are completed in sand zones within the Newmarket aquitard (Fig. 6.5). PW06 and PW21 have isotopic signatures (Fig. 6.5) closest to the deeper and protected aquifer signatures observed by Husain et al. 2007 (Fig. 6.1), agreeing with the original interpretation that these two wells have less signs of anthropogenic impact. Wells significantly below the

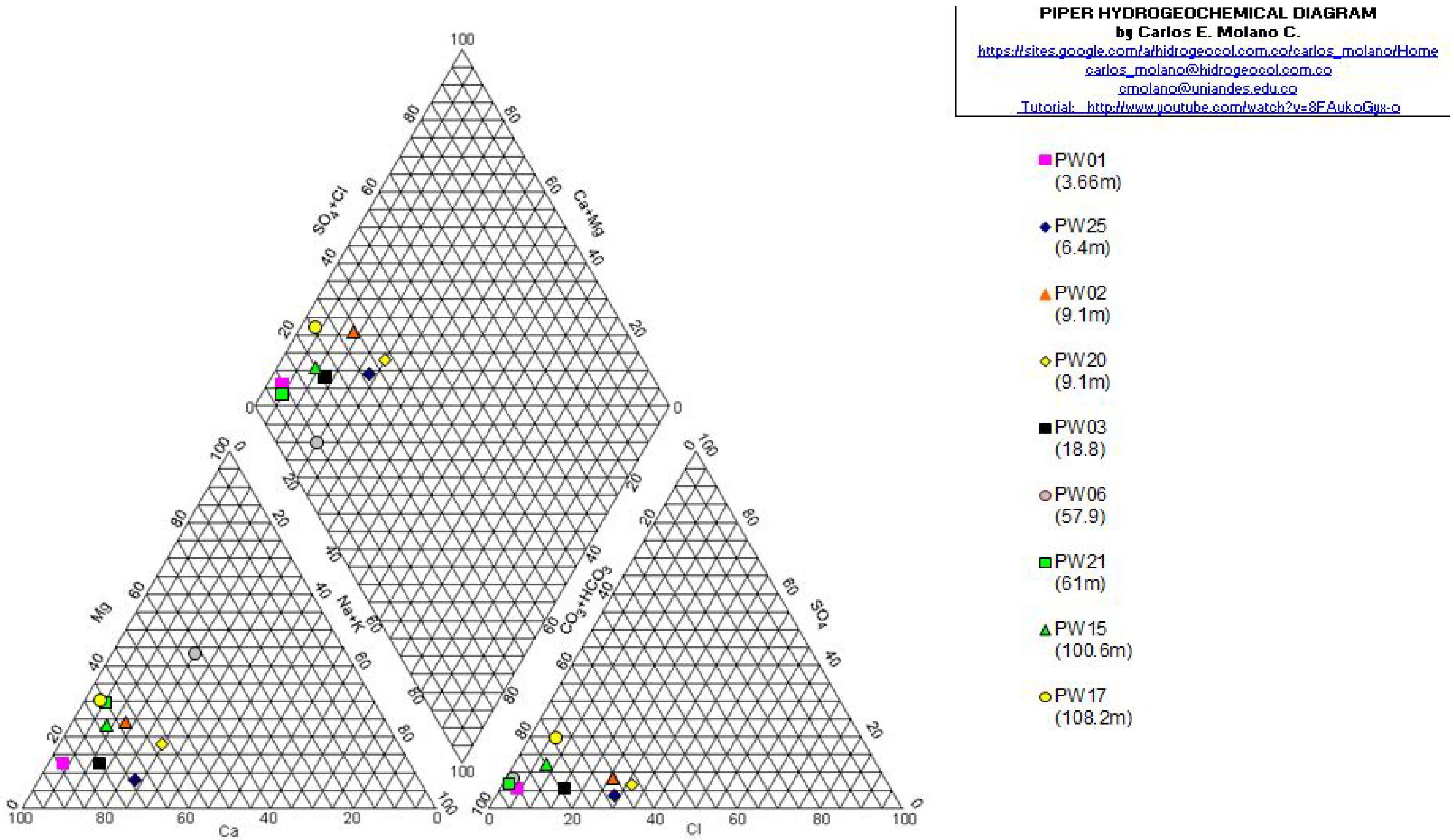


Fig. 6.5: Piper plot of major ion concentrations associated with private wells located around the site. Private wells are completed in sand zones within the Newmarket aquitard and sand within the Thorncliffe aquifer. This major ion plot shows very similar trends in all locations and depths. This suggest most of the groundwater flow to aquifers within the area are through preferential pathways, allowing for similar major ion concentrations in all aquifer systems. The major ion concentrations are very similar to those found in the Husain et al. study for shallow wells, and similar to the concentrations found in Fig.6.2

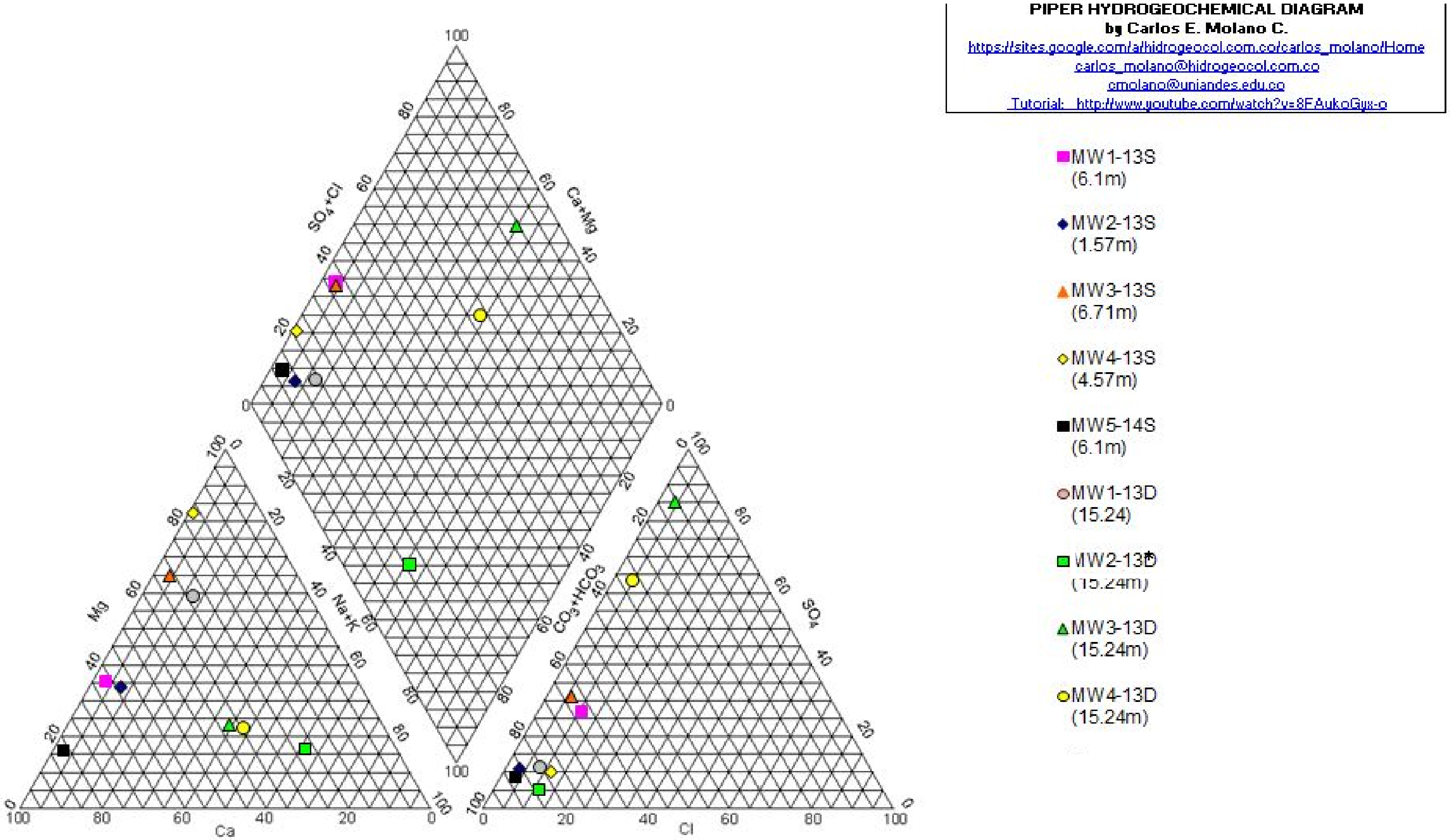


*Fig. 6.6: Piper plot of major ion concentrations associated with monitoring wells located around the site. Monitoring wells consist of wells screened within the Newmarket Till aquitard. This major ion plot shows no trend in groundwater geochemistry within the aquitard with depth.MW5-14I and MW5-14D located 40.1 and 55m respectively were not included in this plot due to very large ion balance issues (approximately 20%). *MW2-13D had a charge balance of 9%, close to the 5% acceptability and are therefore kept in this plot.*

Thorncliffe/Newmarket contact do not show isotopic signatures close to those found in deeper wells by Husian et al. (2007), and appear to have closer signatures to those found within the ORM. All wells on and off the TS site match the overburden groundwater chemistry from a few nearby locations associated with the regional OGS study, providing additional confidence that groundwater within this area is affected by modern groundwater and anthropogenic effects (Fig. 6.2). Bedrock geochemical signatures from the OGS geochemical study did not match any of the major ion concentration trends associated with shallower depths at this site (Fig. 6.3). Figure 6.6 are monitoring wells screened within the Newmarket aquitard, and no trend of major ion concentrations within the till is observed.

