SUBSURFACE STRATIGRAPHY AND HYDROGEOLOGY OF THE PETERBOROUGH DRUMLIN FIELD, SOUTHERN ONTARIO, CANADA

SUBSURFACE STRATIGRAPHY AND HYDROGEOLOGY OF THE PETERBOROUGH DRUMLIN FIELD, SOUTHERN ONTARIO, CANADA

By

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ABSTRACT

The Peterborough Drumlin Field in southern Ontario, Canada (PDF; Crozier 1975, Karrow 1981, Boyce and Eyles 1991) is a well-documented and extensive drumlin field that hosts many communities dependent upon groundwater resources. Population growth in the area and concerns for the long-term sustainability of these resources has prompted considerable interest in determining the location, extent and potential productivity of subsurface aquifers in the region. The origin of the drumlins within the PDF is still widely debated, despite many years of study, and there is little understanding of the nature, geometry, and connectivity of aquifers within the Quaternary-age sediments beneath the drumlins.

This study involves detailed analysis of sedimentological data available from water well logs from selected drumlins and adjacent low areas (swales) in the PDF. These data are used to investigate the subsurface stratigraphy of the drumlins, contribute to the understanding of drumlin formation, and establish hydrogeological characteristics of drumlins within the PDF. A relatively consistent subsurface stratigraphy can be identified in the studied drumlins consisting of patchy units of sand and gravel overlying a southward sloping bedrock surface, a thick diamict (till) package containing discontinuous coarse-grained sand and gravel units, and surface veneers of sand, silt or clay in low areas (swales) between drumlins. This subsurface stratigraphy can be traced between drumlins and adjacent swales and suggests that the drumlins within the PDF formed largely as a result of subglacial erosion of pre-existing sediment.

Two major aquifers can be identified beneath the PDF from the water well records; one is a basal aquifer within fractured bedrock and overlying coarse-grained sands and gravels, and the second (upper aquifer) is formed by the discontinuous zone of sands and gravels within till. These coarse-grained interbeds within the till allow it to function as a 'leaky aquitard' and produce groundwater flow pathways that are not easy to predict, may not be high-yielding, and may be susceptible to anthropogenic sources of contamination; these characteristics will likely prevent further development of this aquifer for multi-user (communal) water supply. The Hiawatha First Nations (HFN) community is located within the Peterborough Drumlin Field and has been attempting to find a more sustainable, and possibly communal, groundwater supply in the drumlizined terrain. Examination of lithological and hydrogeological data from water well records together with information obtained from four recently drilled on-site wells allowed for a detailed analysis of the till stratigraphy within this portion of the drumlin field. The stratigraphy identified at this site is consistent with that identified elsewhere in the PDF and a basal bedrock aquifer and an upper discontinuous Quaternary aquifer can be discriminated. It is recommended that the HFN community continue to upgrade/maintain individual private wells in the discontinuous upper aquifer and utilize the basal bedrock aquifer for developments that require greater water yields. This study provides insight into the subsurface stratigraphy that may be found beneath drumlins in an extensive drumlin field and may help in determining the origin of these enigmatic landforms. Enhanced understanding of the hydrogeological characteristics of Quaternary-age sediments underlying drumlin fields will assist in the development of appropriate exploration, protection, and remediation strategies for valuable groundwater resources.

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And finally an extra special thank you to Mike – you are always there for me, provide never-ending support and encouragement. I wouldn't be where I am without you!

And yes, John, I am done now.

Contents

List of Figures

List of Tables

CHAPTER 1 - INTRODUCTION

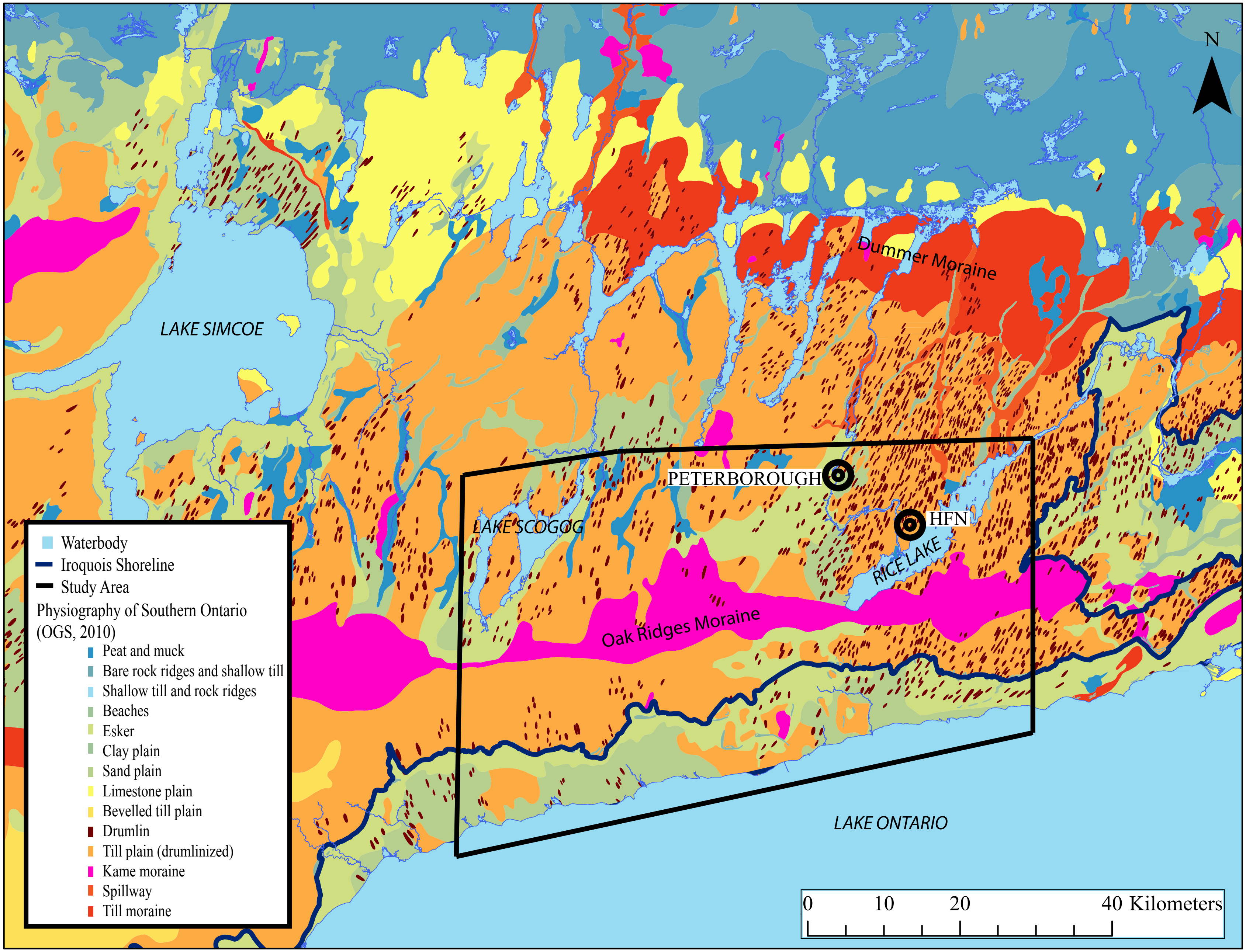
1.1 Introduction

In Peterborough County, Ontario thousands of homes are supplied with drinking water from wells supplied by aquifers hosted in and beneath Quaternary sediments. There is growing concern about the sustainability of these drinking water resources given the demands of an increasing population and environmental stressors. The Quaternary sediments were deposited during the last major glacial event (Wisconsin) and consist primarily of subglacial tills with interbedded coarse-grained glaciofluvial sediments. The surface topography of the Peterborough area is characterized by an extensive drumlin field and some of the rural water wells penetrate drumlins (Fig. 1.1). The origin of the Peterborough Drumlin Field (PDF) is a topic of considerable debate (e.g. Shaw, 1983; Boulton and Hindmarsh, 1987; Shaw and Sharpe, 1987; Shaw and Gilbert, 1990; Boyce and Eyles, 1991; Gilbert and Shaw, 1994; Stokes, et al., 2011; Maclachlan and Eyles, 2013) which is still not resolved. The PDF contains upwards of 3000 drumlins which have varying length, width and relief (Boyce and Eyles 1991; Maclachlan and Eyles 2013). This lack of understanding of the nature of sediments underlying the PDF is a major obstacle to the development of effective groundwater exploration and protection programs. It is apparent that a thorough analysis of subsurface conditions in the PDF is required to both enhance understanding of drumlin genesis and to determine the local and regional hydrogeological properties of the drumlinized sediments.

