Characterizing the Quaternary Hydrostratigraphy of Buried Valleys using Multi-Parameter Borehole Geophysics, Georgetown, Ontario

Characterizing the Quaternary Hydrostratigraphy of Buried Valleys using Multi-Parameter Borehole Geophysics, Georgetown, Ontario

By

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A Thesis

Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements for the Degree

Master of Science

McMaster University

MASTER OF SCIENCE (2011) McMASTER UNIVERSITY

(Earth & Environmental Science) Hamilton, Ontario

TITLE:	Characterizing the Quaternary Hydrostratigraphy of Buried Valleys Using Multi-Parameter Borehole Geophysics, Georgetown, Ontario
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SUPERVISOR:	Dr. J.I. Boyce
NUMBER OF PAGES:	*xii* + 139

Abstract

In 2009, the Regional Municipality of Halton and McMaster University initiated a 2-year collaborative study (Georgetown Aquifer Characterization Study-GACS) of the groundwater resource potential of Quaternary sediments near Georgetown, Ontario. As part of that study, this thesis investigated the Quaternary infill stratigraphy of the Middle Sixteen Mile Creek (MSMC) and Cedarvale (CV) buried valley systems using newly acquired core and borehole geophysical data. Multi-parameter geophysical log suites (natural gamma, EM conductivity, resistivity, magnetic susceptibility, full-waveform sonic, caliper) were acquired in 16 new boreholes (16 m to 55 m depth), pre-existing monitoring wells and from archival data. Characteristic log responses (electrofacies) were identified and correlated with core to produce a detailed subsurface model of a 20-km^2 area to the southwest of Georgetown. Nine distinctive lithostratgraphic units were identified and their geometry mapped across the study area as structure contour and isochore thickness maps. The subsurface model shows that the CV valley truncates the Late Wisconsin MSMC stratigraphy along a channelized erosional unconformity and is a younger (post-glacial?) sediment-hosted valley system. Model results demonstrate the high level of stratigraphic heterogeneity and complexity that is inherent in bedrock valley systems and provides a geological framework for understanding groundwater resource availability.

Principal component analysis (PCA) was applied to selected log suites to evaluate the potential for objective lithologic classification using log data. Gamma, resistivity and conductivity logs were most useful for lithologic typing, while p-wave velocity and resistivity logs were more diagnostic of compact diamict units. Cross plots of the first and second principal components of log parameters discriminated silts and clays/shales from sand/gravel and diamict lithofacies. The results show that PCA is a viable method for predicting subsurface lithology in un-cored boreholes and can assist in the identification of hydrostratigraphic units.

Acknowledgements

Funding for this research was provided by an NSERC grant to Dr. J.I. Boyce. Additional support was provided through the Regional Municipality of Halton. I would like to thank Tim Lotimer of Tim Lotimer & Associates Inc. for his encouragement and enthusiasm in working with McMaster and for providing access to geophysical data. The experience I gained working with you is invaluable.

I would like to thank my loving fiancée Kristen who has worked tirelessly to support us over the last two years. Your patience and belief in me has been unwavering, and for that I am ever grateful. You have been there through the highs and the lows, and without you, none of this would have been possible.

To Dr. Carolyn Eyles and the Glacial Sedimentology lab I would like to thank all of you for your help and collaboration on this project. Working alongside you has been a rewarding experience and I am appreciative for all that I have learned. In particular, I would like to thank Jess Slomka whom I've worked closely with on this project and whose work logging all the core drilled over the course of this study and assistance in the field has been instrumental in getting to this point. I wish you all the best as you continue your work on this project.

A special thanks goes out to Peter Dao for all the help you've been over the past few years. You have been a great friend and a better field assistant, and I can't thank you enough for all you've done, particularly the long hours spent with me in the field logging through day and night. I was always able to count on you for help, and you never complained about the long hours, even after 40 hours straight without sleep. I couldn't have done this without you.

Thanks to my other lab mates Lisa and Nicole for making the past two years as enjoyable as they have been, and for helping me through times of frustration in the lab.

Thanks also to my parents and sister, for believing in me and pushing me to work hard and pursue my dreams. You have always been there for me and I couldn't have gotten here without your love and support.

Finally and most importantly, I would like to thank Dr. Boyce for asking me to be a part of this research endeavor and for all your support throughout the course of this project. Your guidance and expertise has been instrumental in preparing this thesis and I truly value all that I have learned from you.

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CHAPTER 2

Preface

The following two chapters have been prepared for publication in various academic journals. As stated by the school of graduate studies, the following paragraphs document the authors and their contributions to each paper.

Chapter 2, **Characterizing the Quaternary Hydrostratigraphy of Buried Valleys using Multi-parameter Borehole Geophysics, Georgetown, Ontario**, will be submitted to *Ground Water*. This author was involved in the collection, processing and interpretation of the data. Dr. J.I. Boyce provided funding through a research grant from NSERC and provided assistance with writing in the role as M.Sc. supervisor.

Chapter 3, **Principal Component Analysis (PCA) of Multi-parameter Geophysical Logs: Applications for Lithologic Discrimination of Buried Valley Hydrostratigraphy, Georgetown, Ontario**, will be submitted to *The Journal of Applied Geophysics.* As with the previous chapter, this author was involved in the collection, processing and interpretation of the data. Dr. J.I. Boyce provided funding through a research grant from NSERC and provided assistance with writing in the role as M.Sc. supervisor.

CHAPTER 1: INTRODUCTION

1.1 Background and Rationale

About one-third of Canadians (approx. 9 million people) depend directly on groundwater for drinking water and domestic uses (Stat. Canada, 2003). A large proportion of these resources are obtained from thick, regionally-extensive Pleistocene glacial deposits. In the Regional Municipality of Halton (‘Halton Region’, HR), located in the rapidly developing western GTA (Figure 1-1A), more than 30% of residents rely on groundwater abstracted from municipal or private wells. The rapid growth of residential communities in HR is placing increasing demands on municipal groundwater. Demand is most acute in the Halton Hills (HH) area (towns of Acton and Georgetown; Figure 1-1B) where more than 55,000 residents are currently dependent on groundwater. Due to a water shortfall, restrictions have been placed on new development here until additional, sustainable groundwater sources can be located and a comprehensive management strategy put in place to safeguard aquifers and recharge areas.

As identified in HR’s recent Water Budget and Water Quantity Risk Assessment (Halton Region, 2008) a fundamental obstacle to locating new sustainable groundwater sources is the lack of a detailed subsurface geological framework for Halton Hills. The area is underlain by thick (> 50 m), stratigraphically-complex Quaternary deposits that infill a series of broad buried bedrock valleys (Figure 1-2; Puckering, 2011). The buried valleys and Quaternary infill sediments are host to significant aquifer systems but the location and extent of aquifer units and their degree of interconnectedness are poorly defined. Previous subsurface work in the HH area (Meyer and Eyles, 2007) has identified a thick succession of tills and intervening glaciolacustrine and glaciofluvial deposits that include coarse-grained units capable of hosting high yield aquifer

Figure 1-1: [A] Inset map illustrating location of Georgetown within the Regional Municipality of Halton. [B] Georgetown subwatershed study area with borehole locations and contour mapping area defined.

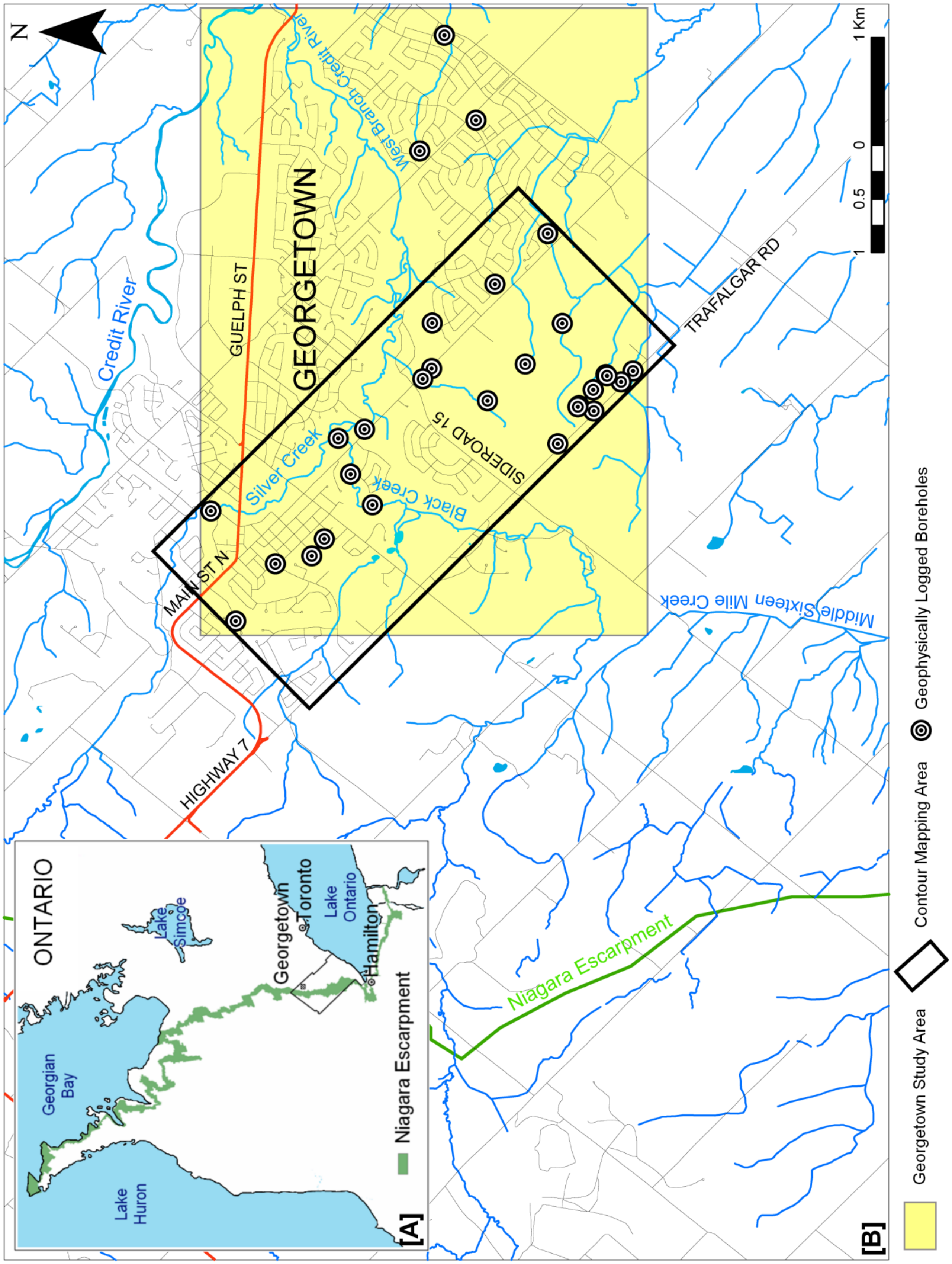
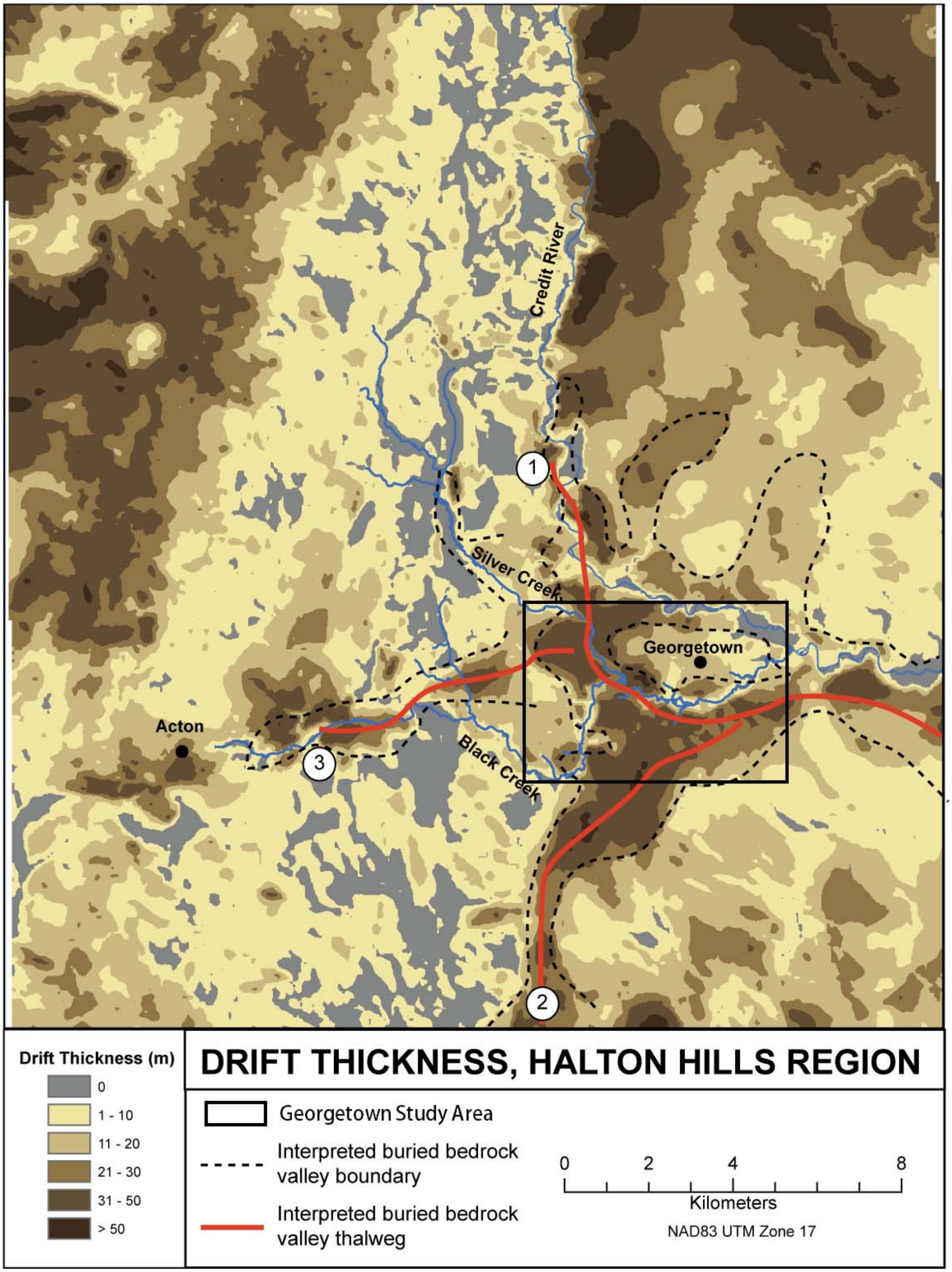

N
1 Km
0.5
0
1
West Branch Credit River
GEORGETOWN
GUELPH ST
Credit River
Silver Creek
Black Creek
SIDEROAD 15
TRAFALGAR RD
MAIN ST N
HIGHWAY 7
Middle Sixteen Mile Creek
Niagara Escarpment
[A]
ONTARIO
Lake Simcoe
Georgian Bay
Lake Huron
Georgetown
Toronto
Lake Ontario
Hamilton
Niagara Escarpment
[B]
Georgetown Study Area
Contour Mapping Area
Geophysically Logged Boreholes

Figure 1-2: Location of interpreted bedrock valleys and valley thawlegs in the Halton Hills area. Drift thickness aids in identification of (1) Georgetown Buried Valley ; (2) Sixteen Mile Creek Buried Valley; (3) Limehouse Buried Valley (Figure 3.31, Puckering, 2011). In this thesis, the tentatively named Georgetown Buried Valley is referred to as the Cedarvale (CV) buried valley for its relationship with the Cedarvale well field at the heart of Georgetown while the Sixteen Mile Creek Buried Valley is named here as the Middle Sixteen Mile Creek (MSMC) bedrock valley.


Credit River
Silver Creek
Black Creek
Georgetown
Acton
1
2
3
Drift Thickness (m)
0
1 - 10
11 - 20
21 - 30
31 - 50
> 50
DRIFT THICKNESS, HALTON HILLS REGION
Georgetown Study Area
Interpreted buried bedrock valley boundary
Interpreted buried bedrock valley thalweg
0
2
4
8
Kilometers
NAD83 UTM Zone 17

systems. The 3-dimensional geometry, extent and sedimentary characteristics of these deposits however, are not well understood, and need to be better resolved in order to guide further groundwater exploration in the HH area.

In order to address these knowledge gaps and to assist the search for new and sustainable groundwater sources HR partnered with McMaster University in 2009 to undertake a two-year study of the subsurface Quaternary geology and hydrogeology of the Georgetown area (*Georgetown Aquifer Characterization Study* - *GACS*). This work included drilling of 16 new continuously-cored and mud-rotary boreholes and a comprehensive program of surface and borehole geophysical investigations. A primary aim of this work was to develop a detailed subsurface geological framework for the Georgetown area to assist groundwater resource exploration and source protection studies. As a component of the GACS project, this thesis develops a detailed geological framework and subsurface geological model for a 20 km^2 area of southwest Georgetown (Figure 1-1B) using newly acquired core and borehole geophysical data. These data were collected as part of a larger regional Tier 3 groundwater investigations conducted by HR in the Middle Sixteen Mile Creek (MSMC) and Cedarvale (CV) well fields. The borehole geophysical database used in this study consisted of 29 geophysical log suites (Figure 1-1B) established from a combination of 11 multi-parameter log suites acquired during the Tier 3 investigations, 18 log suites collected by McMaster University in 2009-2010 and 10 archived log suites digitized for this study.

1.2 Study Objectives

The overall objective of this thesis was to construct a detailed subsurface geological model that will provide a framework for future groundwater exploration and groundwater modeling in the Georgetown area. The study also aimed to evaluate the use of multi-parameter log suites for correlation of Quaternary lithostratigraphic units and for prediction/classification of lithologic type. The specific objectives of the thesis were to:

1) construct a detailed 3-dimensional subsurface geological model for the 20 km^2 study area using core lithofacies and well log (electrofacies) data;

2) characterize the infill stratigraphy of buried bedrock valley infill sediments, including their lithofacies and electrofacies characteristics, thickness, geometry and lateral continuity;

3) determine the characteristic log responses of lithostratigraphic units and evaluate which log parameters are most useful for lithologic classification and correlation

4) evaluate the use of Principal Component Analysis (PCA) of log parameters for quantitative classification of subsurface lithology.

1.3 Study Area

The study area includes a 20 km^2 area on the southwestern limits of Georgetown in Halton Hills, Ontario (Figure 1-1B). The study site is located on the Halton Till plain physiographic region, which lies to the east of the Niagara Escarpment and to the south of the Oak Ridges Moraine. The area is located within the Credit River watershed and includes portions of the Middle Sixteen Mile Creek, Silver Creek and Black Creek sub-watersheds (Figure 1-1B). These sub-watershed areas are host to two existing well fields (Cedarvale and Princess Anne) and were a primary focus of the Halton Region Tier 3 study.

1.3.1 Bedrock Geology and Buried Bedrock Valleys

The bedrock below the study area consists of the Ordovician Queenston Formation shale and shaley siltstone (Karrow 2005; Davies and Holysh, 2007). The shale bedrock is overlain by a 'head' unit of weathered and fractured shale and red clay that is up to 5 m in thickness. The bedrock has an overall low relief but is cut locally by broad bedrock valleys that are up to 40 m deep and up to 1-2 km in width.

The generalized bedrock topography of HR has been mapped previously using water well and municipal test well data (Holysh, 1995; Eyles and Boyce 1997; Brennand et al., 1997; Davies and Holysh, 2007), but the location and depth of bedrock valleys remain poorly resolved because few water wells fully penetrate to bedrock. Other work in southern Ontario has also identified the presence of sediment-hosted valleys within the Quaternary sequence that are infilled with coarse-grained sediments. These valleys form important local high-yield aquifers (Pugin et al., 1999) and have been interpreted as subglacial tunnel channels, ascribed to the erosion and rapid infilling by catastrophic subglacial meltwater floods (Barnett et al. 1998; Pugin et al. 1999; Russell et al, 2002; Sharpe et al., 2002, 2003). However, many researchers do not endorse the subglacial meltwater flood hypothesis (Clarke et al., 2005; Benn and Evans, 2006) as there is no unequivocal evidence to attribute the formation and infilling of buried valleys to catastrophic flood events rather than 'normal' glacial and/or fluvial processes.

1.3.2 Quaternary Geology

The subsurface geology of HR has been investigated during previous regional groundwater and Quaternary mapping studies. The surficial geology was first mapped in part by Karrow (1967) who recognized two regional till sheets recording separate (Late Wisconsin) ice re-advances. Retreat of the Lake Simcoe and Georgian Bay ice lobes to the north and the Ontario ice lobe to the southeast below the Niagara Escarpment allowed meltwater to drain over and between the Escarpment and Ontario ice front, forming outwash deposits down the Credit River valley and into an ice damned lake (Peel Pond) (Costello and Walker, 1972). The lowermost till unit (Newmarket Till; formerly Wentworth Till) is a sandy till present in the subsurface below much of HR. The age and stratigraphic position of this till unit remains unresolved, but likely represents the main phase of Late Wisconsin ice advance (Nissouri Stadial; ca. 18-25 Ka; Meyer and Eyles, 2007). The overlying finer-grained Halton Till records a brief, final re-advance of ice out of the Ontario basin at ca. 12-13.5 Ka (Port Huron Stadial) and forms broad surface till plains across HR (Barnett, 1992). The two tills are separated by stratified outwash sand and gravel deposited during a brief ice-free phase (Mackinaw Interstadial) prior to the Halton ice re-advance (Costello and Walker, 1972). The interstadial gravels are of primary hydrogeologic importance, as they host shallow aquifers with yields capable of sustaining municipal wells (Holysh, 1995). Locally the Halton Till is capped by a succession of interbedded diamict and glaciolacustrine silt and clay termed the Wildfield Till Complex (White, 1975). More recently, Meyer and Eyles (2007) have described the infill stratigraphy of several poorly-defined buried bedrock valleys up to 75m deep between Milton and Georgetown that are broadly consistent with previous subsurface investigations across Halton Region. They identified six distinctive stratigraphic units including coarse-grained fluvial and colluvial sediment (SU1), fine grained silts and clays (SUII), rippled, laminated, and massive sands (SU III), sand-rich sub-glacial till (SU IV), coarse grained sands and gravels (SU V), and interbedded fluvial, lacustrine, and glacial deposits (SU VI).

Till deposits represent regional confining layers in the regional hydrostratigraphy (Holysh, 1995) but their sedimentology and hydrogeologic properties remain to be quantified. In previous work, tills have often been assumed to be homogeneous, low permeability aquitards, capable of restricting the flow of groundwater and contaminants to underlying aquifers. Recent hydrogeological evaluations of the thick (> 60 m) regionally-extensive Newmarket Till, in the eastern GTA, however, have demonstrated an active groundwater flow system and rapid rates of groundwater recharge through the till (up to 1m/yr; Boyce et al., 1995; Gerber and Howard, 1996). Flow pathways in the till are controlled primarily by fractures and coarse-grained sand and gravel interbeds (Boyce and Eyles, 2000; Gerber et al., 2001). Similar levels of heterogeneity also characterize tills in HR (Holysh, 1995; Meyer and Eyles, 2007) but further detailed work is needed to establish their extent and recharge function within the regional hydrostratigraphy.

1.3.3 Core and Geophysical Log Database

Borehole geophysical and subsurface geological data used in this thesis were collected from several sources and integrated into the study database. Data made available from the Regional Municipality of Halton at the onset of the project included 10 archived geophysical log suites (caliper, gamma, resistivity, conductivity) digitized from consulting reports and drillers' logs from existing monitoring wells. The Ontario Ministry of Environment (MOE) water well and borehole database was used to aid in developing a bedrock topography map of the study area.

New continuous PQ-cored, exploratory mud rotary and sonic borehole records have been acquired in 16 boreholes drilled since January 2009 and were added to the borehole database used in this thesis. In total, greater than 425m of continuous core was drilled using diamond drilling techniques that produce high quality large-diameter PQ (83 mm) sediment cores suitable for detailed lithofacies logging (sediment composition, colour, bedding structure, texture etc.).

1.4 Methods

A major component of this thesis involved the characterization of Quaternary deposits through the analysis and correlation of geophysical logs suites. This approach is now employed widely in groundwater resource studies (Pullan et al., 2002; Hunter et al., 1998; Keys, 1997; Greenhouse and Karrow, 1994) as its application is cost effective relative to continuous coring (commonly 10% of the total cost to drill a typical 50m deep cored borehole) (Lotimer, pers. com, 2011). An important advantage of geophysical logs is the ability to distinguish geophysical 'markers' and log signatures (electrofacies) that can assist correlation between boreholes and integration with surface geophysical methods (Pullan et al., 2002; Boyce et al., 1995). Natural gamma and conductivity/resistivity logs are commonly used as 'hydrostratigraphic logs' to differentiate aquifer and aquitard assemblages (i.e. clean sands/gravels vs clays/shales) (Pullan et al., 2002; Boyce & Eyles, 2000; Greenhouse & Karrow, 1994). Additional physical parameters (i.e. velocity, magnetic susceptibility) offer the possibility of a more complete characterization of the formation properties, and the synergistic nature of log responses can be used to characterize important hydrostratigraphic formations (Keys, 1997) which is particularly useful in the complex glacial terrains (Collins, 2004).

The geophysical logging methods employed in this thesis are summarized in the following sections along with a brief review of the log operating principles.

1.4.1 Well Log Acquisition

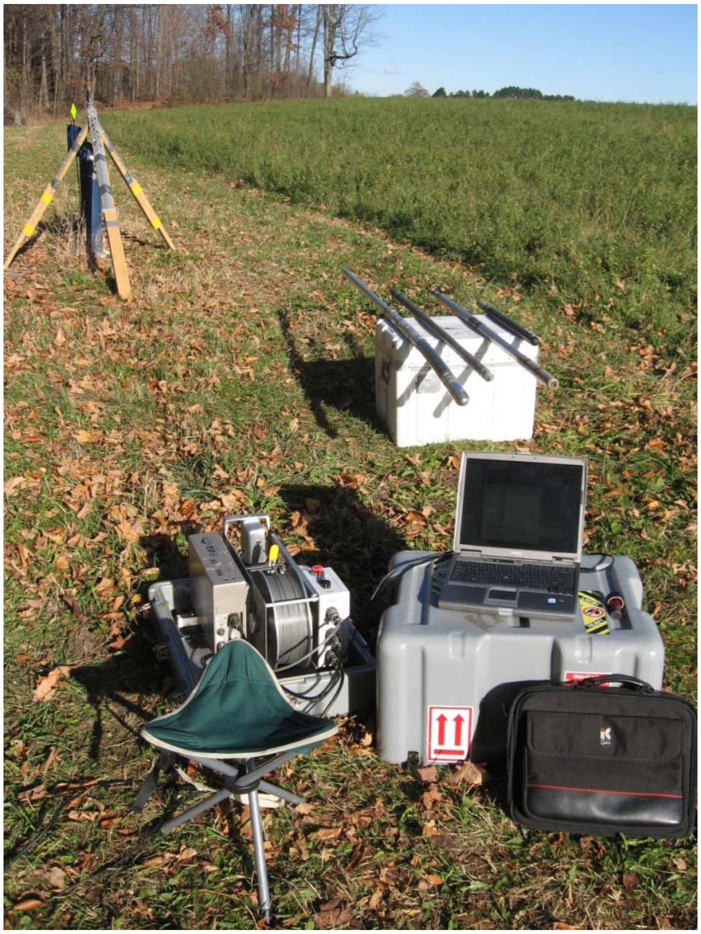
Open mudded-hole geophysical logs (resistivity, gamma, caliper) were acquired in 15 of the recently drilled boreholes (16 m to 55 m depth) prior to installation of PVC casings. Subsequent downhole geophysical logs (gamma, conductivity, magnetic susceptibility, full-waveform sonic) were collected by McMaster in 11 of the 15 boreholes with open-hole geophysical logs and in 3 pre-existing monitoring wells not previously logged using a Mount Sopris Matrix portable digital logging system. The logging system consisting of a surface unit (cable winch and mounted data console with a laptop interface and depth measuring wheel) (Figure 1-3A) and borehole probes (Figure 1-3B) run through 63.5mm PVC cased holes. In the following sections, the principles of each physical parameter logged are briefly summarized, followed by a description of the interpretation and modeling approach. For a more complete description of principles of operation and logging techniques, the reader is referred to Keys (1997).

Natural Gamma Log

In sedimentary strata, natural gamma logs measure the concentrations of radioactive K, U and Th present in the formations surrounding the borehole and respond primarily to proportionate increases in clay content due mostly to the presence of ^{40}K in clay minerals. To a lesser degree, igneous and metamorphic clasts in gravels and diamict units may also contribute to the total gamma emissions (Boyce et al, 1995). In this study, the Mount Sopris 2PGA-1000 natural gamma sonde was used by McMaster and was run at a logging speed of 1.2m/min and sampled at 1 cm intervals.

Figure 1-3: [A] Logging system employed by McMaster. [B] Geophysical probes used by McMaster.

[A]



[B]


SONIC Probe
CONDUCTIVITY Probe
MAGNETIC SUSCEPTIBILITY Probe
GAMMA Probe

Electrical Logs

Electrical parameters investigated in this study included normal resistivity (32”) and EM conductivity. Archival geophysical records include 0.25ft and 2.5ft resistivity. Resistivity measures the combined electrical resistance of formation sediment and pore waters, and is restricted to open-hole logging. EM conductivity is more versatile and can be collected in both open-hole and PVC cased boreholes and measures the apparent conductivity of the formation using electromagnetic induction. The conductivity log responds to the presence of conductive clays and increases in porewater conductivity, and is inversely proportional to resistivity such that formations with low clay content and low porewater conductivity typically have the highest resistivity values (Greenhouse & Karrow, 1994).

Conductivity data collected by McMaster utilized the Mount Sopris 2PIA-1000 electromagnetic induction probe and was run in combination with the gamma probe at 1.2m/min and 1 cm sample intervals. The conductivity probe is subject to temperature drift and was therefore allowed to stabilize in the borehole for 20-30min prior to tool calibration and logging at every borehole.

Sonic (Velocity) Log

Sonic logging utilizes the transmission of acoustic energy within a fluid filled borehole to measure the travel time through the surrounding formation from transmitter to receivers. P-wave velocity is calculated in this study from the difference between arrival times at three receivers on the sonic probe. P-wave velocity is dependent on the density of the medium it is being transmitted through (Pullan et al, 2002), and when logged in PVC cased boreholes, formations with velocities lower than that of the PVC cannot be accurately identified. Consequently the sonic tool is useful for discriminating more compact till units and depth to bedrock, however some gravel layers with velocities in excess of 2000m/s have been noted in previous studies (Pullan et al., 2002). Sonic logging by McMaster utilized the ALT FWS 50 full wave-form sonic probe and was run at 2m/min and sampled at 5cm intervals.

Magnetic Susceptibility Log

Magnetic susceptibility measures the ability of sediments to be magnetized in response to an induced magnetic field. The log response is directly related to the concentration of ferromagnetic minerals (principally magnetite, some illmenite, maghemite and pyrrhotite) in the formation (Collins, 2004). Magnetic susceptibility logs have been useful in separating lithological boundaries (McNeill et al., 1996) and correlation of differing provenances within similar materials (Chopra, 2002). The Mount Sopris 2BSF-1000 magnetic susceptibility sonde was run at 2m/min and sampled at 1cm intervals. The magnetic susceptibility probe is also subject to temperature drift and was therefore allowed to stabilize in the borehole for 20-30min prior to tool calibration and logging at each location.

Caliper Log

Caliper tools measure changes in borehole diameter with depth using spring-loaded arms pressed against the open borehole wall as the tool is raised from the bottom of the borehole (Chopra, 2002). Variations in borehole diameters can indicate changes in sediment texture and cohesion or changes in lithology. The presence of ‘washed-out’ zones is commonly associated with less cohesive sediments such as sands and gravels.