6.5 Discussion

Husain et al. (2007) considers ^{18}O depletions from -13% to -10% to be modern day depletion levels, suggesting that all wells sampled at this site are largely composed of modern day groundwater especially with detectable tritium levels in each well. The ^{18}O and deuterium data provide evidence that leakage of modern groundwater is reaching depths greater than 100 mbgs. This includes sand zones within the Newmarket aquitard and within the Thorncliffe aquifer. There are small fluctuations of less than 1% fluctuations in O^{18} depletion around the site, providing evidence that sand zones within the Newmarket aquitard and the Thorncliffe aquifer are potentially hydraulically connected, or groundwater is coming from the same area. The ^{18}O depletions with depth around the site have produced very similar signatures, which would also normally be evidence of a large extensive aquifer system, providing additional evidence that these zones may be hydraulically connected.

Fluctuations in the groundwater depletions are too small to interpret as significant without long term monitoring. This additional monitoring may provide evidence that the fluctuations are significant, and therefore would agree with the interpretation that pristine level wells may be in isolated sand zones and not a part of a larger aquifer system.

It is also apparent that at our site the Thorncliffe aquifer does not follow the expected major ion trend and all major ion signatures are very similar. Anthropogenic indicators can affect these signatures, which is why Husain et al. (2007) found that the more protected Thorncliffe aquifer had a different signature than wells within the unprotected ORM.

6.6 Conclusion

Geochemical signatures of ^{18}O and Deuterium and tritium data combined suggests that aquifers are subjected to modern day recharge, and are behaving like a large aquifer system with less than 1% fluctuations in ^{18}O. Major ion data also suggests that groundwater to all aquifers below the site is traveling very similar flow paths.

7 Integration and Conclusion

7.1 Summary of findings

Grain size data from surface till at the Clarington TS displayed no significant change in textural composition based on field descriptions, and orientation of drumlins suggests re-advance of an ice sheet is unlikely. In contrast, gamma counts were higher in shallower wells suggesting potential presence of Halton Till, therefore origin of the surface till is unknown. Determination of surface till is not important when assessing hydraulic connectivity of sand zones, and vulnerability assessment can still be completed.

The Newmarket and Thorncliffe contact was determined to be at 75 mbgs (Duggan 2017), however incorporation of Thorncliffe sediments creates transition zone that creates a potential mixing of sediments from 68 mbgs and 75 mbgs (184 masl and 177 masl). This determination was based on the apparent grain size composition change in the till at 68 m depth and the presence of deep sand zones that may be hydraulically connected to the Thorncliffe Formation due the deformation till located at the bottom of the Newmarket. However, PW18 at 76 mbgs displayed TU levels at the detection limit compared to other deep wells that exhibited higher TU levels (e.g. PW15 at 100.6 mbgs), and this may suggest that Thorncliffe contact in this area may be greater than 76 mbgs.

Elevated tritium levels were found in wells reaching approximately 100 mbgs, displaying an atypical tritium concentration with depth for an aquitard. Tritium-helium data dated the groundwater approximately 100 mbgs at 14 years old and shallower depths of groundwater ranged from 5-23.5 years old. Vertical velocity estimates from triaxial samples showed discrepancies with slug test and from vertical velocity estimates from age calculations on site suggesting the presence of preferential pathways.

Higher levels of sulfate and chloride in both shallow and deep groundwater suggest shorter/quicker flow paths from surface, providing evidence that the Thorncliffe aquifer at this site may not be a part of a regional groundwater system, and that groundwater must be coming from the local area. Nitrate display high concentration near surface with a decline in concentration with depth, and bacteria counts were found in 4 out of 4 shallow wells and 1 out of 2 deep wells near 100 mbgs.

Isotope signatures of ^{18}O and D show no major fluctuations with depth suggesting the aquifers are behaving as a connected system. Isotopes(^{18}O and D) and major ion signatures of shallow and deep private wells suggest the sand zones within Newmarket Till and Thorncliffe aquifer are hydraulically connected in some way, as no distinct differences in groundwater signatures were observed, suggesting the groundwater is travelling very similar pathways. The irregular isotopic depth plots of similar isotopic signatures with depth also provides evidence that preferential pathways are playing a role in the distribution of modern groundwater leakage at depth, meaning the ^{18}O and deuterium signatures of each aquifer unit agrees with other trends found in the geochemical data (Chapter 4,5).

The different geochemical findings at the Clarington TS suggests there are preferential pathways through the aquitard and underscores the need to complete local, site specific, hydrogeological studies before assuming adequate aquitard integrity.

7.2 Integration of Geological and Geochemical Data Sets

7.2.1 Intro

Based on the existing and new data discussed in this thesis, the groundwater flow system on site may have preferential pathways that allow leakage through the Newmarket aquitard into the underlying Thorncliffe aquifer. However, there are several possible explanations for the geochemical results above and the various values of groundwater flux obtained (Fig. 7.1): 1) fractures or secondary permeability features may be present within the Newmarket Till, 2) recharge maybe coming from the horizontal direction to the Throncliffe aquifer, 3) the wells may be poorly constructed, resulting in short circuiting and contamination via the well itself (Fig. 7.1). It should be noted that one or all of the these explanations can be working in combination with each other to produce this geochemical results observed at this site.

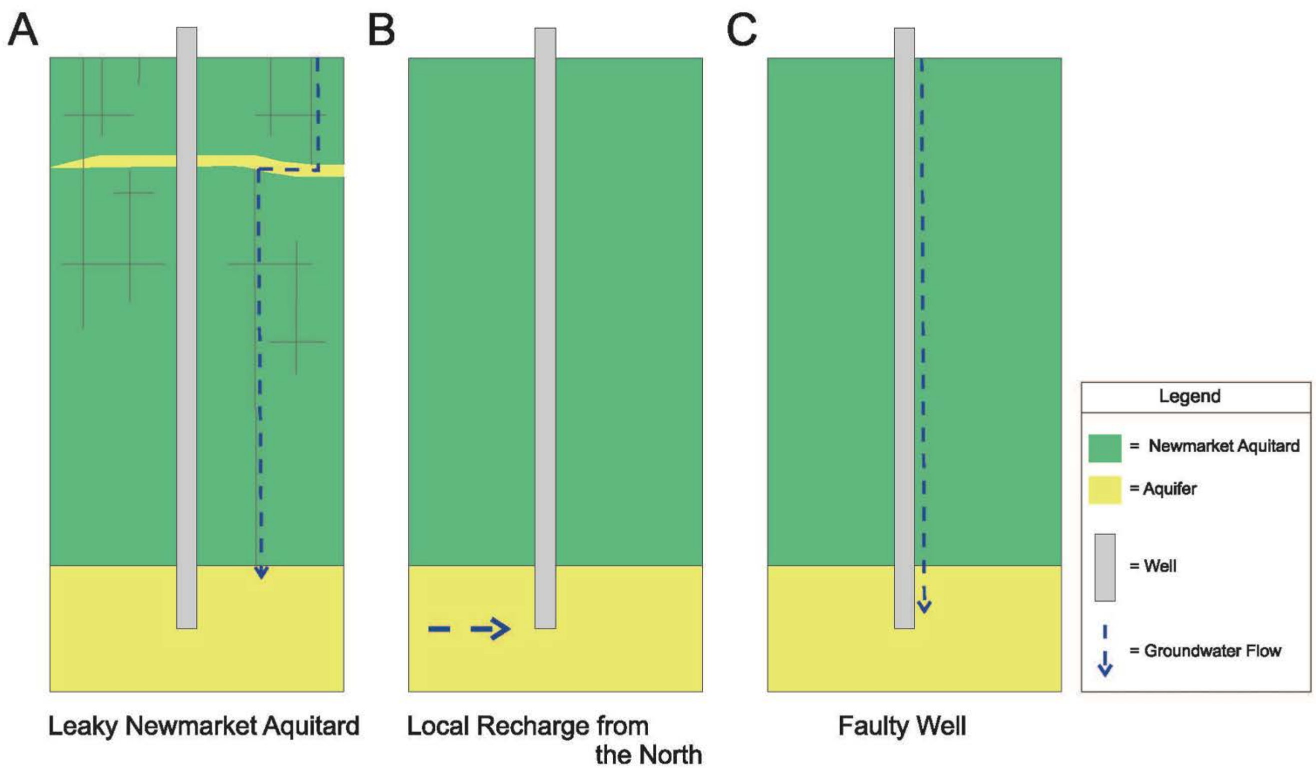


Fig. 7.1: Three different hypotheses proposed to explain the existing data and the nature of recharge or leakage through the Newmarket Till and into lower aquifers. ***A****: A leaky Newmarket aquitard is allowing new water at depths, through high hydraulic conductivity features and fractures.* ***B****: Recharge is coming in the horizontal direction from a location to the North (approximately 1,500m away) where the Newmarket aquitard is thin or non-existent.* ***C****: Well seals are leaky causing a direct pathway into the lower aquifer.*

7.2.2 Fracture or secondary permeability features through the Newmarket Till

The first hypothesis is leakage through the aquitard in the vertical direction (Fig. 7.1A), and geochemical evidence for this hypothesis is summarized below. The tritium concentration with depth indicates active flow upwards of 100 mbgs, by displaying younger water with depth, from tritium helium age estimates suggesting rapid vertical groundwater flow through the aquitard, likely through fractures and sediment heterogeneities (Gerber and Howard, 2002; Fig. 2.3). It is interesting to note however, that tritium levels in samples differed from well to well at similar depths but each well was consistent over time (Fig. 4.8), suggesting some areas of the till may be less vulnerable than other locations.