1.2 Objectives of Research

This study aims to investigate the subsurface geology and stratigraphy of a selected portion of the PDF through analysis of water well data available through the on-line Water Well

Figure 2.1. The physiography of Southern Ontario (OGS 2010). Drumlins in the Peterborough Drumlin Field are shown with brown ovals. Note variable orientation of drumlins. Dummer Moraine to north. Oak Ridges Moraine is found in the center of the drumlin field. Note the Lake Iroquois shoreline close to Lake Ontario (blue line). Study area delineated by black rectangle.


N
LAKE SIMCOE
Dummer Moraine
PETERBOROUGH
HFN
LAKE SCOGOG
RICE LAKE
Oak Ridges Moraine
LAKE ONTARIO
Waterbody
Iroquois Shoreline
Study Area
Physiography of Southern Ontario (OGS, 2010)
Peat and muck
Bare rock ridges and shallow till
Shallow till and rock ridges
Beaches
Esker
Clay plain
Sand plain
Limestone plain
Bevelled till plain
Drumlin
Till plain (drumlinized)
Kame moraine
Spillway
Till moraine
0 10 20 40 Kilometers

Information System (WWIS; http://www.ontario.ca/environment-and-energy/map-well-record-data). Over 90000 drilled or dug wells used for monitoring, municipal or domestic water supply in the area of the PDF have records hosted in the WWIS. During the installation of all drinking water wells in Ontario a summary of sediments encountered is recorded as well as other information regarding groundwater characteristics (static water level, results of short pumping test, type of water, depth water found). In hydrogeologic investigations, water well data are often the first to be analyzed as they are readily available and provide a framework from which to structure further work. .

A previous geomorphological study of a portion of the PDF (Maclachlan and Eyles 2013) performed a quantitative analysis that identified the form and spatial distribution of drumlins using Geographic Information Systems (GIS). This analysis produced GIS data that can be used as a spatial framework to identify water wells that specifically penetrate drumlins and adjacent low areas (swales). The current study therefore uses the same portion of the PDF to study the subsurface geology and hydrogeology of selected drumlins (Fig. 1.1).

Although the WWIS is a rich source of data, the information it contains regarding subsurface sedimentological conditions must be used with caution as material types and well locations are not always reported accurately. However, detailed sedimentological analysis of material properties and careful checking of well location data allowed the construction of numerous stratigraphic cross sections to provide insight into the subsurface stratigraphy of drumlins in the PDF and their hydrostratigraphic properties.

1.3 Quaternary History of the Peterborough Drumlin Field

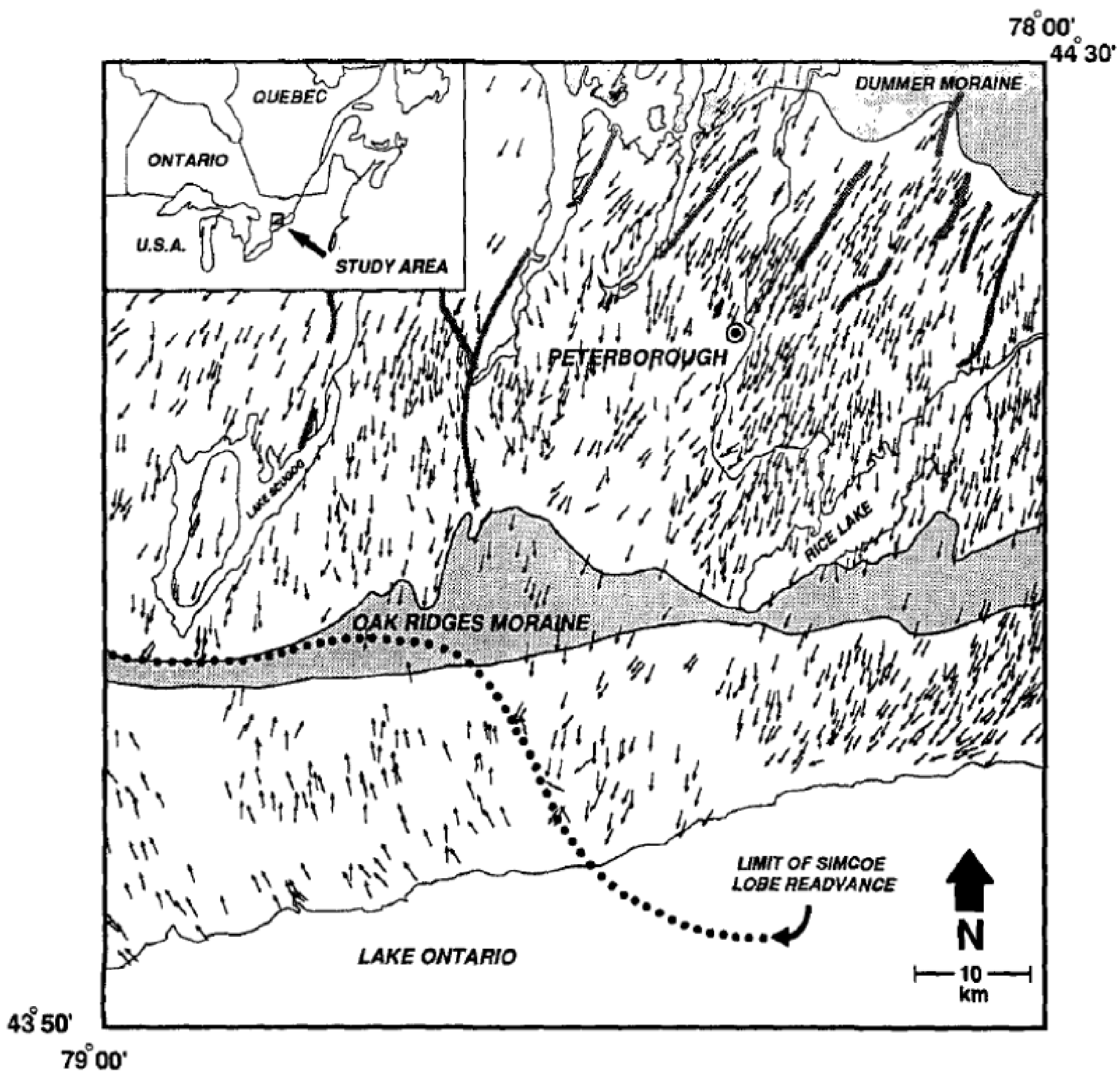
The Peterborough Drumlin Field extends from undrumlinized glacial deposits near Lake Simcoe in the west to the limits of glacial sediment cover and Paleozoic limestone in the north (Fig. 1.1; Crozier 1973). In the northeast, the drumlin field merges with the Dummer moraine. Drumlins can be found from south of the Dummer moraine, underneath the Oak Ridges Moraine, all the way to Lake Ontario in the south. The PDF is thought to be underlain by late Wisconsin till (predominantly the Northern/Newmarket Till; Boyce and Eyles 1991) deposited between 13.3 ka and 25 ka below the Lake Ontario ice stream of the Laurentide Ice Sheet (LIS; Boyce et al. 1995; Boyce and Eyles 2000; Mariano and Eyles 2008; Gerber and Howard 1996; Gerber and Howard 2000; Gerber et al. 2001). Drumlinization may have occurred during this period and/or during readvance of the ice sheet shortly after 13,000 y.B.P. when an ice stream within the Simcoe lobe thrust southward and overrode the eastern portion of the Oak Ridges moraine (Boyce and Eyles 1991). The southward flow of the Simcoe lobe of the LIS resulted in the northern and eastern drumlins in the PDF orientated predominantly in a south-southwest direction; the south-western portion of the drumlin field records the northwestward movement of the Ontario lobe out of the Ontario basin and the drumlins are orientated similarly (Fig. 1.2; Boyce and Eyles 1991; Maclachlan 2011).