1.4.2 Well Log Processing

As a first step in the processing of well log datasets, individual physical parameter data files (in log ASCII standard (LAS) format) were imported, screened and edited in VIEWLOG®. Raw data was depth shifted relative to ground surface to correct for casing height and measuring point locations on individual probes. Field data was collected at the highest possible resolution which sometimes results in noise spikes due to sensor errors (Collins, 2004). To reduce the impact of short wavelength noise on longer wavelength features, a 7-point boxcar filter was applied to smooth the gamma log curves when necessary to improve the resolution of longer wavelength signals. Corrections for changes in hole diameters were evaluated and deemed unnecessary for electrofacies analysis in this study. Once edited, LAS files were exported from VIEWLOG® and were subsequently imported into SMT Kingdom Suite® for well log picking.

1.4.3 Well Log Picking/Correlation

Log picking and correlation was performed within SMT Kingdom Suite®, an industry-standard software package for analysis and interpretation of core, petrophysical and seismic data. As a first step, composite log plots illustrating all available log parameters and core lithological data were generated for each borehole. Preliminary geophysically-based lithological interpretations involved subdivision of the log signatures into a number of distinct electrofacies (Doveton, 1986). The identification of eletrofacies involves the visual analysis of a variety of log atrributes, including the amplitude, frequency of log responses, location of peaks, troughs and inflection points and the change in the relative log responses from one unit to the next (Collins, 2004; Greenhouse and Karrow, 1994). The initial picks were then compared with core lithofacies and driller's logs where available to compare the geophysically defined picks with the lithological picks determined from core data. Detailed visual analysis of the log responses (i.e. fining/coarsening upwards cycles), curve shapes and unit transitions helped to establish the characteristic responses for each log parameter. These were then evaluated as a suite in the composite plot to establish log signatures or electrofacies characteristic of the unit as a whole. The electrofacies of interpreted hydrostratigraphic units were then compared to detailed sedimentological core lithofacies (Slomka, 2011) to improve confidence in final interpretations and are presented as a series of cross sections in Chapter 2.

Once picks and correlations had been established within Kingdom Suite®, formation tops of all major units were exported for three-dimensional analysis and contour mapping. Sub-units identified in units 3 and 6 (Chapter 2) were discontinuous and were collapsed together to simplify modeling and formation top exporting.

1.4.4 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) is a data transformation method that has been applied in a variety of natural science applications for exploration of multivariate data sets (Kassenaar, 1991; Barrash and Morin, 1997; Collins, 2004; Tan, 2005; Raspa et al, 2008). In borehole geophysics PCA can be applied to obtain a linear combination of log parameters or ‘factors’ such that the maximum variance is extracted from the multi-log suite. It then removes this variance and seeks a second linear combination, in order to progressively describe the maximum proportion of original total variability which explains the remaining variance (Collins, 2004). In borehole geophysical logs, variation between physical parameter log responses are commonly influenced by groups of variables that represent and can highlight underlying physical phenomena (e.g. clay content, sediment compaction, etc.) (Kassenaar, 1991). In applying PCA to suites of borehole geophysical data, the factors responsible for the majority of the variance in the measured data can be interpreted from the relative contributions of each geophysical log and are plotted as principal component score logs. Cross plotting of these score logs (ie. log variation associated with clay content plotted against the log variation attributed to sediment compaction) allows contrasting lithologies to be effectively identified.

PCA was conducted on selected log suites in this study using the principal component analysis toolkit in VIEWLOG® software. Simple cross-plotting and log parameter cluster analysis was completed in SMT Kingdom Suite™. The display and selection of desired log parameters within VIEWLOG® is the first step in the PCA process, from which the mean and standard deviation of the logs is calculated over a user-defined depth interval constrained by the starting and ending depths of the individual log traces. This allows for standardization of the log data with subsequent calculations in standard deviation (SD) units (Kassenaar, 1991).

Next, the symmetrical correlation matrix was calculated (as opposed to the covariance matrix) with each diagonal element of the correlation matrix (maximum value) being equal to 1.0 (Kassenaar, 1991). In the related covariance matrix, if there are large differences in the variances of the logs being compared (ie. natural gamma counts may vary by more than 100cps but acoustic (p-wave) velocities can vary by more than 1000m/s) then the variables whose variances are largest (ie. velocity) will dominate the first few principal components (Jolliffe, 2002). Conversely, the correlation matrix reduces the effects of differing measurement units and scales in the original geophysical logs such that the standardized log data can be readily combined to provide principal component scores or eigenvectors (Kassenaar, 1991).

Implementation of the PCA algorithm requires solving the eigenvalue problem for the correlation matrix of the original data set. This defines a set of vectors for the new orthogonal coordinate system in terms of the old system such that the resulting eigenvectors (aka principal components or factors) are defined as a linear combination of the old vectors (Tan, 2005). Therefore, the eigenvector with the largest corresponding eigenvalue is the first principal component which contains the most variance. The second principal component is the eigenvector corresponding to the next largest eigenvalue with the second most variance along a new vector orthogonal to the first (Tan, 2005). This progression continues to the eigenvalue that corresponds to the eigenvector with the least variance of the data points. Consequently, the eigenvalues are a ranking (or score) for the amount of variance of the data set along each corresponding eigenvector (Tan, 2005). The percent of the total variation accounted for by each principal component is calculated based on the relative size of the eigenvalues. The relative size of the eigenvector elements indicate the degree to which each geophysical log contributes to the variation described by that component. The amount of unique information provided by each original log can be estimated from analysis of the eigenvalues and eigenvectors (Kassenaar, 1991).

The next step involved calculation of principal component ‘scores’ at each depth interval to produce a score log (standard deviation units). The uncorrelated score logs represent the combined variance loadings from the original logs and once displayed, the score logs can be compared to the original logs in aid in understanding the underlying geologic property that may be represented by the score log (Kassenaar, 1991). This interpretation requires a fundamental understanding of the geophysical logging methods and the response of different logs to changes in geologic properties. While strong correlation between the computed score logs and original geophysical logs indicates a probable casual relationship with underlying geologic properties (ie. clay content), PCA is a mathematical procedure and consequently the primary basis of the correlation may be indirect and unknown (Kassenaar, 1991; Tan 2005).

The final step required cross plotting of the principal component score logs to investigate the uniqueness of different lithologies in principal component space (ie. gravel/sand vs diamict vs clay-rich sediments). In this thesis, cross plots were generated in the SMT Kingdom Suite™ facies modeling toolkit that allows polygons to be drawn around clusters of data points and the depth intervals colour-coded to match the points contained within the user-defined polygons. Patterns and trends can then be developed and repeated for additional wells.

1.5 Subsurface Modeling

A detailed subsurface model was generated within Rockworks® v.15 and Geosoft's Oasis Montaj® using the subsurface geophysical and core database assembled in this study. The subsurface model was constructed by interpolation of the formation tops and unit thicknesses (isochore) of each lithostratrigraphic unit (e.g. Logan et al., 2001). The surfaces provided a lithostratigraphic framework for generation of three-dimensional fence diagrams in Rockworks®.

Within Rockworks® v.15, interpolated surfaces were gridded as a series of three dimensional 50m x 50m x 1m cells and modeled separately for each unit using an inverse distance gridding algorithm. Declustering and grid smoothing was employed to the data prior to gridding to reduce noise associated with clustered data and a maximum distance filter was applied to null grid nodes beyond 1 km from a control point. The stacked modeled surfaces were then sliced along user-defined profiles to reveal the subsurface geometry of unit surfaces. Logan et al. (2001) note that the quality of interpolated surfaces is dependent in part on the quantity and spatial distribution of borehole data and it is particularly important to accurately define layer pinch-outs and erosive truncations. Within Rockworks®, zero-thickness units were used to represent truncated stratigraphic units, resulting in modeled unit boundary pinch-outs rather than more abrupt truncations believed to exist along the modern Cedarvale valley. Despite this, the modeled subsurface stratigraphy is consistent with both the known geological conditions and honours both the core and geophysical data.

Within Oasis Montaj®, the top and base of units 1-9 were interpolated as discrete surfaces across the entire study area prior to grid subtraction to define unit thickness. Individual units were discontinuous and varied in thickness and elevation, but their upper and lower surfaces were treated as continuous across model domain to facilitate generation of sediment thickness maps. Where a unit was observed to pinch out or had been truncated, the top of the underlying unit was used to ‘pull-up’ the base elevations for the overlying unit. The MSMC lithostratigraphy is interpreted to have been truncated by the younger CV stratigraphy, producing zero thickness layers in most isochore maps. Accurate sediment thickness maps aid in the constraint of hydrogeological models (Logan et al., 2001), however, when borehole data are clustered the validity of interpolated surfaces decreases with increasing distance from borehole locations, particularly when model layers pinch-out and incise underlying formations. The gridding and interpolation of surfaces are therefore restricted to a smaller subset of the study area, which includes the highest density of high quality data (Figure 1-1B).

1.6 Organization of Thesis

This thesis has been organized as a ‘sandwich thesis’ with the results presented in two papers for publication in various academic journals. In Chapter 2 a detailed 3-dimensional subsurface model is constructed for the Georgetown area using a large core and geophysical well log database. In this model, the infill stratigraphy of the MSMC and CV are represented by 9 distinctive lithostratigraphic units identified based on their lithofacies/electrofacies characteristics. Isochore and structure contour maps are used to investigate the spatial distribution and geometry of the lithostratigraphic units across the study area. Chapter 3 evaluates the log parameters most useful for lithologic classification of lithostratigraphic units using principal component analysis (PCA). Analysis of each principal component (PC) permits interpretation of the geologic factors influencing them and subsequent plotting of PC score logs effectively classifies subsurface lithologic type. It is demonstrated how a simple division of log data in PC space can be used to identify the principle sediment types (till, sand, clay). The approach provides a viable method for classifying lithologic type for boreholes where core is absent.

CHAPTER 2: Characterizing the Quaternary Hydrostratigraphy of Buried Valleys using Multi-parameter Borehole Geophysics, Georgetown, Ontario

Abstract

Quaternary deposits are exploited widely across North America for groundwater but their stratigraphic complexity can present many challenges for groundwater resource exploration. In 2009, Halton Region and McMaster University initiated a regional investigation of the geology and hydrostratigraphy of Quaternary sediments near Georgetown, Ontario to assist the search for new high yield aquifers. The project included drilling of 16 new continuously cored boreholes (16 m to 55 m depth) and borehole geophysical investigations to characterize the infill stratigraphy of the Middle Sixteen Mile Creek (MSMC) and Cedarvale (CV) buried valley systems. Multi-parameter log suites (natural gamma, EM conductivity, resistivity, magnetic susceptibility, full-waveform sonic, caliper) were acquired in 16 recently drilled boreholes, 3 pre-existing monitoring wells and digitized from 10 archived log suites to assist in subsurface correlation and the identification of potential aquifer and aquitard units. Characteristic log responses (electrofacies) were identified by visual analysis and cross-plotting of log parameters and correlated with core lithofacies.

In the MSMC buried valley 6 distinctive lithostratigraphic units were identified within a thick (> 55 m) interbedded sequence of diamict (aquitards), laminated silts and coarse-grained glaciofluvial deposits (aquifers) overlying shale bedrock. Gamma, magnetic susceptibility, resistivity and conductivity logs were most useful for lithologic typing. Downhole changes in p-wave velocity and resistivity were also important for discriminating and correlating more compact diamict units. In a number of locations the lowermost diamict unit was thinned or erosionally truncated, allowing direct communication of the upper and lower aquifers. The infill stratigraphy of the CV valley comprised a complex succession of glaciofluvial sand and gravel up to 45 m thick. The CV sediments truncate the older MSMC stratigraphy across a well-defined erosional unconformity and were deposited in a sediment-hosted valley.

The results demonstrate that the Quaternary sediments below Georgetown are complex and characterized by significant lateral and vertical sedimentary variability. The geophysical log responses of a number of hydrostratigraphic units were distinctive and provided useful subsurface marker horizons for correlation of the Quaternary deposits in areas where core data are unavailable. The subsurface model produced in this study demonstrates a distinctive stratigraphic character between the MSMC buried bedrock valley and the sediment-hosted CV valley as indicated by their respective electrofacies. MSMC electrofacies were generally predictable, whereas the CV valley and adjacent valley walls were more complex and variable, with the differences in the two valley systems attributed to their contrasting depositional environments. This study demonstrates the advantages of borehole geophysical logging of complex buried valley sequences that can be broadly applied to various regions where investigations of buried valleys and previously glaciated terrains are planned.

Keywords: Borehole geophysics, buried bedrock valleys, Georgetown, Ontario

2.1 Introduction

Late Quaternary glacial deposits are the predominant surficial materials across a large area of mid-latitude North America and are host to highly-productive regional aquifer systems (Stephenson et al., 1989). In southern Ontario, Canada, more than one-third of residents are dependent on groundwater supplies for drinking water but in some communities demand is outstripping the available groundwater supply. Groundwater shortages are particularly acute in communities outlying the rapidly expanding Greater Toronto Area, including the town of Georgetown, which is located about 60 km north of Lake Ontario, in north Halton Region (Figure 2-1). More than 30% of Georgetown residents are dependent on groundwater abstracted from municipal and private wells but due to a current groundwater shortage, restrictions have been placed on new development.

In response to the shortfall, the Regional Municipality of Halton initiated regional groundwater investigations in 2007 to locate and exploit new groundwater resources. The investigations included drilling of 21 continuously cored boreholes, surface and downhole geophysics and installation of a well monitoring network. A primary target of the investigations was to determine the groundwater resource potential of thick (> 50 m) Quaternary sediments that infill several bedrock valley systems below north Halton (Figures 1-2, 2-1). The bedrock valley systems were described in earlier regional groundwater studies (Davies and Holysh, 2007; Meyer and Eyles, 2007) but major knowledge gaps existed as to the location, sedimentary infill characteristics and the extent of aquifer and aquitard units within the bedrock valley systems. In 2009, Halton Region partnered with McMaster University in 2-year study of the Quaternary stratigraphy and hydrogeology of buried valleys in an effort to fill these knowledge gaps.

A primary objective of the joint study was to develop a detailed 3-dimensional stratigraphic framework that would provide a basis for groundwater exploration that would inform regional groundwater planning decisions.

In this paper, we report on the results of detailed subsurface investigations of two buried bedrock and sediment-hosted valleys in the Georgetown area (Middle Sixteen Mile Creek and Cedarvale valley systems; Figures 1-2, 2-2B) and present a detailed subsurface model, which integrates both core and downhole geophysical data. The modeling results demonstrate the high level of stratigraphic heterogeneity and complexity that is inherent in bedrock valley systems in southern Ontario and provides a geological framework for understanding groundwater resource availability. The approach used in this study, involving the correlation and integration of multi-parameter geophysical logs with core lithofacies data can be applied more broadly in many other regions of North America, where glacial sediments and bedrock valley systems are being exploited for groundwater resources.

2.2 Study Area and Geologic Setting

The study area (20-km^2) is located in the Credit River watershed to the southwest of Georgetown, Ontario (Figure 2-1). The area lies on a low relief glacial till plain (Halton Till Plain) that extends northward from Lake Ontario to the Oak Ridges Moraine and westward to the Niagara Escarpment (Davies and Holysh, 2007; Karrow, 2005). The till plain consists of low relief table lands, which are dissected by the Credit River Valley and it’s tributary channels to a depth of 40-50 m (Figures 2-1, 2-2). The bedrock below the study areas consists of Mid-Ordovician Queenston shales, which are overlain in western Halton Region by more resistant carbonates and sandstones of the Niagara

Figure 2-1: A) Location of Georgetown within the Regional Municipality of Halton. B) Georgetown study area showing locations of continuously core and geophysically logged boreholes and cross-sections. Inset area shows 8-km^2 included in the structure contour and isochore mapping of lithostratigraphic units.

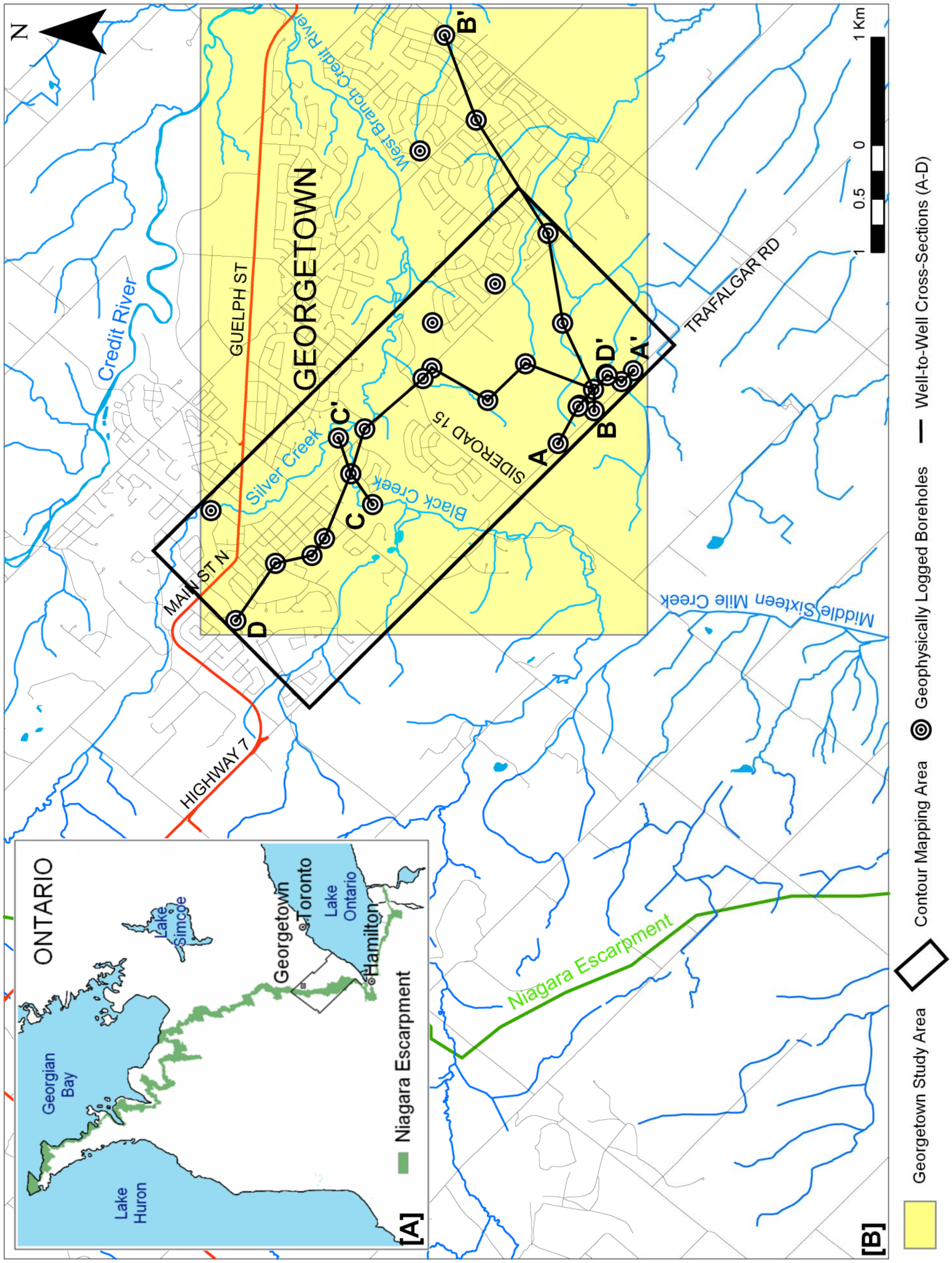
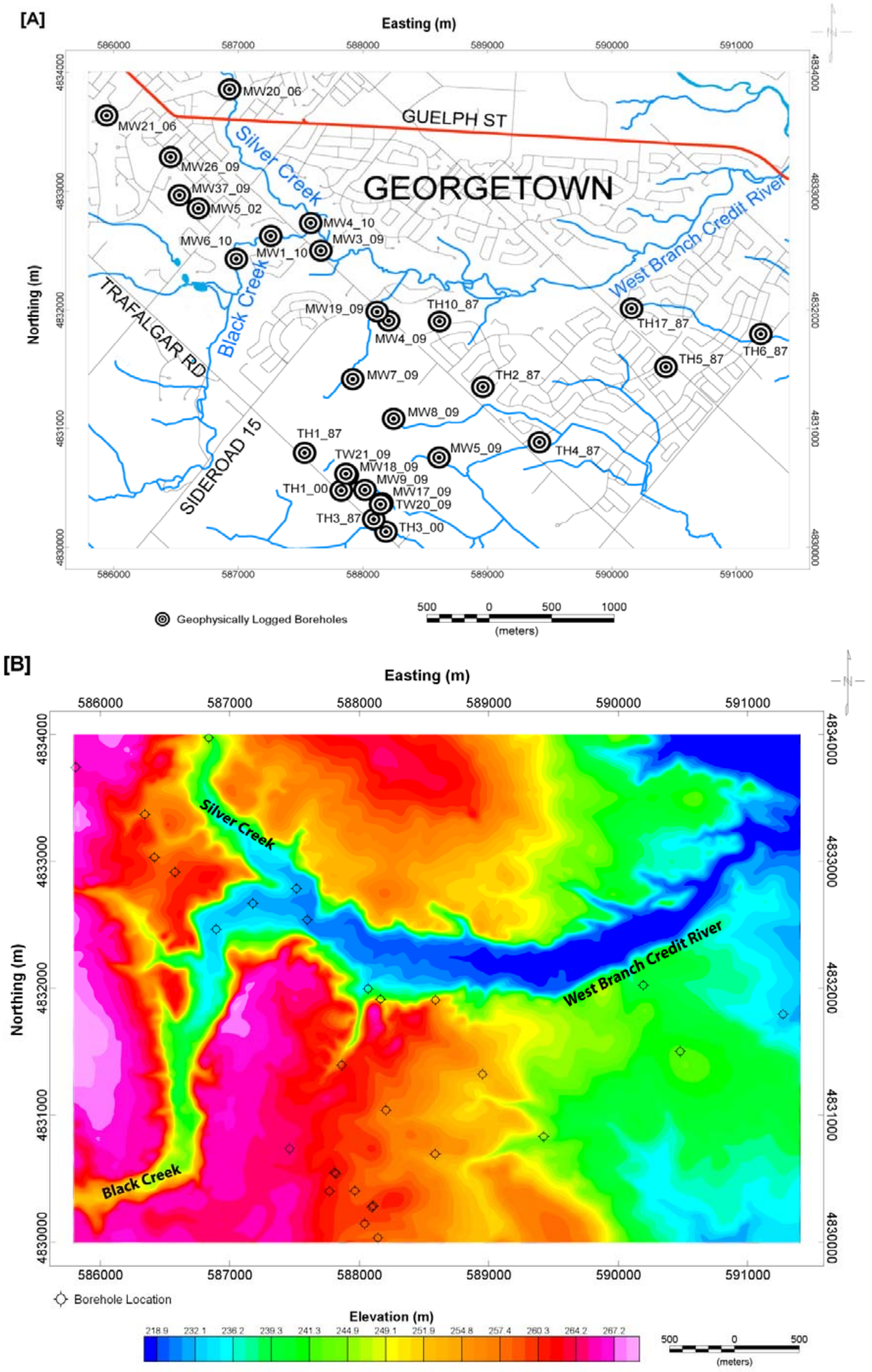

[A]
ONTARIO
Georgian Bay
Lake Huron
Lake Simcoe
Georgetown
Toronto
Lake Ontario
Hamilton
Niagara Escarpment
[B]
N
GEORGETOWN
Credit River
West Branch Credit River
GUELPH ST
Silver Creek
Black Creek
SIDEROAD 15
MAIN ST N
HIGHWAY 7
TRAFALGAR RD
Middle Sixteen Mile Creek
Niagara Escarpment
A
A'
B
B'
C
C'
D
D'
1
0.5
0
1 Km
Georgetown Study Area
Contour Mapping Area
Geophysically Logged Boreholes
Well-to-Well Cross-Sections (A-D)

Figure 2-2: A) Georgetown study area with locations of geophysically logged boreholes, B) Digital elevation model (DEM) for Georgetown study area (10 m grid cells) showing surface topography and locations of Black and Silver Creek valleys.


[A]
Easting (m)
586000
587000
588000
589000
590000
591000
Northing (m)
4834000
4833000
4832000
4831000
4830000
N
GUELPH ST
GEORGETOWN
Silver Creek
Black Creek
West Branch Credit River
TRAFALGAR RD
SIDEROAD 15
MW20_06
MW21_06
MW26_09
MW37_09
MW5_02
MW4_10
MW3_09
MW6_10
MW1_10
MW19_09
MW4_09
TH10_87
TH17_87
TH6_87
TH5_87
MW7_09
TH2_87
MW8_09
TH1_87
TW21_09
MW5_09
TH4_87
MW18_09
MW9_09
TH1_00
MW17_09
TW20_09
TH3_87
TH3_00
Geophysically Logged Boreholes
500
0
500
1000
(meters)
[B]
Easting (m)
586000
587000
588000
589000
590000
591000
Northing (m)
4834000
4833000
4832000
4831000
4830000
N
Silver Creek
Black Creek
West Branch Credit River
Borehole Location
Elevation (m)
218.9
232.1
236.2
239.3
241.3
244.9
249.1
251.9
254.8
257.4
260.3
264.2
267.2
500
0
500
(meters)

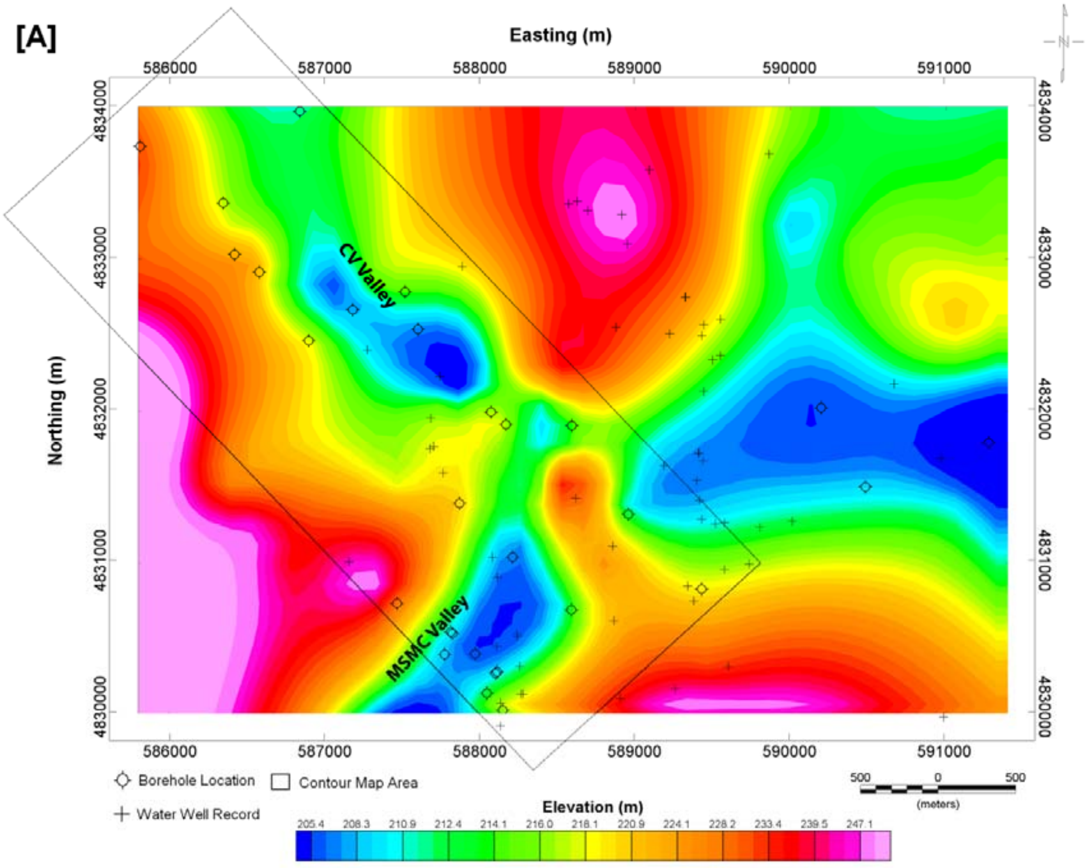
Escarpment (Figure 2-3). The shale bedrock surface is cut by several broad bedrock valleys that extending north to south along the base of the escarpment and below the modern river valleys of the Middle Sixteen Mile Creek (MSMC), Silver Creek and Credit River. The bedrock surface and the general form of the bedrock valleys have been mapped in several previous studies using water well and borehole data (Davies and Holysh, 2007; Eyles and Boyce 1997; Brennand et al., 1998) and most recently by Puckering (2011) as part of the McMaster study in Georgetown.

The bedrock valleys are infilled by Late Quaternary sediments that reach a maximum thickness >50m within the MSMC valley (Davies and Holysh, 2007; Meyer and Eyles, 2007). Meyer and Eyles (2007) documented the infill stratigraphy of several poorly-defined buried bedrock valleys underlying the towns of Milton and Georgetown. Six distinctive stratigraphic units were identified in the infill sediments, including a lowermost interbedded succession of fluvial sands, gravels and laminated lacustrine silts and clays overlain by two Late Wisconsin till units. The till units were separated by coarse-grained sands and gravels interpreted as Mackinaw Interstadial deposits. The lower till unit was attributed to the main phase of Late Wisconsin ice advance (ca. 18-25 Ka), suggesting a regional correlation with the Newmarket Till to the east (Boyce and Eyles, 2000; Sharpe et al., 2002, 2003), while the upper till records a brief, final re-advance of ice out of the Ontario basin at ca. 12-13.5 Ka (Halton Till, Port Huron Stadial) and forms a broad finer-grained till plain at or near surface across Halton Region (Davies and Holysh, 2007). The ages and associated deposits near Georgetown are highlighted in Figure 2-4.

Surficial geology maps (Davies and Holysh, 2007; Karrow, 2005) illustrate that near Georgetown, Halton Till and coarse grained ice contact deposits are the predominant surficial materials. Along Black and Silver Creeks, modern alluvium (gravel to clay) is observed to infill the valleys and hosts the Cedarvale municipal well field at their confluence (Figure 2-5). Slomka (2011) recently described similar sand and gravel deposits exposed in pits in the Halton Hills area.

Figure 2-3: A) Bedrock topography map of Georgetown study area showing Cedarvale (CV) and Middle Sixteen Mile Creek (MSMC) bedrock valleys. Location of borehole and water well records used to create bedrock map also shown. B) Drift thickness map for Georgetown study area produced by subtraction of surface topography from bedrock surface grid. The thickest sediments are found in Princess Anne well field within the MSMC bedrock valley.