Chloride and sulfate levels depicted in Fig 7.1 in PW17 (108 mbgs) on the right side of the diagram are elevated and are around the same levels found in the shallow groundwater (MW3-13D/S and MW4-13D/S). This suggests shorter vertical flow paths because the concentration should be lower due to sulfate reduction and the arrival of chloride should be prevented in better protected aquifers and regionally recharged systems. Sulfate averages in deep wells (Table 5.2) suggest that the aquifer may be recharged from the surface through the Newmarket aquitard and may provide evidence that the majority of leakage is coming from fractures and other high hydraulic conductivity features within the till. If vertical leakage was occurring through intergranular flow only, pristine levels of chloride and lower average sulfate would be expected because of the much slower velocities associated with the till matrix. Though chloride levels are lower than the average shallow concentration, they are still elevated at depth. Furthermore, the high sulfate concentration within the Thorncliffe suggests that heterogeneities and fractures are facilitating preservation of higher sulfate concentrations at depth before it has a chance to be reduced.

Sulfate concentrations are lower in the intermediate zone (e.g. PW06 at 57.9 and PW21 at 61 mbgs) (Table 5.2), providing evidence of slower velocities recharging the intermediate wells within the area. This may be due to the lower frequency and size of fractures at these greater depths that in turn would reduce connectivity between these sand zones and other conductive sedimentary features.

The piper plots of private well aquifer signatures all displayed similar signatures from shallow to deep sand zones, suggesting all aquifers are connected from surface, suggesting that high hydraulically conductivity features or preferential pathways exist at this site and contribute to observed anthropogenic effects with depth. This suggests that the groundwater pathways of lower aquifers are very similar to that of the Newmarket sand zones, however the exact location of recharge from surface to the water table is still unknown meaning the recharge could be coming from an area off site. The

Thorncliffe aquifer has displayed evidence of being better protected in other areas such as Markham and Stouffville (Husain et al. 2007), but the Clarington TS site geology does not appear to provide the same level of protection.

It was determined that many of the private wells were completed near the boundary of Newmarket aquitard and the Thorncliffe Formation at approximately 68-75 mbgs or 184 masl to 177 masl range. Although wells PW06 and PW21 are within the masl range (Figs. 3.22 and 3.23), the geochemistry data suggests they may be completed in isolated sand zones within the Newmarket Till. Fracture spacing typically increases with depth, making the probability of an isolated sand zone crossing a hydraulically active fracture low at this depth. This may explain why PW06 and PW21 have lower concentrations of tritium and chloride, than other wells within this same depth range.

These anthropogenic indicators are not considered an equally distributed source making interpretation of these constituents difficult, and providing an explanation of why these constituents were not found within these wells but displayed similar isotopic and major ion signatures to other wells around the site. Equally distributed sources such as tritium from precipitation allow for the best comparison of intrinsic aquifer vulnerability. The very low, almost identical tritium levels, associated with pristine levels of anthropogenic indicators also suggest these wells might be more protected that other wells within the area despite the lack of difference in the isotope data between these two wells and the rest of the more clearly impacted other wells.

The modern-day groundwater associated with all wells on site does not change the interpretation of the potentially more protected sand zone aquifers (PW06 and PW21) that had tritium values <2.5 TU. Tritium levels should be under detections limits and show ^{18}O depletions closer to -16% in areas where intrinsic aquifer vulnerability is low, meaning PW06 and PW21 may be relatively more protected than other PWs around the site, but does not mean they should be considered well protected in terms of contamination risk. The tritium-helium data provided evidence that these two wells have the oldest groundwater (15-20 years), even when compared to groundwater near 100 mbgs, also suggesting these sand zones are slightly more protected. However, the groundwater in PW06 and PW21 is young enough to display modern day ^{18}O depletions, and the absence of anthropogenic indicator levels may just be from the non-equally distributed source factor.

7.2.3 Horizontal Recharge

The second hypothesis is that groundwater is being recharged in the horizontal direction to the Thorncliffe Formation (Fig. 7.1B and 7.2). It is estimated the ORM is located just approximately 5 km north of the TS (Howard et al. 1995) and flow is predominantly to the south within the Thorncliffe aquifer (Gerber and Howard 2002), creating the possibility of recharge through the ORM, and directly into the Thorncliffe aquifer.

The groundwater age of Thorncliffe aquifer ranged from 14-15 years old. The average horizontal linear pore water velocity would need to be approximately 360 m/yr, if recharge to the Thorncliffe aquifer was coming in the horizontal direction from 5,000-6,000 m north of the site, which is faster than the estimated travel time of 100 m/yr (SLR 2015). Hydraulic conductivity ranges of a few orders of magnitude are not uncommon, however additional data is need to determine if these flow rates are plausible within this unit.

However, horizontal flow from the potential recharge area, through the regionally extensive Thorncliffe aquifer over approximately 5km should also create long enough travel times to allow sulfate to become reduced to a concentration near 2 mg/L (Dyke 1999), which was not the case at this site. Though more data is needed to rule out this possibility completely the observed high sulfate concentrations (Table 5.2) may provide additional evidence that recharge from the ORM is not likely. Alternatively, recharge may be coming from an area where the Newmarket aquitard is completely eroded by a meltwater channel to the North of the site, provided gradients are downward at those locations. Sharpe et al. (2005b) created an isopach map of the

Newmarket aquitard thickness in southern Ontario, displaying very thin or absent Newmarket Till approximately 3-4 km to the northwest and northeast of the TS (Fig. 7.2). Flow through erosional windows 3-4 km away (Fig. 7.2) within the Newmarket Till down into the Thorncliffe aquifer and over to the TS site would make travel times approximately 5.28 x 10^{-6} m/s or 167 m/yr. It should be noted that much of the data in this area to define the location of erosional windows (Fig. 7.2) is coming from water well records, so there are uncertainties with the exact thickness and distribution of the Newmarket and consequently the estimated distance of travel.

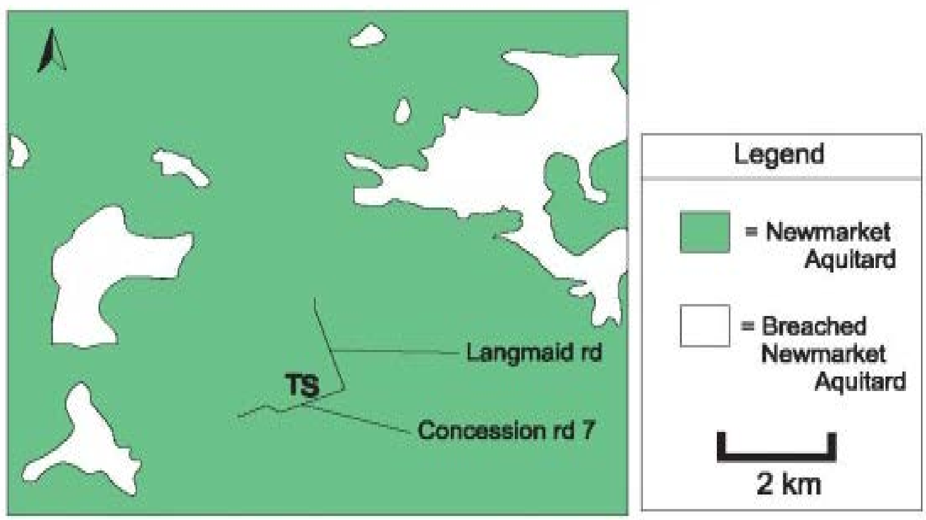


Fig. 7.2: Distribution of Newmarket Till near the Clarington Transformer Station (TS) simplified from Sharpe et al. 2005b. Non-existent Newmarket Till is located towards the Northwest and Northeast of the TS. Areas with nonexistent Newmarket Till are potential areas of recharge to the Thorncliffe Formation (Sharpe et al. 2005b).