1.4 Identifying drumlins in the PDF

The most widely credited definition of drumlins is after Menzies (1979) who describes drumlins as "smooth, oval shaped hills or hillocks of glacial drift resembling in morphology an inverted spoon or an egg half buried along its axis." Further to this definition, Menzies (1979) alludes to the long-axis being parallel to the direction of ice flow with the lee face (down-ice) having a more gentle slope than the stoss (up-ice) face. More recently, Spagnolo et al. (2010)

quantitatively studied over 29 000 drumlins and using a statistical approach to defining the absolute highest point of a drumlin, found that the "classically asymmetric shape" that has been previously reported is not very common. More often, drumlin shape tends towards a symmetric profile, thus eliminating the ability to conclude palaeo ice flow direction (other than north-south or east-west) with any certainty (Spagnolo et al., 2010). Kerr and Eyles (2007) present a method of defining drumlins as "topographic highs with at least three enclosed contours" on maps at a certain scale with a specific contour interval. In a recent review of drumlin types, Stokes et al (2010) suggest that it is significant to distinguish between the composition (the constituents of a drumlin) and the structure (the "spatial arrangement of the constituents and their relationship to each other"). Previous studies of the types of drumlins suggest that describing internal structure is sufficient. Menzies (1979) and others (Boyce and Eyles 2000; Kerr and Eyles 2007) describe drumlins as being comprised of everything from "stratified sand to unstratified till to solid bedrock". In this study, the computational methodology proposed by Maclachlan (2011) and Maclachlan and Eyles (2013), to identify drumlins with relief of greater than 20m from closed loop contours on a 10 meter DEM, was used.

Figure 1.2. Schematic map of the orientation of drumlins in the Peterborough Drumlin Field and the extent of the Simcoe lobe readvance. Note the change in drumlin orientation in the south-western portion of the figure. (Boyce and Eyles, 1991)


78°00'
44°30'
QUEBEC
ONTARIO
U.S.A.
STUDY AREA
DUMMER MORAINE
PETERBOROUGH
LAKE SCUGOG
RICE LAKE
OAK RIDGES MORAINE
LIMIT OF SIMCOE
LOBE READVANCE
LAKE ONTARIO
N
10
km
43°50'
79°00'

1.5 Origin of drumlins

There are many theories to account for the formation of drumlins. These include hypotheses ascribing drumlins (1) an accretionary origin resulting from successive deposition of subglacial till beds (Menzies et al. 1997), (2) an origin through erosional streamlining as a result of deformation of pre-existing sediments (Boulton and Hindmarsh 1987; Boyce and Eyles 1991), (3) formation by infilling of cavities at the base of ice sheets by catastrophic subglacial megafloods (Shaw 1983) and (4) formation by erosion of pre-existing subglacial sediment by catastrophic subglacial floods (Shaw and Sharpe 1987). There have been many attempts to further develop these hypotheses and two theories have garnered the most attention. The first theory, introduced originally by Shaw (1983), involves subglacial meltwater floods. The second hypothesis, supported by Boulton and Hindmarsh (1987) is drumlin formation by subglacial deformation. Currently, there is no unifying theory of drumlin formation. Neither of the aforementioned theories have been widely adopted, although both have been widely criticised.

1.5.1 *Subglacial Meltwater Flood Hypothesis*

The subglacial meltwater flood hypothesis suggests that drumlins are largely the result of catastrophic subglacial meltwater discharges and form when cavities are eroded into overlying ice by subglacial floodwaters, and are subsequently infilled with sediment (Fig. 1.3; Shaw 1983). He supports this theory by stating that flow requirements, large sources of melt water, and the potential for melt water storage and release exist in a glacier system (Shaw 1983). Gilbert and Shaw (1994) suggest that these megafloods have occurred repeatedly in the Great Lakes region.

Drumlins formed in this way would be expected to be composed primarily of stratified or sorted sediments, or deformed beds with varying lithologies.

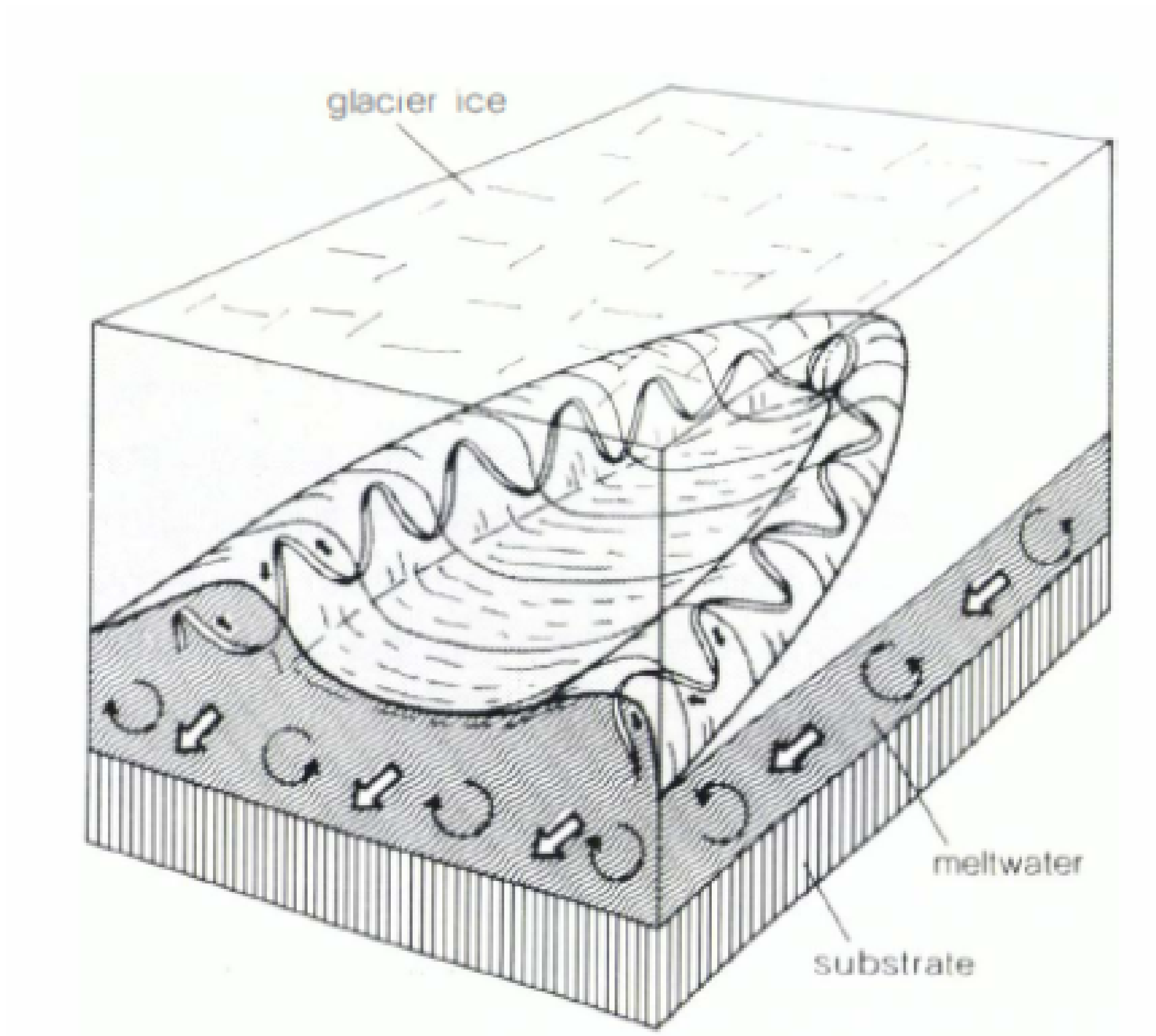
To account for drumlins of different composition, the subglacial meltwater flood hypothesis was later modified by Shaw and Sharpe (1987) to include an erosional component, which proposes that some drumlins are remnant ridges left upstanding between areas of substrate that has been scoured by subglacial megafloods (Shaw and Sharpe 1987).