[A]


Easting (m)
586000
587000
588000
589000
590000
591000
Northing (m)
4834000
4833000
4832000
4831000
4830000
CV Valley
MSMC Valley
N
Borehole Location
Contour Map Area
Water Well Record
500
0
500
(meters)
Elevation (m)
205.4
208.3
210.9
212.4
214.1
216.0
218.1
220.9
224.1
228.2
233.4
239.5
247.1

[B]

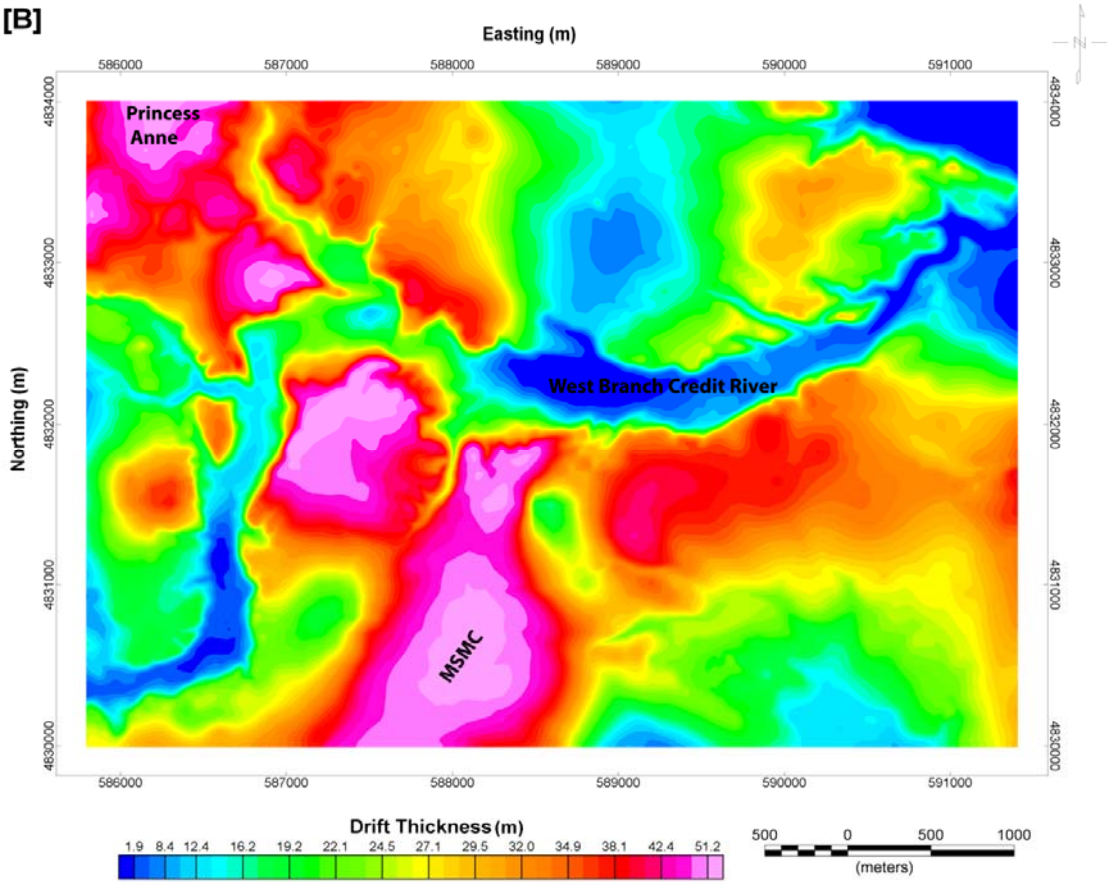
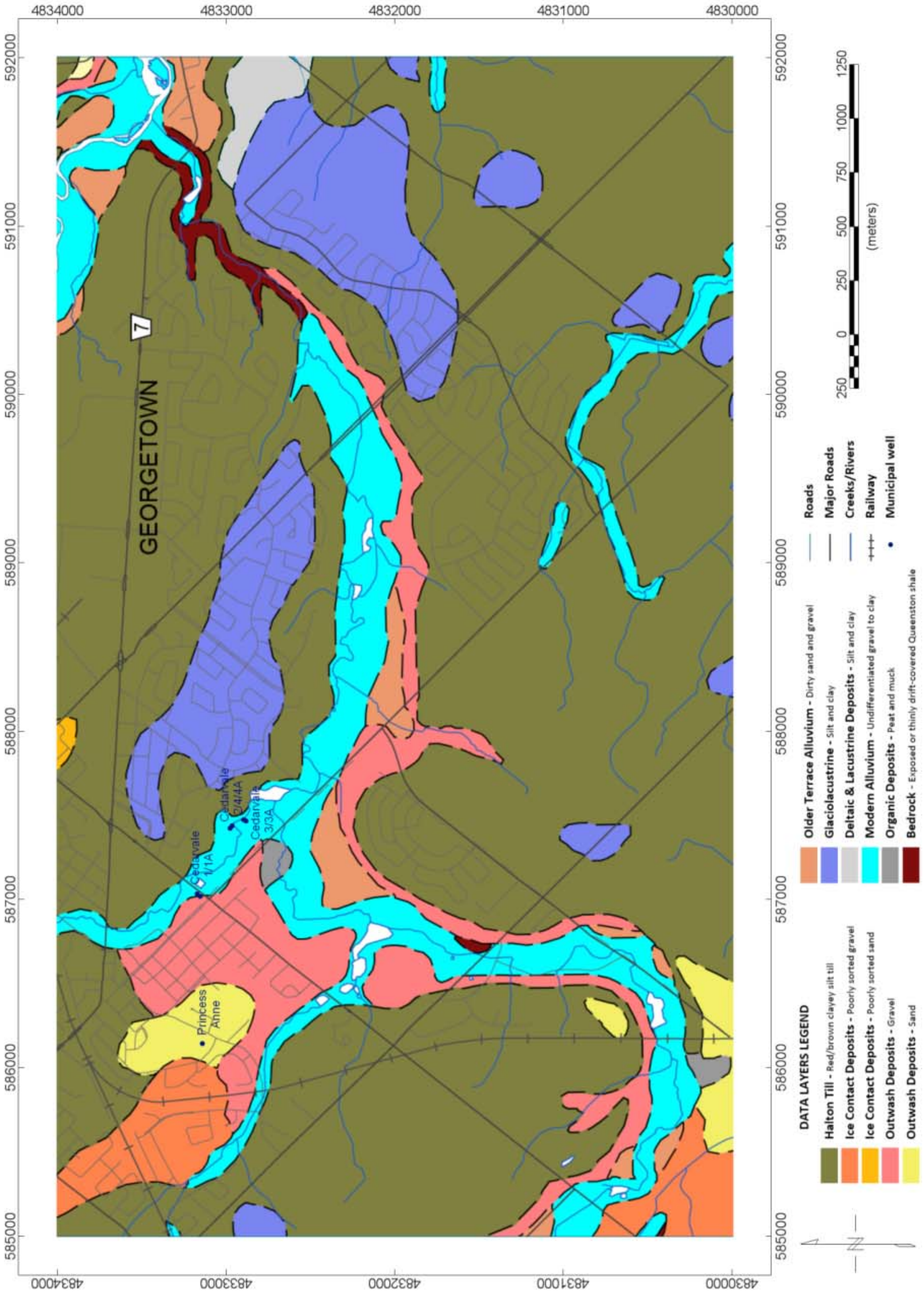

Easting (m)
586000
587000
588000
589000
590000
591000
Northing (m)
4834000
4833000
4832000
4831000
4830000
Princess Anne
West Branch Credit River
MSMC
N
Drift Thickness (m)
1.9
8.4
12.4
16.2
19.2
22.1
24.5
27.1
29.5
32.0
34.9
38.1
42.4
51.2
500
0
500
1000
(meters)

Figure 2-4: Late Wisconsinan stratigraphic subdivisions for the Georgetown Area, after Meyer & Eyles (2007)

Age (year BP)	Period	Glacial Stage	Substage	Glacial Stadial/ Interstadial	Associated Deposits	Meyer & Eyles (2007) Stratigraphy
7 000	Quaternary	Wisconsinan	Late Wisconsinan	Post Iroquois and Pre-Lake Ontario Events	Post Iroquois and Pre-Lake Ontario Events	-
11 500				Two Creeks Interstadial	Shoreline formation Glaciolacustrine depositio	-
12 000				Port Huron Stadial	Halton Till Complex, Wildfield Till	SU VI
13 200				Mackinaw Interstadial	Outwash sands and gravels	SU V
14 000				Port Bruce Stadial	(No sediments deposited in this area)	-
15 500				Erie Interstadial		
18 000				Nissouri Stadial	Northern/ Newmarket Till	SU IV SU I/II/III
25 000 53 000 80 000			Early to Mid-Wisconsinan		Thorncliffe Formation Meadowcliffe Diamict Seminary Diamict Sunnybrook Diamict	-

Figure 2-5: Surficial geology of the Georgetown area with locations of municipal wells (adapted from Karrow and Easton, 2005; Ontario Geological Survey, Map sheet 2223)


GEORGETOWN
7
Cedarvale 1/1A
Cedarvale 2/4/4A
Cedarvale 3/3A
Princess Anne
4834000
4833000
4832000
4831000
4830000
592000
591000
590000
589000
588000
587000
586000
585000
DATA LAYERS LEGEND
Halton Till - Red/brown clayey silt till
Ice Contact Deposits - Poorly sorted gravel
Ice Contact Deposits - Poorly sorted sand
Outwash Deposits - Gravel
Outwash Deposits - Sand
Older Terrace Alluvium - Dirty sand and gravel
Glaciolacustrine - Silt and clay
Deltaic & Lacustrine Deposits - Silt and clay
Modern Alluvium - Undifferentiated gravel to clay
Organic Deposits - Peat and muck
Bedrock - Exposed or thinly drift-covered Queenston shale
Roads
Major Roads
Creeks/Rivers
Railway
Municipal well
250
0
250
500
750
1000
1250
(meters)
N

2.3 Methodology

2.3.1 Borehole Database

The borehole subsurface database employed in this study comprised 21 borehole records (Figure 2-2A) acquired during recent hydrogeological investigations and an additional 8 archival wireline records. Core lithofacies data were obtained from 11 high-quality PQ cores totalling more than 425m of continuous core drilled since January 2009 as part of the MSMC and Tier 3 groundwater studies. The data were augmented by driller's logs from 5 mud rotary boreholes, 3 pre-existing monitoring wells and 2 archival boreholes (Table 2-1). In 8 of the archival borehole records, however, no lithological information was provided and the available data consisted exclusively of geophysical logs.

2.3.2 Borehole Geophysical Data

The geophysical logs suites used in this study were collected for 29 borehole locations from a variety of sources, including cased-hole logs collected by McMaster, open-hole logs provided by the Regional Municipality of Halton (collected by Lotowater), and digitized archived log suites (Table 2-2). Open-hole geophysical logs (resistivity, gamma, caliper) were acquired in 15 of the recently drilled boreholes (16 m to 55 m depth) prior to installation of PVC casings. Subsequent downhole geophysical logs (gamma, conductivity, magnetic susceptibility, full-waveform sonic) were collected in 11 of the recently drilled boreholes and 3 existing PVC cased monitoring wells not previously logged. A Mount Sopris Matrix portable digital logging system consisting of a surface unit (cable winch and mounted data console with a laptop interface and depth

	New Boreholes Drilled Since Jan. 2009 (16 used in this study)	**Existing Monitoring Wells (3 used in this study)**	**Archived Data (10 used in this study)**
# of Boreholes with Continuous PQ Core	11	0	0
# of Boreholes with Driller's Logs	5 (Mud Rotary drilling)	3 (Hollow Stem Auger & Sonic drilling)	2

Table 2-1: Lithological data by availability and source of information for study area. Of the total 29 borehole locations investigated in this study, all 16 recently drilled boreholes and 3 pre-existing monitoring wells had core information. Conversely, only 2 of the 10 archived datasets had core information.

	New Boreholes Drilled Since Jan. 2009 (16 used in this study)	**Existing Monitoring Wells (3 used in this study)**	**Archived Data (10 used in this study)**
Cased-hole Geophysical Logs	11 (McMaster)	3 (McMaster)	2 (gamma & conductivity)
Open-hole Geophysical Logs	15 (Lotowater)	N/A	8 (caliper, gamma, resistivity)

Table 2-2: Borehole geophysical logs used in this study. Of the 16 recently drilled boreholes used in this study, 15 were logged with open-hole geophysical tools (caliper, gamma, resistivity) prior to casing installation and 11 of them were logged within PVC casings by McMaster (gamma, conductivity, magnetic susceptibility, full waveform sonic). Pre-existing monitoring wells had not been previously logged and were only available for cased-hole logging by McMaster. Two archived datasets had gamma and conductivity logs while the other 8 records consisted of caliper, gamma and resistivity (0.25ft and 2.5ft) log suites.

measuring wheel) and borehole probes run through 2.5-3” PVC cased holes was used to collect new geophysical data. For additional information on geophysical acquisition parameters, the reader is referred to Chapter 1. Figure 2-6 shows the complete suite of logs obtained in MW9_09, the deepest borehole in the study area.

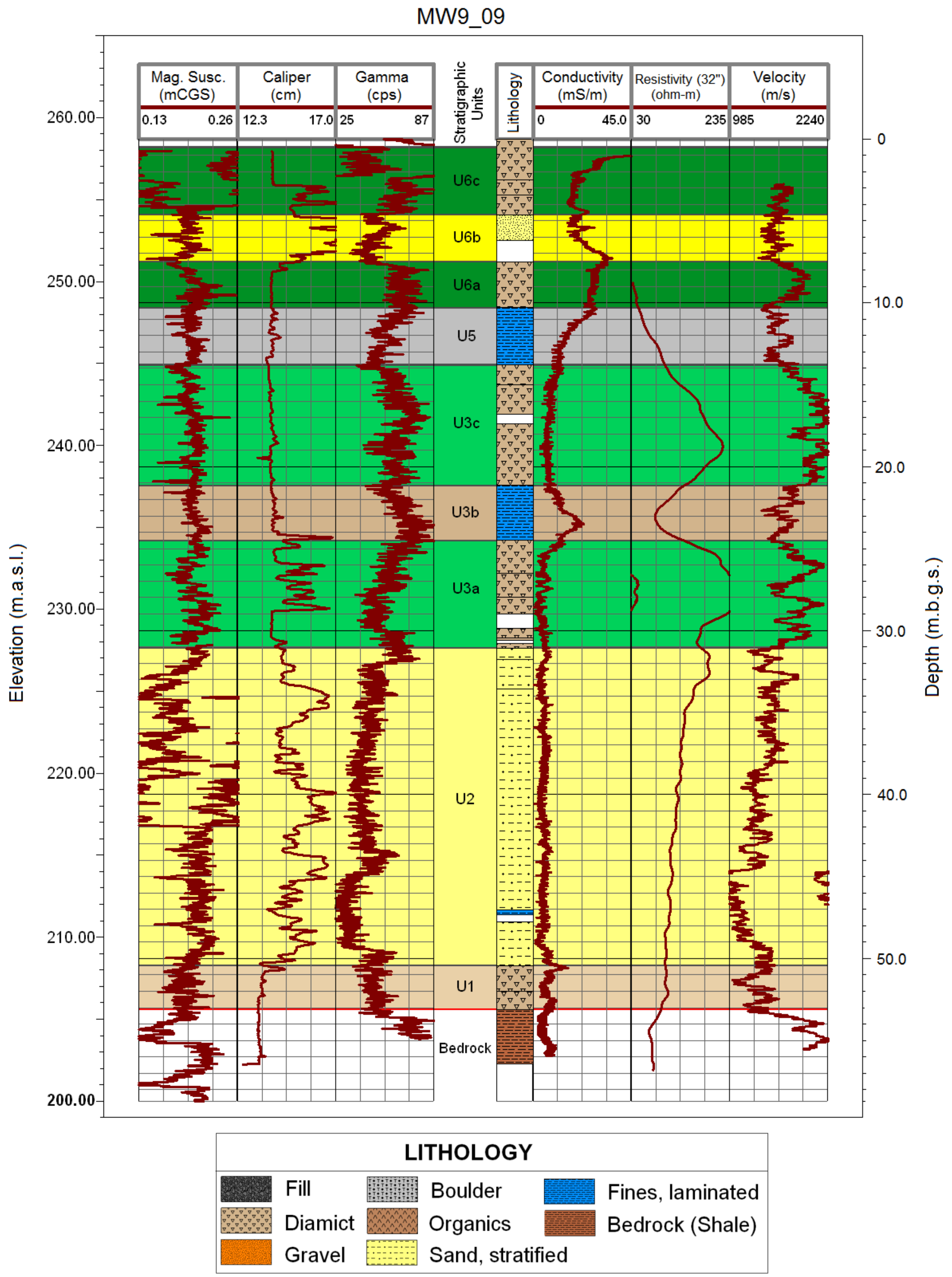
2.3.3 Data Processing and Interpretation

The raw borehole geophysical logs collected in this study were imported, screened and edited for stick-up and measurement point corrections. On some gamma logs, 7-point boxcar filters were applied to smooth the log curves where necessary to improve the resolution of larger scale features. Composite plots of log traces were generated to facilitate geophysically-based lithological interpretations from visual analysis of log signatures. The initial picks were compared with core lithofacies data and the driller’s logs where available to confirm the lithological classifications and location of unit boundaries. Detailed geophysical interpretations of individual trends (i.e. fining/coarsening upwards cycles), curve shapes and abruptness of transitions helped to establish characteristic log signatures (electrofacies). Electrofacies of interpreted hydrostratigraphic units were then compared to detailed sedimentological core lithofacies (Slomka, 2011) to improve confidence in final interpretations and are presented as a series of cross sections (Figures 2-7 – 2-10).

2.3.4 Subsurface Model

A subsurface model was generated for a subset of the 20-km^2 study area using Rockworks® v.15 and Geosoft Oasis Montaj®. The geophysical and lithostratigraphic picks for each borehole were used to generate structure contour maps of the formation tops and isochore thickness maps units 1-9 (Figures 2-11, 2-12, 2-13). The isochore maps

Figure 2-6: Composite plot of MW9_09 showing MSMC correlations. Log curves collected in open hole by Lotowater Ltd. included caliper and resistivity (32”). Cased hole logging by McMaster included magnetic susceptibility, natural gamma, EM conductivity and full-waveform sonic (p-wave velocity). Note characteristic ‘dual-peak’ resistivity and high velocity of middle diamict in MSMC.


MW9_09
Mag. Susc. (mCGS)
0.13
0.26
Caliper (cm)
12.3
17.0
Gamma (cps)
25
87
Stratigraphic Units
Lithology
Conductivity (mS/m)
0
45.0
Resistivity (32") (ohm-m)
30
235
Velocity (m/s)
985
2240
U6c
U6b
U6a
U5
U3c
U3b
U3a
U2
U1
Bedrock
Elevation (m.a.s.l.)
260.00
250.00
240.00
230.00
220.00
210.00
200.00
Depth (m.b.g.s.)
0
10.0
20.0
30.0
40.0
50.0
LITHOLOGY
Fill
Boulder
Fines, laminated
Diamict
Organics
Bedrock (Shale)
Gravel
Sand, stratified

were produced by grid subtraction of structure contour surface for each lithostratigraphic unit. A subsurface model, consisting of a series of 2-D fence diagrams was then constructed in Rockworks® by interpolation of the formation tops across the subset area. The fence diagram clearly shows the geometry of the lithostratigraphic units and the cross-cutting relationships between the MSMC and CV valley systems (Figure 2-13).

2.4 Results

The borehole geophysical data and lithostratigraphic correlations are presented as a series of cross-sections in Figures 2-7 to 2-10. These demonstrate that the Quaternary sediments below Georgetown are stratigraphically complex but can be correlated across much of the 20-km^2 study as laterally continuous units. Analysis of geophysical log patterns and comparison with core lithofacies (Figure 2-6) allowed identification of 9 distinctive lithostratigraphic units and recognition of 13 distinctive electrofacies as summarized in Table 2-4. The geophysical log responses exhibited a range of values but electrofacies patterns were distinctive for many units and allow correlation of the Quaternary deposits in areas where core data are unavailable. Gamma, resistivity, conductivity and magnetic susceptibility logs were most useful for lithologic discrimination. Downhole changes in resistivity and p-wave velocity were also important for discriminating and correlating more compact diamict units in the MSMC area.

Detailed cross-sections discussed below highlight correlations between lithological data (where available) and the characteristic ‘hydrostratigraphic’ gamma and electrical logss (conductivity and resistivity) collected for each borehole. Not all geophysical parameters were collected at every borehole, owing to site-specific conditions (i.e. cased monitoring wells could not facilitate open-hole logging) and incorporation of archived log suites with fewer logged parameters.

Subsurface modeling allows interpretation of unit geometries across the Georgetown study area while analysis of a three dimensional fence diagram slicing through the model provides additional information on discontinuous unit surfaces, pinchouts and hydrogeologic connectivity. Detailed contour mapping of lithostratigraphic units as discrete surfaces produced a series of sediment thickness (isochore) maps that focus on the differences between the MSMC and CV valleys. Analysis of upper and lower lithostratigraphic surfaces provides useful information on accommodation space and mode of deposition (higher energy erosive contacts and coarse grained deposition versus low energy fine grained lacustrine infill of topographic lows) and supports interpretation of contrasting MSMC and CV depositional systems. Isochore maps detail unit thicknesses and are useful for studying unit geometries, relationships of surface relief to formation deposition and continuity of deposited sediments preserved at the confluence of Black and Silver Creeks. In the following sections, the lithostratigraphy and characteristic electrofacies are broken down to highlight the differences between the MSMC and CV valleys.

2.4.1 Lithostratigraphy - MSMC Valley

In the MSMC buried valley six distinctive litho-stratigraphic units were identified (U1 – U6) within a thick (> 55 m) interbedded sequence of diamict, laminated silts and coarse-grained glaciofluvial deposits depicted in Figures 2-7 and 2-8. Cross-section A-A’ (Figure 2-7) highlights the litholostratigraphy across the MSMC valley along a roughly NW-SE transect while cross-section B-B’ (Figure 2-8) follows the MSMC as a W-E transect that depicts the thinning and subsequent termination of the MSMC buried valley at a bedrock high near MW5_09 (Figure 2-2A).

Figure 2-7: Cross section A-A’ trending NW-SE. across the Middle Sixteen Mile Creek (MSMC) buried valley.

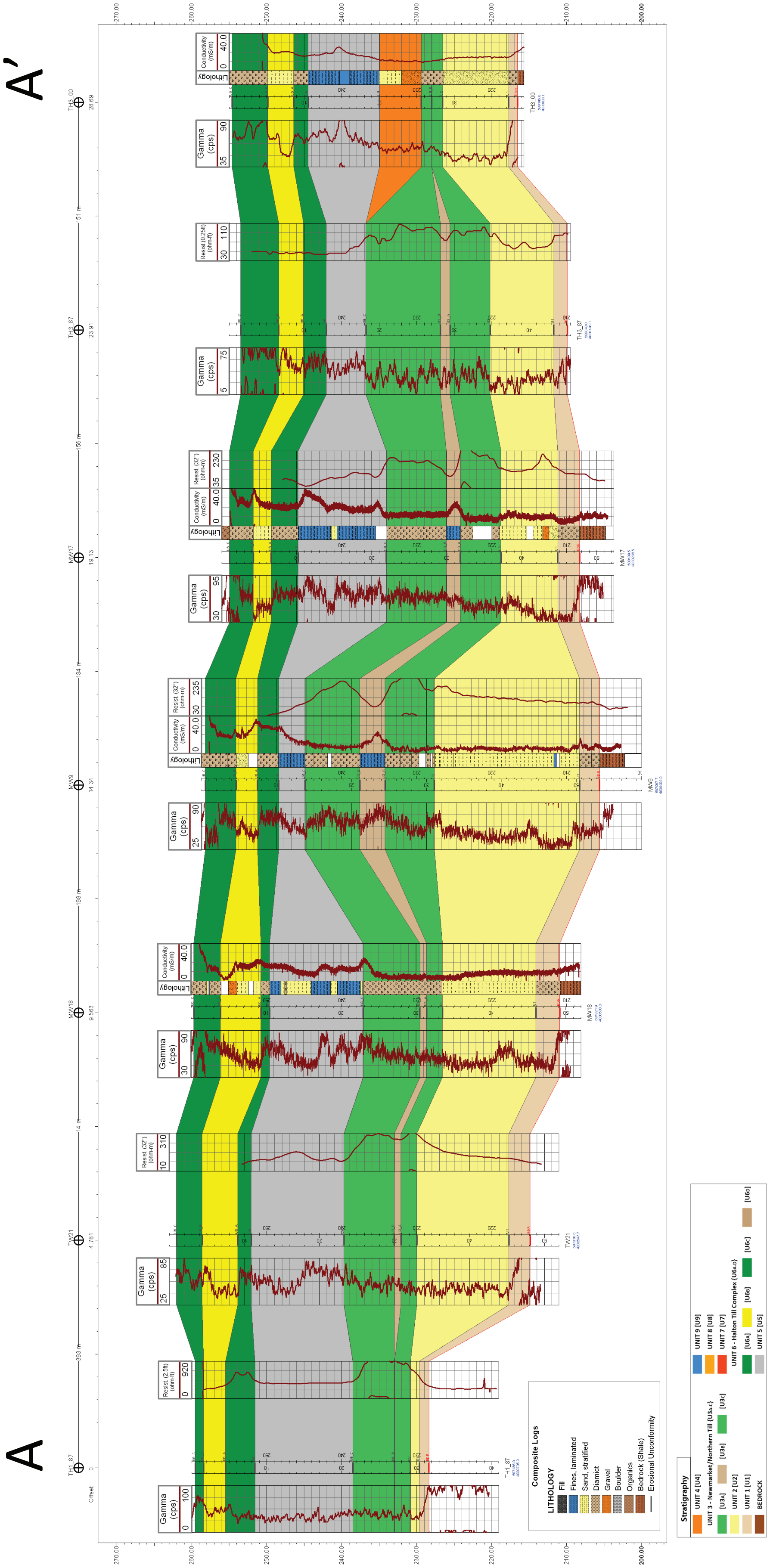
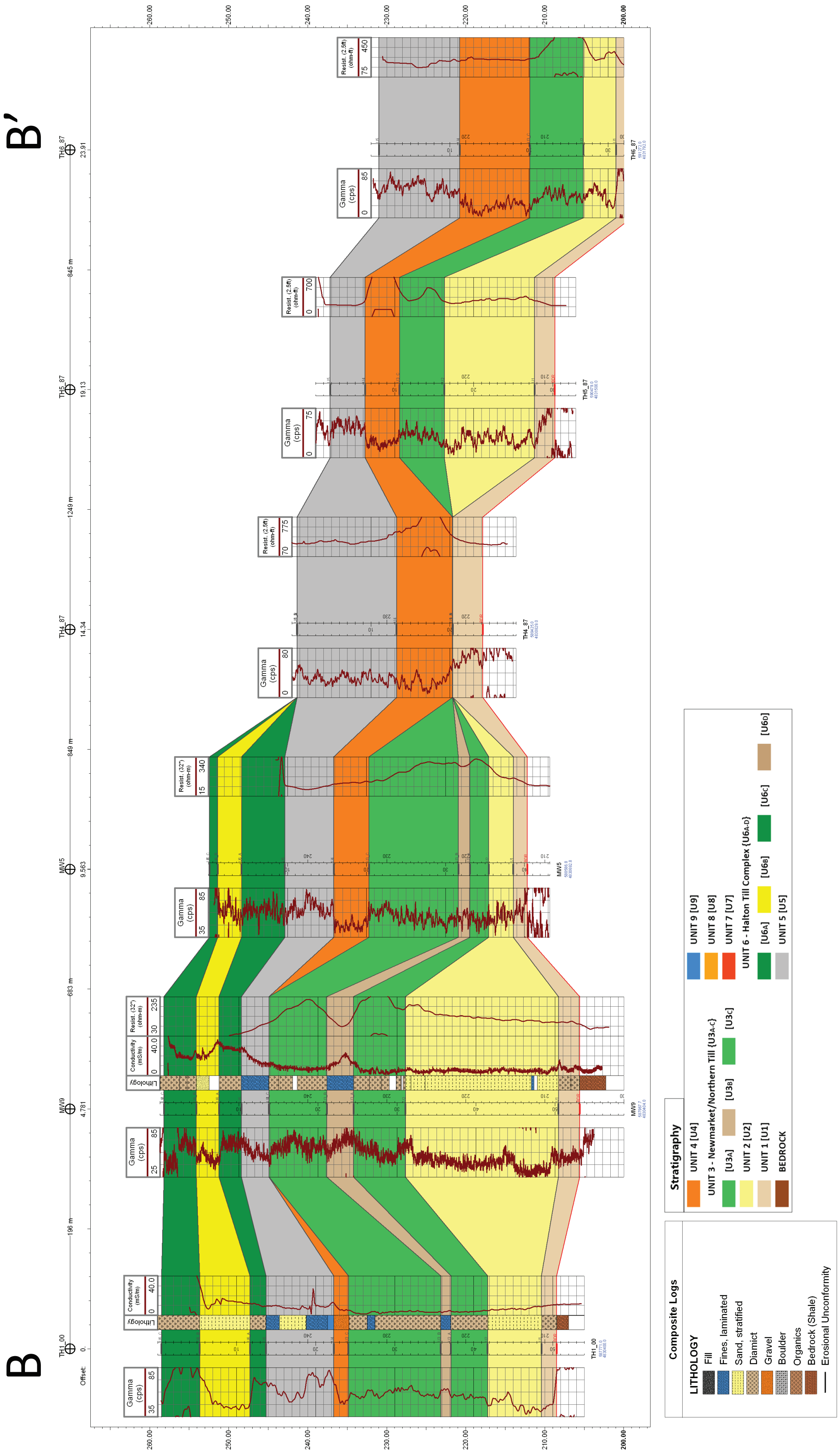

A
A′
Offset:
TH1_87
TW21
MW18
MW9
MW17
TH3_87
TH3_00
Gamma (cps)
Resist (2.5ft) (ohm.ft)
Resist (32") (ohm.m)
Conductivity (mS/m)
Lithology
Resist (0.25ft) (ohm.ft)
270.00
260.00
250.00
240.00
230.00
220.00
210.00
200.00
Composite Logs
LITHOLOGY
Fill
Fines, laminated
Sand, stratified
Diamict
Gravel
Boulder
Organics
Bedrock (Shale)
Erosional Unconformity
Stratigraphy
UNIT 9 [U9]
UNIT 8 [U8]
UNIT 7 [U7]
UNIT 6 - Halton Till Complex {U6A-D}
[U6A]
[U6B]
[U6C]
[U6D]
UNIT 5 [U5]
UNIT 4 [U4]
UNIT 3 - Newmarket/Northern Till {U3A-C}
[U3A]
[U3B]
[U3C]
UNIT 2 [U2]
UNIT 1 [U1]
BEDROCK

Figure 2-8: Cross Section B-B’ trending roughly W-E from the MSMC buried valley to the eastern limit of the study area. Note the rise in bedrock and pinchout of the lower sands near MW 5_09 corresponding with the termination of the MSMC buried valley in this area.


B
B’
Offset:
TH1_00
0.
196 m
MW9
4.781
683 m
MW5
9.563
849 m
TH4_87
14.34
1249 m
TH5_87
19.13
845 m
TH6_87
23.91
Gamma (cps)
Lithology
Conductivity (mS/m)
Resist. (32") (ohm-m)
Resist. (2.5ft) (ohm-ft)
260.00
250.00
240.00
230.00
220.00
210.00
200.00
Composite Logs
LITHOLOGY
Fill
Fines, laminated
Sand, stratified
Diamict
Gravel
Boulder
Organics
Bedrock (Shale)
Erosional Unconformity
Stratigraphy
UNIT 9 [U9]
UNIT 8 [U8]
UNIT 7 [U7]
UNIT 6 - Halton Till Complex {U6A-D}
[U6A]
[U6B]
[U6C]
[U6D]
UNIT 5 [U5]
UNIT 4 [U4]
UNIT 3 - Newmarket/Northern Till {U3A-C}
[U3A]
[U3B]
[U3C]
UNIT 2 [U2]
UNIT 1 [U1]
BEDROCK

Underlying the base of the MSMC sedimentary succession is red Ordovician Queenston shale (Barnett, 1992; Meyer and Eyles, 2007). The upper 3-5m of bedrock is typically weathered (Davies and Holysh, 2007; Meyer and Eyles, 2007) and is incorporated into a clast-supported diamict with abundant shale clasts and poorly-sorted sandy-clay matrix. This unit (U1, Figure 2-6) is regionally extensive and generally thin in the 1-2m range, but exceeds 4m in some areas.

Confined to bedrock lows and the MSMC bedrock valley, U2 is a fining upwards sequence of fluvial sand with some silt and laminated silty clays (Figures 2-7 and 2-8). Above U2 lies an over-consolidated massive to crudely stratified sand-rich diamict (U3) (Figure 2-6). Across much of the MSMC buried valley, U3 can be subdivided into lower (U3A) and upper diamict (U3C) sub-units separated by sand and silt interbeds (U3B) up to 2.5m thick (Figure 2-7).

Above U3 lies a sequence of discontinuous coarse sands and gravel, interpreted as glaciofluvial outwash (U4, Figure 2-8). Resting atop U4 is a sequence of interstratified fine sand, silt and clay with repeated fining-upward cycles (U5, Figure 2-7 and 2-8).

The surface layer (U6, Figure 10) in the MSMC area comprises a sequence of clay-rich diamicts interspersed with sand and gravel that can be divided into three distinct subunits (U6A-C) based on their electrofacies and sedimentological characteristics. U6A and U6C are the lower and upper clay-rich diamicts, while U6B represents intervening sand and gravel up to 6m thick.