While the fracture hypothesis is more likely to have played a major role on site, this study suggests that recharge may be coming from a relatively closer breached aquitard area to the north or an area where the aquitard is thin. Data collected in this study suggests the recharge area would be approximately 1,500 m away if travel time estimates of 100 m/yr (SLR 2015) and age estimates of 14-15 years old are correct. The shorter distance in both scenarios of 3-4 km away or 1.5 km away would both allow for higher sulfate and chloride levels within the aquifer, as observed on site.

7.2.4 Well Construction Issues

The third hypothesis is that leaky wells are contributing to geochemical results that are indicative of short flow paths (Fig. 7.1 C) (Jackson and Heagle 2016). There are two ways that monitoring wells and private wells can contribute to the migration of water at quicker rates than an aquitard would allow. If MW and private wells are screened across an area where a head differential within an aquitard is present, “short circuiting” affects might cause the migration of water to be unintentionally enhanced. Wells through areas of head differential can also contribute to the migration of water where wells are not properly sealed. Both scenarios can allow relatively newly recharged water to make its way deeper into aquifers that could have been adequately protected prior to well installations. With very few reliable methods for determining issues with well seals, water can unknowingly migrate on the outside of well casing (Cherry et al. 2006).

If well construction issues are determined to be an issue at this site, the private wells located north of the site (Fig. 2.1) could be acting as the “breached” Newmarket aquitard.

The likelihood of leaking wells causing the groundwater chemistry observed in these wells is relatively low, other than the hand dug shallow wells that may be of low quality construction and which are known to not be as reliable (Goss et al. 1998) (Table 5.1). This is based on several observations: 1)The private wells sampled for tritium and isotopes were 4 inch steel casing wells, 2.) during sampling they did not appear to be near any contamination source and 3.) were properly capped and on level ground, meaning water runoff would not migrate to the wells directly (table 5.1). The likelihood that a 4 inch diameter wells are behaving as a point source for the geochemistry consistently observed on an off the site, as opposed to the likelihood that the groundwater parameters are entering the groundwater flow system over the entire surface area is low. The high quality MWs have displayed the same major ion signatures as PWs, suggesting this is not a leaky wells issue and the samples are representative of the groundwater chemistry.

7.2.5 Conclusion

Based on previous studies where the Newmarket Till aquitard integrity has been discovered to be low in some areas and high in others, the need for local site specific studies is important.

The groundwater chemistry at this site is displaying groundwater chemistry typical of a leaky aquitard, rather than display evidence that the lower aquifers are a part of the regional groundwater system. Based on this analysis to date, It is most probable that fractures connected to higher conductivity features within the till are contributing to the increased intrinsic aquifer vulnerability at this site. Using the various data sets from this study, the geological framework determined at the TS based on geological cross-sections, grain size data, and previous knowledge of typical till and aquifer properties within the area (Fig. 3.24), is here updated to improve the understanding of the hydrogeology of each unit (Fig. 7.3). The hydrogeological conceptual model incorporates geological and geochemical data from Hydro One monitoring wells and boreholes as well as private wells located on and off of the transformer station. Flow direction through the Newmarket Till and within the Scarborough Formation is based on high-resolution borehole cluster gradients and the Thorncliffe aquifer flow direction is assumed from preexisting literature (Fig. 4.6 and 4.7).

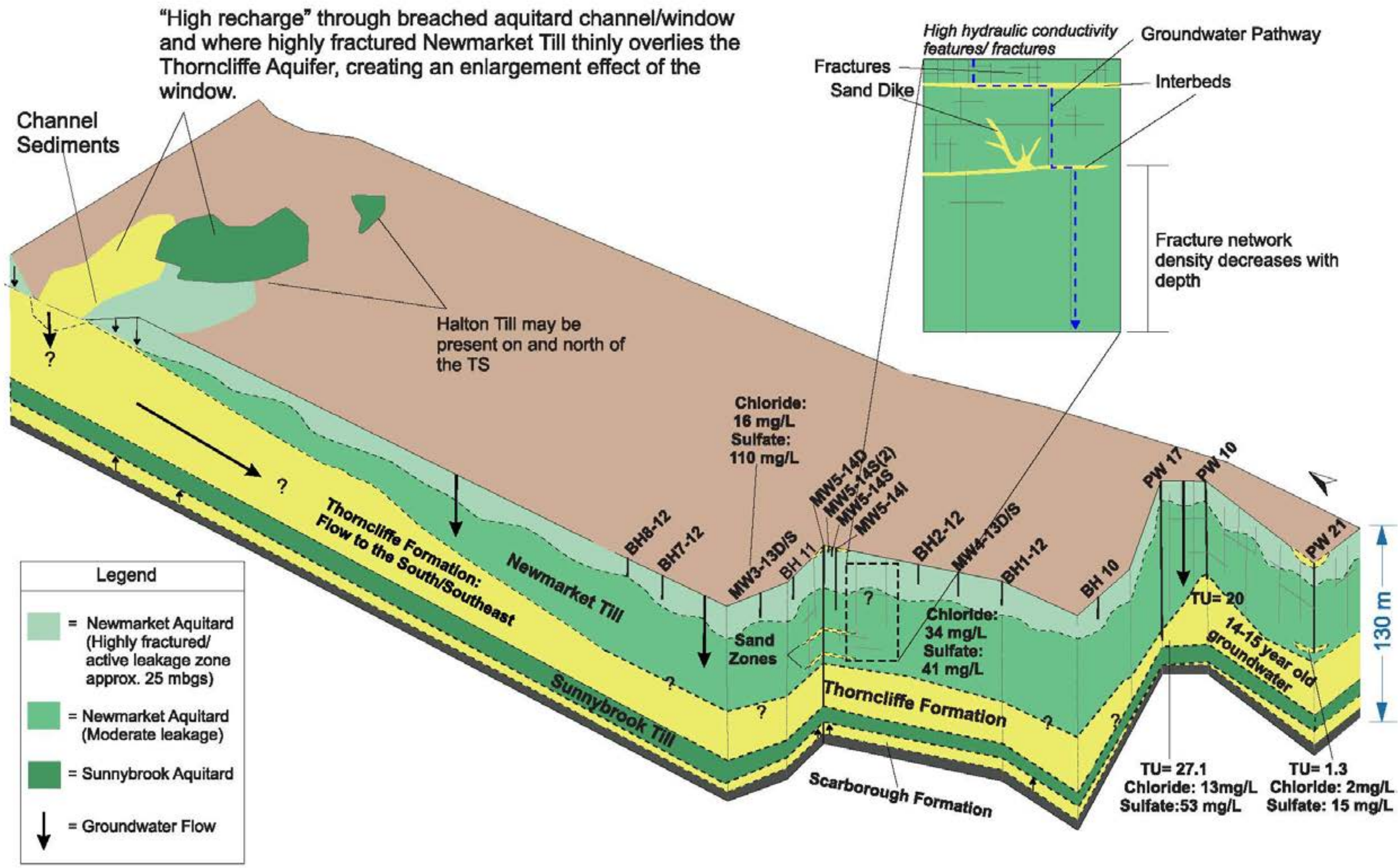

"High recharge" through breached aquitard channel/window and where highly fractured Newmarket Till thinly overlies the Thorncliffe Aquifer, creating an enlargement effect of the window.
Channel Sediments
Halton Till may be present on and north of the TS
High hydraulic conductivity features/ fractures
Groundwater Pathway
Fractures
Sand Dike
Interbeds
Fracture network density decreases with depth
Chloride: 16 mg/L Sulfate: 110 mg/L
Thorncliffe Formation: Flow to the South/Southeast
Newmarket Till
Sunnybrook Till
Sand Zones
Chloride: 34 mg/L Sulfate: 41 mg/L
Thorncliffe Formation
Scarborough Formation
BH8-12
BH7-12
MW3-13D/S
BH 11
MW5-14D
MW5-14S(2)
MW5-14S
MW5-14I
BH2-12
MW4-13D/S
BH1-12
BH 10
PW 17
PW 10
PW 21
TU= 20
14-15 year old groundwater
130 m
TU= 27.1 Chloride: 13mg/L Sulfate:53 mg/L
TU= 1.3 Chloride: 2mg/L Sulfate: 15 mg/L
Legend
= Newmarket Aquitard (Highly fractured/ active leakage zone approx. 25 mbgs)
= Newmarket Aquitard (Moderate leakage)
= Sunnybrook Aquitard
= Groundwater Flow

Fig. 7.3: Hydrogeology conceptual model based on all current available data from the TS. Horizontal recharge within the Thorncliffe Formation based on typical travel times of 100 m/yr and elevated levels of chloride and sulfate suggests recharge could be coming from an area north of the site < 1,500 m away. Sulfate and Chloride levels noted in the subsurface indicate groundwater is from short/local groundwater pathways, and the majority of water is not a part of regional flow systems. ***Inset.*** *High hydraulic conductivity features/fractures are likely playing a role in vertical leakage through the till and into the lower aquifer units. Upper 20 m of Newmarket aquitard is behaving like a highly conductive fractured zone, however lack of data throughout the middle section of the aquitard makes the exact depth of this zone unknown. Vertical groundwater flow direction through Newmarket aquitard and upwards in the Scarborough Formation is based on well cluster gradients in fig. 4.5 and 4.6. Horizontal flow in Thorncliffe assumed based on literature (Gerber and Howard 2002).*

Most of the geochemical data was available within the private wells located on the right side of the diagram where these high hydraulic conductivity features (sand zones and fractures) are depicted. Based on the current available data to date and the pre-existing literature (Gerber et al. 2001 and Boyce et a. 1995), it is likely these features extend below the TS site and to the north (Fig. 7.3).