1.5.2 *Subglacial Deformation*

The formation of individual drumlins according to the subglacial deformation theory involves the remobilization of water-saturated sediment beneath the moving glacier (Boulton and Hindmarsh 1987; Eyles at al. 1999; Kerr and Eyles 2007; Maclachlan and Eyles 2013). In this scenario, pre-existing bed materials undergo streamlining by a deforming fine-grained, and water-saturated till layer moving below the ice sheet. Coarser grained sediments overridden by ice drain and are less easily deformed becoming streamlined into drumlinized forms (Boulton and Hindmarsh 1987). Drumlins formed in this way should also have a core of coarse grained sediments with a thin covering of finer-grained deformation till on the surface (Boulton and Hindmarsh 1987; Boyce and Eyles 1991; Maclachlan and Eyles 2013). Drumlin shape should also change down gradient because of changes in the length and extent of subglacial deformation (Maclachlan and Eyles 2013). Substrate type and overburden thickness will also play a role in deformation processes (Kerr and Eyles 2007).

Boyce and Eyles (1991) proposed that the drumlins of the PDF formed as a result of erosion of pre-existing sediment into drumlin forms by streams of deforming till. They suggest that the cores of many drumlins in the PDF consist of relatively undeformed, coarse-grained outwash deposits that were resistant to erosion (Fig. 1.4; Boyce and Eyles 1991). It is hoped that this study of selected drumlins within the PDF will provide additional information regarding the substrate stratigraphy of drumlins that may help resolve the origin of these drumlins.

Figure 1.3. Schematic model for subglacial meltwater flow conditions required for the production of an erosional mark on the underside of a glacier (Shaw, 1983). These erosional marks are hypothesized to later fill with sediment to form drumlins.


glacier ice
meltwater
substrate

1.6 Thesis Structure

The findings of the research reported in this thesis are presented in two chapters:

CHAPTER 2: THE SUBSURFACE GEOLOGY OF THE PETERBOROUGH DRUMLIN FIELD: IMPLICATIONS FOR DEVELOPING DOMESTIC WATER SUPPLIES

This chapter reports on a study of water well data from 13 selected drumlins and associated low areas (swales) in the PDF. Analysis of stratigraphic cross-sections constructed from the data indicates that the bedrock surface slopes toward Lake Ontario and is overlain by a thin, discontinuous veneer of sand and gravel that, together with fractured bedrock, form a lower, regionally continuous aquifer. The bulk of the subsurface stratigraphy beneath the PDF consists of diamict with a discontinuous horizon of sands and gravels that form an upper aquifer. The elevation of this upper aquifer decreases from north to south across the region. The presence of coarse-grained interbeds within the till allow it to function as a 'leaky aquitard' (Gerber and Howard 1996; Gerber and Howard 2000; Gerber et al. 2001) producing groundwater flow pathways that are not easy to predict and which can have significant implications for contaminant transport and groundwater supply. The data presented in this chapter do not indicate the presence of substantial thicknesses of coarse-grained outwash beneath the PDF (as suggested by Boyce and Eyles 1991). The stratigraphic continuity of sedimentary units beneath both drumlins and swales suggests that the drumlins have formed largely as the result of erosion of the pre-existing stratigraphy with minor amounts of sediment remobilization and deformation.

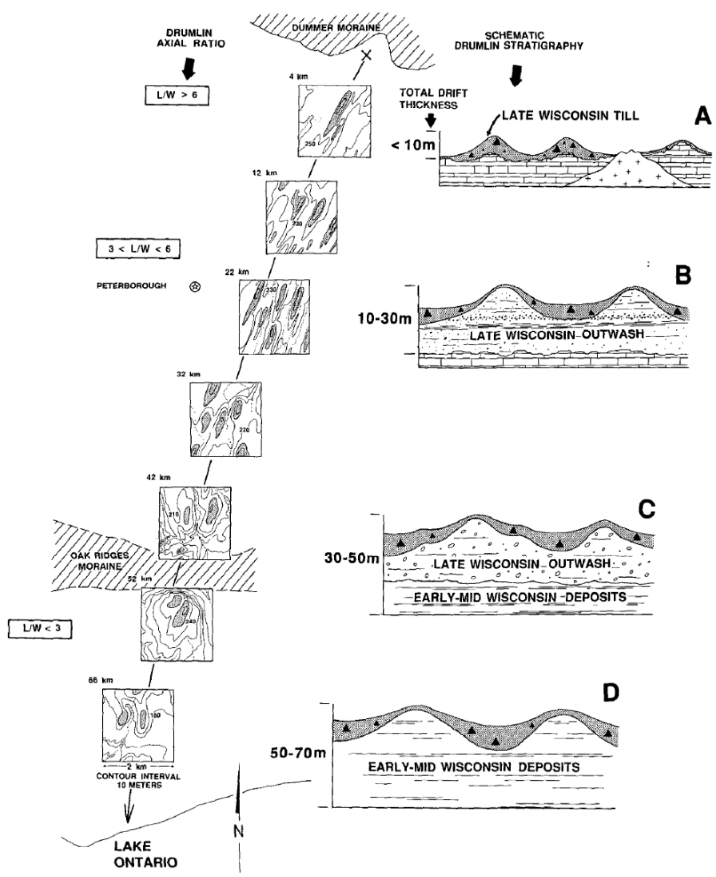
CHAPTER 3: THE HIAWATHA FIRST NATION RESERVE: DEVELOPING GROUNDWATER SUPPLIES IN DRUMLINIZED TERRAIN

This chapter reports on a detailed study of water well records and a cored borehole on the Hiawatha First Nation (HFN) reserve which lies on the northern shores of Rice Lake within the

PDF. Analysis of the subsurface stratigraphy below the mega-drumlin on which the HFN reserve lies gives results consistent with those reported in Chapter 2. Two aquifers, a basal bedrock and upper sand and gravel, can be identified. The upper aquifer appears to be discontinuous and is unlikely to have the capacity to support additional (communal?) wells whereas the basal bedrock aquifer has the potential for further development.

The final chapter of the thesis provides a list of conclusions and suggestions for further research.