In the Princess Anne (PA) region in the northwestern corner of the study area (Figure 2-10), thick successions of sand inter-stratified with gravel and fine grained silts and clays form productive municipal aquifers and are tentatively related to the MSMC valley stratigraphy described above. Consequently, the PA stratigraphy is assigned and related in this study to units U2, U4, U5, and U6B. At surface in PA, a distinctly red clay-rich diamict with silt clasts and round gravels differs from U6C identified in the MSMC area and is therefore termed U6D. While geophysically similar and occupying an equivalent stratigraphic position to U6C, the unique sedimentologic properties identified in core warrant its separation as a distinctive sub-unit of U6. A summary of the MSMC litho-stratigraphy is presented in Table 2-3.

2.4.2 Lithostratigraphy – Cedarvale Valley

Along the upper reaches of the Cedarvale valley at the confluence of Black and Silver Creeks, coarse gravels and sands (U7, Figure 2-10) sit atop an erosional unconformity that thins and truncates the underlying diamict complex at the valley margin. Within the modern CV valley incised into the surrounding sediment sequence, cross section C-C’ (Figure 2-9) identifies coarse sands and gravels (U8) that form the base of the channel infill above an erosional unconformity. The uppermost formation within the valley is U9 (Figure 2-9), a sequence of medium to fine sand that fines upwards to interbedded sandy silt with some clay and organic soil. Substantial deposits of fill are also noted near surface in some boreholes and are incorporated into this unit, owing to past use of the valley as municipal waste sites. A summary of the CV valley litho-stratigraphy is presented in Table 2-4.

Cross section D-D’ (Figure 2-10) trends roughly N-S across much of western Georgetown and highlights three distinctive regions (Middle Sixteen Mile Creek [MSMC], Cedarvle [CV], and Princess Anne) based on differences in depositional character and divisions between existing municipal well fields (municipal wells, Figure 2-5). The CV sediments truncate the older MSMC stratigraphy across a well-defined erosional unconformity and were deposited in a sediment-hosted valley that separates the MSMC buried valley and the Princess Anne well field.

Unit	MSMC Lithostratigraphy
U6C	Interbedded clay-rich diamict with some silt, sand and organic soil at surface
U6B	Coarse, poorly sorted sand and gravel
U6A	Clay-rich diamict
U5	Deltaic and glaciolacustrine inter-stratified fine sand, silt and laminated clay fining-upwards
U4	Glaciofluvial outwash coarse sands and gravel
U3C	Massive to crudely stratified sandy subglacial till; very dense
U3B	Glaciofluvial/glaciolacustrine sand and silt interbed(s) up to 3m thick
U3A	Massive to crudely stratified sandy subglacial till; very dense
U2	Stratified fining-upwards sequence of fluvial sand, some silt and laminated silty clays occupying bedrock lows including MSMC bedrock valley
U1	Weathered bedrock & clast-supported diamict with abundant shale clasts and poorly-sorted sandy-clay matrix
Bedrock	Ordovician Queenston shale (red)

Table 2-3: Middle Sixteen Mile Creek Lithostratigraphy

Unit	CV Lithostratigraphy
U9	Medium to fine sand fining upwards – modern CV valley infill
U8	Coarse gravel and sand – modern CV valley infill
U7	Glaciofluvial gravel and sand outwash – upper margin of CV valley
U1	Weathered bedrock & clast-supported diamict with abundant shale clasts and poorly-sorted sandy-clay matrix
Bedrock	Ordovician Queenston shale (red)

Table 2-4: Cedarvale Lithostratigraphy

Figure 2-9: Cross Section C-C’ trending W-E across the CV valley infill from Black Creek to its confluence with Silver Creek.

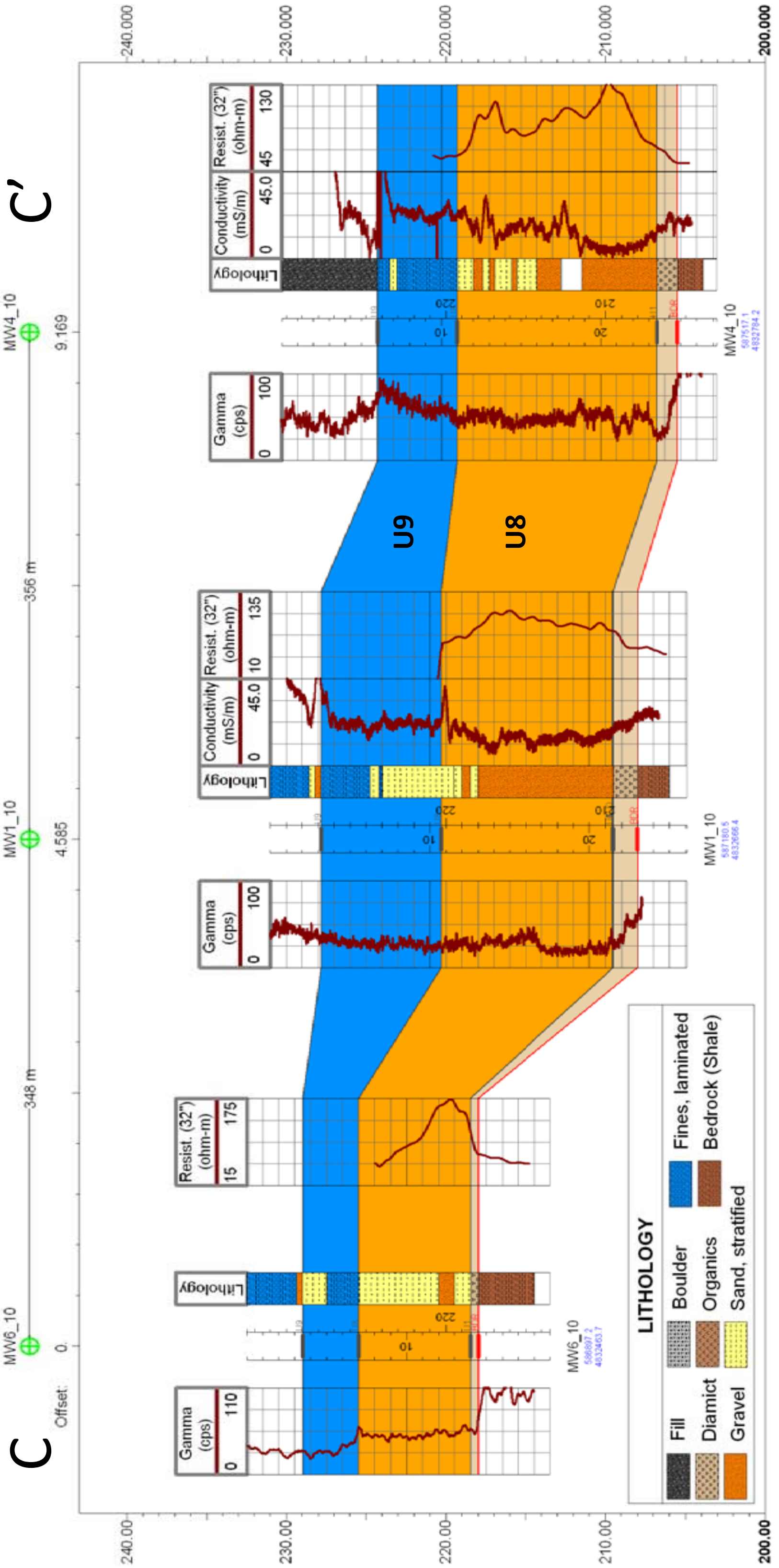
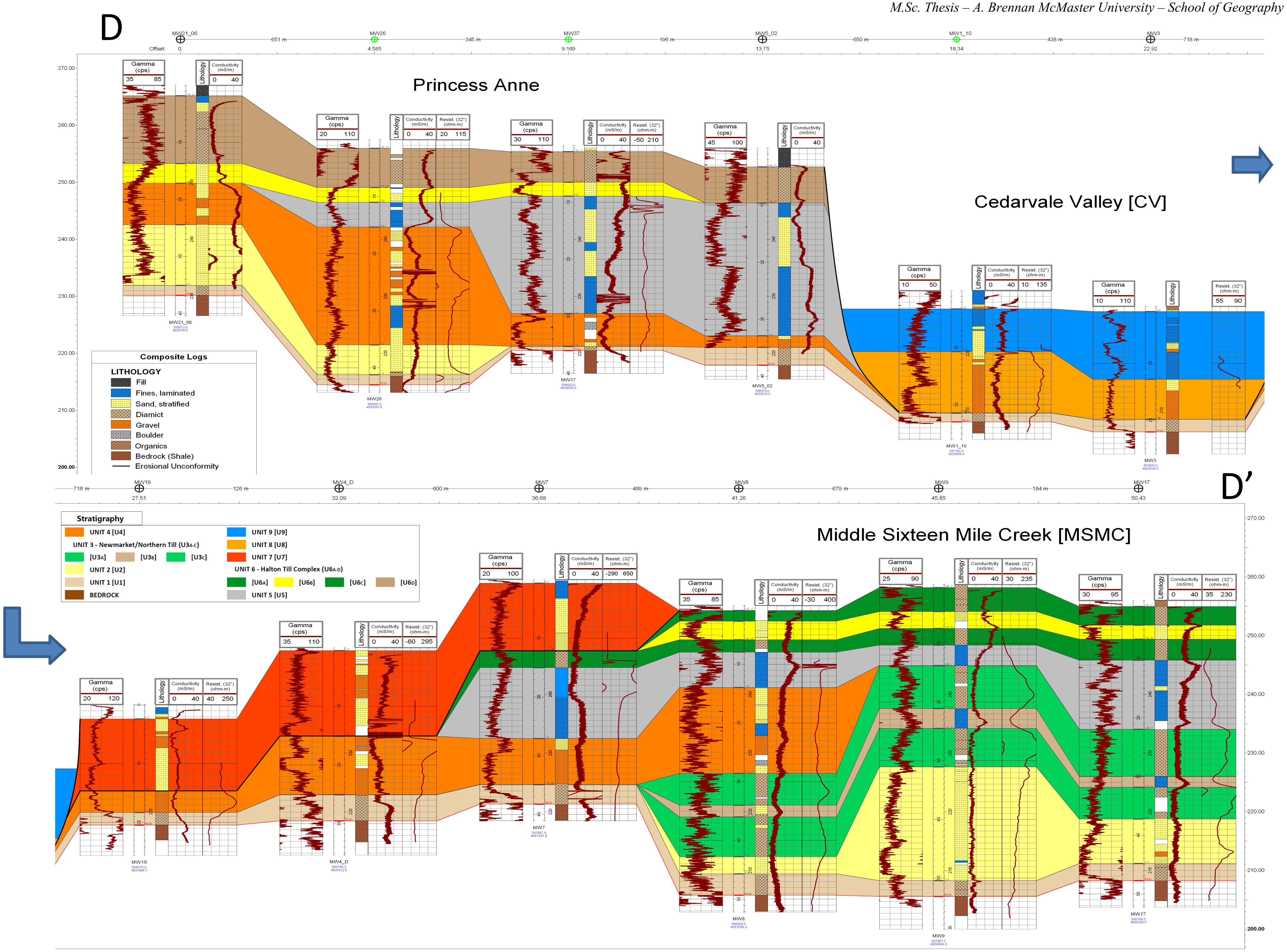

C
C′
Offset: 0.
MW6_10
348 m
MW1_10
4.585
356 m
MW4_10
9.169
240.000
230.000
220.000
210.000
200.000
240.00
230.00
220.00
210.00
200.00
Gamma (cps)
0
110
100
Lithology
Resist. (32") (ohm-m)
15
175
10
135
45
130
Conductivity (mS/m)
0
45.0
10
20
U9
U8
LITHOLOGY
Fill
Diamict
Gravel
Boulder
Organics
Sand, stratified
Fines, laminated
Bedrock (Shale)

Figure 2-10: Cross section D-D' trending roughly N-S across western Georgetown (MW 21-26-37-5-1-3-19-4-7-8-9-17). Illustrates correlated gamma, resistivity, conductivity and core lithologies for all 9 major litho-stratigraphic units (U1-9) resting over Ordovician Queenston shale bedrock.


D
D’
Princess Anne
Cedarvale Valley [CV]
Middle Sixteen Mile Creek [MSMC]
MW21_06
MW26
MW37
MW5_02
MW1_10
MW3
MW19
MW4_D
MW7
MW8
MW9
MW17
Gamma (cps)
Lithology
Conductivity (mS/m)
Resist. (32") (ohm-m)
Composite Logs
LITHOLOGY
Fill
Fines, laminated
Sand, stratified
Diamict
Gravel
Boulder
Organics
Bedrock (Shale)
Erosional Unconformity
Stratigraphy
UNIT 4 [U4]
UNIT 3 - Newmarket/Northern Till {U3A-C}
[U3A]
[U3B]
[U3C]
UNIT 2 [U2]
UNIT 1 [U1]
BEDROCK
UNIT 9 [U9]
UNIT 8 [U8]
UNIT 7 [U7]
UNIT 6 - Halton Till Complex {U6A-D}
[U6A]
[U6B]
[U6C]
[U6D]
UNIT 5 [U5]
270.00
260.00
250.00
240.00
230.00
220.00
210.00
200.00
651 m
345 m
196 m
650 m
438 m
718 m
126 m
600 m
489 m
679 m
184 m

2.4.3 Electrofacies – MSMC Valley

Beneath Georgetown, the Queenston shale possesses a distinctive log signature that can be readily distinguished in composite plots by a sharp increase in gamma counts (>120-100 cps), overall low resistivity/high conductivity values and high velocity (>2000 m/s) at the base of the boreholes (Figures 2-7 & 2-8). Above this, weathered bedrock and clast-supported diamict with abundant shale clasts (U1, Figure 2-7) is characterized by decreasing upwards high gamma counts (>100-90 cps), upwards decreasing velocity and low resistivity (EU1, Table 2-5). In composite plots, the log pattern of EU1 appears as a transition from the high gamma and velocity values of consolidated shale bedrock to much lower gamma and velocity values of overlying unconsolidated sediments. Estimating depth to bedrock strictly from geophysical logs presented some challenges when compared to core, due principally to variations in depth of bedrock weathering, clast size and matrix content of this basal diamict.

Within the MSMC buried bedrock valley, U2 sands are identified by an upwards increase in resistivity, low gamma and variable caliper (EU2, Table 2-5). Above U2, the overconsolidated diamict of U3 stands out in MSMC (Figures 2-7 & 2-8) for its ‘dual-peak’ resistivity pattern and high velocities. Where subdivisions in U3 are present, U3A can be distinguished by high velocity (>2000m/s), moderate gamma increasing upwards and higher resistivity at the base of the unit (EU3, Table 2-5). U3B can be characterized by lower gamma, velocity and resistivity values than in subunit U3A and U3C (EU4, Table 2-5), and U3C can be identified by high resistivity decreasing towards the top of the unit, increased velocity (>2000m/s) and moderate-high gamma values (Figures 2-7 & 2-8; EU5, Table 2-5).

Above U3, coarse sands and gravel (U4) are characterized by low, variable gamma counts, sharp resistivity spikes and increased magnetic susceptibility values (EU6, Table 2-4). Deflections in the caliper log indicate coarse sand and gravel zones while velocity spikes indicate coarse gravels (Pullan et al., 2002). Fining upwards from U4, U5 is characterized by an upwards increase in gamma & conductivity values indicating normal grading (Figure 2-10; EU7, Table 2-5).

At surface in the MSMC area are U6 diamict, sand and gravel subunits (U6A-C) that can be separated based on their electrofacies (Figure 2-7). U6A is clay-rich diamict characterized by decreasing upwards high gamma, smooth caliper, variable conductivity and increased velocity (EU8, Table 2-5). U6B is a coarse, poorly sorted sand and gravel layer, differentiated by a distinctively sharp drop in gamma counts, variable conductivity and significantly increased variability in caliper response (EU9, Table 2-5). U6C is a clay-rich diamict observed in the MSMC area identified by increasing upwards high conductivity, high gamma (90-120cps) and increased magnetic susceptibility (EU10, Table 2-5).

Possessing a nearly identical geophysical signature to U6C, U6D is a red clay-rich diamict with silt clasts and rounded gravel found only in the Princess Anne area (Figure 2-10). Consequently, U6D is assigned to the same electrofacies unit (EU10, Table 2-5).

Electro-facies Unit (EU)	Litho-strat Unit	Interpreted Lithology	Characteristic Log Responses	# Boreholes (Modeled) Encountering EU
Bedrock		Queenston shale	high gamma (>100 cps); low resistivity; high velocity (>2000m/s)	29
(EU 1)	U1	clast-supported diamict	decreasing upwards velocity & high gamma (>90 cps); low resistivity	29
(EU 2)	U2	fining-upwards sequence of stratified sand	upwards increase in resistivity; low gamma; variable calliper	16
(EU 3)	U3A	massive to crudely stratified diamict with sand/silt interbed	variable gamma; distinctive dual peak and trough pattern in the resistivity & high velocity (>2000m/s) separates interebeds	14*
(EU 4)	U3B			10
(EU 5)	U3C			10*
(EU 6)	U4	gravel & coarse sand	low, highly variable gamma & caliper; resistivity spikes; increased mag. susc.; low velocity	17
(EU 7)	U5	stratified deposits - mostly silt, some sand	Upwards increase in gamma & conductivity,	20
(EU 8)	U6A	clay-rich diamict	high gamma, smooth caliper, variable conductivity and increased velocity	14*
(EU 9)	U6B	poorly-sorted sand and gravel	sharp drop in gamma and increased caliper; moderate conductivity	15
(EU 10)	U6C	clay-rich diamict	high conductivity & high gamma (90-120cps); increased mag. susc.	12*
	U6D	red, clay-rich diamict with silt clasts and round gravels		4

* where interbeds pinch out, upper/lower diamict sub-units are considered lower sub-unit during modeling

Table 2-5: MSMC electrofacies with associated lithostratigraphic interpretations, characteristic log responses and the number of boreholes encountering each unit.

2.4.4 Electrofacies– Cedarvale Valley

U7 outwash sands and gravels are identified above U6 along the CV valley margins and are identified by large variations in caliper, moderate conductivity increasing upwards and low gamma counts (EU11, Table 2-6). Within the modern CV valley U8 is characterized by decreasing upwards variation in caliper, low conductivity increasing upwards, increased resistivity and low gamma counts (EU12, Table 2-6) that fines upwards into U9 defined by high conductivity and high gamma increasing upwards, indicating normal grading (EU13, Table 2-6).

2.4.5 Subsurface model

Correlation of electrofacies and lithostratigraphy across the study area allows bedrock valleys, primary aquifer and regional aquitards to be identified and their geometries defined through subsurface modeling and generation of a three dimensional fence diagram. Contour and isochore mapping permit a more detailed analysis of individual surfaces along the highly complex intersection of the CV and MSMC bedrock valleys and confluence of the modern Black and Silver Creeks.

Two views of the fence diagram are provided in Figure 2-11 and highlight the CV incision between the Princess Anne well field to the northwest and MSMC buried valley further south. The undulating bedrock surface and discontinuous MSMC valley is also prominently displayed. The sands of U2 are thickest along the MSMC buried valley thawleg and pinch out along the bedrock valley margins. U3 is observed exclusively in the MSMC area where it thickest above the MSMC thawleg and thins towards the valley margins. At the southern extent of the study area along a bedrock high separating the

Electro-facies Unit (EU)	Litho-strat Unit	Interpreted Lithology	Characteristic Log Responses	# Boreholes (Modeled) Encountering EU
(EU 11)	U7	coarse sand & gravel	Variable caliper, moderate conductivity increasing upwards; low gamma	4
(EU 12)	U8	fining-upwards gravel & sand channel fill	decreasing upwards variable caliper, low conductivity increasing upwards, increased resistivity; low gamma	5
(EU 13)	U9	fining-upwards silty sand to sandy silt	high conductivity; high gamma increasing upwards	5

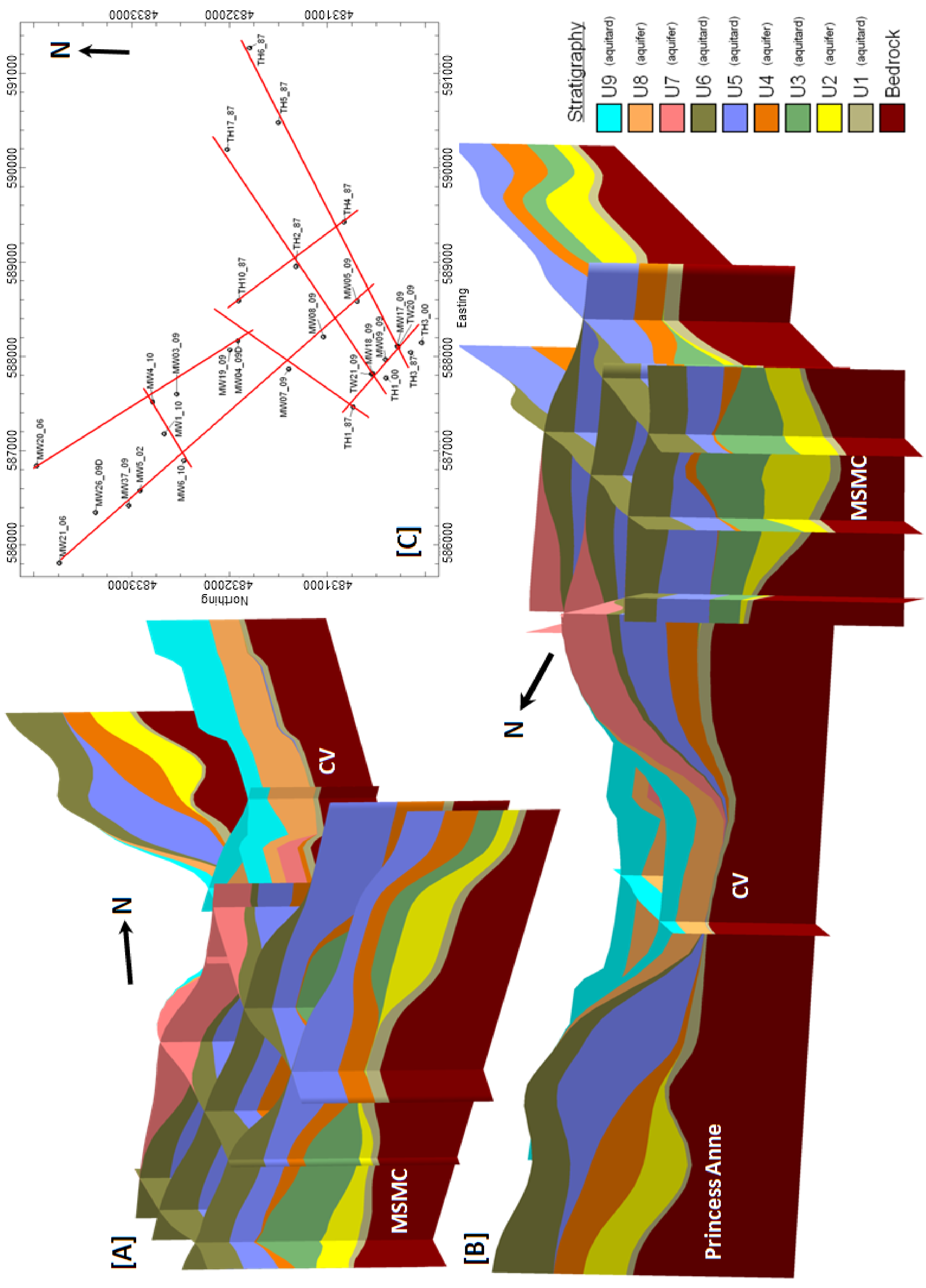
Table 2-6: Cedarvale Electrofacies

Figure 2-11: Three dimensional fence diagram showing complex litho-stratigraphy of MSMC and Cedarvale buried valleys. Aquifers include U2, U4, U7, U8; aquitards include U1, U3, U5, U6 and U9.

[A] Fence diagram highlighting discontinuous basal aquifer (U2) infilling bedrock lows in MSMC and relative geometries of overlying units.

[B] Fence diagram highlighting subsurface geometries and relationship of CV incision between Princess Anne well field to the northwest and MSMC further south.

[C] Inset map showing location of modeled fence lines and borehole locations near Georgetown.


[A]
[B]
[C]
N
N
N
MSMC
CV
CV
MSMC
Princess Anne
Stratigraphy
U9 (aquitard)
U8 (aquifer)
U7 (aquifer)
U6 (aquitard)
U5 (aquitard)
U4 (aquifer)
U3 (aquitard)
U2 (aquifer)
U1 (aquitard)
Bedrock
Easting
Northing
586000
587000
588000
589000
590000
591000
4831000
4832000
4833000
MW20_06
MW21_06
MW26_09D
MW37_09
MW5_02
MW4_10
MW1_10
MW6_10
MW03_09
MW19_09
MW04_09D
MW07_09
MW08_09
MW05_09
MW18_09
MW09_09
MW17_09
TW20_09
TW21_09
TH1_87
TH1_00
TH3_87
TH3_00
TH10_87
TH2_87
TH4_87
TH17_87
TH5_87
TH6_87

MSMC bedrock valley and bedrock lows dipping further to the east, both U2 and U3 are absent (Figure 2-11A). U4 gravels are thickest in Princess Anne and to the west of the MSMC buried valley, but are sporadically present above MSMC. Fining upward sequences of U5 sand silt and clay are extensive across most of the study area, except where removed by the CV incision, and are interpreted as the surface formation east of the MSMC buried valley. Above both Princess Anne and the MSMC valley, U6 is the extensive surface formation. U7 is limited to the upper reaches of the CV valley and dips towards the modern valley where U8 and U9 are observed to infill the modern CV valley occupied by Black and Silver Creeks.

Within the contour mapping area (Figure 2-1) geophysical data density is highest, which is particularly important for accurately modeling layer pinchouts and incised formations and improves confidence in the modeled unit geometries. Upper and lower contoured surfaces were gridded for each lithostratigraphic unit and differenced to produce sediment thickness maps that identify the older MSMC lithostratigraphy being truncated by the younger CV stratigraphy (Figures 2-12 – 2-14).

Surface relief and isochore maps of the MSMC lithostratigraphy reveal that U2 is up to 20m thick where it infills the MSMC bedrock valley and pinches out towards the CV valley. Along the bedrock high noted in the fence diagram, U2 thins but remains connected to the U2 sands noted further to the east (Map F, Figure 2-12). U3 deposits up to 17m thick blanket the MSMC valley, pinching out along the valley margins (Map G, Figure 2-12) and fully burying the MSMC valley (Map D, Figure 2-12). Where present in the MSMC area, U4 occupies lows in the upper surface of the underlying diamict and is notably absent in U3 topographic highs (Map L, Figure 2-13). U5 is regionally extensive and continues to infill topographic lows in the underlying sediments. In

MSMC, U5 is thinnest over the thickest portion of U3 (Map M, Figure 2-13) and possesses a flat upper surface between 240 and 245m (Map J, Figure 2-13), suggesting low energy glaciolacustrine deposition. At surface in MSMC and Princess Anne, U6 is >13m thick and thins towards the east.

Preserved along the upper banks of the modern river valley, glaciofluvial outwash of U7 occurs as a localized unit >12m thick that truncates U6 and dips towards the CV valley (Map S, Figure 2-14). Confined within the modern CV valley, U8 is the basal channel fill aquifer currently supporting the productive Cedarvale municipal well field in Georgetown. U8 is up to 16m thick (Map T, Figure 2-14) with the thickest portions of this unit found at the confluence of Black and Silver Creeks. Above U8, U9 deposits up to 18m thick occur at surface within the CV valley and are thickest upstream along Silver Creek (Map U, Figure 2-14).

Figure 2-12: Contour surface maps (A-D) and isochore maps (E-G) developed from grid subtraction showing Middle Sixteen Mile Creek lithostratigraphic units (U1-U3) within contour mapping area (Figure 2-1).

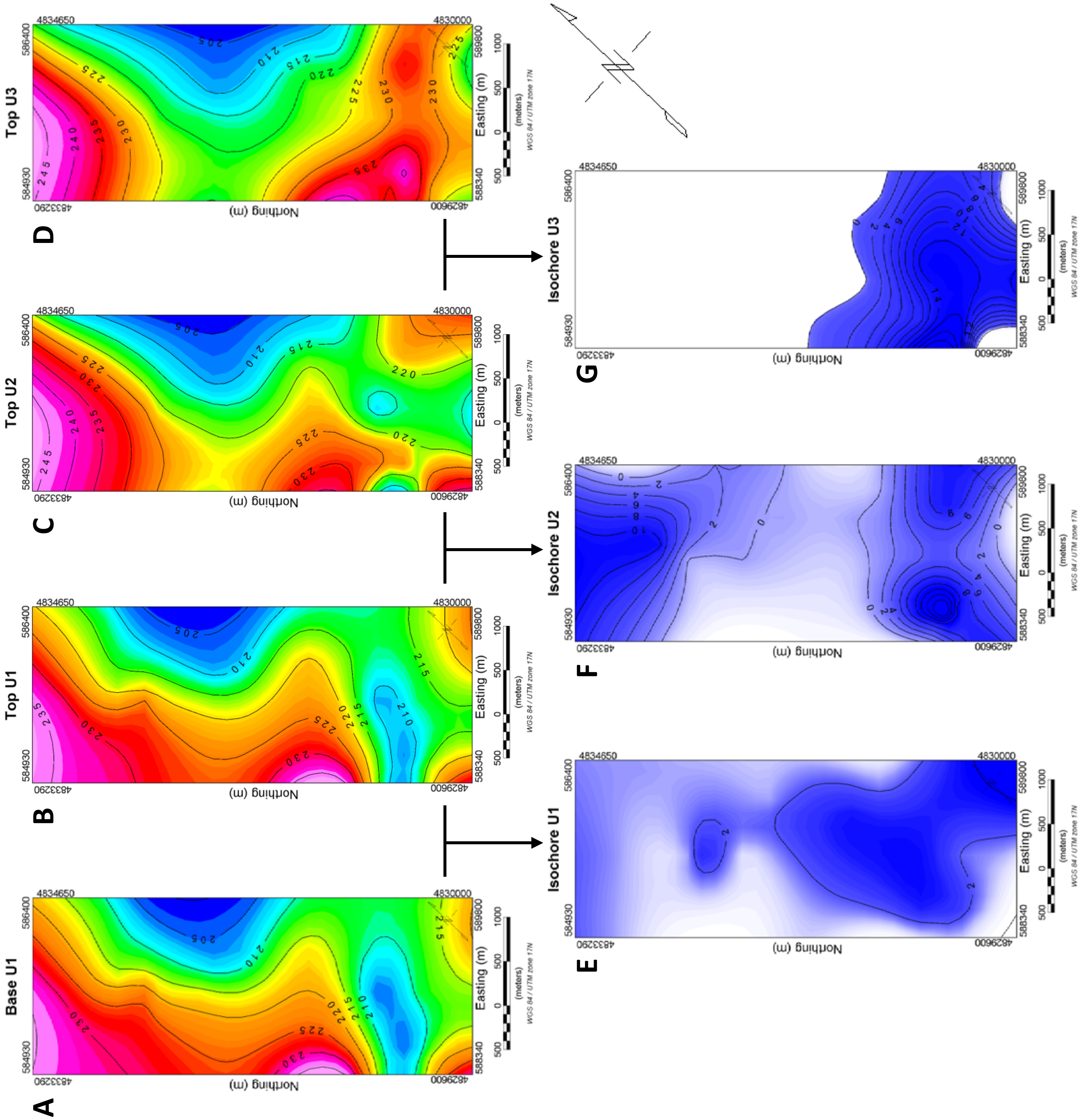

A
Base U1
B
Top U1
C
Top U2
D
Top U3
E
Isochore U1
F
Isochore U2
G
Isochore U3
Northing (m)
Easting (m)
4833290
4829600
4834650
4830000
584930
586400
588340
589800
500
0
500
1000
(meters)
WGS 84 / UTM zone 17N
205
210
215
220
225
230
235
240
245
0
2
4
6
8
10
12
14

Figure 2-13: Contour surface maps (H-K) and isochore maps (L-N) developed from grid subtraction showing Middle Sixteen Mile Creek lithostratigraphic units (U4-U6) within contour mapping area (Figure 2-1).