It should also be noted that majority of groundwater monitoring data were from wells 15 mbgs or shallower, giving a biased look into the subsurface. However wells shallower than 25 mbgs consistently displayed evidence of anthropogenic impacts, such as high chloride, sulfate, and nitrate, and is therefore labeled a highly active fracture or recharge/leakage zone in Fig. 7.3. The lack of wells with depth makes it difficult to establish the base of the highly active zone due to a gap in data from 25- 35 mbgs. There were nine (9) wells located 40 mbgs to 108 mbgs and only six (6) of them had additional geochemical data available, compared to twenty three (23) wells located 3.66 mbgs to

25 mbgs with twenty two (22) of the twenty three (23) wells having additional geochemical data available. In this context, the base of the fractured zone is tentatively set at 22 mbgs though additional studies are needed to better define the location of this boundary.

Heterogeneity within the till is expanded in the inset of fig 7.3 and shows a highly fractured shallow zone with decreasing fractures density with depth based on previous knowledge of the aquitard’s fracture and heterogeneity network (Gerber et al. 2001). This is likely the result of a release of stress when the overlying continental ice sheet retreated and isostatic rebound and expansion of a till deposit occurs (Cherry et al. 2016). Evidence of expansion of the Newmarket Till was observed when cores were recovered at the TS site and expansion of fractures and joints mapped from test pits within 1-2 hours of being exposed were also observed in other study sites (Gerber 1999). Looking at trends of the anthropogenic indicators and the tritium studied on and around the site, fractures and sand zones appear to be well connected within the first 20mbgs, providing a network of preferential flow paths. Wells within the Newmarket aquitard and Thorncliffe transition are generally displaying the same anthropogenic impacts suggesting some fracture may be extending through the entire thickness of the till.

Though no fractures were observed in the vertical high resolution borehole, the Newmarket Till is not behaving like a typical heterogeneous aquitard (Bradbury et al.

2006). Where present, fractures combined with sediment heterogeneity form preferential pathways and allow for rapid groundwater and contaminant transport (Bradbury et al. 2006), if connectivity of fractures is high. Generally, aquitards are rarely homogenous and most contain features such as sand zones and interbeds however, even with these heterogeneities, only a very small amount of vertical leakage is allowed and the aquitard still behaves as a protective barrier against contamination (Bradbury et al. 2006). If no fractures or high hydraulic conductivity features were present in the till, tritium concentrations with depth would steadily decline. Where tritium levels begin to approach non-detect levels, hydraulically active, closely space fractures become less likely (Ruland et al. 1991).

Angled boreholes would increase the probability of intersecting vertical fractures to determine how fracture spacing changes with depth on site, but tritium concentrations with depth can also be used to infer that fractures must be present within a system where angled boreholes are not present (Ruland et al. 1991). The molecular diffusion of tritium into the matrix of low flow materials allows for the detection of tritium in wells that are otherwise hydraulically isolated. The diffusion envelope or halo around a hydraulic active fracture is much more likely to be detected in a nearby vertical borehole with the presence of tritium, rather than detecting the fracture itself (Ruland et al. 1991).

The major factor within the till, that allows ground water to migrate at this rate is most likely the presence of fractures or preferential pathways (Gerber et al. 2001), and where fracture connectivity is high, rapid groundwater leakage can occur through apparent low flow material, such as a diamicton. Gerber et al. (2001) determined fracture spacing within the till was, at a minimum, 0.02 m apart and maximum fracture spacing appeared to be 50m apart. Limited outcrop data made it difficult for Gerber et al. (2001) to get an accurate representation of the Newmarket aquitard fracture network for deeper depths. The upper portions of the till generally showed that fracture spacing is more closely spaced at shallow depths in field data compared to deeper depths, which is consistent with how all the shallow data analyzed in this study are impacted. The geochemical and water quality data in some of the deeper wells suggest they may be more hydraulically isolated from these preferential pathways while other deeper wells suggest evidence of impacts from preferential pathways.

7.3 Future Work

Various additional work is recommended to further evaluate the three hypotheses that have been proposed to explain the current data set and to evaluate the plausibility and relative role of the three groundwater flow paths at this site. This includes 1) installation of a high resolution multilevel monitoring system as recommended by Duggan (2016); 2) Tritium-helium and groundwater quality sampling of the onsite monitoring well cluster; as well as the newly installed MLS to provide additional data at depth, 3) geochemical sampling of wells offsite and up gradient to assess the hypothesis of lateral recharge to the Thorncliffe aquifer, 4) additional geological data both on and off site to help constrain the nature and distribution of the Thorncliffe aquifer, the potential for Halton Till to exist at the surface in some areas, and the nature of Newmarket heterogeneity at depth, 5) aquifer connectivity assessment with large scale pumping tests and 6) hydrogeological analysis of the Thorncliffe aquifer upgradient of the site to further evaluate the plausibility of hypothesis #2.

Duggan (2016) recommended the installation of a high-resolution monitoring station, including the installation of a state-of-the-science multilevel monitoring system (MLS). This study also recommends the high-resolution monitoring system, with sampling ports within the Thorncliffe aquifer and throughout the Newmarket aquitard as it will greatly improve the hydrogeological understanding of the TS. This monitoring station would provide a more robust and high resolution data set through the Newmarket aquitard, which compared to the PW, would not be subject to well construction concerns invoked by Jackson and Heagle (2016). The proposed MLS will allow for vertical gradients to be calculated from the Newmarket aquitard to the Thorncliffe aquifer. This is turn will help determine if vertical leakage is occurring through the Newmarket aquitard and into the Thorncliffe aquifer. It will also allow for hydraulic testing to better constrain what aquifer(s) the private wells are connected to, and improve the understanding of the lateral connectivity of these sand zones. Detailed analysis of head profiles from the MLS will also help determine areas of greatest head loss within the Newmarket Till, improving the understanding of what sections of the till are most active in terms of groundwater flow. This additional data will help determine the role that each of the three hypotheses are playing in recharge and leakage at this site.

Sampling for Tritium and Oxygen-18 and Deuterium in the monitoring nests and clusters on site specifically from the High resolution wells cluster (including MW5-14S, MW5-14S(2), MW5-14I, and MW5-14D, three of which are screened within the Newmarket Aquitard) will provide additional data which will help to assess aquitard integrity. All tritium and isotope signatures with depths currently produced in this study are from sand zones within the Newmarket or within the Thorncliffe and do not directly assess porewater within the aquitard itself. These additional data points would refine our understanding of the heterogeneity of the aquitard. This high resolution profile of tritium and isotopes will also help evaluate the potential of leaking wells. If the profiles are atypical of the aquitard in a higher quality monitoring system, the likelihood that the private wells are leaky will be much lower.

Tritium and isotope sampling with the MLS similar to those done to date and the ones suggested above will, in combination with head profiles, help to determine the nature of groundwater flow through the aquitard, and what areas of the aquitard may be contributing to the Thorncliffe Aquifer.

Additionally, geochemical sampling of PWs to fill in the missing gap in the data would specifically include tritium samples for the deep well PW15 that would allow an age estimate to be directly compared to the results in the nearby and slightly deeper PW17 which is thought to be completed in the Thorncliffe aquifer. Water quality analysis of PW10, PW ALT, and PW18 would allow for additional comparison between anthropogenic indicators and tritium-helium data (Table 5.1). This comparison would help refine the stratigraphic position of wells near the Thorncliffe/Newmarket contact as well as identify areas that are potentially more protected based on pristine anthropogenic indicators and lower tritium concentrations. If the tritium and chloride relationship is true, wells with elevated TU values, PW10 and PWALT, should display anthropogenic impacts similar to the wells within the Thorncliffe Formation and at shallow depths. If PW10 and PWALT show similar chemical trends to those wells within the Thorncliffe, this may suggest possible lateral connection to this extensive aquifer system. If PW06, PW21, and PW18 display pristine levels of contaminants this may suggest they are within a more protected area of the Newmarket aquitard. These new data sets may consequently also provide insight into the relief and lateral variability of the Thorncliffe aquifer.

Both monitoring wells and private wells on site should also be sampled for additional contaminant types such as pesticides, pharmaceutical chemicals, and human and animal viruses, and volatile organics. This additional sampling will be an appropriate follow up to what the indicator chemicals analyzed in this thesis are indicative of.