Figure 1.4. Schematic representation of the changing form and composition of drumlins from north to south in the PDF. Drumlin contour interval is 10m. (from Boyce and Eyles, 1991)


DRUMLIN AXIAL RATIO
DUMMER MORAINE
SCHEMATIC DRUMLIN STRATIGRAPHY
L/W > 6
TOTAL DRIFT THICKNESS
LATE WISCONSIN TILL
A
< 10m
3 < L/W < 6
PETERBOROUGH
B
10-30m
LATE WISCONSIN OUTWASH
C
30-50m
LATE WISCONSIN OUTWASH
EARLY-MID WISCONSIN DEPOSITS
OAK RIDGES MORAINE
L/W < 3
D
50-70m
EARLY-MID WISCONSIN DEPOSITS
CONTOUR INTERVAL 10 METERS
LAKE ONTARIO
N

REFERENCE LIST

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Chapter 2

The Subsurface Geology of the Peterborough Drumlin Field

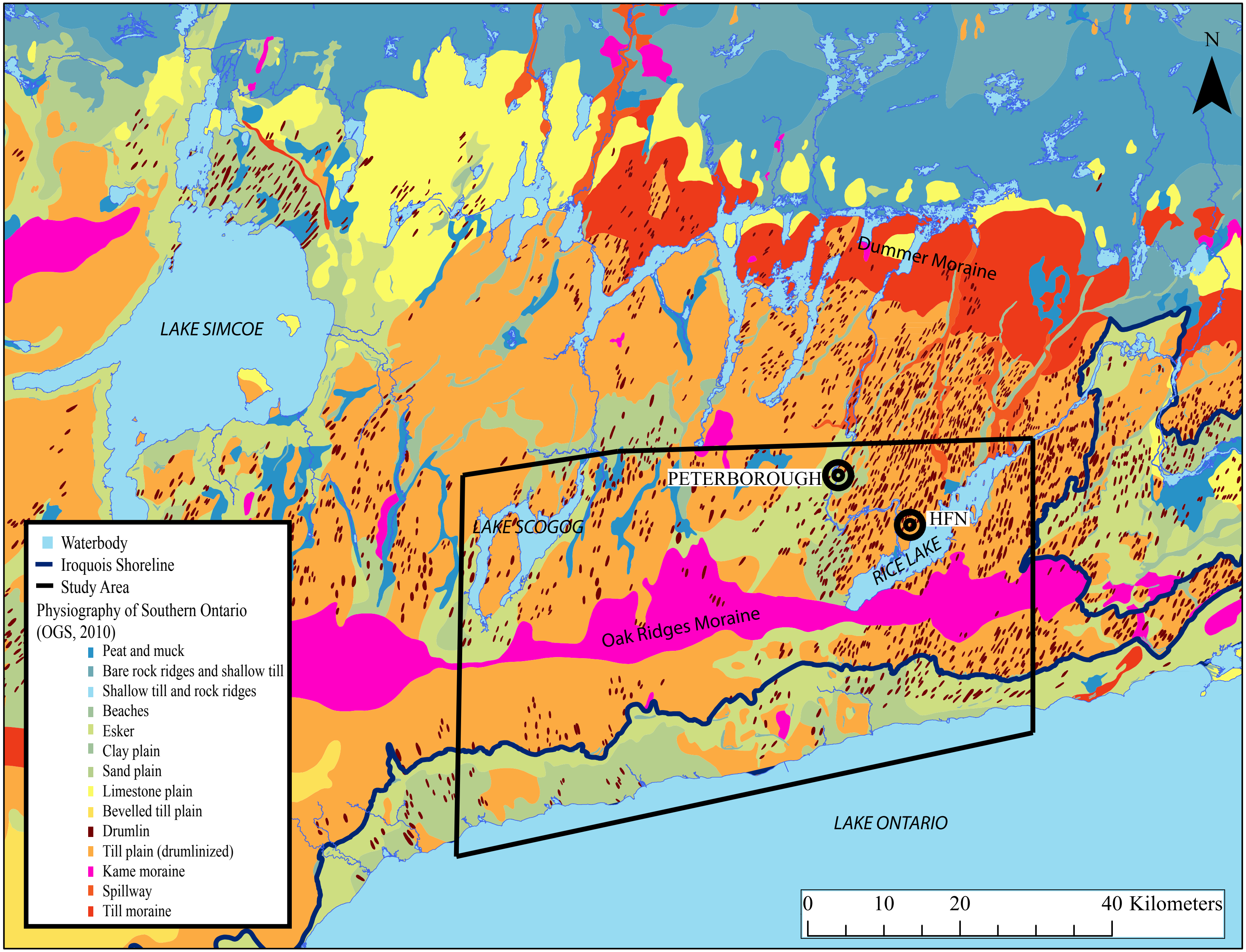
Implications for developing domestic water supplies

2.1 INTRODUCTION

The Peterborough Drumlin Field (PDF) is an extensive drumlin field located in Southern Ontario (Fig. 2.1). The drumlin field covers over 5000 km^2 and contains upwards of 3000 drumlins (Boyce and Eyles 1991). The area is home to over 900 000 people in four regional counties (Durham, Northumberland, Peterborough and Kawartha Lakes; Statistics Canada 2011). Many homes rely on groundwater extracted from individual water wells that are installed and maintained by the homeowner. The drumlin field contains upwards of 90 000 municipal and private water wells that utilize aquifers hosted in Quaternary sediments or the underlying fractured bedrock.

The origin of drumlins has been a topic of considerable research and debate (e.g. Shaw 1983; Shaw and Sharpe 1987; Shaw and Gilbert 1990; Boyce and Eyles 1991; Gilbert and Shaw 1994; Clark et al. 2009; Stokes, et al. 2011) yet there is still a need for information about the internal composition of these enigmatic landforms given the paucity of natural exposures or outcrop sections. Enhanced understanding of the internal stratigraphy of drumlins provides valuable data that may be used to elucidate the processes by which they formed, and may also help understanding of their hydrostratigraphic behaviour. The majority of drumlins in the PDF are composed of low permeability diamict (till) (Crozier 1975; Boyce and Eyles 1991) but coarse-grained heterogeneities within the landforms serve as high permeability zones and have significant implications for groundwater resource development and contaminant pathways (Gerber and Howard 1996; Gerber and Howard 2000; Gerber et al. 2001). It is therefore extremely important to understand the location and spatial extent of such heterogeneities. There is considerable interest in enhanced understanding of the subsurface geology and groundwater resources of the PDF region of southern Ontario given a critical need to remediate existing water

Figure 2.1: The physiography of Southern Ontario (OGS 2010). Drumlins in the Peterborough Drumlin Field are shown with brown ovals. Note variable orientation of drumlins. Dummer Moraine to north. Oak Ridges Moraine is found in the center of the drumlin field. Note the Lake Iroquois shoreline close to Lake Ontario (blue line). Study area delineated by black rectangle.


N
LAKE SIMCOE
Dummer Moraine
PETERBOROUGH
HFN
LAKE SCOGOG
RICE LAKE
Oak Ridges Moraine
LAKE ONTARIO
0 10 20 40 Kilometers
Waterbody
Iroquois Shoreline
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Bare rock ridges and shallow till
Shallow till and rock ridges
Beaches
Esker
Clay plain
Sand plain
Limestone plain
Bevelled till plain
Drumlin
Till plain (drumlinized)
Kame moraine
Spillway
Till moraine

wells and drill new wells for an ever-growing population. There is also ongoing interest amongst smaller communities in the area, currently serviced by individual water wells, to transition to centralized systems that allow for the distribution of better treated and safer water to home owners.