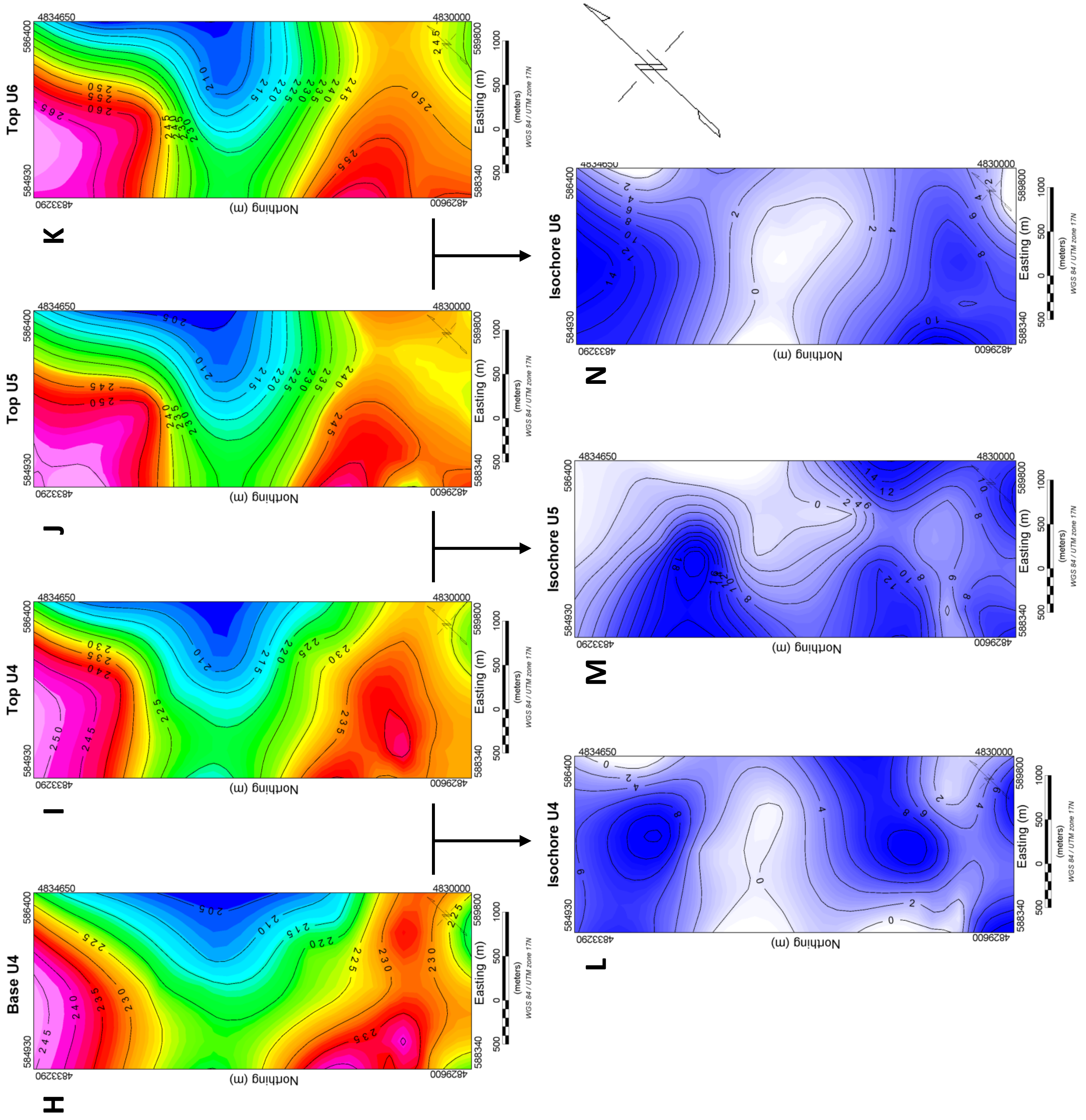
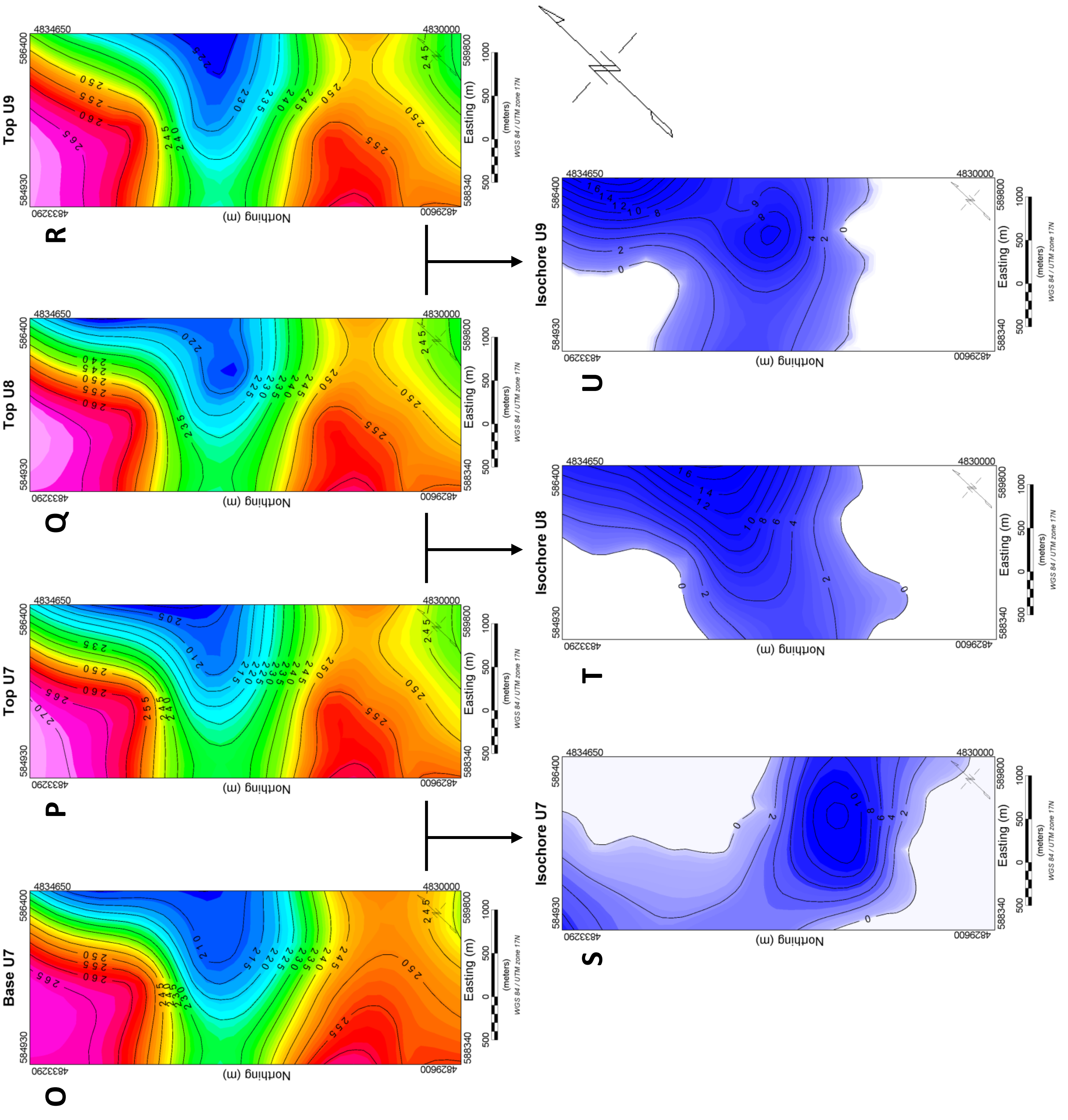

H
Base U4
I
Top U4
J
Top U5
K
Top U6
L
Isochore U4
M
Isochore U5
N
Isochore U6
Northing (m)
Easting (m)
(meters)
WGS 84 / UTM zone 17N
4834650
4830000
4833290
4829600
584930
586400
588340
589800
500
0
500
1000

Figure 2-14: Contour surface maps (O-R) and isochore maps (S-U) developed from grid subtraction showing Cedarvale (CV) lithostratigraphic units (U7-U9) within contour mapping area (Figure 2-1). Deposition within the CV valley is characterized as channel infill with the modern sediment-hosted valley that occurs above an erosional unconformity (interpreted post-Halton deposition).


O
Base U7
P
Top U7
Q
Top U8
R
Top U9
S
Isochore U7
T
Isochore U8
U
Isochore U9
Northing (m)
Easting (m)
4834650
4830000
4833290
4829600
584930
586400
588340
589800
500
0
500
1000
(meters)
WGS 84 / UTM zone 17N

2.5 Discussion

2.5.1 Hydro-stratigraphy of Georgetown area

To further groundwater modeling in the Georgetown area, the lithostratigraphic units have been assigned to hydrostratigraphic units (aquifers and aquitards) based on their lithologic characteristics and physical properties (lithology, clay content, level of compaction) (Table 2-7). Borehole geophysical data is ideally suited to this task as physical parameters respond to changes in properties of the subsurface material including grain size and the electrical response of sediments and porewater that are important indicators of aquifer and aquitard status. Commonly, hydrogeological investigations use electrical or electromagnetic techniques to delineate major hydrostratigraphic units with the assumption that aquifers are more resistive units while aquitards are more conductive (Pullan et al., 2001). In contrast to this assumption, Pullan et al. (2001) observed the Newmarket Till owes its role as an aquitard to its compaction instead of its clay content. Consistent with this description, the middle till identified in the MSMC area is sand-rich and over-consolidated, as noted by its increased velocity, ‘dual-peak’ resistivity, and moderate gamma counts. This reaffirms the use of natural gamma and conductivity/resistivity logs as standard ‘hydrostratigraphic logs’ and suggests that velocity data also be collected in investigations of previously glaciated terrains where other over-consolidated sediments may act as aquitards.

The hydrostratigraphic framework of the Georgetown area is a result of the complex interaction of buried bedrock valleys, modern valley incisions, the hydraulic confinements of the Niagara Escarpment and thick multi-phase sediment packages deposited and reworked by the interactions of advancing and retreating ice. Correlatable electrofacies of coarse, fine grained and over-consolidated units are used to infer unit continuity and model the geometry of aquifers and aquitards in the study area. The hydrostratigraphic units described here and summarized in Table 2-7 are discontinuous throughout the study area, but their geometries are instructive and can be used to guide further groundwater investigations that refine the unit configurations.

Underlying Georgetown, the Queenston shale formation is considered a poor aquifer due largely to its fine-grained nature (Davies and Holysh, 2007), but the upper weathered 3-5m may function as an adequate aquifer for domestic water supply (Singer et al., 1994; Davies and Holysh, 2007; Meyer and Eyles, 2007). The weathered bedrock component of the thin but extensive clast-rich U1 diamict may function in a similar capacity, but the variability in fine grained sediment content of this diamict make it a poor aquifer for municipal use. Confined to buried bedrock valleys and bedrock lows (Figure 2-11), U2 is a discontinuous permeable sandy aquifer that supports municipal groundwater extraction in the Princess Anne area, however its limited and discontinuous extent may reduce its potential as a municipal aquifer in the MSMC area.

Overlying the U2 aquifer in the MSMC area, the interbedded and overconsolidated sandy diamict of U3 is thickest over the MSMC bedrock valley and thins towards the bedrock valley margins, suggesting it may act as a suitable confining layer for the underlying aquifer. Troughs in the resistivity and velocity signatures, however, allow correlation of silty to sandy interbeds within the till (U3B) and are interpreted as potential hydraulic windows, suggesting the till functions as a leaky aquitard (Boyce and Eyles, 2000; Gerber et al., 2001).

Infilling lows in the upper surface of U3 and directly overlying sands of U2 in the Princess Anne area (Figure 2-11), the coarse grained glaciofluvial outwash of U4 may be suitable as a communal aquifer, but interbedded finer grained material and its limited extent may reduce its municipal aquifer potential. The deltaic and glaciolacustrine sediments of U5 extend across the study area and exhibit significant lateral variability. In the Princess Anne area multiple fining upward sequences within U5 suggest limited potential for private aquifers may exist within this unit, however the predominance of fine-grained sediments suggest U5 functions principally as a poor regional aquitard.

The hydrostratigraphic unit at surface across most of the study area is U6, interpreted as the regionally extensive Halton Till Complex, an interbedded regional diamict known to show considerable textural variability (Meyer and Eyles, 2007). The sandy sub-unit (U6B) acts much like the U3B interbed hydraulic window, limiting the confining abilities of U6 to that of a leaky aquitard (Boyce and Eyles, 2000; Gerber et al., 2001). Also at surface along the upper reach of the modern river valley near the confluence of Black and Silver Creek is U7, a permeable outwash unit that permits direct communication with the underlying U4 aquifer and may also connect to the U2 aquifer along the MSMC buried valley margin. In this area U3 thins and may have been truncated by U4, allowing additional hydraulic connections between discontinuous aquifers. Although only observed in 3 boreholes in this study, the strong similarities of this unit with surface geology maps (Figure 2-5) suggests the unit exists along a larger reach of the river valley. Within the modern Black and Silver Creek valleys lies U8, coarse channel fill currently supporting the municipal Cedarvale well field. Above U8,

Unit	Interpreted Geology / Equivalent Formation	Hydrostratigraphy
U1	Weathered bedrock & clast-rich diamict	Poor aquifer to aquitard
U2	Stratified sands in bedrock lows	Good aquifer (Princess Anne well field)
U3	Interbedded sandy diamict / Newmarket Till	Leaky aquitard
U4	Glaciofluvial outwash / Mackinaw Interstadial	Good aquifer
U5	Deltaic and glaciolacustrine deposits / Mackinaw Interstadial	Poor aquitard
U6	Clay-rich diamict with coarse sand interbeds / Halton Till Complex	Leaky aquitard
U7	Glaciofluvial outwash / Halton outwash	Aquifer
U8	Coarse grained modern valley infill / possible paleo Credit River	Municipal aquifer (Cedarvale well field)
U9	Fine grained valley infill & recent deposits	Poor aquitard

Table 2-7: Georgetown Hydrostratigraphy

fine grained sediments of U9 act as a confining layer providing moderate protection to the underlying aquifer.

To protect groundwater resources in urban areas such as Georgetown that are built on and around bedrock valleys, it is important to understand the geometry, continuity and character of aquifers and aquitards within the valleys and in surrounding formations, particularly those at and near surface. Coarse grained interbeds of U6 and the high permeability of U7 make shallow aquifers highly susceptible to surface contamination including road salts, pesticides and agricultural runoff (Meyer and Eyles, 2007).

2.5.2 Depositional history and regional stratigraphic correlations

The stratigraphic framework of the Credit River watershed east of the Niagara Escarpment is well established from previous work (Karrow, 1987; 2005; Davies and Holysh, 2007) with a strong focus in these studies on the regionally extensive Newmarket and Halton Till sheets that blanketed much of the area. South of the study area between Milton and Georgetown, Meyer and Eyles (2007) used detailed facies analysis to evaluate more than 500m of continuous core and identified tentative correlations with known surficial deposits from the sediment characteristics and stratigraphic relationships observed in core. A compariosn of the nine unit lithostratigraphic framework (Table 2-3 & 2-4) presented in this study with the six unit stratigraphy (SU-I – SU-VI) of Meyer and Eyles (2007) identifies direct correlations and unit similarities between the two studies (Figure 2-15). The youngest deposits identified in this study (U7-9) occur along and within modern valleys and have no direct comparison to facies identified by Meyer and Eyles (2007).

Across much of the study area, weathered bedrock is incorporated in a thin, clast supported diamict (U1) that is similar to the remnant coarse grained fluvial and colluvial sediment (SU-I) observed by Meyer and Eyles (2007). U2 correlates with SU-II/SU-III of Meyer and Eyles (2007), which are collectively interpreted to record deposition in fluvial and lacustrine environments that preceded ice advance during the Nissouri Stadial (Figure 2-15).

The massive to crudely stratified sandy diamict with sand/silt interbeds (U3[A-C]) observed in the MSMC portion of the study area directly correlates with the sand rich interbedded diamicts of SU IV interpreted by Meyer and Eyles (2007) as being possibly equivalent to the Northern/Newmarket sub-glacial till deposited during the Nissouri Stadial (25-18ka) (Karrow, 1974; 2005; Boyce et al 1995; Boyce and Eyles, 2000; Pugin et al, 1999). Thin sand interbeds (sub-unit U3B; EU4 in Table 2-5) suggest localized meltwater deposition and possible incorporation/deformation of underlying sands beneath overlying ice (Meyer and Eyles, 2007; Boyce and Eyles, 2000). Reduced and fluctuating velocity values in the lower portion of U3A are interpreted as zones in which the till also incorporated more of the underlying sandy unit Although sediment dating is unable to confirm the age of formation, the sandy nature, characteristically high velocity (>2000m/s) and stratigraphic position as a middle till below the Niagara Escarpment strongly supports interpretation of U3 as a probable Newmarket/Northern Till deposit consistent with the regionally extensive till sheet observed further to the east in the GTA (Pullan et al, 2001; 2002; Boyce et al, 1995; Boyce and Eyles, 2000).

Figure 2-15: Regional stratigraphic relationships comparing interpreted sediment ages encountered in this study with those of other authors

Glacial Substage	Glacial Stadial / Interstadial	Age	THIS STUDY	Meyer & Eyles (2007)	Karrow (2005)		Boyce et al. (1995)
Holocene	Post Lake Iroquois	7 ka 11.5 ka	-	-	-		-
Late Wisconsinan	Two Creeks Interstadial	12 ka	? U7, U8, U9 ?	-	Lake Iroquois Peel Ponds		Lake Iroquois
	Port Huron Stadial	13.2 ka	U6 (A,B,C,D)	SU VI	Halton Till		Halton Till
	Mackinaw Interstadial	14 ka	U5 U4	SU V	Mackinaw Interstadial		Mackinaw Interstadial
	Port Bruce Stadial	15.5 ka	-	-	Port Stanley Till	-	-
	Erie Interstadial	18 ka			Glaciolacustrine		
	Nissouri Stadial	25 ka	U3 (A,B,C)	SU IV	Catfish Creek Till	Newmarket Till	Northern Till
Mid-Wisconsinan			? U2 ?	SU II, SU III	Thorncliffe Formation		Thorncliffe Fm.
		40 ka	? U1 ?	SU I			
		80 ka	-	-	Sunnybrook Till		

Overlying the middle till, U4 is interpreted as glaciofluvial outwash deposits equivalent to SU-V of Meyer and Eyles (2007) and based on their stratigraphic position are believed to correlate with the Mackinaw Interstadial sands and gravels identified elsewhere in southern Ontario (Karrow, 1987; Boyce et al., 1995). U5 is interpreted here as deltaic and glaciolacustrine sediments deposited in a lower energy environment either as a late, waning phase of the Mackinaw Interstadial or as deposition within an ice-damned proglacial lake formed as Ontario basin ice re-advanced towards the study area during the Port Huron stadial (Meyer and Eyles, 2007).

The upper surface across much of the study area is comprised of Unit 6, a complex package of interstratified clay-rich diamict, sand and gravel that can be divided into four distinctive subunits (U6A-D). Based on their stratigraphic position and sedimentologic characteristics, these deposits are assigned to the Halton Till complex (Karrow, 1987), which correlates with unit SU-VI of Meyer and Eyles (2007). The Halton Till complex overlies Mackinaw Interstadial gravels in outcrop across the GTA (Boyce and Eyles, 2000), and is interpreted to record the advance of the ice margin onto proglacial lake deposits, resulting in the formation of fine grained sub-glacial and glaciolacustrine diamicts (U6A, U6C) deposited during the Port Huron stadial (Barnett 1992; Meyer and Eyles, 2007). Interbedded sands within the diamict (U6B) may represent localized fluvial deposition flowing into ponded water (Meyer and Eyles, 2007). At surface in the Princess Anne area in the northwest corner of the study area, red diamict with silt clasts and rounded gravel is interpreted as sub-unit U6D, ice-marginal deposits of slumped material mixed with ice marginal glaciofluvial gravels. While geophysically similar to U6C, the unique sedimentologic properties identified in core warrant its separation as a distinctive sub-unit.

Overlying the U6 till complex above an erosional unconformity along a narrow tract of the upper reach of the modern river valley sits a localized deposit of very coarse sand and gravel (U7) interpreted as high energy glaciofluvial sediments and possible Halton outwash.

Within the modern Black and Silver creek valleys are U8 and U9, coarse channel fill consisting of gravel and coarse sand (U8) overlain by fining upwards sequence of sand to sandy silt capped by modern deposits (U9). U8 gravels are interpreted as high energy fluvial sediments deposited in the modern Cedarvale valley above an erosional unconformity (possible paleo Credit River) that fine upwards to U9, indicating deposition in a lower energy environment.

2.6 Conclusions

This study demonstrates that multi-parameter borehole geophysical logging can be used to effectively investigate complex glaciated terrains and buried valley infill. Geophysical logging of boreholes represents a strong potential to improve the usefulness of boreholes drilled for hydrogeological investigations. As demand from population pressures and source water protection efforts increase the need to better understand groundwater systems, improved knowledge of borehole geophysical applicability and electrofacies analysis are likely to become more important for hydrogeologists.

The primary objective of this study was to characterize the lithostratigraphy and hydrostratigraphy of the Middle Sixteen Mile Creek and Cedarvale buried bedrock valley infills using core lithofacies and well log (electrofacies) data to produce a detailed 3-dimensional subsurface geological model for the 20km^2 Georgetown study area. The characteristic log responses of lithostratigraphic units near Georgetown and the log parameters most useful for lithologic classification and correlation were also evaluated.

A detailed examination of borehole geophysical data has contributed substantially to the understanding of the depositional history near Georgetown, in particular the characterization and connectivity of buried bedrock valleys known to exist in the area. Analysis of geophysical data and comparisons to continuous core data has allowed the development of distinctive electrofacies that can be readily applied in geophysically logged boreholes lacking high quality core to infer the encountered lithostratigraphy.

Well-to-well correlations, individually contoured surface and isochore maps and the three-dimensional fence diagram presented in this study collectively demonstrate that the Quaternary sediments below Georgetown possess complex discontinuous geometries and are characterized by significant lateral and vertical sedimentary variability. The detailed subsurface geological model developed for this study provides a framework for future groundwater exploration and groundwater modeling in the Georgetown area and offers improved understanding of the hydrostratigraphic continuity and aquifer interconnectivity between the MSMC and CV buried valleys.

In the MSMC buried valley, 6 distinctive lithostratigraphic units were identified within a thick (> 55 m) interbedded sequence of diamict (aquitards), laminated silts and coarse-grained glaciofluvial deposits (aquifers) overlying shale bedrock. The lithologies encountered downhole were generally predictable and electrofacies more distinctive (eg velocity and ‘dual-peak’ resistivity of Newmarket Till) than the Cedarvale or Princess Anne areas, owing to differences in their depositional history. The depositional history of the MSMC buried valley infill is consistent with the regional stratigraphy noted both locally (Meyer & Eyles, 2007) and regionally (Davies & Holysh 2007; Karrow, 2005) and has been heavily influenced by the regionally extensive Newmarket and Halton till sheets, both of which are found in the MSMC area. The MSMC buried valley hosts up to 20m thick deposits of sands (possible Thorncliffe Formation equivalent) capped by the Newmarket Till and may be suitable for additional groundwater extraction.

In contrast, the Cedarvale valley, which hosts the Cedarvale well field currently suppling water to Georgetown is composed of a complex succession of younger glaciofluvial gravel, sand and silt up to 45m thick that truncate the older MSMC stratigraphy across a well-defined erosional unconformity and were deposited in a sediment-hosted valley. Opposite the MSMC buried valley, the Princess Anne municipal well field is located in the northwestern corner of the study area where the lowermost diamict unit (Newmarket Till) was thinned or erosionally truncated, allowing direct communication of the upper and lower aquifers. The Princess Anne wells have been tentatively related to the MSMC stratigraphy in this study, but more work is needed to confirm the relationship between the two areas.

Natural gamma, resistivity and conductivity logs were generally observed to be the most important geophysical parameters for hydrostratigraphic characterizations in this study, while downhole changes in p-wave velocity and resistivity were also important for discriminating and correlating more compact diamict units. Generally accepted hydro-geophysical assumptions that aquitards are more conductive while aquifers are more resistive were insufficient to characterize the hydrostratigraphy of Georgetown. The regionally extensive subglacial Newmarket Till and its Nissouri stadial equivalents (eg Catfish Creek Till; Bajc & Shirota, 2007) associated with the last major ice advance are characteristically sandy (when overriding coarse grained lower deposits) yet act predominately as aquitards due to their high compaction (Karrow, 2005; Pullan et al.,

2001) and are best characterized by increased velocity (Pullan et al., 2002). Consequently, the optimal suite of geophysical parameters to fully characterize the hydrostratigraphy of an area should include p-wave velocity with gamma and electrical logging methods.

CHAPTER 3: Principal Component Analysis (PCA) of Multi-parameter Geophysical Logs: Applications for Lithologic Discrimination of Buried Valley Hydrostratigraphy, Georgetown, Ontario

Abstract

Borehole geophysical data are employed increasingly in hydrogeological investigations to characterize subsurface lithology and sediment physical properties. Multi-parameter log suites are now collected routinely as part of these studies but interpretation and correlation of the log parameters can be difficult when multiple log parameters must be analyzed. Analysis of multi-parameter log suites using principal component analysis (PCA) provides an alternative objective, quantitative approach to log classification that combines correlated portions of log responses to better understand the remaining data variation. The eigenvectors calculated in the PCA correlation matrix identifies the relative loadings contributed by each of the physical parameters, permitting interpretation of the geologic factors influencing each principal component. Subsequent plotting of PCA score logs effectively highlights the lithologies uniquely defined by geophysical parameters.

The purpose of this study is to evaluate the use of PCA for objective classification of subsurface lithology from multi-parameter geophysical log suites. The method is applied to a multi-log dataset (natural gamma, EM conductivity, resistivity, magnetic susceptibility, full-waveform sonic, caliper) acquired in the Middle Sixteen Mile Creek (MSMC) buried valley collected as part of a regional investigation of the geology and hydrostratigraphy of Quaternary sediments near Georgetown, Ontario. Cross plots of the first and second principal components were successful in objectively discriminating silts and clays/shales from sand/gravel and diamict lithofacies in most boreholes and support the development of a hydrostratigraphic framework for the study area. Analysis of the correlation matrix and factor loadings (eigenvectors) generated in the PCA process for each borehole allows the dominant physical properties of principal component score logs to be inferred.

Keywords: Borehole geophysics, principal component analysis, lithologic classification

3.1 Introduction

As groundwater demands and source water protection efforts expand across southern Ontario, there is a growing need to better understand the subsurface geology of thick Pleistocene deposits that are host to regional aquifer and aquitard systems (Davies and Holysh, 2007; Sharpe et al., 2002; Pullan et al., 2002; Meyer and Eyles, 2007). Multi-parameter geophysical suites are increasingly employed in these studies to complement the standard ‘hydrostratigraphic’ logs (e.g. neutron, gamma, electric logs). Multi-parameter geophysical logging can provide additional insights into the subsurface physical properties but multi-log suites can be difficult to analyze and interpret. Many physical parameters exhibit a characteristic response to changes in lithology and other formation properties (e.g. water content, density) and this is the basis on which geophysical boundaries are identified. Conventionally, characteristic log responses or ‘electrofacies’ are identified by qualitative visual analysis and cross-plotting of log parameters. The electrofacies are then compared and with core lithofacies data to identify a characteristic set of log responses that can be used to predict the vertical sequence of lithofacies in uncored boreholes. This is a subjective process and is highly dependent on the log analyst’s interpretive skills and ability to discern the dependencies between physical properties and core lithofacies.

In addition to visual analysis of electrofacies, cross plots of two or more geophysical parameters can be used to classify a particular lithology based on the uniqueness of its geophysical parameters. On a cross plot, lithologies with distinctive electrofacies are represented by discrete clusters of points. The degree to which the points cluster in conjunction with the extent of separation between the individual clusters defines the uniqueness of the lithology. While this technique can be effective for homogenous sediment types with distinctly separate electrofacies, it has less utility for heterogeneous sediments with variable log responses. When cross plots show weak clustering, data clouds overlap, preventing the classification of sediments from the raw data. Collins (2004) also notes that multi-log datasets with a large number of physical parameters require the creation of a series of cross plots to understand relationships between the variables. This process is slow, and its limited applicability highlights the need for a better way to study the interrelationships of the data.

Keys (1997) notes the importance of understanding of the subsurface lithologic variability prior to collection of borehole geophysical data, as this information can be used to select which log parameters would be most effective. Typically, the greater the number of geophysical logs used, the better the textural, mineralogical and lithological characteristics will be defined and the less ambiguity and error there will be the final interpretation. Logs are interpreted as a combination of all the parameter values rather than individually to increase the accuracy of analysis because geophysical logs do not have unique responses (Keys, 1997). Groupings of characteristic log responses identified by visual analysis and core comparisons in Chapter 2 were distinctive and allowed recognition of 9 major lithostratigraphic units that were correlated across Georgetown. Gamma, resistivity, conductivity and magnetic susceptibility logs were most useful for lithologic typing while downhole changes in p-wave velocity and resistivity were important for discriminating and correlating more compact diamict units.

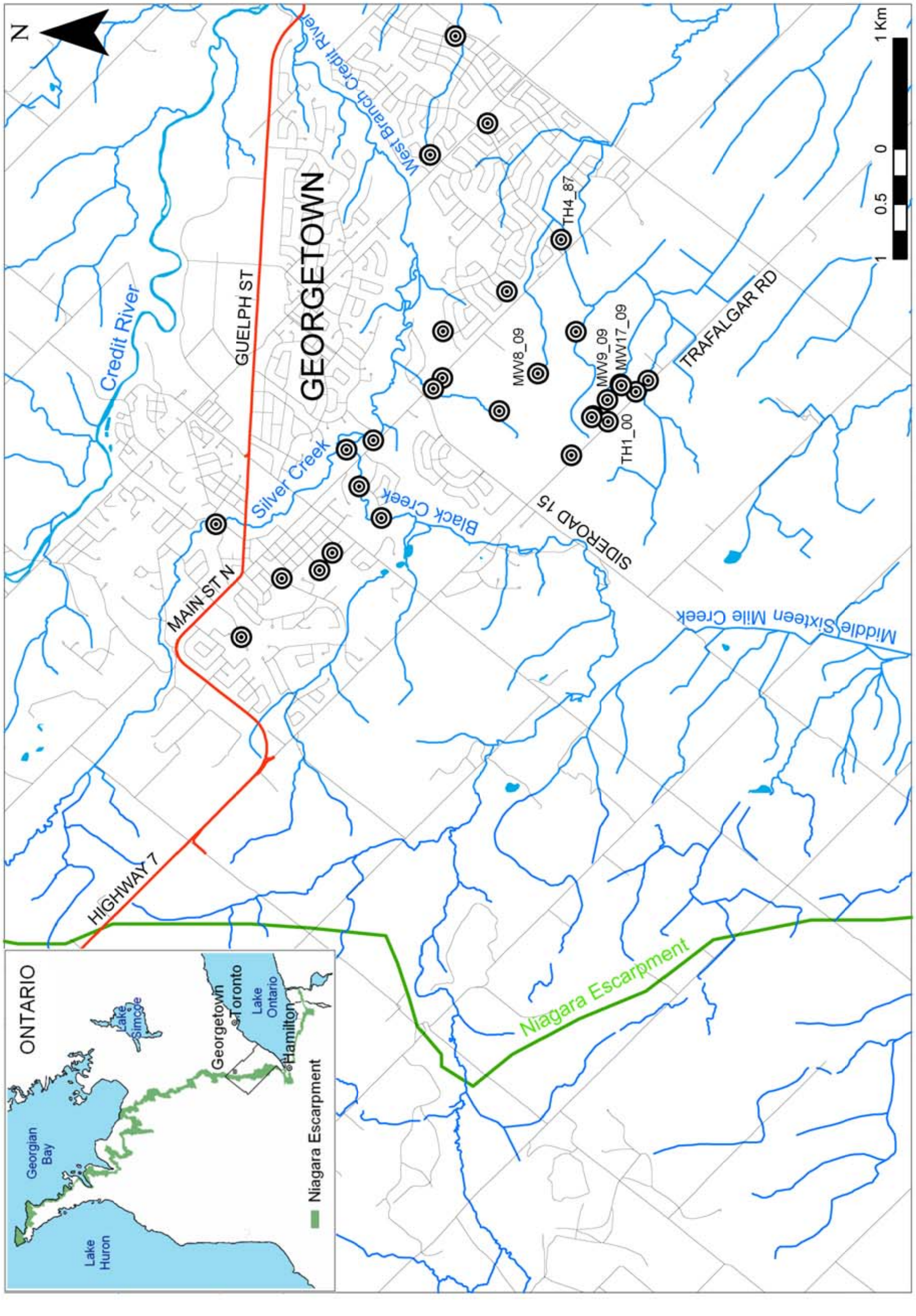
Principal component analysis (PCA) provides an alternative approach for objective classification of lithology and for determining the underlying physical properties factors (e.g. clay content) that influence the various log responses. PCA has been employed successfully in a number of previous studies for classification of log suites, but has not gained wide usage to date in groundwater studies. In essence, PCA combines the correlated portion of the geophysical parameters, allowing the data variation to be independently studied (Kassenaar, 1991). PCA is ideally suited to the large volumes of inter-related data collected in geophysical surveys and has been used successfully in investigations utilizing borehole geophysics (Collins, 2004; Barrash and Morin, 1997; Kassenaar, 1991) to classify distinctive lithologies based on the uniqueness of their downhole electrofacies. This paper evaluates PCA as an objective, quantitative method for determining lithology from borehole geophysical data. A selection of multi-parameter logs from the Georgetown area were analyzed and used to refine the hydrostratigraphic interpretation of thick Quaternary sediments infilling bedrock valleys. The results show that PCA cross plots provide an improved means for identifying and classifying Quaternary lithofacies and can be used in conjunction with conventional log visual inspection and interpretation (e.g. Chapter 2; Collins, 2004).