The MLS design by Duggan (2016) with recovered rotosonic core and potential additional high resolution boreholes off site, will allow for additional near surface grain size analyses and geophysics to ensure the Newmarket Till is at surface, along with constraining heterogeneities connectivity within the till. Additional high resolution boreholes drilled on and off site would also aid in improving the understanding of the lateral variability within the lower sediment package, with geological analysis and pumping tests. Many of the private wells used in this study were assumed to be within the Thorncliffe aquifer. Improving the understanding of lower sediment variability will aid in determining where local residences are getting their water from, in turn allowing for a more in depth analysis of specific aquifer susceptibility.

Additional work with surface and borehole geophysics across and off the site will help determine surface till origin by giving the potential to differentiate between Newmarket and Halton Till if both are discovered to be on site once more data become available. Surface geophysics may also provide a relatively quicker way for determining where the Newmarket Till may be thin or nonexistent north of the site and to assess or define potential source areas for direct lateral recharge to the Thorncliffe aquifer. If thin

Newmarket Till is not found upgradient north of the site, the lateral recharge hypothesis becomes less likely

To evaluate the third hypothesis which concerns the integrity of the wells sampled, pumps could be removed from deep wells to allow for video examination signs of compromised walls or seals (e.g. leaks above water level, corrosion perforations below the water level, compromised screens, thin casings identified through a casing thickness survey below water level). If there is no evidence of faulty wells, the vertical leakage and/or horizontal recharge hypotheses would become stronger and more probable scenarios contributing to younger water at depths greater than 100 m.

Additional to the MLS, a larger well with a conventional water well design could be drilled and installed within the Thorncliffe aquifer for large scale pumping tests to better determine aquifer connectivity around the site. This would help to assess the stratigraphic position (lower Newmarket or Thorncliffe) of private wells, and therefore improve the understanding of the geological framework, and in turn allow for better use of the groundwater chemistry data by better studying the chemical evolution of these constituents, improving the understanding of groundwater flow paths.

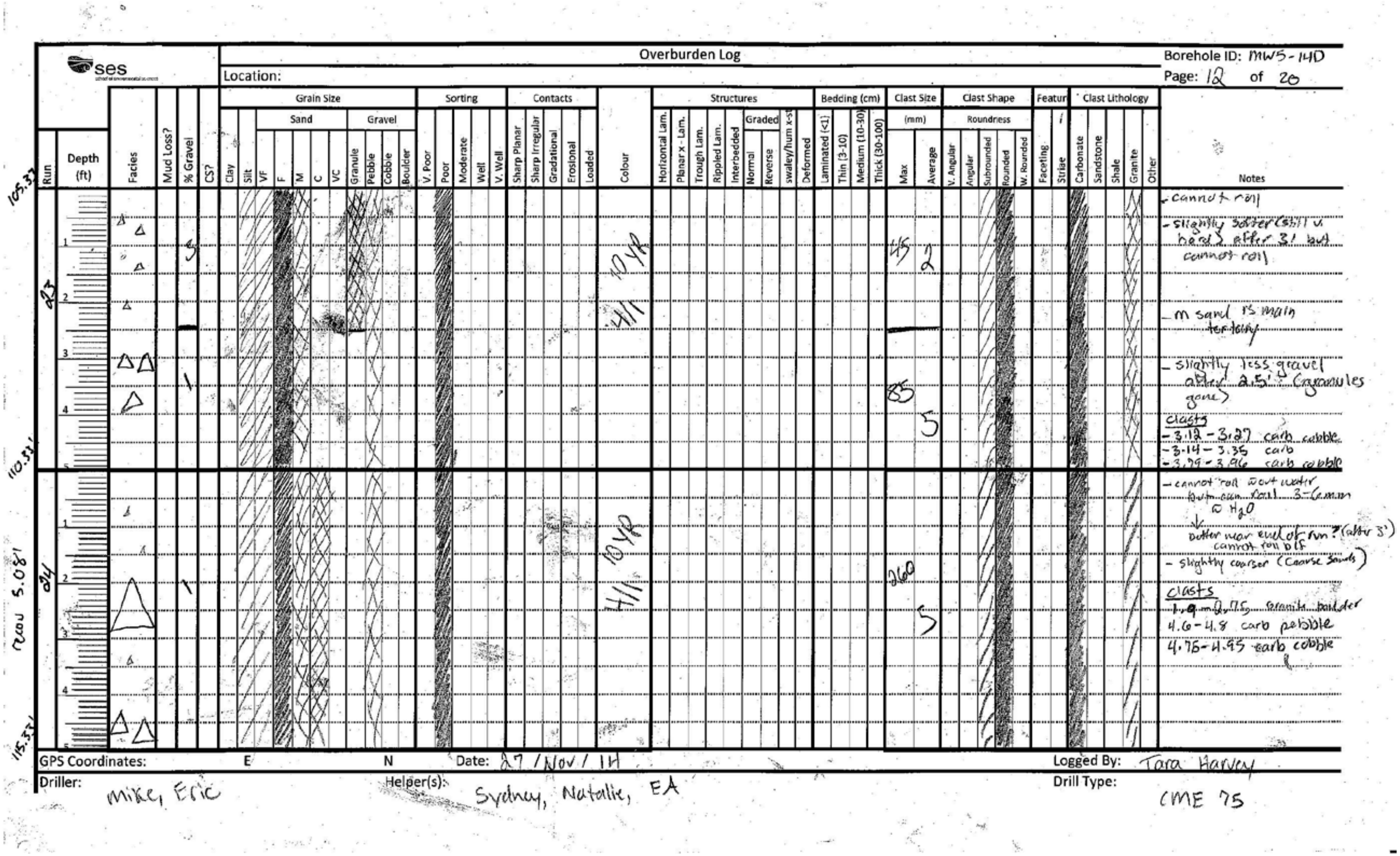
Appendix

A

B

Fig. A1: (A) MW5-14D 5 foot run section of diamict, with reference color card (passport colorchecker) located to the right of the marker board. (B) MW5-14D 1 foot detailed section of diamict.

Fig. A2: Picture of trailer set up, with photo station in the background and logging station in front.


Overburden Log

Borehole ID: MW5-14D

Page: 12 of 20

Location:

Notes:

- cannot roll
- slightly softer (still v. hard) after 3' but cannot roll
- m sand is main ~~texture~~
- slightly less gravel after 2.5' (granules gone)

clasts

- 3.12 – 3.27 carb cobble
- 3.14 – 3.35 carb
- 3.79 – 3.96 carb cobble

- cannot roll w/out water ~~(with can roll)~~ 3–6 mm @ H_2O
- wetter near end of run? (after 3') cannot roll b/f
- slightly coarser (coarse sands)

clasts

- ~~1.9~~ – 0.75 granite boulder
- 4.6 – 4.8 carb pebble
- 4.75 – 4.95 carb cobble

Colour: 10YR 4/1

GPS Coordinates: E N

Date: 27 / Nov / 14

Logged By: Tara Harvey

Driller: Mike, Eric

Helper(s): Sydney, Natalie, EA

Drill Type: CME 75

Fig. A3.: MW5-14D run 23 detailed lithology log example used in the field.

Fig. A4: MW5-14D grain size sampling with hammer and chisel where Newmarket Till became very dense. Grain size samples were collected in approximately six (6) inch cores.