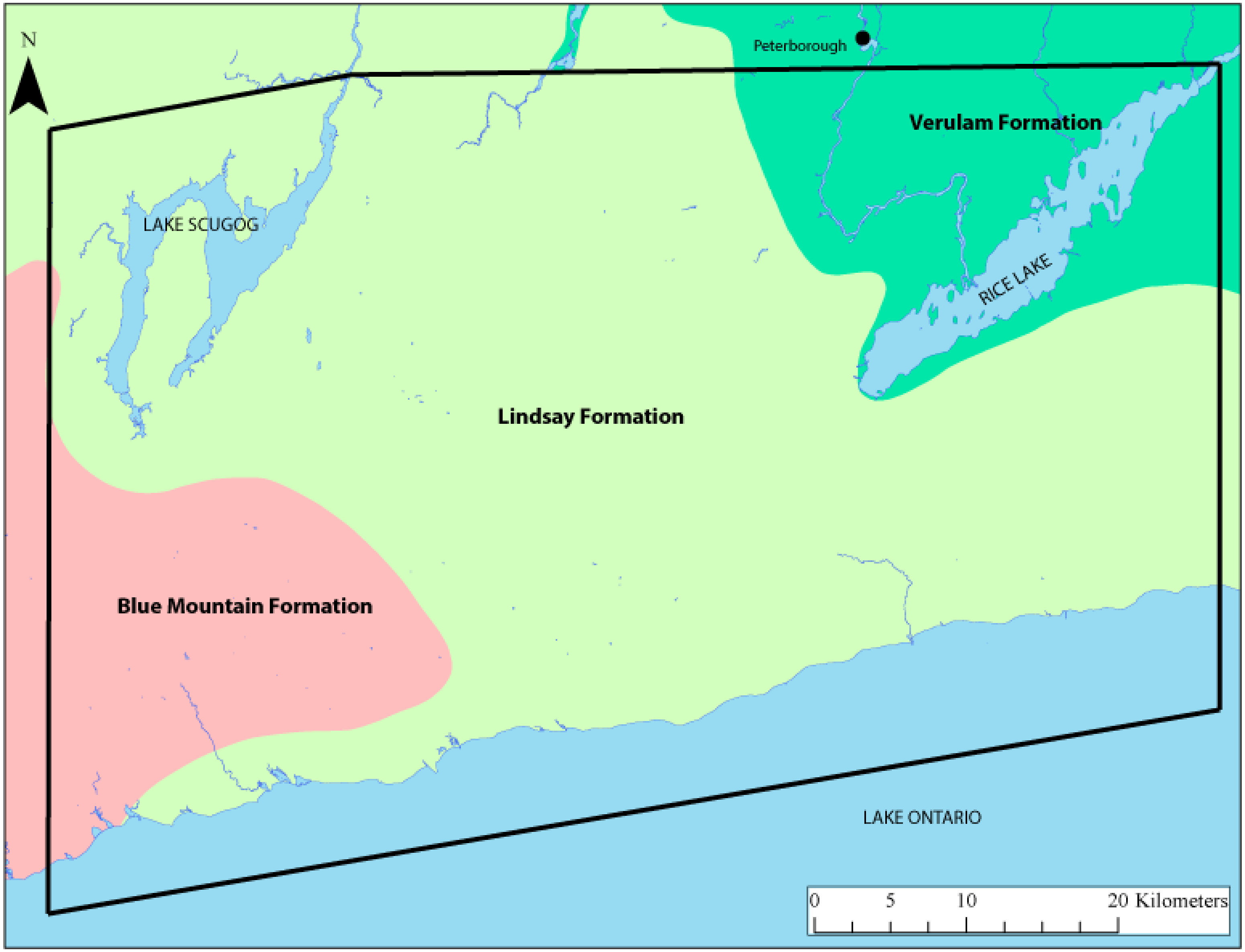
This study aims to establish details of the subsurface geology and the likely hydrostratigraphy of selected drumlins within the PDF by utilizing information available in water well drillers logs (Water Well Information System; http://www.ontario.ca/environment-and-energy/map-well-record-data). Over 90 000 well logs are available for the area of the PDF and, given the scarcity of outcrops that expose sediments within the region, interpretation of selected logs will be used to provide insight into the nature of the subsurface geology and hydrostratigraphy of this drumlinized terrain. This work will considerably enhance understanding of the subsurface variability of sediment types and stratigraphies across a drumlin field and the nature and potential connectivity of aquifers and aquitards in the region. These findings have application to the exploration and protection of groundwater resources in the Peterborough area and in drumlinized terrains elsewhere.

2.1.1 *Geological Background*

The Peterborough Drumlin Field (PDF; Fig. 2.1) is underlain by late Quaternary sediments overlying Ordovician-age shale and limestone bedrock (Fig. 2.2; OGS, 2010). The stratigraphy in the area varies considerably as it contains the record of several advances and retreats of the interlobate southern margin of the Laurentide Ice Sheet (LIS; Crozier 1975; Boyce and Eyles 2000).

In the western part of the PDF bedrock consists of the Upper Ordovician Blue Mountain Formation shale (Fig. 2.2; Sanford 1995; Singer et al. 2003). Towards the east, in the central portion of the PDF between Lake Scugog and Rice Lake, bedrock belongs to the Lindsay

Figure 2.2. Bedrock formations beneath the study area (OGS 2010). Blue Mountain Formation (pink) in the south-western corner, Lindsay Formation (light green) through north-west to south east, and Verulam Formation (green) in the north-east corner of the study area.


N
Peterborough
Verulam Formation
LAKE SCUGOG
RICE LAKE
Lindsay Formation
Blue Mountain Formation
LAKE ONTARIO
0 5 10 20 Kilometers

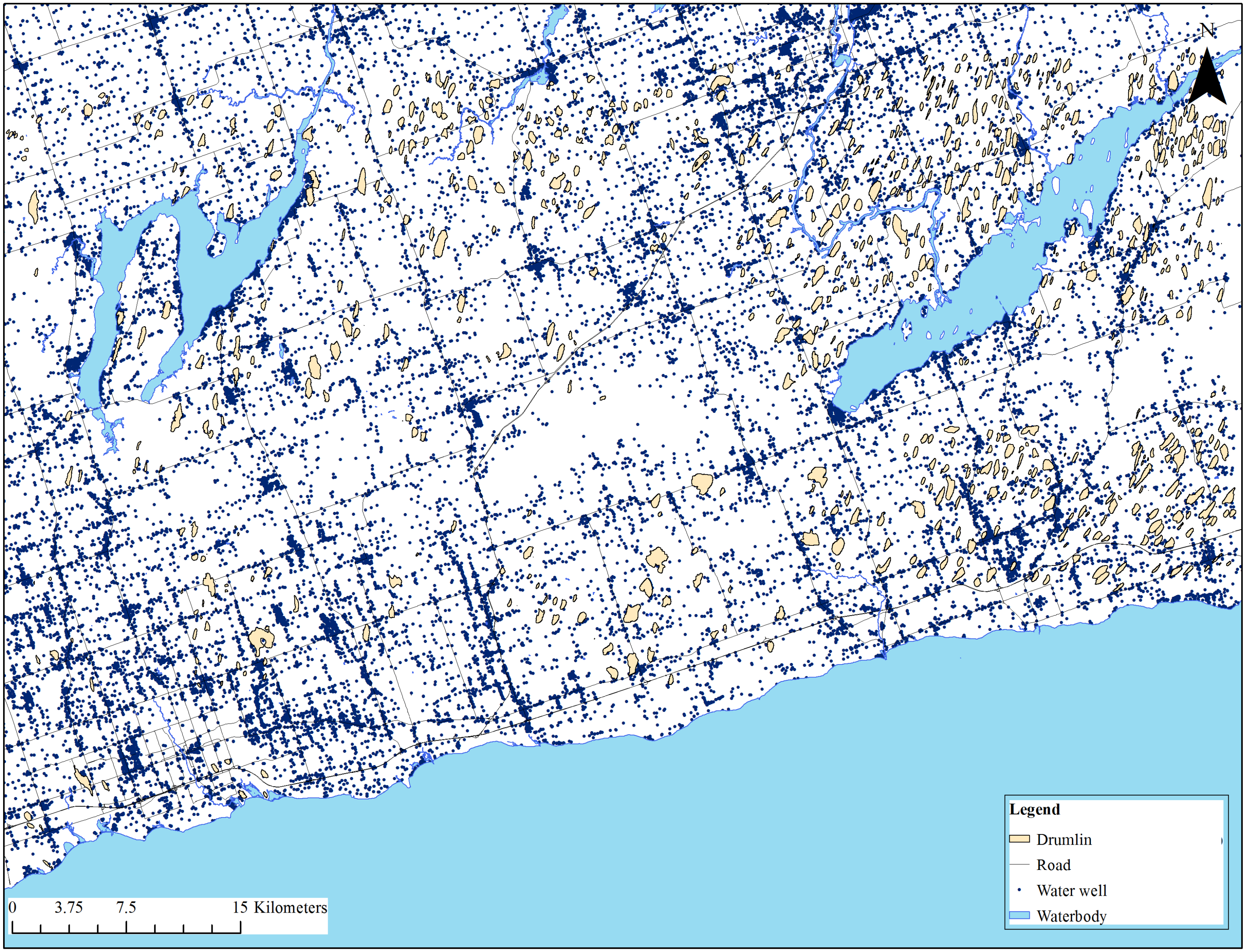
Formation which has a lower member of limestone, and an upper member of limestone and calcareous shale (Fig. 2.2; Sanford 1995; Singer et al. 2003). The easternmost portion of the PDF is underlain by limestone with interbedded shales of the Verulam Formation (Fig. 2.2; Sanford 1995; Singer et al. 2003). The bedrock surface slopes gently to the southwest, towards Lake Ontario (Liberty 1969) and is broadly undulating with an elongate low in the vicinity of Rice Lake that trends northeast – southwest (Russell et al. 2003; Maclachlan and Eyles 2013). There is also evidence of a network of ancient bedrock channels that have a north-south orientation and probably reflect erosion along bedrock weaknesses that developed in response to a mid-continent stress field (Eyles et al. 1985; Eyles et al. 1993; Eyles et al. 1997).