3.2 Study Area and Geological Setting

The study area consists of a 20-km^2 portion of the Credit River watershed located to the southwest of Georgetown within the Regional Municipality of Halton (Figure 3-1). The area is located to the east of the Niagara Escarpment within the Black Creek and Silver Creek subwatershed areas of the Credit River Valley (Figure 3-1). The bedrock below the study area consists of Paleozoic Queenston shales, which are overlain by Late Pleistocene surficial sediments that reach a thickness of >50 m within several broad bedrock valleys (Costello and Walker, 1972; Karrow, 2005; Meyer and Eyles, 2007). The infill sediments are host to a number of local aquifer systems that provide municipal water supplies to the nearby towns of Acton and Georgetown (Davies and Holysh, 2007; Slomka, 2011).

Due to a current shortfall in groundwater supply, Halton Region is seeking to further develop new reliable groundwater resources in the Georgetown area and is currently evaluating

Figure 3-1: Location of Georgetown study area within the Regional Municipality of Halton (inset map). Locations of boreholes drilled during regional groundwater resource investigations and four geophysically logged boreholes used in this study are shown.


N
Credit River
West Branch Credit River
GUELPH ST
GEORGETOWN
TH4_87
MW8_09
MW9_09
MW17_09
TH1_00
TRAFALGAR RD
Silver Creek
Black Creek
SIDEROAD 15
MAIN ST N
Middle Sixteen Mile Creek
HIGHWAY 7
Niagara Escarpment
ONTARIO
Lake Simcoe
Georgian Bay
Lake Huron
Georgetown
Toronto
Lake Ontario
Hamilton
Niagara Escarpment
1
0.5
0
1 Km
Geophysically Logged Boreholes

the resource potential of buried valleys below the Middle Sixteen Mile Creek (MSMC) and Cedarvale (CV) areas to the west and southwest of Georgetown (Figure 3-1). Theses areas were recently investigated as part of a regional Tier 3 groundwater evaluation, involving a detailed program of surface and borehole geophysics, and drilling of 21 new continuously-cored boreholes (see Section 3.3). The stratigraphy of the MSMC buried valley was previously investigated by Meyer and Eyles (2007) as part of a previous groundwater investigation. The valley infill stratigraphy consists of a thick (> 55 m) interbedded sequence of diamicts, laminated silts (aquitards) and coarse-grained glaciofluvial deposits (aquifers) overlying Queenston shale bedrock.

3.3 Borehole Data

New continuous PQ-cored, exploratory mud rotary and sonic borehole records totaling >425 m have been acquired in 16 boreholes (16 m to 55 m depth) drilled since January 2009 as part of the Tier 3 investigations of the geology and hydrostratigraphy of Quaternary sediments near Georgetown. Open mudded-hole geophysical logs (resistivity, gamma, caliper) were acquired in 15 boreholes prior to installation of PVC casings. Subsequent downhole geophysical logging in PVC cased holes (gamma, conductivity, magnetic susceptibility, full-waveform sonic) was conducted by McMaster in 11 of the 15 boreholes with open-hole geophysical logs and in 3 pre-existing monitoring wells not previously logged using a Mount Sopris Matrix portable digital logging system. Other archival geophysical data employed in this study included 10 log suites (caliper, gamma, resistivity, conductivity) obtained from regional test wells.

The borehole subsurface database was used to construct a series of composite log plots consisting of all available geophysical and borehole data for a total of 29 borehole locations. In this study, three geophysical log suites with continuous core data (MW17, MW9 and MW8) and one archival geophysical log suite without core (TH4_87) were used in the PCA analysis to evaluate whether the important lithologic types could be objectively classified using geophysical log data (Figures 3-2 & 3-3).

3.4 Methods

3.4.1 Principal Component Analysis (PCA)

Principal component analysis is a multivariate data analysis technique that combines statistical and data transformation methods and has been applied by several authors to multi-parameter geophysical datasets (Kassenaar, 1991; Barrash and Morin, 1997; Collins, 2004). PCA seeks to obtain a linear combination of variables or factors such that the maximum variance is extracted from the variables. It then removes this variance and seeks a second linear combination, in order to progressively describe the maximum proportion of original total variability which explains the remaining variance (Collins, 2004). Kassenaar (1991) applied PCA to multi-parameter geophysical log suites to clarify relationships within and between the log data in the Waterloo, Ontario area while Barrash and Morin (1997) used PCA to differentiate sands and gravels from geophysical logs within poorly recovered coarse grained sediments in Iowa. Both authors used cross plots of principal component score logs to quantitatively characterize lithology through analysis of clustered data points and were able to interpret the geologic factors (ie. clay content) responsible for the majority of observed variation in geophysical log responses.

More generally, PCA can be thought of as a technique to re-plot data that introduces no bias or model on the original data (Kassenaar, 1991). PCA can therefore be used to determine a

Figure 3-2: Composite log plots showing lithostratigraphic correlations for boreholes. A) MW17_09 and B) MW9_09 (see Chapter 2 for details). Log curves include natural gamma, caliper and resistivity (32”), magnetic susceptibility, EM conductivity and full-waveform sonic (p-wave velocity). Bold dashed lines indicates the depth interval analyzed using the VIEWLOG® PCA toolkit.

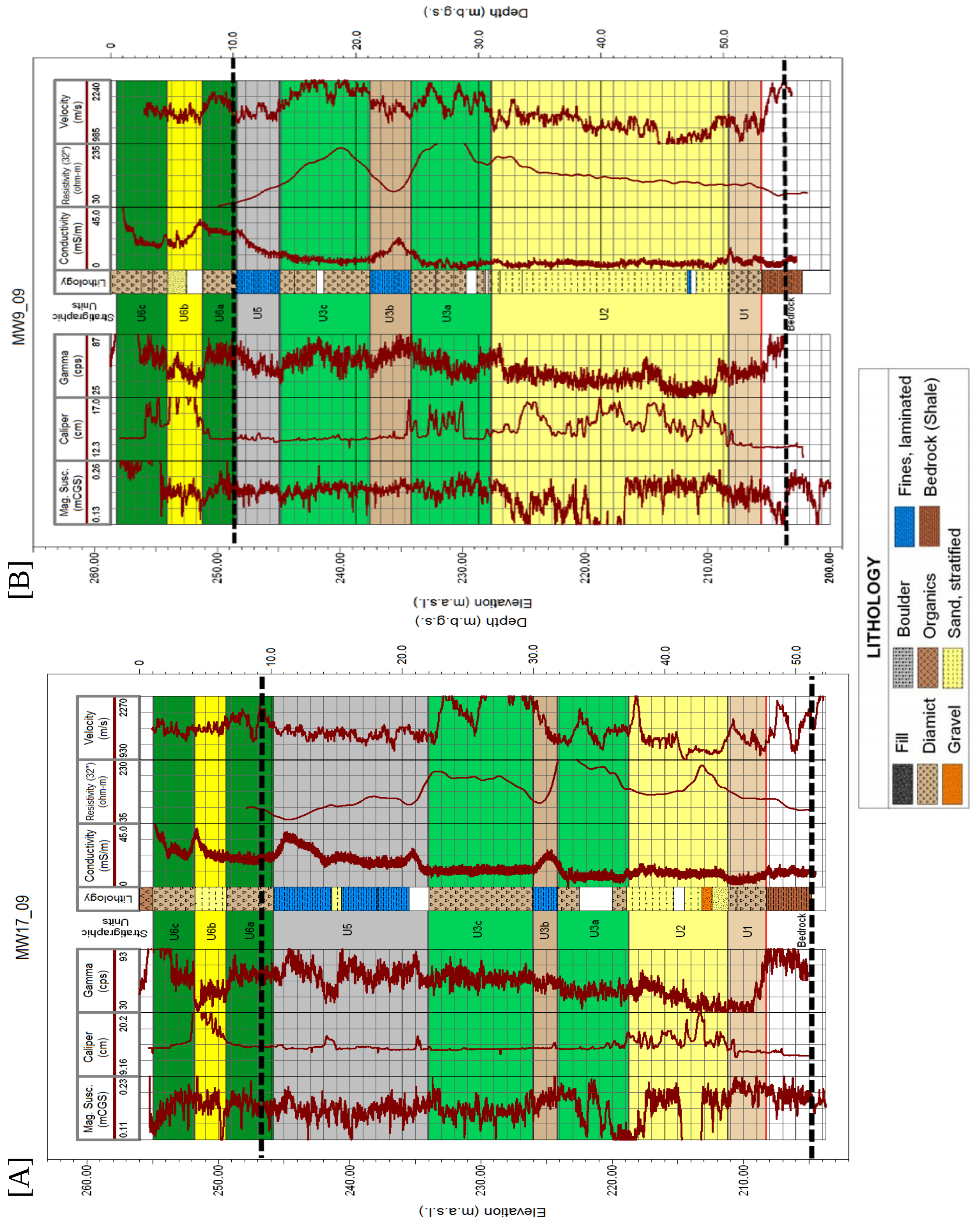
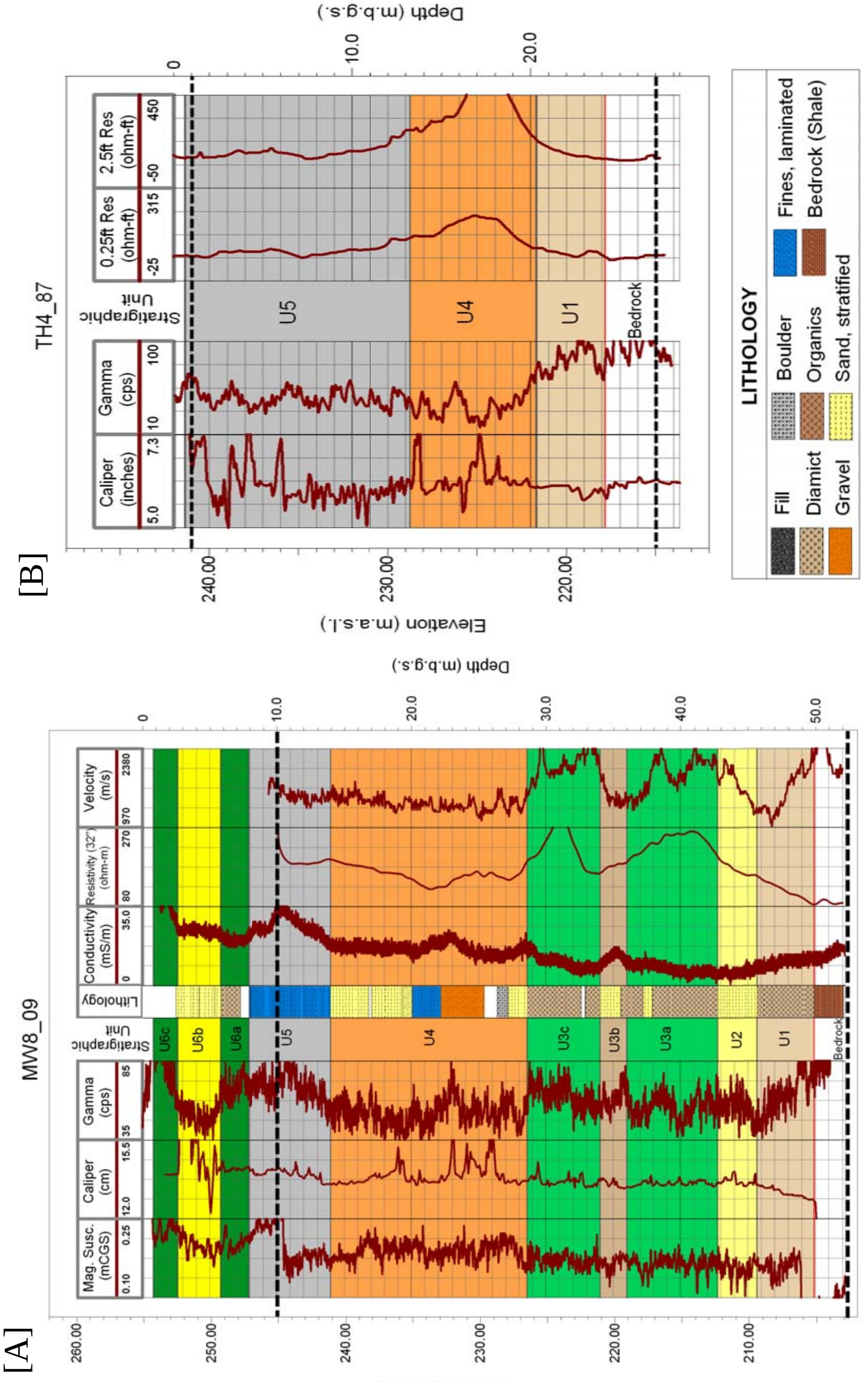

[A]
MW17_09
[B]
MW9_09
Elevation (m.a.s.l.)
Depth (m.b.g.s.)
Mag. Susc. (mCGS)
Caliper (cm)
Gamma (cps)
Stratigraphic Units
Lithology
Conductivity (mS/m)
Resistivity (32") (ohm-m)
Velocity (m/s)
U6c
U6b
U6a
U5
U3c
U3b
U3a
U2
U1
Bedrock
LITHOLOGY
Fill
Diamict
Gravel
Boulder
Organics
Sand, stratified
Fines, laminated
Bedrock (Shale)

Figure 3-3: A) Composite plot showing litho-stratigraphic correlations for borehle MW8_09. B) Composite plot showing litho-stratigraphic correlations for archived TH4_87. Log curves include natural gamma, caliper and resistivity (32"), magnetic susceptibility, EM conductivity and full-waveform sonic (p-wave velocity), resistivity. Bold dashed lines indicates the depth interval analyzed using the VIEWLOG® PCA toolkit.


[A]
MW8_09
Mag. Susc. (mCGS) 0.10 0.25
Caliper (cm) 12.0 15.5
Gamma (cps) 35 85
Stratigraphic Unit
U6c
U6b
U6a
U5
U4
U3c
U3b
U3a
U2
U1
Bedrock
Lithology
Conductivity (mS/m) 0 35.0
Resistivity (32") (ohm-m) 80 270
Velocity (m/s) 970 2380
Elevation (m.a.s.l.)
260.00
250.00
240.00
230.00
220.00
210.00
Depth (m.b.g.s.)
0
10.0
20.0
30.0
40.0
50.0
[B]
TH4_87
Caliper (inches) 5.0 7.3
Gamma (cps) 10 100
Stratigraphic Unit
U5
U4
U1
Bedrock
0.25ft Res (ohm-ft) -25 315
2.5ft Res (ohm-ft) -50 450
Elevation (m.a.s.l.)
240.00
230.00
220.00
Depth (m.b.g.s.)
0
10.0
20.0
LITHOLOGY
Fill
Diamict
Gravel
Boulder
Organics
Sand, stratified
Fines, laminated
Bedrock (Shale)

]

set of orthogonal axes or components in an n-dimensional space aligned parallel to the direction of maximum variance in the data and proceeds progressively through subsequent sources of variation. Figure 3-4 illustrates this concept with a hypothetical two-dimensional system cross-plotting two measured parameters. The axes encompassing the maximum variation in the plotted data cloud corresponds to the principal components of the data with the longest axis describing the majority of data variation, and the second axis describing additional variation not associated with the first principal component (Kassenaar, 1991).

3.4.2 PCA Methodology

PCA was performed in the VIEWLOG® PCA toolkit using the general processing flow shown in Figure 3-5. As a first step the logs types and depths interval are selected for PCA analysis and displayed in VIEWLOG®. The mean and standard deviation of the logs is calculated over a user-defined depth interval in order to standardize of the log data in (SD) units (Kassenaar, 1991). Next, a correlation matrix is calculated to reduce the effects of differing measurement units and scales in the original geophysical logs such that the standardized log data can be readily combined to provide principal component scores or eigenvectors (Kassenaar, 1991). The amount of unique information provided by each original log can then be estimated from analysis of the eigenvectors and their eigenvalues (Kassenaar, 1991). The percent of the total variation accounted for by each principal component is calculated based on the relative size of the eigenvalues and the relative size of the eigenvector elements indicate the degree to which each geophysical log contributes to the variation described by that component.

The next step involves calculation of principal component 'scores' at each depth interval to produce a score log (in standard deviation units). The uncorrelated principal component score

Figure 3-4: Schematic illustrating principal of PCA cross plot. The PCA component axes are rotated into direction of maximum variation in a hypothetical two-dimensional system (adapted from Kassenaar, 1991, Figure 1).

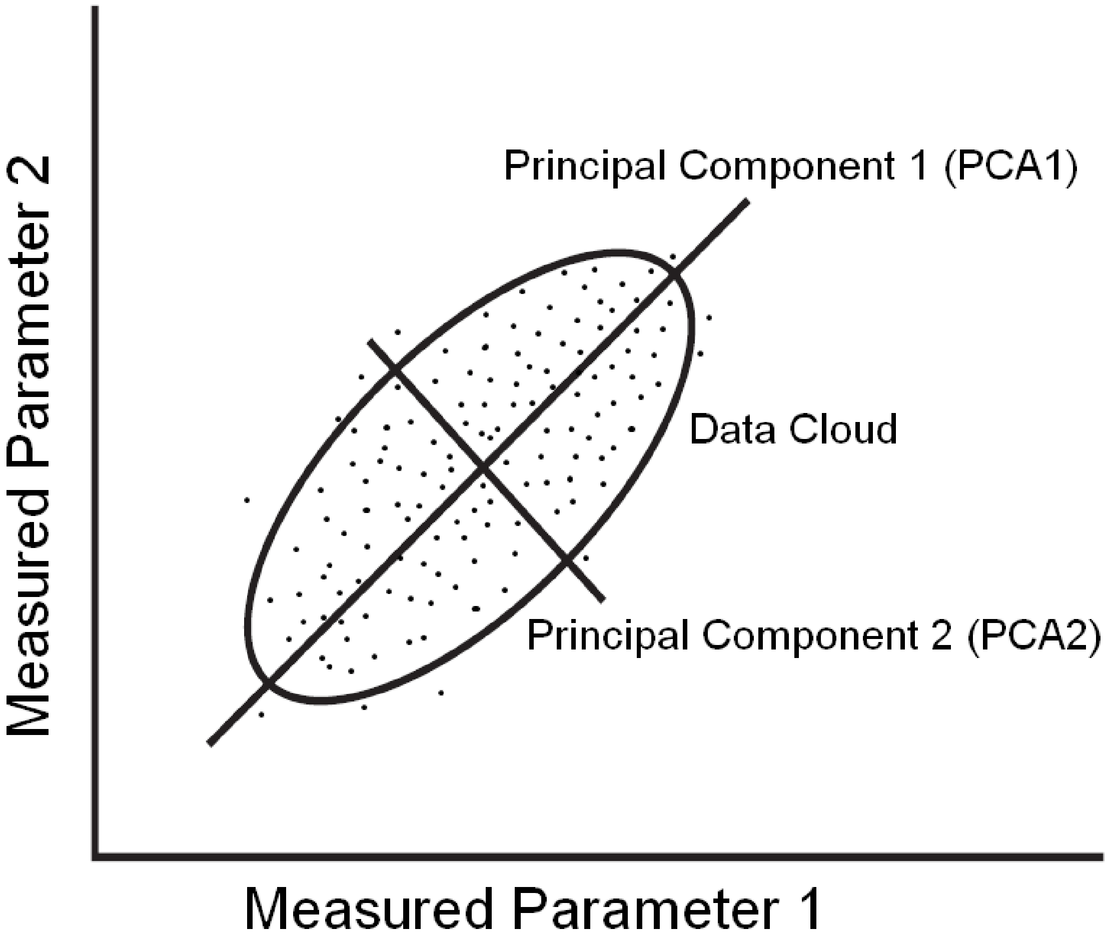
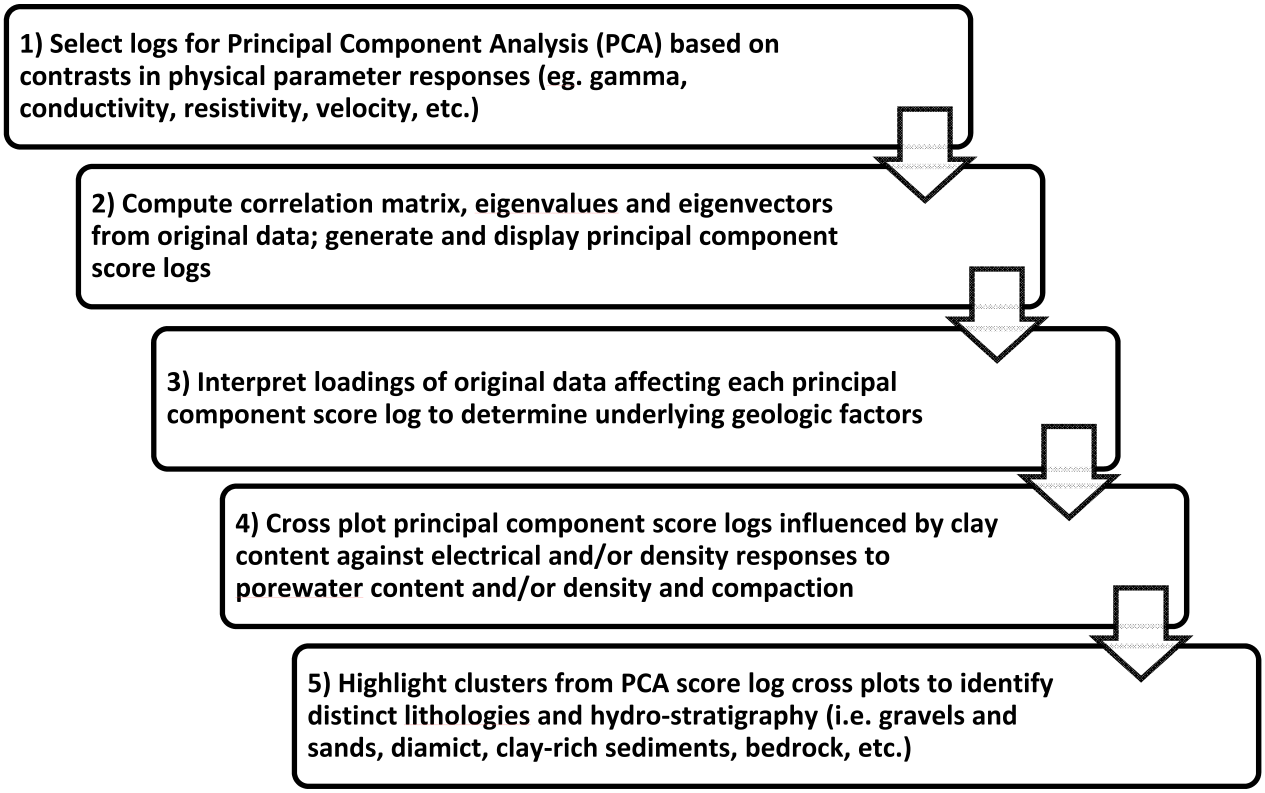

Principal Component 1 (PCA1)
Data Cloud
Principal Component 2 (PCA2)
Measured Parameter 2
Measured Parameter 1

Figure 3-5: Idealized process flow developed in this study for optimizing clustering of distinct lithologies from multi-parameter geophysical log suites.


1) Select logs for Principal Component Analysis (PCA) based on contrasts in physical parameter responses (eg. gamma, conductivity, resistivity, velocity, etc.)
2) Compute correlation matrix, eigenvalues and eigenvectors from original data; generate and display principal component score logs
3) Interpret loadings of original data affecting each principal component score log to determine underlying geologic factors
4) Cross plot principal component score logs influenced by clay content against electrical and/or density responses to porewater content and/or density and compaction
5) Highlight clusters from PCA score log cross plots to identify distinct lithologies and hydro-stratigraphy (i.e. gravels and sands, diamict, clay-rich sediments, bedrock, etc.)

logs represent the combined variance loadings from the original logs and once displayed, the score logs can be compared to the original logs in aid in understanding the underlying geologic property that may be represented by the score log (Kassenaar, 1991). This interpretation requires a fundamental understanding of the geophysical logging methods and the response of different logs to changes in geologic properties. While strong correlation between the computed score logs and original geophysical logs indicates a probable casual relationship with underlying geologic properties (ie. clay content), PCA is a mathematical procedure and consequently the primary basis of the correlation may be indirect and unknown (Kassenaar, 1991; Tan 2005).

The final step requires cross plotting of the principal component score logs to investigate the uniqueness of different lithologies in principal component space (ie. gravel/sand vs diamict vs clay-rich sediments). In this study, cross plots were generated in the SMT Kingdom Suite™ facies modeling toolkit that allows polygons to be drawn around clusters of data points and the depth intervals colour-coded to match the points contained within the user-defined polygons. Patterns and trends can then be developed and repeated for additional wells.

3.5 Results

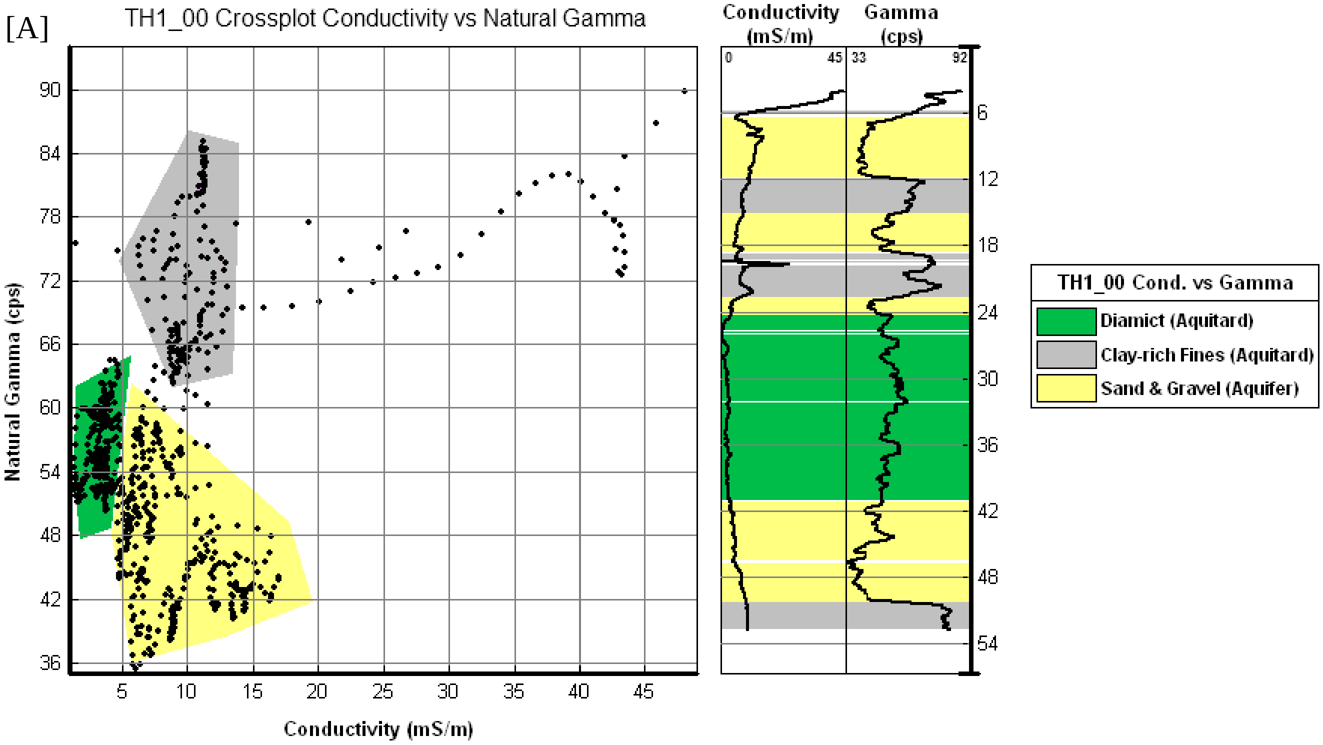
Prior to the application of PCA, cross plots of various log parameters were generated for each borehole log suite but these generally failed to clearly separate lithologies or stratigraphic units recognized in the borehole. In several boreholes, including TH1_00 (Figure 3-6A), gamma and conductivity were cross plotted, and the derived electrofacies were sufficiently unique to allow for successful classification of diamict, clay-rich (includes clay, silt and shale bedrock), and sand/gravel formations. More commonly however, limited or no relationships between the electrofacies were apparent as the data overlapped and no clusters could be separated from the data cloud for identification and classification (Figure 3-6B). The initial review of the data

Figure 3-6: Example showing conventional cross plot analysis of log parameters.

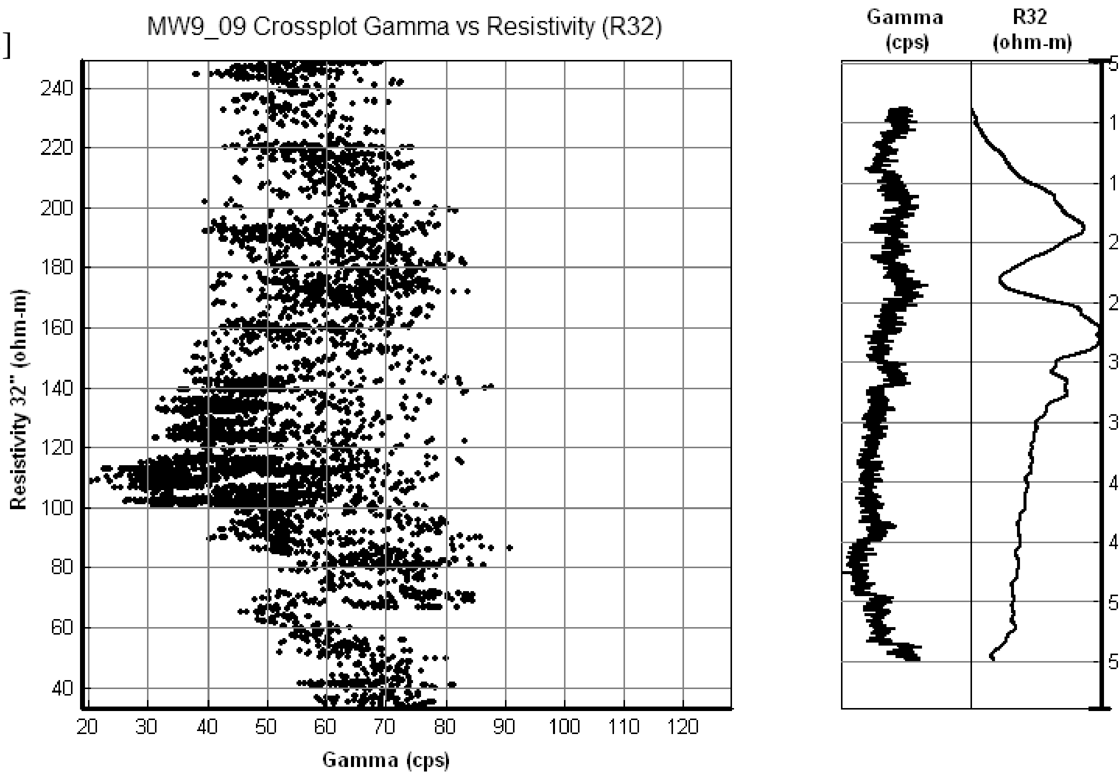
A) Gamma vs conductivity plot for borehole TH1_00 showing effective clustering of data points. Note cross plotting alone permits distinction between clay-rich units (shale bedrock, clay rich diamicts and laminated silts and clays), sands/gravels and the middle diamict (Newmarket Till).