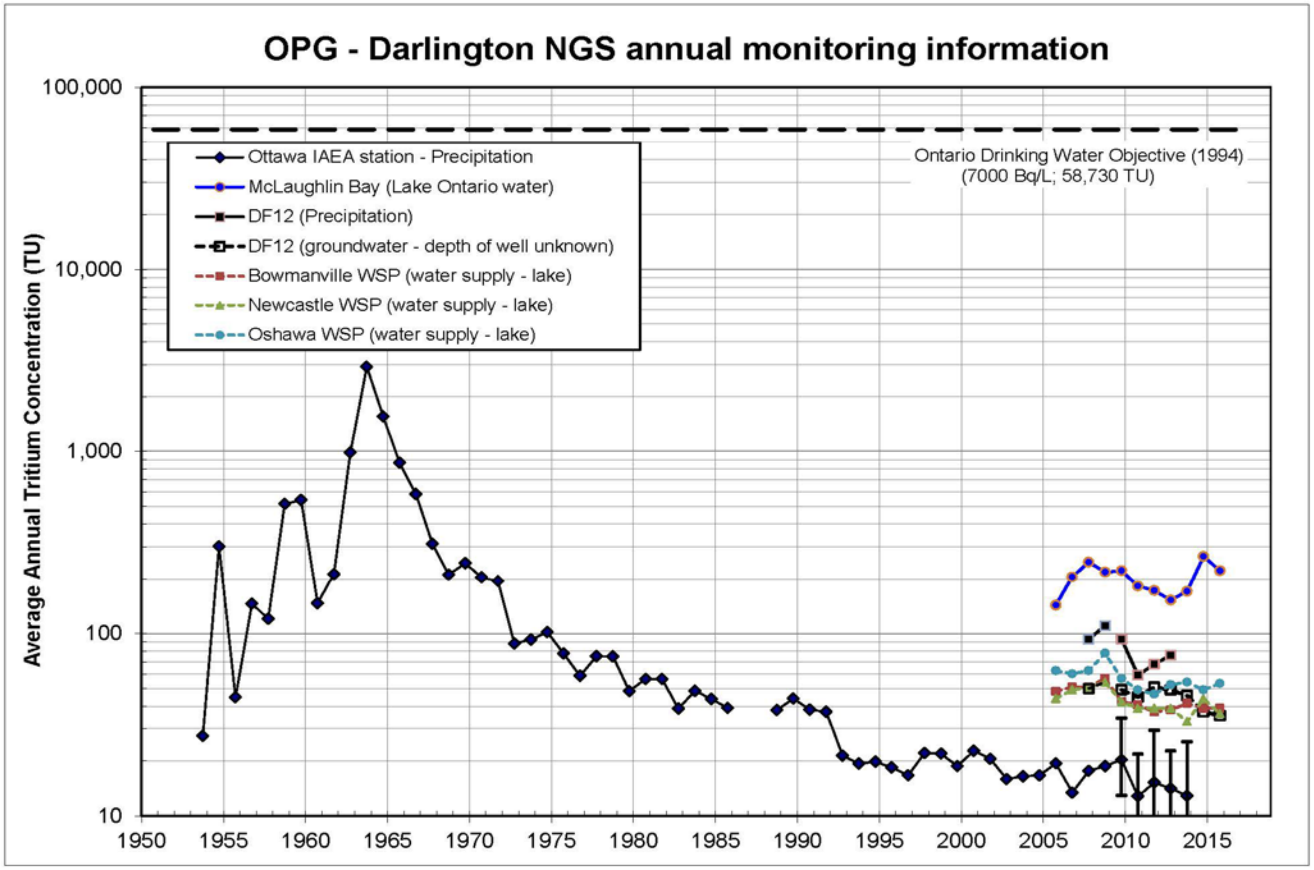


Fig.A5 Darlington Monitoring of tritium at a number of nearby sites (Rick Gerber, Pers. Comm.) Data in graph includes range of data from annual monitoring reports from the Ontario Power Generation. Reports span from 1977-2015 (Knight 1977 and OPG 2015). Precipitation TU concentration from the DF12 Darlington plant monitoring station (2.3 km to the south from the Clarington TS) ranges from 60-110 TU, whereas Oshawa groundwater from DF12 ranges from 45-80 TU.

Fig. A6: Copper and Silicon tube diffusion samplers used from collecting helium concentration from groundwater.

Fig. A7: Diffusion samplers anchored outside of the well and suspended from fishing line.

Fig. A8: Crimping of copper tube diffusion samplers used for collected helium concentration in groundwater

Fig. A9: Copper and Silicon tube diffusion samplers after crimping occurred. Plastic silicon ends were placed on crimped area to avoid damage or opening of sampler during shipping.

References

Aeschbach-Hertig, W., Schlosser, P., Stute, M., Simpson, H.J., Ludin, A. and Clark, J.F. (1998), A $^3H/^3He$ Study of Ground Water Flow in a Fractured Bedrock Aquifer. Ground Water, 36: 661–670. doi:10.1111/j.1745-6584.1998.tb02841.x

Alkalinity Conversions, (2009) Retrieved from http://www.cdph.ca.gov/certlic/drinkingwater/Documents/Drinkingwaterlabs/AlkalinityConversions.pdf

Barnett, P. (1992). Quaternary Geology of Ontario. *In* Geology of Ontario. *Edited by* P.C. Thurston, H.R.Williams, R.H. Sutcliffe, G.M. Scott. Queens Printer for Ontario: 1011-1088.

Barnett, P.J., Sharpe, D.R., Russell, H., et al (1998) On the Origin of the Oak Ridges Moraine. Can J Earth Sci 35:1152–1167. doi: 10.1139/e98-062

Boyce, J.I., Eyles, N., Pugin, A. (1995) Seismic Reflection, Borehole and Outcrop Geometry of Late Wisconsin Tills at a Proposed Landfill near Toronto, Ontario. Can J Earth Sci 32:1331–1349.

Boyce JI, Eyles N (2000) Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. GSa Bulletin: 98-118

Bradbury, K.R., Cherry, J.A., Parker, B.L. (2006) Contaminant Transport Through Aquitards: a State-of-the-Science Review and Technical Guidance for Aquitard Assessment. AWWA Research Foundation

Berman, E., Levin, N., Landais, A., Shuning, L.i, and Owano, T. (2013) Measurement of $\delta^{18}O$, $\delta^{17}O$, and ^{17}O-excess in Water by Off-Axis Integrated Cavity Output Spectroscopy and Isotope Ratio Mass Spectrometry, Anal. Chem. 85: 10392−10398

Brennand, T.A. (1998) Surficial Geology of the Oshawa Area.

Cherry, J., Parker, B., Levison, A., (2013) Hydrogeological Concerns for the Clarington Transformer Station Class Environmental Assessment Draft Environmental Study Report.

Cherry, J.A., Parker, B.L., Bradbury, K.R., Eaton, T.T., Gotkowitz, M.B., Hart, D.J., Borchardt, M.A., (2006). Contaminant transport through aquitards: A state-of-the-science review. AWWA Research Foundation.

Clark, I.D., Fritz, P. (1997) Environmental Isotopes in Hydrogeology. Taylor & Francis

Clark, I.D (2015) Groundwater Geochemistry and Isotopes. CRC Press

CLOCA (2011) Black/Harmony/Farewell Creek watershed existing conditions report, Chapter 14 - Hydrogeology. Central Lake Ontario Conservation Authority, Oshawa, Ontario: 45

Craig, H., 1961. Isotopic Variations in Meteoric Waters. Science 133: 1702–1703.

Desbarats, A., Hinton, M., Logan, C., Sharpe, D. (2001) Geostatistical Mapping of Leakance in a Regional Aquitard, Oak Ridges Moraine area, Ontario, Canada. Hydrogeol J 9:79–96. doi: 10.1007/s100400000110

Dillon, 1990. P1 Contigency landfill site. Report prepared for the Regional Municipality of Durham.

Duggan SJ (2016) Hydrogeological Assessment at the ClaringtonTransformer Station. M.Sc., McMaster University

Dyke L (1999) Regional Groundwater and Stream Chemistry Survey, Oak Ridges Moraine, Ontario. In Current Research 1999-E; Geological Survey of Canada: 111-121.

Edwards, Thomas W. D., Brent B. Wolfe, and Glen M. Macdonald (1996) Influence of Changing Atmospheric Circulation on Precipitation δ18O–Temperature Relations in Canada during the Holocene. Quaternary Research 46.3: 211-8.

Eyles, C.H., Eyles, N. (1983) Sedimentation in a large lake: A reinterpretation. Geology 11:146–152.

Eyles N, Eyles CH, Woodworth-Lynas C, Randall TA (2005) The sedimentary record of drifting ice (early Wisconsin Sunnybrook deposit) in an ancestral ice-dammed Lake Ontario, Canada. Quat Res 63:171–181.

Farah EA, Parker BL, Cherry JA (2012) Hydraulic Head and Atmospheric Tritium to Identify Deep Fractures in Clayey Aquitards: Numerical Analysis. AQUA mundi, am06051:89-99 doi: 10.4409/Am-051-12-0045

Foster SSD (1975) The Chalk Groundwater Tritium Anomaly A Possible Explanation. J Hydrol 25:159–165.

Freeze, R.A., Cherry, J.A., (1979) Groundwater. Prentice Hall, Inc., Englewood Cliffs, NJ 07632

Frind E., Molson JW, Rudolph DL (2006) Well Vulnerability: A quantitative Approach for Source Water Protection. Groundwater 44:732–742.

Fulton, R.J., Karrow, P.F., Lasalle, P., Grant, D.R. (1986) Summary of Quaternary Stratigraphy and History, Eastern Canada. Quat Sci Rev 5:211–228. doi: 10.1016/0277-3791(86)90188-5

Gerber R (1999) Hydrologic Behaviour of the Northern Till Aquitard near Toronto, Ontario. Phd, University of Toronto

Gerber, R.E., Howard, K.W.F. (1996) Evidence for Recent Groundwater Flow Through Late Wisconsinan Till Near Toronto, Ontario. Can Geotech J 33:538–555. doi: 10.1139/t96-080-302

Gerber, R.E., Howard, K. (2002) Hydrogeology of the Oak Ridges Moraine Aquifer System: Implications for Protection and Management from the Duffins Creek Watershed. Can J Earth Sci 39:1333–1348. doi: 10.1139/e02-058

Gerber, R.E., Boyce, J.I., Howard KW (2001) Evaluation of Heterogeneity and Field-scale Groundwater Flow Regime in a Leaky Till Aquitard. Hydrogeol J 9:60–78. doi: 10.1007/s100400000115

Gerrie, V., Holysh, S., Boyce, J., et al (2003) Borehole Geophysics and its Potential for Mapping the Geological Framework of the Oak Ridges Moraine, Southern Ontario.