The PDF extends from undrumlinized glacial deposits near Lake Simcoe in the west to the limits of glacial sediment cover and Paleozoic limestone in the north, and to the northern shores of Lake Ontario in the south (Crozier 1975; Boyce and Eyles 1991; Kerr and Eyles 2007). In the northeast, the drumlin field merges with the Dummer moraine (Fig. 2.1). The Quaternary sediment cover of the PDF is up to 100 metres thick and consists of a complex succession of presumed early Wisconsin deposits composed of sands, silt, clay and diamict (Crozier 1975; Karrow 1984; Eyles et al. 1985; Sharpe et al. 1996) overlain by a sandy diamict known regionally as the Northern/Newmarket Till (Boyce and Eyles 2000). The Northern/Newmarket Till was deposited by the Simcoe Lobe of the Laurentide Ice Sheet during the Port Bruce Stade (Brookfield et al. 1982) and subsequent glacial overriding is thought to have led to the development of the drumlin field (Boyce and Eyles 1991). The majority of drumlins in the field are aligned parallel to the direction of flow of the Simcoe ice lobe which was predominantly from northeast to southwest (Fig. 2.1); however, the south-western portion of the drumlin field records the northwestward movement of the Ontario lobe during a short-lived ice margin advance during the Port Huron Stade (Karrow 1981, 1984) and the drumlins are orientated similarly. A silty till (known as the Halton Till) was deposited in the southwestern part of the area, up to the southern flank of the Oak Ridges Moraine (ORM; Logan et al. 2001; Russell et al. 2003; Sharpe et al. 2004; Sharpe et al. 2011) during this time. North of the ORM, the finer grained Kettleby Till was deposited and is the likely stratigraphic equivalent to the Halton Till (Logan et al. 2001). The Oak Ridges Moraine (ORM; Fig. 2.1), which formed between the Ontario and Simcoe lobes of the Laurentide Ice Sheet, overlies drumlins in parts of the PDF (Karrow 1981; Barnett 1992). The ORM is upwards of 150 meters thick and consists mainly of interbedded layers of sand and fine silt with some localized sand and gravel (Karrow 1984; Chapman 1984; Barnett et al. 1997; Logan et al. 2001). The final event that influenced the PDF area was the development of a large post-glacial lake, Lake Iroquois. The former high water levels of Lake Iroquois modified drumlins found south of the Oak Ridges Moraine and close to the shoreline of Lake Ontario (Fig. 2.1; Karrow 1981).

2.2 METHODOLOGY

Despite extensive study of the drumlins within the PDF (e.g. Crozier 1975; Shaw and Sharpe 1987; Boyce and Eyles 1991; Boyce and Eyles 2000; Maclachlan and Eyles 2013), the subsurface stratigraphy is not well understood. The distribution of aquifers in the region is largely unknown and it is therefore extremely difficult to either locate or protect drinking water resources. This study will use previously recorded data, found in water well records, to analyze the subsurface geology of portions of the PDF (Fig. 2.3). The water well records provide a source of both local and regional scale subsurface data that may help establish patterns in the underlying stratigraphy to better predict the distribution of aquifer systems and adequately inform drinking water resource development in the region.

Figure 2.3: All of the water wells (domestic, municipal, other; blue dots) found in the study area as reported by the Ministry of the Environment (WWIS). Drumlins identified by Maclachlan and Eyles (2013) are marked in beige. There are 30000+ wells in the study area. Wells are typically located along roads, hence the seemingly linear pattern and there are noticeably fewer wells on drumlins (beige shapes) than the remaining areas.


N
Legend
Drumlin
Road
Water well
Waterbody
0 3.75 7.5 15 Kilometers

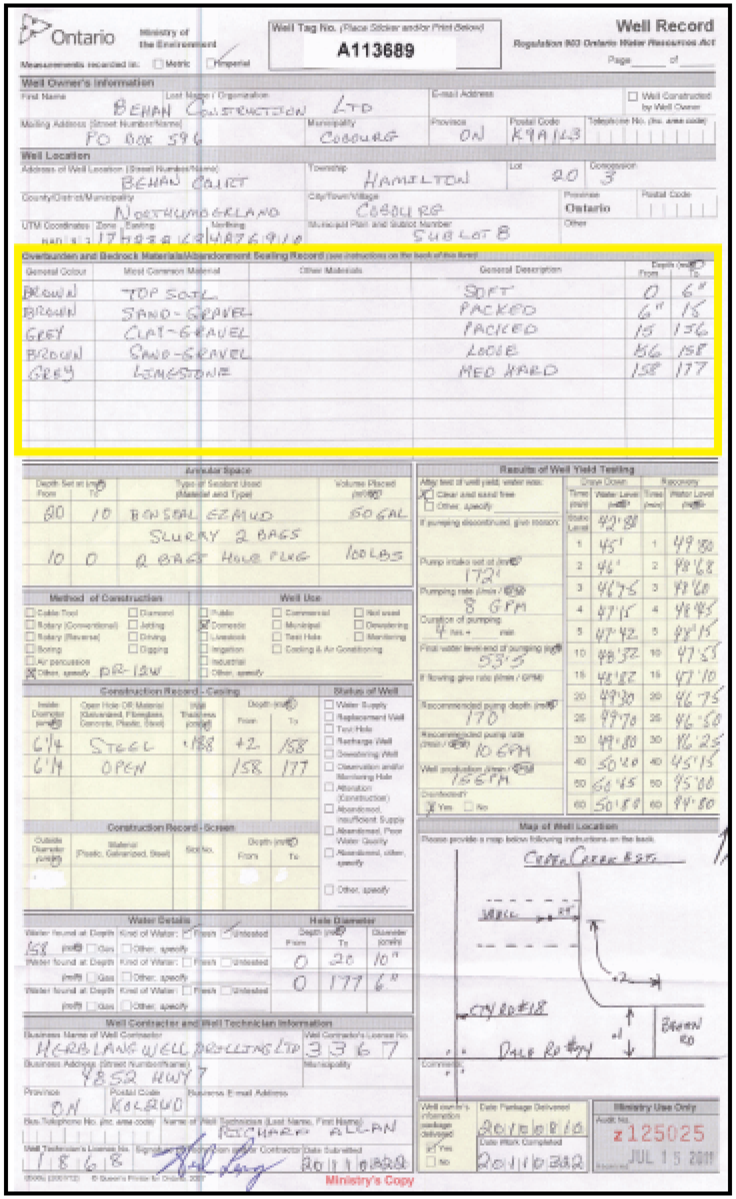
The area of the PDF used for this study is based on that of Maclachlan and Eyles (2013; Fig. 2.3) who utilized GIS spatial analysis to accurately establish the location and characteristics of 812 (of 3000) drumlins within a 1700 km^2 area of the PDF. The study area also overlaps with that of Boyce and Eyles (1991).