B) Gamma vs R32 (32" resistivity) plot for borehole MW9_09 showing poor clustering of data points as a result of a high degree of lithologic heterogeneity.

[A]


TH1_00 Crossplot Conductivity vs Natural Gamma
Natural Gamma (cps)
90
84
78
72
66
60
54
48
42
36
5
10
15
20
25
30
35
40
45
Conductivity (mS/m)
Conductivity (mS/m)
Gamma (cps)
0
45
33
92
6
12
18
24
30
36
42
48
54
TH1_00 Cond. vs Gamma
Diamict (Aquitard)
Clay-rich Fines (Aquitard)
Sand & Gravel (Aquifer)

[B]


MW9_09 Crossplot Gamma vs Resistivity (R32)
Resistivity 32" (ohm-m)
240
220
200
180
160
140
120
100
80
60
40
20
30
40
50
60
70
80
90
100
110
120
Gamma (cps)
Gamma (cps)
R32 (ohm-m)
5
10
15
20
25
30
35
40
45
50
55

illustrates the challenges posed by stratigraphic complexity, instrument error and shoulder effects on the collected geophysical logs. Collins (2004) notes the shoulder effect occurs when a contact between two units is a gradual one. Should the gradual contact between two units be large and the sampling frequency of the tool is high, a large percent of the data will be an intermediate value between the two formations, which effectively masks the separation between units when cross plotted.

Initial principal component analysis was applied to wells with all available data parameters to assess the applicability of each parameter to additional analysis. While it is advantageous to investigate all the data interactions, initial PCA results indicated that more parameters do not necessarily correlate with better clustering of principal component score logs or improve characterization of formations present in the borehole. Reviewing each parameter and considering what it is responding to allows for optimization of physical parameters included in PCA analysis such that the resulting principal component score logs are more likely to represent geologic factors that are useful for hydrostratigraphic characterizations. Caliper logs, where increases in hole diameter are often associated with less cohesive sediments such as sands and gravels, did not accurately separate clay rich formations from sands and gravels. As a result, removal of caliper logs from analysis generally improved the PCA results. In archived datasets where fewer geophysical logs and no core were available, the effect of removing the caliper logs was more pronounced and allowed significantly more variation to be contained in the first two principal component score logs. Principal component cross plots and associated correlation matrices for 3 cored boreholes (MW17_09, MW9_09, MW8_09) and one uncored archived borehole (TH4_87) are evaluated below and demonstrate the applicability of PCA for objective, quantitative hydrostratigraphic classifications.

Beginning with the cored boreholes MW17, MW9 and MW8, the five physical parameters used for PCA were natural gamma, resistivity (32”), conductivity, velocity (P-wave) and magnetic susceptibility. The correlation matrix with calculated eigenvalues and eigenvectors and cross plots with lithologic classifications are displayed in Figures 3-7 – 3-9. The correlation matrix for each borehole is provided as a means to evaluate the relative and combined influences of the original parameters on each principal component. The physical meaning of each principal component score log is inferred from its variance loadings and is discussed in order of descending variance. Cross plots of the score logs for the first two principal components are evaluated and visually compared to the original data.

Without prior knowledge of formation boundaries (ie. core data), unit identifications and polygon placements in principal component cross plots are arbitrary where data clusters are not obvious. Where original geophysical log curves have gradational contacts, so too are gradational separations of clusters in principal component cross plots. One way to address this problem is to utilize the way in which the principal component score logs are calculated and displayed. Because the principal component score logs are in standard deviation units, positive and negative associations relative to the mean of each score log (ie. the zero lines in cross plot space) provide useful polygon margins, even when data clouds remain clustered.

3.5.1 MW17_09 PCA

For the borehole MW17_09, the correlation matrix (Figure 3-7A) indicates that conductivity and resistivity have the strongest correlation, which is expected since both respond to the electrical response of formation sediment and pore waters, while gamma and conductivity had the highest correlation between electrical and non-electrical logs. The least correlatable parameter was magnetic susceptibility, indicating it is not responding to the same physical properties. Analysis of the eigenvalues and eigenvectors for MW17_09 (Figure 3-7A) shows that roughly 87% of the total variation observed in the multi-parameter dataset can be described by the first three principal components. This confirms that there is a significant amount of redundancy in the original data that can be better studied through PCA.

PCA1, the first principal component accounts for most of the variation (42.2%) and has strong positive contributions from conductivity and to a lesser degree gamma, and a strong negative contribution from resistivity. Furthermore, the PCA1 log curve (Figure 3-7B) most closely resembles the original resistivity (R32) log curve (Figure 3-2A), suggesting this response is related to formation clay content, particularly the electrical response to conductive clays and high resistivity over-consolidated diamicts and cobble-dominated units (Chapter 2; Barrash and Morin, 1997). As clay content increases, so too does the gamma and conductivity response (positive association) while resistivity decreases (negative association).

PCA2, the second principal component accounts for the second highest amount of variation unrelated to PCA1 (25.2%), and has very strong positive association with velocity and a strong positive association with gamma. Examination of the PCA2 log curve (Figure 3-7B) indicates a strong resemblance to the original velocity log curve (Figure 3-2A), indicating a strong association with compaction as it aids in identifying the dense middle diamict (interpreted as Newmarket Till (Chapter 2). The middle diamict is observed to have a slightly higher gamma count relative to low velocity and low gamma sands underlying it (Figure 3-2A), which helps to explain the association of gamma with this unit.

The third principal component accounts for 19.5% of the total variation and can be attributed almost exclusively to the magnetic susceptibility curve, which in unsurprising given the low correlatability noted in the correlation matrix. The fourth and fifth principal components account for a collective 13% of total variance and are most likely related to logging measurement noise. Based on these results, PCA1 and PCA2 are the best candidates for cross plotting.

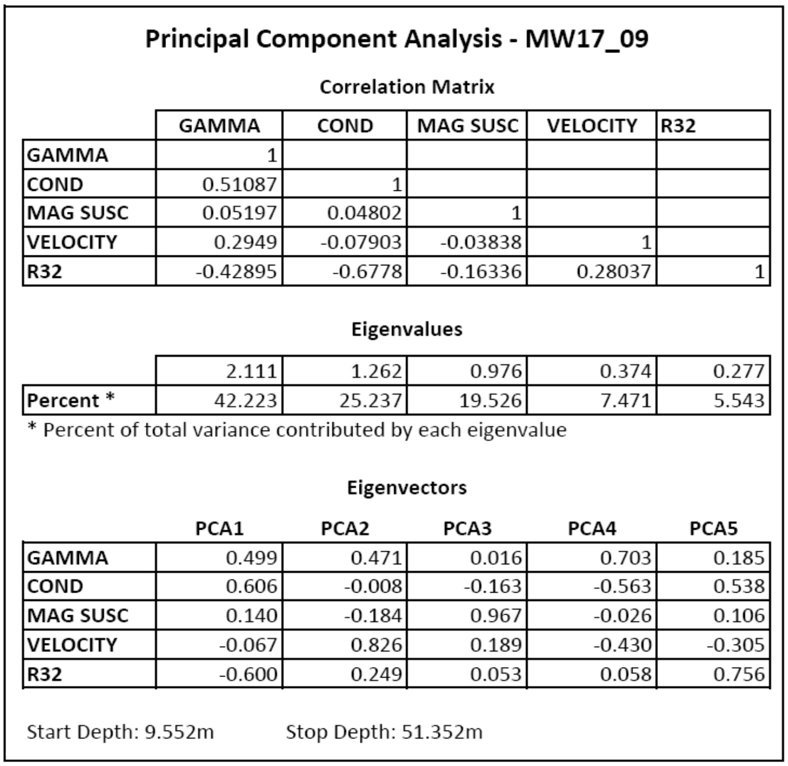
The cross plot of PCA1 vs PCA2 (Figure 3-7B) clearly separates the data such that the relationship between formation conductivity and compaction are more apparent. PCA1 values less than zero are associated with clay-rich sediments, identifying shale bedrock and laminated silts and clay units, while values great than zero are associated with clay-poor sediments (sand-rich diamicts, sand and gravel). PCA2 values less than zero are associated with dense, high velocity diamict (Newmarket Till), while PCA2 values greater than zero separate low velocity, poorly compacted units (sands and gravels). Taken collectively, the MW17_09 cross plot of PCA1 vs PCA2 allows for successful hydro-stratigraphic differentiation between the Newmarket Till (aquitard), clay-rich sediments and bedrock (aquitards) from sands and gravels (aquifer) (Figure 3-7B).

Figure 3-7: Principal Component Analysis for borehole MW17_09.

A) Correlation matrix, eigenvalues and eigenvectors for MW17_09. Note strong correlation of PCA1 with conductivity and resistivity (electrical response of conductive clay and pore waters) and PCA2 with velocity (compaction/density response).

B) Crossplot of PCA1 and PCA2 for MW17_09. PCA1 values accurately separate clay-poor and clay-rich units while PCA2 accurately separates dense diamict (Newmarket Till) from loose sands and gravel.

[A]



Principal Component Analysis - MW17_09

Correlation Matrix

	GAMMA	COND	MAG SUSC	VELOCITY	R32
GAMMA	1				
COND	0.51087	1			
MAG SUSC	0.05197	0.04802	1		
VELOCITY	0.2949	-0.07903	-0.03838	1	
R32	-0.42895	-0.6778	-0.16336	0.28037	1

Eigenvalues

	2.111	1.262	0.976	0.374	0.277
Percent *	42.223	25.237	19.526	7.471	5.543

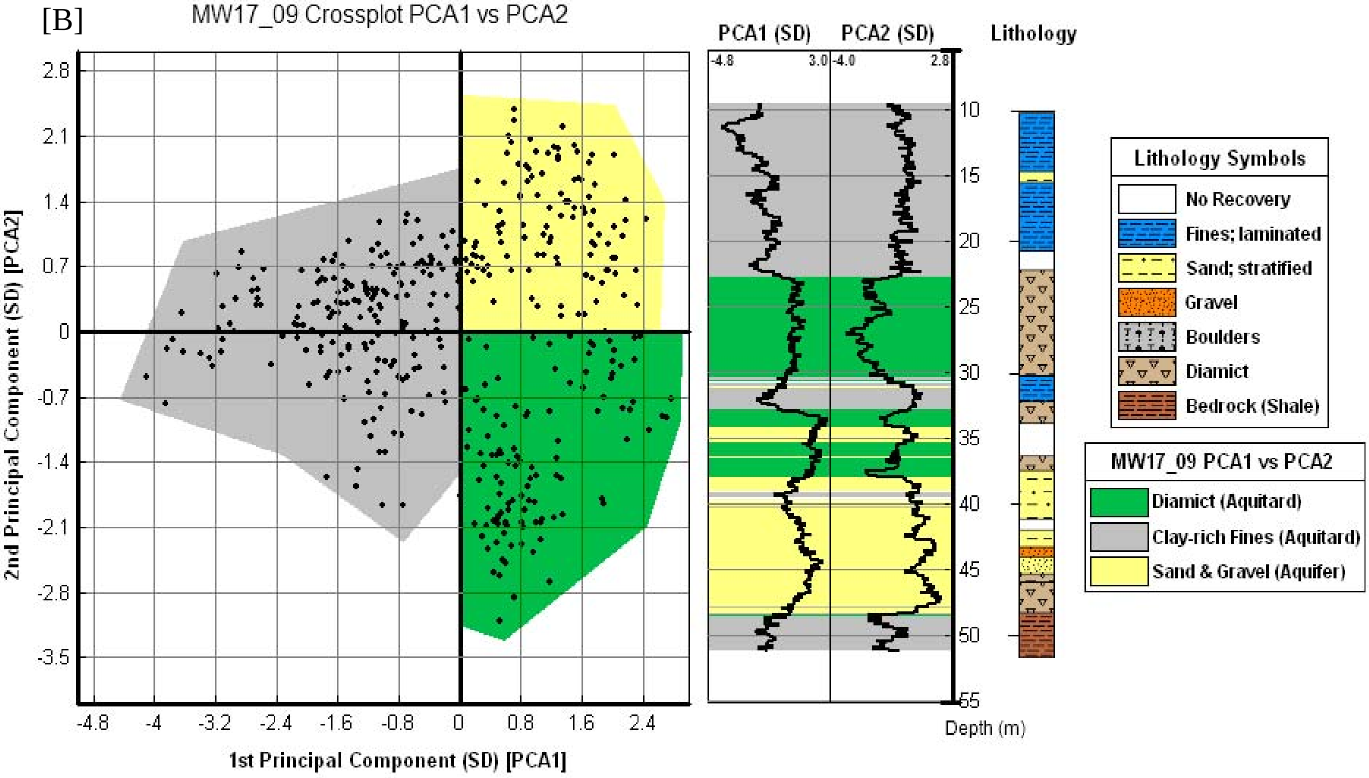
* Percent of total variance contributed by each eigenvalue

Eigenvectors

	PCA1	PCA2	PCA3	PCA4	PCA5
GAMMA	0.499	0.471	0.016	0.703	0.185
COND	0.606	-0.008	-0.163	-0.563	0.538
MAG SUSC	0.140	-0.184	0.967	-0.026	0.106
VELOCITY	-0.067	0.826	0.189	-0.430	-0.305
R32	-0.600	0.249	0.053	0.058	0.756

Start Depth: 9.552m Stop Depth: 51.352m

[B]



3.5.2 MW9_09 PCA

For MW9_09, the correlation matrix (Figure 3-8A) illustrates that gamma and velocity have the strongest correlation, with conductivity and resistivity and gamma and conductivity also having strong correlations. The least correlatable parameter overall was magnetic susceptibility, however the lowest correlation exists surprisingly between gamma and resistivity. Analysis of the eigenvalues and eigenvectors for MW9_09 (Figure 3-8A) show that roughly 90% of the total variation observed is contained within the first three principal components.

For MW9, the first principal component accounts for 38.9% of the variation with strong to moderate positive contributions (in order of decreasing contribution) from gamma, velocity, conductivity and magnetic susceptibility. The PCA1 log curve (Figure 3-8B) resembles a hybrid of the gamma and velocity logs (Figure 3-2B), and given the loadings from numerous parameters suggests this score log represents clay content.

The second principal component score log contains 32.7% of the total variation and is dominated by resistivity and conductivity, with a moderate contribution from velocity. The PCA2 log curve also strongly resembles the original resistivity log shape (Figure 3-2B), further supporting the interpretation of this score log as responding to the presence of pore waters. Pore water responds strongly to both electrical methods, and pore space is less available in over-consolidated sediments, which explains the dominance of these three parameters on PCA2.

PCA3 accounts for 18.4% of the total variation and is attributed primarily to magnetic susceptibility with a limited contribution for other parameters. The fourth and fifth principal components account for less than 10% of total variance and are again most likely related to logging measurement noise.

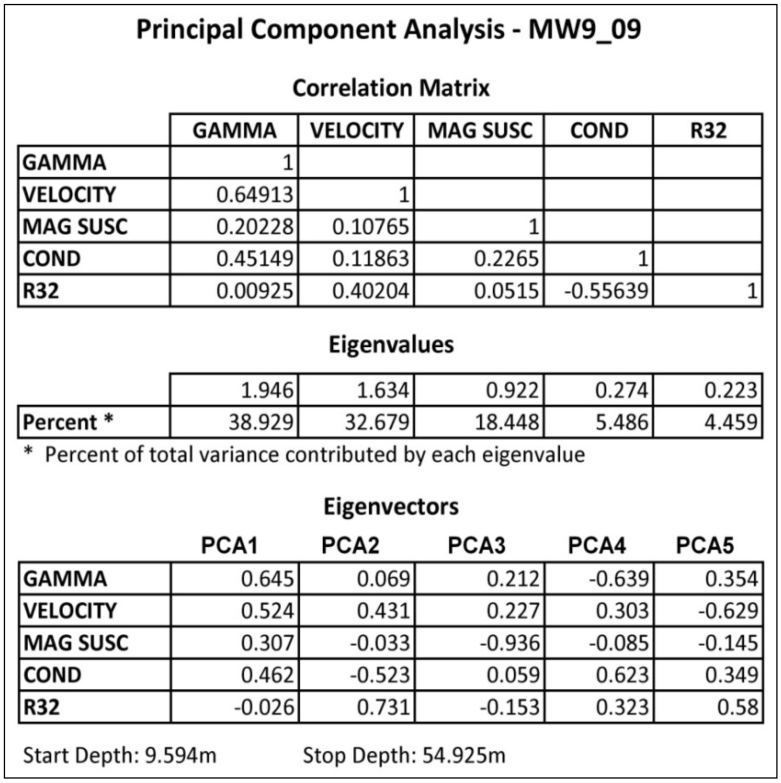
Cross plotting of PCA1 vs PCA2 for MW9 (Figure 3-8B) focuses on the relationship between clay content and pore water. PCA1 values less than zero are associated with clay-rich sediments, identifying shale bedrock, laminated silts and clays and diamict with increased clay content units, while values great than zero are associated with clay-poor sediments (sandy diamict interbeds, sand and gravel). PCA2 values less than zero separate dense, highly resistive over-consolidated diamict (Newmarket Till) from conductive clay-rich sediments. In combination, PCA1 vs PCA2 differentiates diamicts (aquitard) from sands and gravels (aquifer) and from silts and clays (aquitard).

Figure 3-8: Principal Component Analysis for borehole MW9_09. Cross plotting PCA score logs produces nearly identical results to visual analysis of electrofacies (Figure 2), confirming utility of PCA.

A) Correlation matrix, eigenvalues and eigenvectors for MW9_09. Note strong correlation of PCA1 with gamma, velocity and conductivity (clay content response) and PCA2 with conductivity and resistivity (electrical response of pore water).

B) Crossplot of PCA1 and PCA2 for MW9_09. PCA1 values accurately separate clay-poor and clay-rich units. PCA2 accurately separates diamict from silts/clays and shale.

[A]



Principal Component Analysis - MW9_09

Correlation Matrix

	GAMMA	VELOCITY	MAG SUSC	COND	R32
GAMMA	1				
VELOCITY	0.64913	1			
MAG SUSC	0.20228	0.10765	1		
COND	0.45149	0.11863	0.2265	1	
R32	0.00925	0.40204	0.0515	-0.55639	1

Eigenvalues

	1.946	1.634	0.922	0.274	0.223
Percent *	38.929	32.679	18.448	5.486	4.459

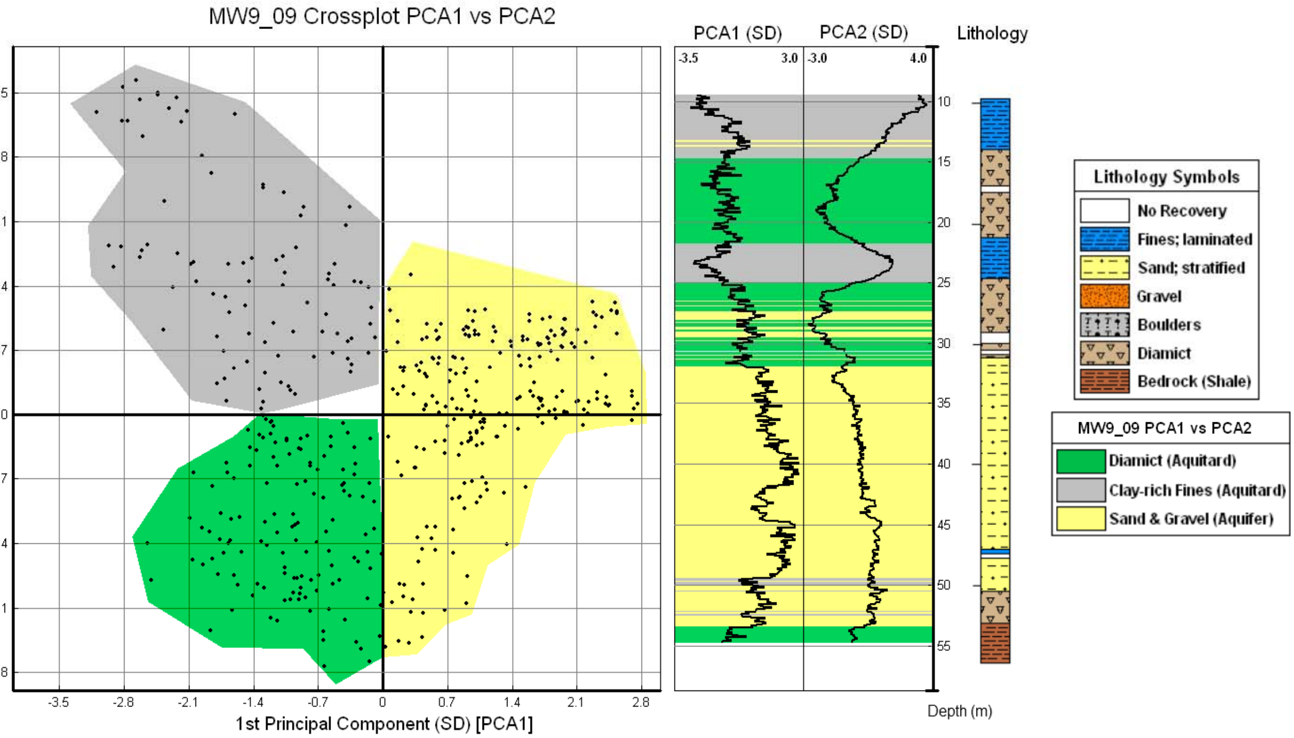
* Percent of total variance contributed by each eigenvalue

Eigenvectors

	PCA1	PCA2	PCA3	PCA4	PCA5
GAMMA	0.645	0.069	0.212	-0.639	0.354
VELOCITY	0.524	0.431	0.227	0.303	-0.629
MAG SUSC	0.307	-0.033	-0.936	-0.085	-0.145
COND	0.462	-0.523	0.059	0.623	0.349
R32	-0.026	0.731	-0.153	0.323	0.58

Start Depth: 9.594m Stop Depth: 54.925m

[B]



3.5.3 MW8_09 PCA

For MW8_09, the correlation matrix (Figure 3-9A) highlights a more complex series of correlations, owing to the complexity of sediments at this location (Figure 3-3A). Relatively strong to moderate correlations exist between several parameters with the strongest correlations belonging to magnetic susceptibility and gamma, and on par with correlations between conductivity and velocity, magnetic susceptibility and velocity and gamma and velocity. Paradoxically, the least correlatable relationship exists between gamma and conductivity, but this can be attributed to the contrasts in the conductivity signature split between a response to conductive clays (a positive correlation to gamma in roughly half the borehole) and conductive porewater (negative correlation to gamma in the other half of the borehole). At this location the positive and negative correlations cancel out to produce a lower than expected correlation value in the correlation matrix. Analysis of the eigenvalues and eigenvectors for MW8_09 (Figure 3-9A) show that over 87% of the total variation observed is contained within the first three principal components.

For MW8, the first principal component accounts for 42% of the variation with strong positive contributions from velocity and gamma, and strong negative contributions from magnetic susceptibility and conductivity. The PCA1 log curve (Figures 3-9B, 3-9C) most closely resembles the velocity log, indicating a strong association with compaction and limited water filled pore spaces. Limited pore spaces provide less room for conductive pore water in over-consolidated sediments (particularly the Newmarket Till, characterized by a ‘dual-peak’ resistivity signature in the Georgetown area (Chapter 2).

The second principal component score log for MW8 contains 29.7% of the total variation and is dominated by resistivity with moderate negative contributions from gamma and conductivity. The PCA2 log curve (Figures 3-9B, 3-9D) resembles a combination of the original resistivity and conductivity log shapes, suggesting this score log is dominated by the electrical response of the sediments unrelated to compaction. Clay-rich units and water-bearing gravels are more conductive while clay-poor sandy units yielding limited water are more resistive.

PCA3 accounts for 16.0% of the total variation in MW8 and is dominated by positive contributions from conductivity and gamma, and more moderate contributions from all the other parameters. The PCA3 log curve (Figure 3-9C-D) is a hybrid of the gamma and conductivity logs, indicating PCA3 is responding to clay content with the conductivity contribution attributed to clay response 'corrected' to remove the effect of porewater conductivity. The fourth and fifth principal components account for slightly more than 12% of total variance and are related to the uncorrelated portion of magnetic susceptibility response and logging measurement noise.

Given the increased complexity of MW8 revealed by analysis of the correlation matrix, cross plotting of both PCA1 vs PCA2, PCA1 vs PCA3, and PCA2 vs PCA3 were completed for MW8 (Figures 3-9B, 3-9C-D) to clarify the relationship between the principal component score logs. PCA1 values less than zero are associated with dense/compact tills and bedrock and accurately identifies shale bedrock and both the middle (Newmarket) and lower diamicts. PCA1 values greater than zero identify unconsolidated sediments including sands, gravels, silts and clays. Within the unconsolidated sediments, PCA2 values less than zero group conductive clay-rich fines and porous gravels while less conductive sands have PCA2 values greater than zero. PCA3 also highlights differences in the unconsolidated sediments with negative values associated with clay-rich silts and clays and positive values associated with clay-poor sands and gravels.

In combination, PCA1 vs PCA2 (Figure 3-9B) is useful for identifying dense and compact diamict and bedrock from unconsolidated sediments, and provides a practical way to characterize distinct sand units within a complex sequence of glaciofluvial outwash. Gravel units, however, are lumped with fine grained sediments, failing to clarify the hydro-stratigraphic framework of this borehole. Most interestingly for hydro-stratigraphic characterization of MW8 is the cross plot of PCA1 vs PCA3 (Figure 3-9C) that makes the same distinction between dense and unconsolidated units but more clearly identifies sands and gravels (aquifers) from silts and clays (aquitards). Of least value is the PCA2 vs PCA3 cross plot (Figure 3-9D) which fails to accurately resolve lithologic or hydro-stratigraphic formations of interest as diamict presence is overstated in upper portion of borehole while sand, gravel and finer sediments are also poorly resolved. This emphasizes the importance of understanding the physical properties described by each principal component score log and their underlying relationships prior to cross plotting in order to produce the most meaningful results.

Figure 3-9: Principal Component Analysis for borehole MW8_09.

A) Correlation matrix, eigenvalues and eigenvectors for MW8_09. Note strongest correlation of PCA1 with velocity (compaction/density response), PCA2 with resistivity, conductivity and gamma (electrical response unrelated to compaction) and PCA3 with conductivity and gamma (clay content).

B) Crossplot of PCA1 and PCA2 for MW8_09. PCA1 values accurately separate dense/compact tills and bedrock from loose sand, gravel and fine-grained sediments. PCA2 accurately separates sands within variably textured glaciofluvial outwash, but lumps gravels and fines together.

[A]

Principal Component Analysis - MW8_09

Correlation Matrix

	GAMMA	COND	R32	MAG SUSC	VELOCITY
GAMMA	1				
COND	0.02574	1			
R32	-0.14842	-0.27048	1		
MAG SUSC	-0.49184	0.29349	0.26295	1	
VELOCITY	0.42114	-0.47433	0.35515	-0.45551	1

Eigenvalues

	2.103	1.484	0.799	0.347	0.267
Percent *	42.061	29.687	15.981	6.941	5.33

* Percent of total variance contributed by each eigenvalue

Eigenvectors

	PCA1	PCA2	PCA3	PCA4	PCA5
GAMMA	0.436	-0.416	0.531	0.548	0.236
COND	-0.412	-0.404	0.615	-0.524	-0.119
R32	0.11	0.701	0.453	-0.208	0.498
MAG SUSC	-0.524	0.358	0.297	0.579	-0.417
VELOCITY	0.595	0.211	0.215	-0.215	-0.713

Start Depth: 11.179m Stop Depth: 51.145m

[B]

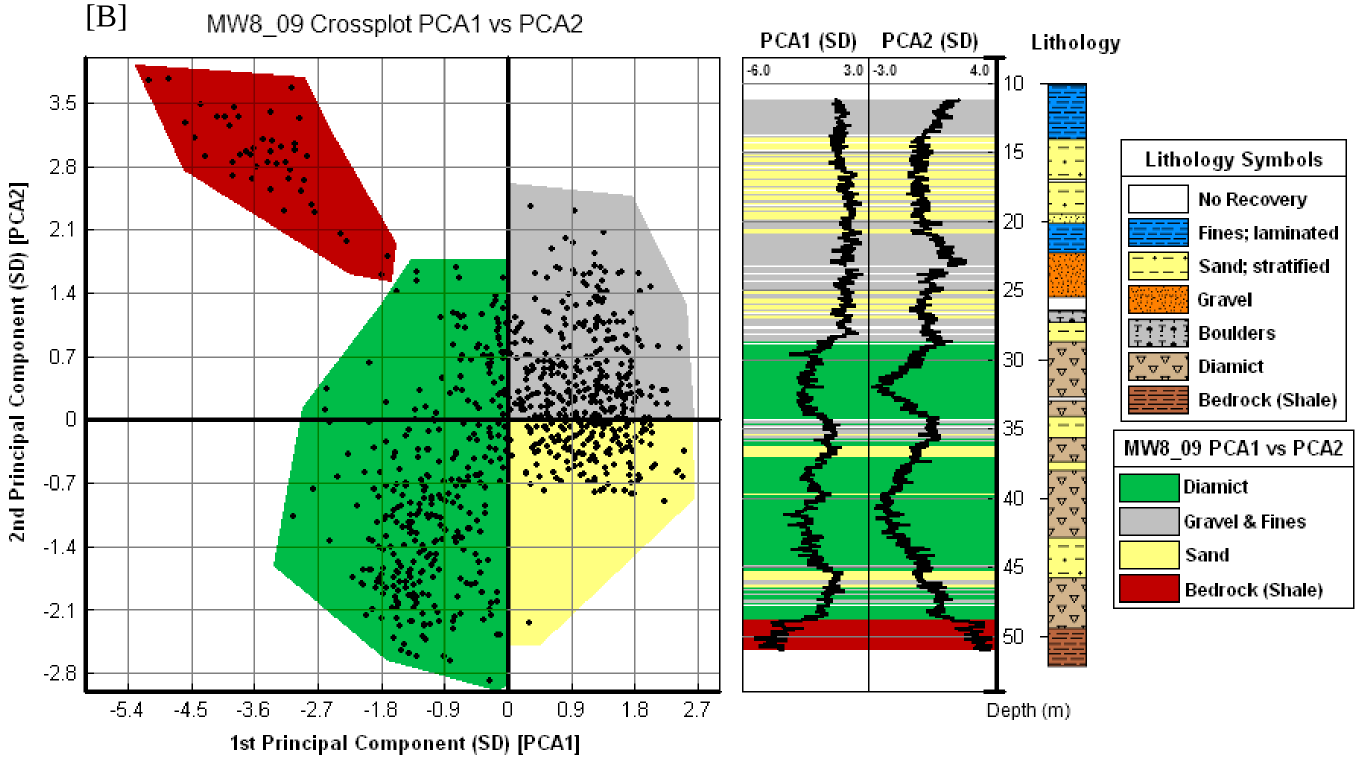
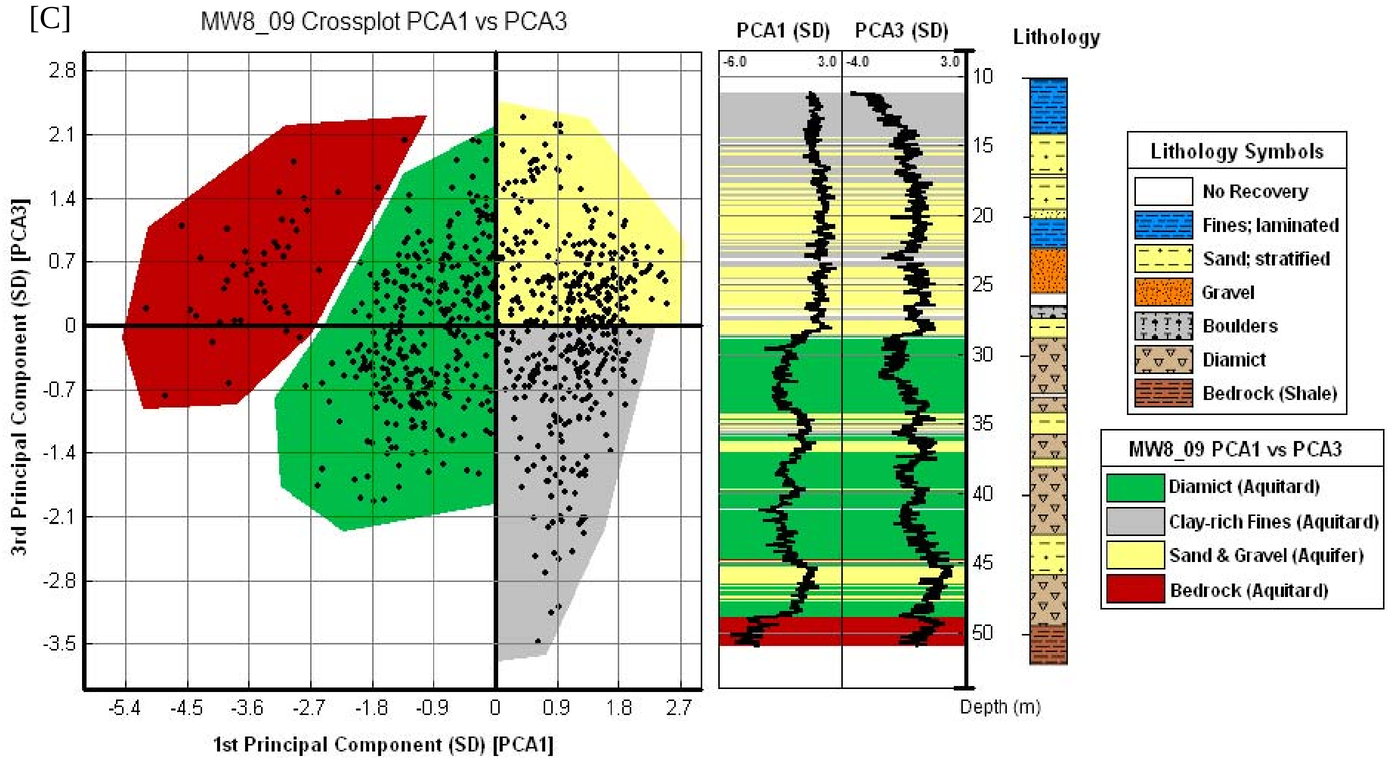


Figure 3-9 (continued): Principal Component Analysis for borehole MW8_09.