Graham DJ, Midgley NG (2000) Graphical Representation of Particle Shape Using Triangular Diagrams: An Excel Spreadsheet Method. Earth Surface Processes and Landforms 25:1473–1477.

Goss, M., D. Barry, and D. Rudolph. 1998. Contamination in Ontario farmstead domestic wells and its association with agriculture: 1. Results from drinking water wells. J. Contam. Hydrol. 32:267–293.

Gudkov, A.V., Kamensky, I.L., Melikhova, G.S., et al (2014) The Tritium-Helium-3 Method and its Application to Groundwater Dating by the Example of the Kirovsk Mine region, Murmansk Oblast. Geochem Int 52:587–594. doi: 10.1134/S001670291405005X

Hambrey, M. J., and Glasser, N. F. 2003. Glacial sediments: processes, environments and facies. *In* Encyclopedia of sediments and sedimentary rocks. *Edited by* G. V. Middleton. Kluwer Academic Publishers, Dordrecht: 316–331.

Hamilton, S.M. 2015. Ambient Groundwater Geochemistry Data for Southern Ontario, 2007–2014; Ontario Geological Survey, Miscellaneous Release—Data 283–Revised.

Hicock, S.R., Dreimanis, A. (1989) Sunnybrook Drift Indicates a Grounded Early Wisconsin Glacier in the Lake Ontario basin. Geology 17:169–172.

Howard, K.W.F., Eyles, N., Smart, P.J., et al (1995) The Oak Ridges Moraine of Southern Ontario: A Ground-Water Resource at Risk. Geoscience Canada 22: 101-120

Howard, K.W.F., Beck, P. (1986) Hydrochemical Interpretation of Groundwater Flow Systems in Quaternary Sediments of Southern Ontario. Can J Earth Sci 23:938–947. doi: 10.1139/e86-095

Husain, M., Lee, T., Khazaei, E., et al (2007) Source Water Protection: Source Water Protection: Geochemical and Isotope Trends in Major Water Supply Aquifers within the Oak Ridges Moraine Complex as Indicator of Source Water Quality and it's Response to Stresses. Ottawa Geo The Diamond Jubilee

IAEA/WMO (2017). Global Network of Isotopes in Precipitation. The GNIP Database. Accessible at: http://www.iaea.org/water

Jackson R. E. and Heagle DJ. 2016. Sampling domestic/fam wells for baseline groundwater quality and fugitive gas. Hydrogeology Journal 24: 269-272.

Kessler, T.C (2012) Hydrogeological Characterization of Low-permeability Clayey Tills- The Role of Sand Lenses. PhD, Technical University of Denmark

Logan, C., Russell, H., Sharpe, D.R., Kenny, F.M. (2006) The Role of GIS and Expert Knowledge in 3-D Modelling, Oak Ridges Moraine, Southern Ontario. GIS for the Earth Sciences: 519–542.

McKay LD, Cherry JA, Bales RC, et al (1993) A field example of bacteriophage as tracers of fracture flow. Environ Sci Technol 27:1075–1079. doi: 10.1021/es00043a006

Mikołajków, J. (2010) Laboratory Methods of Estimating the Retardation Factor of Migrating Mineral Nitrogen Compounds in Shallow Groundwater. Geological Quarterly 47:91–96.

Murphy, S., Ouellon, T., Ballard, J.M., Lefebvre R., Clark I.D. (2011) Tritium-helium Groundwater Age Used to Constrain a Groundwater Flow Model of a Valley-Fill Aquifer Contaminated with Trichloroethylene (Quebec, Canada). Hydrogeol J 19:195–207

Nas B, Berktay A (2010) Groundwater Quality Mapping in Urban Groundwater Using GIS. Environ Monit Assess 160:215–227.

Oak Ridges Moraine Concervation Act, (2001) S.O. 2001 c.31

Ontario Geological Survey, 2010. Surficial Geology of Southern Ontario. Miscellaneous Release-Data 128-REV [computer files]. Queen's Printer for Ontario, 2010.

Ontario Power Generation (OPG)(2015) Results of Environmental Monitoring Programs. Document number: N-REP-03443-10015

Pugin, A., Pullan, S.E., Sharpe, D.R. (1999) Seismic Facies and Regional Architecture of the Oak Ridges Moraine area, southern Ontario. Can J Earth Sci 36:409–432. doi: 10.1139/e98-104

Pullan, S.E., Hunter, J.A., Good, R.L. (2002) Using Downhole Geophysical Logs to Provide Detailed Lithology and Stratigraphic Assignment, Oak Ridges Moraine, Southern Ontario. Geological Survey of Canada Current Research 8:1–12.

Rudolph D.L, Barry, D.A.J, Goss M.J (1998) Contamination in Ontario farmstead domestic wells and its association with agriculture:2. Results from multilevel monitoring well installations. J of Contaminant Hydrology 32: 295-311.

Ruland WW, Cherry JA, Feenstra S (1991) The Depth of Fractures and Active Ground-Water Flow in a Clayey Till Plain in Southwestern Ontario. Ground Water 29:405–417.

Russell, H.A.J., Sharpe, D.R, and Logan, C. (2005) Structural Model of the Greater Toronto and Oak Ridges Morain Areas, Southern Ontario: ORM Sediment, Geological Survey of Canada Open File 5065. Scale 1:250,000.

Russell, H. A. J, Arnott, R.W.C., Sharpe, D.R. (2004) Stratigraphic Architecture and Sediment Facies of the Western Oak Ridges Moraine, Humber River Watershed, Southern Ontario. Geographle Phys Quat 58:241. doi: 10.7202/013141ar

Russell, H.A.J., Arnott, R.W.C., Sharpe, D.R. (2003) Evidence for Rapid Sedimentation in a Tunnel Channel, Oak Ridges Moraine, Southern Ontario, Canada. Sediment Geol 160:33–55. doi: 10.1016/S0037-0738(02)00335-4

Russell H.A.J, Sharpe D.R, C ARW (1998) Sedimentology of the Oak Ridges Moraine, Humber River watershed, southern Ontario: a preliminary report. Current Research Canada: 155–166.

Sharpe DR, Dyke LD, Hinton MJ, et al (1996) Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models. Current Research 1996-E 1–11.

Sharpe D.R, Barnett P.J, Russell H., et al (1999) Regional Geological Mapping of the Oak Ridges Moraine, Greater Toronto Area, southern Ontario. Anat Physiol: 123–136.

Sharpe, D.R., Hinton, M.J., Russell, H.A.J., Desbarats, A.J. (2002a) The Need for Basin Analysis in Regional Hydrogeological Studies: Oak Ridges Moraine, Southern Ontario.

Sharpe, D.R., Russell, H. A. J, Logan, C. (2002b) Geological Characterization of a Regional Aquitard : Newmarket Till , Oak Ridges Moraine Area , Southern Ontario Originally Released as : Geological Characterization of a Regional Aquitard : Natural Resources Canada: 219–226

Sharpe DR, Pugin A, Pullan SE, Gorrell G (2003) Application of seismic stratigraphy and sedimentology to regional hydrogeological investigations: an example from Oak Ridges Moraine, southern Ontario, Canada. Can Geotech J 40:711–730. doi: 10.1139/t03-020

Sharpe, D.R, Russell, H.A.J., and Logan, C. (2005a) Structural Model of the Greater Toronto and Oak Ridges Morain Areas, Southern Ontario: Lower Sediment, Geological Survey of Canada

Sharpe, D.R, Russell, H.A.J., and Logan, C. (2005b) Structural Model of the Greater Toronto and Oak Ridges Morain Areas, Southern Ontario: Newmarket Till, Geological Survey of Canada Open File 5066. Scale 1:250,000.

Sharpe, D.R., Russell, H.A.J. (2016) A Revised Depositional Setting for Halton Sediments in the Oak Ridges Moraine Area, Ontario. doi: 10.1139/cjes-2015-0150

Sibul U, Branch OWR, Wang KT (1977) Ground-water resources of the Duffins Creek-Rouge River drainage basins. Ministry of the Environment, Water Resources Branch

SLR Consulting Ltd. (SLR) (2015) Clarington Transformer Station Peer Review Report, Municipality of Clarington.

Stantec Consulting Ltd. (2014) Pre-Station Construction Groundwater and Surface Water Baseline Conditions Report, Hydro One - Clarington Transformer Station.

Stantec Consulting Ltd. (2015a) Annual Groundwater and Surface Water Monitoring Report, Hydro One - Clarington Transformer Station.

Stantec Consulting Ltd. (2015b) Groundwater and Surface Water Baseline Conditions Report, Hydro One- Claringont Transformer Station Addendum 2

Wexler, E.J., Holysh, S., Kassenaar, D., Gerber, R. (B) (2003) Regional and Sub-Regional Groundwater Flow Modelling, Oak Ridges Moraine Area of Southern Ontario.

Wexler, E.J., Holysh, S., Kassenaar, D., Gerber, R. (A) (2003) Regional Modeling of Groundwater Flow in the Oak Ridges Moraine Area of Southern Ontario.