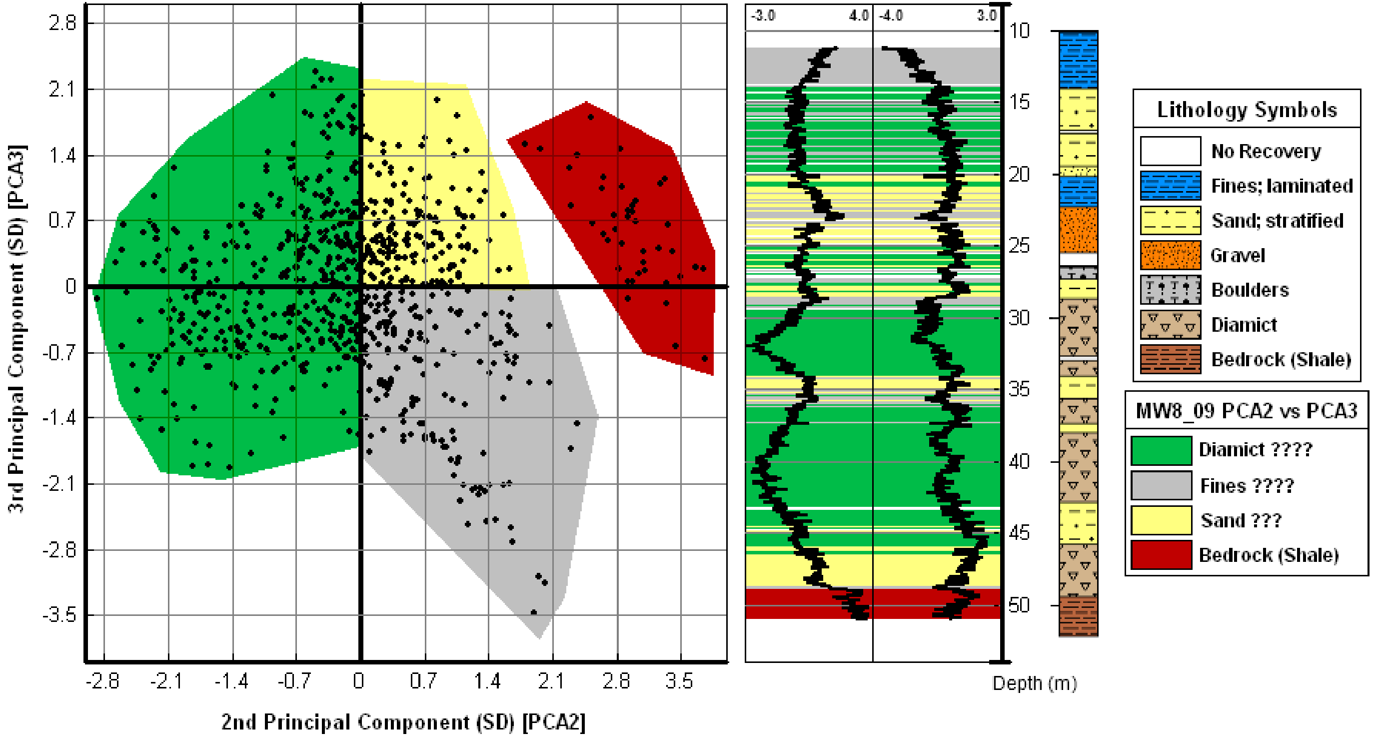
C) Crossplot of PCA1 and PCA3 for MW8_09. PCA1 values accurately separate dense/compact diamict units and bedrock from unconsolidated glaciofluvial outwash. PCA3 accurately separates sands and gravels (aquifers) from silts and clays in variably textured glaciofluvial outwash. This cross plot is most effective for hydro-stratigraphic classification and compares best with PCA1-2 cross plots for boreholes MW17 and MW9 (sections 3.5.1 and 3.5.2).

D): Crossplot of PCA2 and PCA3 for MW8_09 fails to accurately classify important hydro-stratigraphic units. Diamict presence is overstated in the upper portion of the borehole while sand, gravel and finer sediments are also poorly resolved.

[C]


MW8_09 Crossplot PCA1 vs PCA3
3rd Principal Component (SD) [PCA3]
1st Principal Component (SD) [PCA1]
2.8
2.1
1.4
0.7
0
-0.7
-1.4
-2.1
-2.8
-3.5
-5.4
-4.5
-3.6
-2.7
-1.8
-0.9
0
0.9
1.8
2.7
PCA1 (SD)
PCA3 (SD)
-6.0
3.0
-4.0
3.0
10
15
20
25
30
35
40
45
50
Depth (m)
Lithology
Lithology Symbols
No Recovery
Fines; laminated
Sand; stratified
Gravel
Boulders
Diamict
Bedrock (Shale)
MW8_09 PCA1 vs PCA3
Diamict (Aquitard)
Clay-rich Fines (Aquitard)
Sand & Gravel (Aquifer)
Bedrock (Aquitard)

[D]


MW8_09 Crossplot PCA2 vs PCA3
3rd Principal Component (SD) [PCA3]
2nd Principal Component (SD) [PCA2]
2.8
2.1
1.4
0.7
0
-0.7
-1.4
-2.1
-2.8
-3.5
-2.8
-2.1
-1.4
-0.7
0
0.7
1.4
2.1
2.8
3.5
PCA2 (SD)
PCA3 (SD)
-3.0
4.0
-4.0
3.0
10
15
20
25
30
35
40
45
50
Depth (m)
Lithology
Lithology Symbols
No Recovery
Fines; laminated
Sand; stratified
Gravel
Boulders
Diamict
Bedrock (Shale)
MW8_09 PCA2 vs PCA3
Diamict ????
Fines ????
Sand ???
Bedrock (Shale)

3.5.4 TH4_87 PCA

Following the application of PCA to cored holes where the results of cross plotting score logs could be readily verified, PCA was expanded across the database to archived boreholes where core data was unavailable. One such borehole is TH4_87, where the available geophysical log suite is limited to caliper, natural gamma and two resistivity measurements (0.25ft and 2.5ft resistivites). The limited log suites and inability to acquire additional geophysical data simplifies interpretation and provides a straightforward way to assess the impact of reducing physical parameters such as caliper that are poorly correlated to the remaining log curves. Two correlation matrices show the eigenvalues and eigenvectors for TH4_87 where Figure 3-10A includes the caliper log and Figure 3-10B excludes it. At this borehole, the caliper response is variable through the upper 20m (Figure 3-3B) and its inclusion in PCA does not improve discrimination of different lithologies. This is supported by the dominance of caliper for the PCA2 response, which accounts for 25% of the total variation. When caliper is removed however, the total variance incorporated into first two principal components exceeds 98% and allows for unique lithologies to be identified. A cross plot of PCA1 and PCA2 with caliper excluded allows PCA1 to separate clay-rich and clay-poor sediments while PCA2 separates more resistive diamict, gravel and bedrock from more conductive sands and clay/silt. The cross plotting results suggest a gradual fining upward sequence from coarse gravels and sands to clays and silts consistent with the interpretation made in Chapter 2.

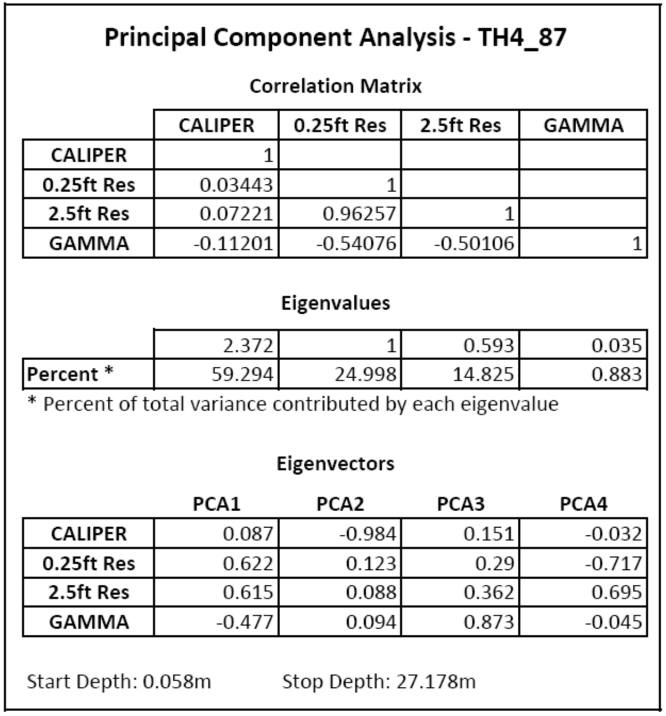
Figure 3-10: Principal Component Analysis for borehole TH4_87.

A) Correlation matrix, eigenvalues and eigenvectors including caliper log. Note dominance of caliper in PCA2 which accounts for 25% of total variation.

B) Correlation matrix, eigenvalues and eigenvectors for TH4_87 with caliper excluded. Total variance incorporated into first two principal components now exceeds 98%.

C) Crossplot of PCA1 and PCA2 for TH4_87 with caliper excluded. PCA1 values accurately separate clay-rich and clay-poor sediments. PCA2 accurately separates more resistive diamict, gravel and bedrock from more conductive sands and clay/silt.

[A]



Principal Component Analysis - TH4_87

Correlation Matrix

	CALIPER	0.25ft Res	2.5ft Res	GAMMA
CALIPER	1			
0.25ft Res	0.03443	1		
2.5ft Res	0.07221	0.96257	1	
GAMMA	-0.11201	-0.54076	-0.50106	1

Eigenvalues

	2.372	1	0.593	0.035
Percent *	59.294	24.998	14.825	0.883

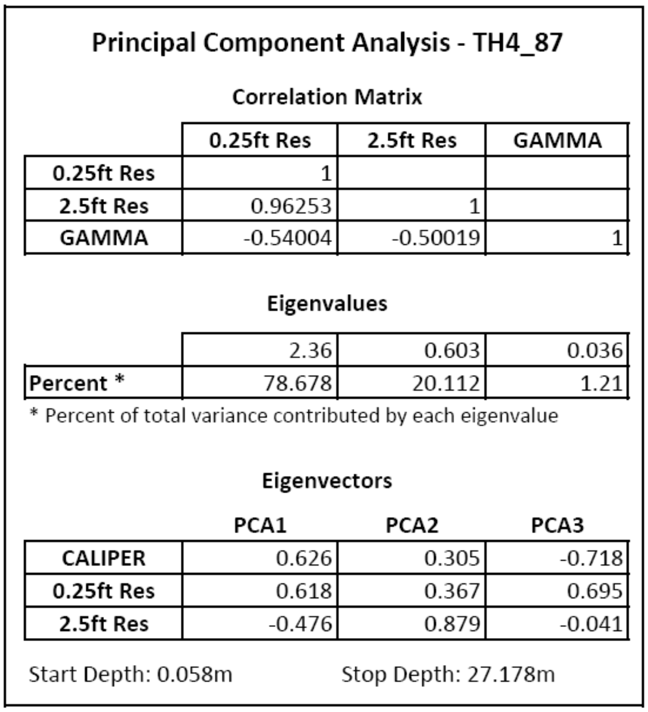
* Percent of total variance contributed by each eigenvalue

Eigenvectors

	PCA1	PCA2	PCA3	PCA4
CALIPER	0.087	-0.984	0.151	-0.032
0.25ft Res	0.622	0.123	0.29	-0.717
2.5ft Res	0.615	0.088	0.362	0.695
GAMMA	-0.477	0.094	0.873	-0.045

Start Depth: 0.058m Stop Depth: 27.178m

[B]



Principal Component Analysis - TH4_87

Correlation Matrix

	0.25ft Res	2.5ft Res	GAMMA
0.25ft Res	1		
2.5ft Res	0.96253	1	
GAMMA	-0.54004	-0.50019	1

Eigenvalues

	2.36	0.603	0.036
Percent *	78.678	20.112	1.21

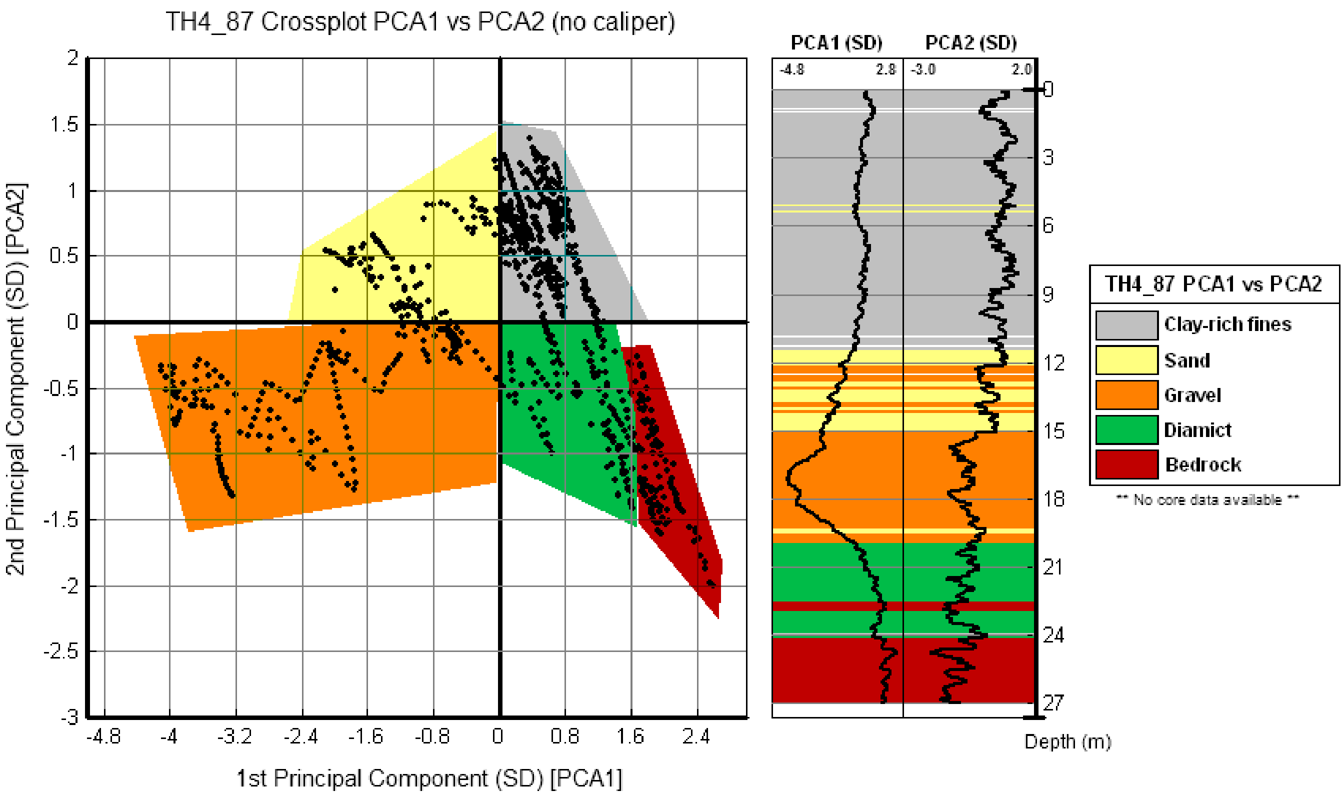
* Percent of total variance contributed by each eigenvalue

Eigenvectors

	PCA1	PCA2	PCA3
CALIPER	0.626	0.305	-0.718
0.25ft Res	0.618	0.367	0.695
2.5ft Res	-0.476	0.879	-0.041

Start Depth: 0.058m Stop Depth: 27.178m

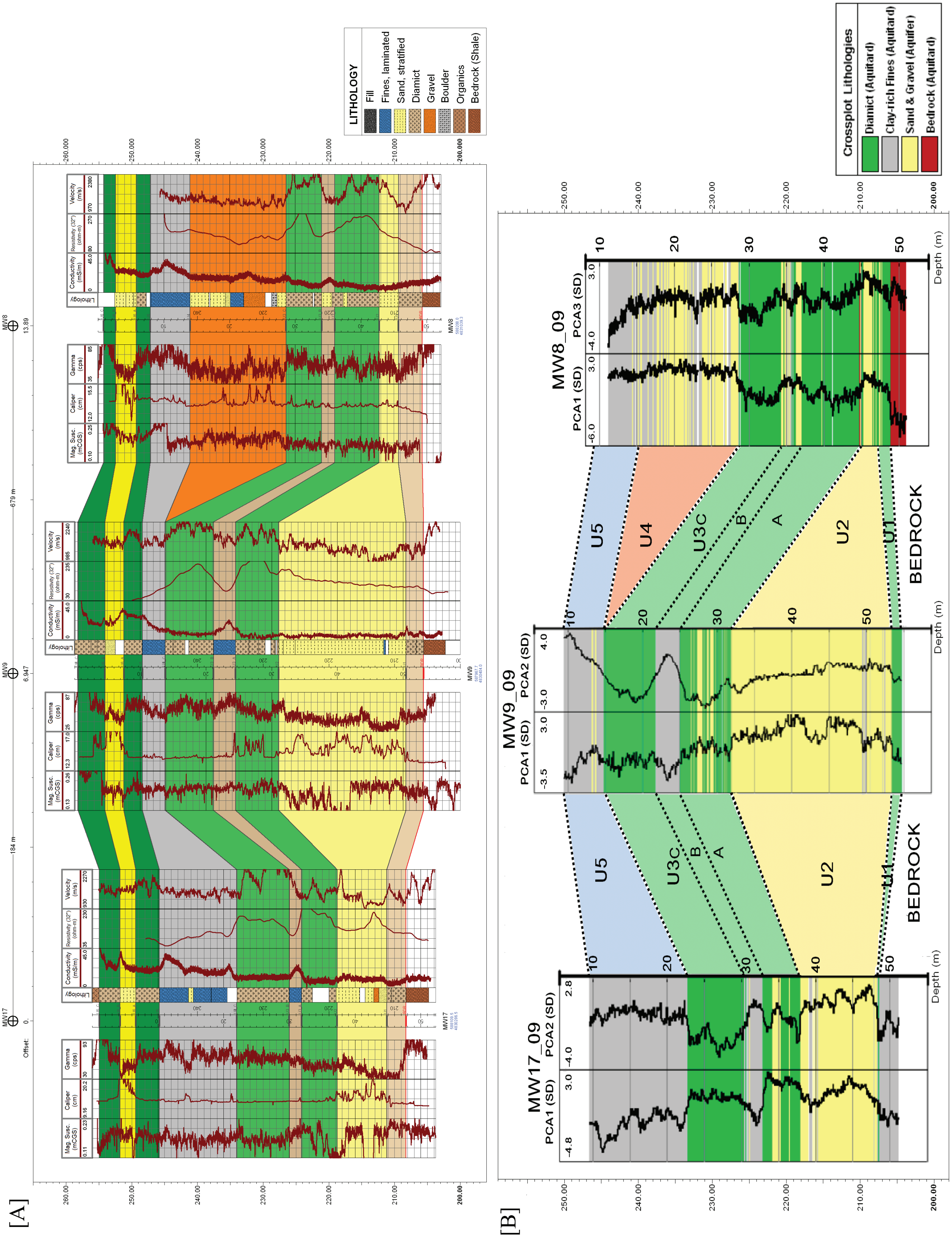
[C]



3.5.5 Correlation comparisons for MW17-9-8

Comparison of well-to-well correlations for MW17 – 9 – 8 from electrofacies and core analysis to correlations based on the results of cross plotting principal components (Figure 3-11) are nearly identical, highlighting the potential of PCA to aid in building a regional hydrostratigraphic framework using borehole geophysical data. Although PCA comparison are limited to the available depths of the geophysical data (in this case below the water table for resistivity and velocity logs), results of PCA can be used to confirm the validity of interpretations made from visual analysis and aid in the interpretation of complex data sets with ambiguous geophysical responses. In MW17_09 and MW9_09 the first and second principal components and in MW8_09 the first and third principal components can be related to hydrostratigraphically important geologic factors. In particular, responses related to clay content and pore waters are readily discernable from analysis of factor loadings on principal component score logs and are derived from 'hydrostratigraphic logs' typically acquired in regional groundwater investigations.

Figure 3-11: Comparison of well-to-well correlations for boreholes MW17, 9 and 8. A) Correlations based on conventional log curve matching and electrofacies analysis. B) Correlations based on objective classification of lithofacies using PCA cross plots. Note PCA analysis is restricted to 250-200 m subsurface interval and excludes information above 10m depth. Cross plotting results illustrate the ability of PCA to objectively classify lithofacies and delineate Quaternary hydrostratigraphic units in the Georgetown buried valleys.


[A]
[B]
LITHOLOGY
Fill
Fines, laminated
Sand, stratified
Diamict
Gravel
Boulder
Organics
Bedrock (Shale)
MW17
MW9
MW8
Offset:
0
184 m
6.947
679 m
13.89
Mag. Susc. (mCGS)
Caliper (cm)
Gamma (cps)
Lithology
Conductivity (mS/m)
Resistivity (32") (ohm-m)
Velocity (m/s)
Crossplot Lithologies
Diamict (Aquitard)
Clay-rich Fines (Aquitard)
Sand & Gravel (Aquifer)
Bedrock (Aquitard)
MW17_09
MW9_09
MW8_09
PCA1 (SD)
PCA2 (SD)
PCA3 (SD)
Depth (m)
U5
U4
U3C
B
A
U2
U1
BEDROCK
260.00
250.00
240.00
230.00
220.00
210.00
200.00

3.6 Discussion and Conclusions

The ability to classify and separate lithologies by geologic factors such as density/compaction, clay content, and porewater conductivity are important for the ability to characterize the downhole hydro-stratigraphy into aquifers and aquitards. While the actual location of PCA score points in principal component cross plots are less important an indicator of a formation as distinct clustering of scores associated with fine grained (aquitard), over-consolidated (aquitard) and coarse grained (aquifer) units, data clouds separated along the zero standard deviation lines can be used to accurately identify separate formations where data clusters are less apparent. Consequently, where borehole geophysical logs are collected for future hydrostratigraphic investigations, PCA represents a valuable tool for objectively identifying these formations.

Identifying the probable geologic factors underlying each of the principal component score logs is important for optimizing the results of PCA. Data variation and factor loadings will expectedly vary from one well to another, consequently evaluation of the dependencies between parameters is required before reducing the parameters used for PCA to those deemed most useful for lithologic and or hydrostratigraphic discrimination.

In the 5 parameter analysis of cored boreholes used in this study, the first three principal components (PCA1-3) were able to account for an average of >86% total variation, and in two of the three examples shown, the third principal component was dominated by a log response that did not correspond with the overall symmetry of log responses. Natural gamma and electrical logs (conductivity and resistivity) were the most important for hydro-stratigraphic classifications as all three methods respond to the presence of clays, but only the electrical logs also respond to changes in porewater conductivity. Therefore using PCA to remove the variation associated with clay content allowed the zones influenced by porewater conductivity to be studied and independently compared. P-wave velocity was useful for improving the clustering of compact diamict layers observed in the MSMC area (Chapter 2) while magnetic susceptibility was useful for comparing textural characteristics, but its variation was typically concentrated in lower order principal components.

Kassenaar (1991) notes that where there is a high degree of correlation between the various measurements, the tools are either responding to common physical properties or the physical properties controlling the measurements (ie. electrical response) are highly correlated. Results of this study suggest that the redundancy in the original log suites are dominated by inter-related physical properties and that cross plots that combine a clay content response with density/compaction or porewater conductivity response will be most effective for classifying the downhole hydrostratigraphy into aquifers and aquitards.

CHAPTER 4: Summary and Conclusions

This thesis has employed multi-parameter borehole geophysical logging to characterize both the lithostratigraphy and hydrostratigraphy of Quaternary sediments within buried bedrock valleys near Georgetown, Ontario. Principal Component Analysis (PCA) was evaluated and has been shown to be a useful approach for quantitative classification of hydrostratigraphic units. This thesis demonstrates the advantages of borehole geophysical logging of complex buried valley sequences that can be broadly applied to various regions where investigations of buried valleys and glacial sediments are planned. The following sections summarize the principal conclusions of each chapter in this thesis.

Chapter 1 provided a review of the study background and highlighted the current groundwater supply challenges facing Halton Region. As outlined, the primary obstacle to further groundwater resource development was a lack of understanding of the subsurface geology and hydrostratigraphy of Quaternary sediments. This thesis contributes to filling this important knowledge gap by better resolving the stratigraphic framework and subsurface characteristics of the Middle Sixteen Mile Creek (MSMC) and Cedarvale (CV) valley infills. A major component of this work involved the correlation and analysis of geophysical log suites, consequently a brief overview of well log acquisition, processing and interpretation including the principles of operation for each probe was discussed. A brief explanation of the theory and application of Principal Component Analysis applied to geophysical log suites and the subsurface modeling methodology employed in this thesis was also summarized.

Chapter 2 presented the results of subsurface modeling of Quaternary strata in the MSMC and CV buried valleys using core and borehole geophysical data. The geophysical log responses exhibited a range of values but electrofacies patterns were distinctive for many units and allowed correlation of the Quaternary deposits in areas where core data are unavailable. In total, 9 distinctive lithostratigraphic units and 13 distinctive electrofacies were identified across the study area with gamma, resistivity, conductivity and magnetic susceptibility logs being most useful for lithologic discrimination while resistivity and p-wave velocity were most important for discriminating and correlating more compact diamict units in the MSMC area.

In the MSMC buried valley, 6 distinctive lithostratigraphic units were identified within a thick (> 55 m) interbedded sequence of diamict (aquitards), laminated silts and coarse-grained glaciofluvial deposits (aquifers) overlying shale bedrock. The lithologies encountered downhole were generally predictable and electrofacies more distinctive (e.g. velocity and ‘dual-peak’ resistivity of Newmarket Till) than the Cedarvale or Princess Anne areas, owing to differences in their depositional history. The depositional history of the MSMC buried valley infill is consistent with the regional stratigraphy noted both locally (Meyer & Eyles, 2007; Slomka, 2011) and regionally (Davies & Holysh 2007; Karrow, 2005) and has been heavily influenced by the regionally extensive Newmarket and Halton ice advances, both of which are recorded in the MSMC stratigraphy. The MSMC buried valley hosts up to 20m thick deposits of sands (possible Thorncliffe Formation equivalent) capped by the Newmarket Till and may be suitable targets for high yield municipal wells.

In contrast, the CV valley, which hosts the Cedarvale well field currently supplying water to Georgetown is composed of a complex succession of younger glaciofluvial gravel, sand and silt up to 45 m thick that truncate the older MSMC stratigraphy across a well-defined erosional unconformity and were deposited in a sediment-hosted valley. Opposite the MSMC buried valley, the Princess Anne municipal well field is located in the northwestern corner of the study area where the lowermost diamict unit (Newmarket Till) was thinned or erosionally truncated, allowing direct communication of the upper and lower aquifers. The Princess Anne wells have been tentatively related to the MSMC stratigraphy in this study, but more work is needed to confirm the relationship between the two areas.

Modeling results (Figure 2-13) demonstrate the high level of stratigraphic heterogeneity and complexity that is inherent in bedrock valley systems in southern Ontario and provides a geological framework for understanding groundwater resource availability. Particularly, the correlation of electrofacies and lithostratigraphy across the study area allows bedrock valleys, primary aquifers and regional aquitards to be identified and their geometries defined through subsurface modeling and generation of a three dimensional fence diagram. Correlated electrofacies of coarse, fine grained and over-consolidated units are used to infer hydrostratigraphic unit continuity and model the geometry of aquifers and aquitards across the study area. Contour and isochore mapping permitted a more detailed analysis of individual surfaces along the highly complex intersection of the CV and MSMC bedrock valleys and confluence of the modern Black and Silver Creeks. Accordingly, the hydrostratigraphic framework of the Georgetown area is a result of the complex interaction of buried bedrock valleys, modern valley incisions, the hydraulic confinements of the Niagara Escarpment and thick multi-phase sediment packages deposited and reworked by the interactions of advancing and retreating ice.

Chapter 3 demonstrates the effectiveness and utility of PCA for lithologic typing and delineation of hydrostratigraphic units using a suite of multi-parameter geophysical logs collected from the MSMC valley. The PCA process combines the correlatable portions of log curves across a suite of geophysical responses, allowing the remaining variability in log responses to be studied independently. This process is repeated until all the variation has been accounted for, after which the dependencies between correlated log responses are evaluated. Geophysical logs respond synergistically to geologic factors such as density/compaction, clay content and porewater conductivity, consequently, downhole lithologies can be objectively classified into aquifer and aquitard status via cross plots of Principal Component score logs, particularly those score logs related to clay content and porewater conductivity. Characteristic clay content and porewater conductivity responses are readily discernable from analysis of factor loadings of the Principal Components and are derived from 'hydrostratigraphic' logs typically acquired in regional groundwater investigations.

Comparison of well-to-well correlations for MW17 – 9 – 8 from electrofacies and core analysis to correlations based on the results of cross plotting principal components (Figure 3-11) were virtually identical, highlighting the potential of PCA to aid in building a regional hydro-stratigraphic framework using borehole geophysical data. These results suggest PCA can also be used to confirm the validity of interpretations made from visual analysis and could aid in the interpretation of more complex or ambiguous log responses.

Of all the geophysical logs collected as part of this thesis, natural gamma, conductivity and resistivity logs were the most useful for hydrostratigraphic classifications using PCA as all three methods respond to the presence of clays, but only the electrical logs respond to changes in porewater conductivity. Therefore, cross plots that combine a clay content response with a porewater conductivity or density/compaction response were most effective in classifying the downhole hydrostratigraphy into aquifers and aquitards.

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