2.2.1 *Water well record data base (WWIS)*

The Ontario Ministry of the Environment (MOE) requires well contractors to submit water well records for all wells drilled in Ontario and these data are stored and made available to the public through the Water Well Information System (WWIS; Fig. 2.4). The Government of Ontario and the MOE have well record data for Ontario dating back to 1899 and legislation requiring water well reports to be submitted to the MOE has been in place since 1946 (Russell et al. 1998). Reports are now published through the WWIS and are available online through an interactive map (http://www.ontario.ca/environment-and-energy/map-well-record-data). There are over 325000 well records in the database (Russell et al. 1998). Each record is created by the well driller at the time of drilling and converted to a digital format by the MOE. Each report contains information on: the date the well was drilled, well location as easting and northing (confirmed at a later date by MOE inspection) and a hand drawn map, overburden and bedrock material encountered, annular space or abandonment sealing, method of construction of the well, well use, status of well, construction record for casing and screen, results of well yield testing and well contractor information (Fig. 2.4a). For the majority of records, the form is incomplete, and is often missing significant parts of the record (for example, subsurface data, water level depth, or exact location of well). Information about the homeowner and the address of the well are blacked out on the online database in accordance with the Privacy Act in Canada. The WWIS information used in this study concerned the location of the wells, materials encountered during drilling, and any hydrologic data available (e.g. static water level). The eastings and

Figure 2.4: Examples of water well records. **(A)** The "original" record available as a PDF. It is a scanned copy of the record as submitted by the well driller (note description of overburden materials highlighted by yellow box). **(B)** The "digital" copy is available in HTML format. . Note in this particular example that the digital version is missing some of the descriptors that are written in the original record under "Overburden and bedrock materials interval" (highlighted by yellow box).

A


Ontario Ministry of the Environment

Well Tag No. A113689

Well Record

Well Owner's Information

BEHAN CONSTRUCTION LTD

PO BOX 596 COBOURG ON K9A 4L3

Well Location

BEHAN COURT HAMILTON Lot 20 Concession 3

NORTHUMBERLAND COBOURG Ontario

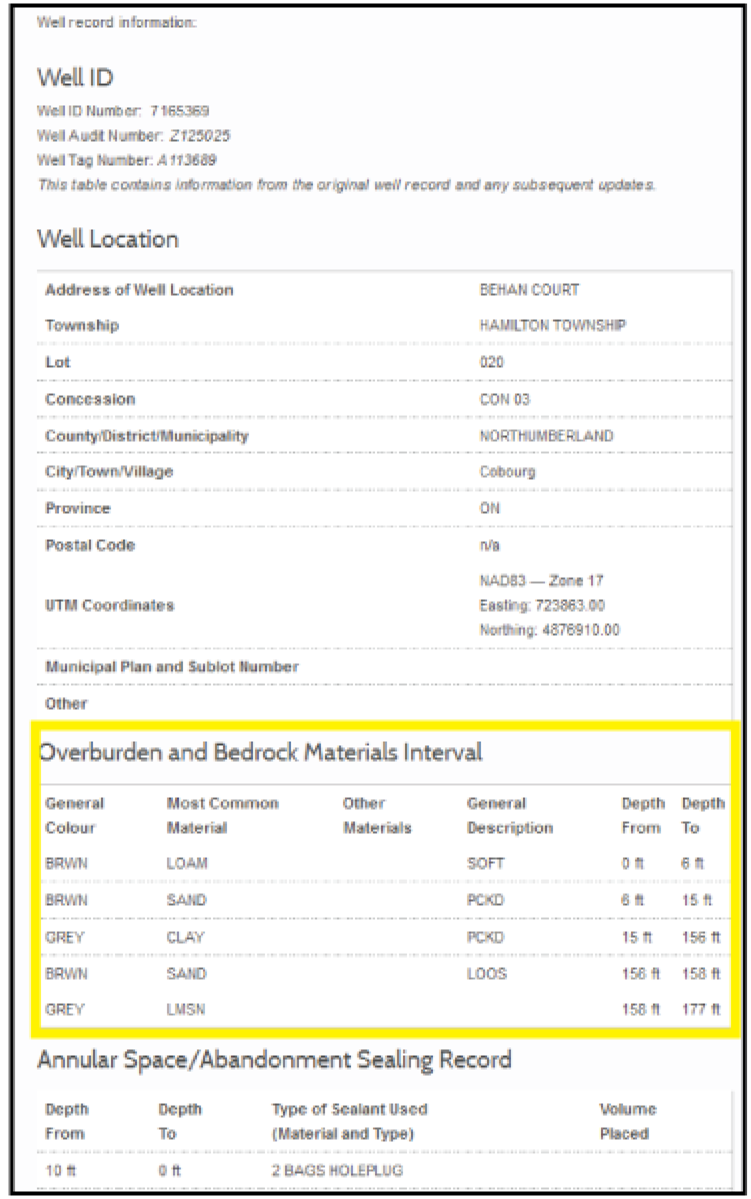
SUB LOT 8

Overburden and Bedrock Materials/Abandonment Sealing Record

General Colour	Most Common Material	Other Materials	General Description	Depth From	Depth To
BROWN	TOP SOIL		SOFT	0	6"
BROWN	SAND-GRAVEL		PACKED	6"	15
GREY	CLAY-GRAVEL		PACKED	15	156
BROWN	SAND-GRAVEL		LOOSE	156	158
GREY	LIMESTONE		MED HARD	158	177

Ministry's Copy

B


Well record information:

Well ID

Well ID Number: 7165369

Well Audit Number: *Z125025*

Well Tag Number: *A113689*

This table contains information from the original well record and any subsequent updates.

Well Location

Address of Well Location	BEHAN COURT
Township	HAMILTON TOWNSHIP
Lot	020
Concession	CON 03
County/District/Municipality	NORTHUMBERLAND
City/Town/Village	Cobourg
Province	ON
Postal Code	n/a
UTM Coordinates	NAD83 — Zone 17 Easting: 723863.00 Northing: 4876910.00
Municipal Plan and Sublot Number	
Other	

Overburden and Bedrock Materials Interval

General Colour	Most Common Material	Other Materials	General Description	Depth From	Depth To
BRWN	LOAM		SOFT	0 ft	6 ft
BRWN	SAND		PCKD	6 ft	15 ft
GREY	CLAY		PCKD	15 ft	156 ft
BRWN	SAND		LOOS	156 ft	158 ft
GREY	LMSN			158 ft	177 ft

Annular Space/Abandonment Sealing Record

Depth From	Depth To	Type of Sealant Used (Material and Type)	Volume Placed
10 ft	0 ft	2 BAGS HOLEPLUG	

northings recorded on the record of each well used were imported into ARCGIS for spatial analysis.

Prior to March 2014, only the digitized version of the well reports were made available through the WWIS (Fig. 2.4b). Recently, scanned copies of the original reports were added to the online database of digitized records (Fig. 2.4a.). During the course of this research project, the addition of original records to the WWIS highlighted some significant deficiencies regarding the interpretation of the record made when the original was converted to a digital form (Fig. 2.4). Each digitized record used in this study was checked with the original and it is estimated that one in ten records have some error or omission in the digital copy. Information on the original records that significantly enhanced the quality of the data used for this study was the availability of hand drawn maps that allowed confirmation of the water well location.

2.2.2 *Water well records*

Each well record contains information about the subsurface materials encountered during drilling. These descriptions are made by the driller from cuttings extracted from the drilling processes. Cuttings often provide an unreliable record of the subsurface materials because they are significantly impacted by the method of drilling, drilling mud thickness (if applicable), and the ability of the driller to interpret and record the geological materials encountered. Typically, unconsolidated sedimentary materials are classified according to colour and grain size, with the most common type being listed first (example: brown sand-gravel; Fig. 2.4a). There are over 80 terms that have been used to describe materials in well records. Drillers are required to give descriptions that are appropriate for basic hydrogeological purposes but are not trained to provide detailed sedimentological descriptions or to give an interpretation of the stratigraphic unit encountered (T. Lotimer, pers. comm., 2014). Frequently, sediment descriptions are incomplete or missing from water well records.

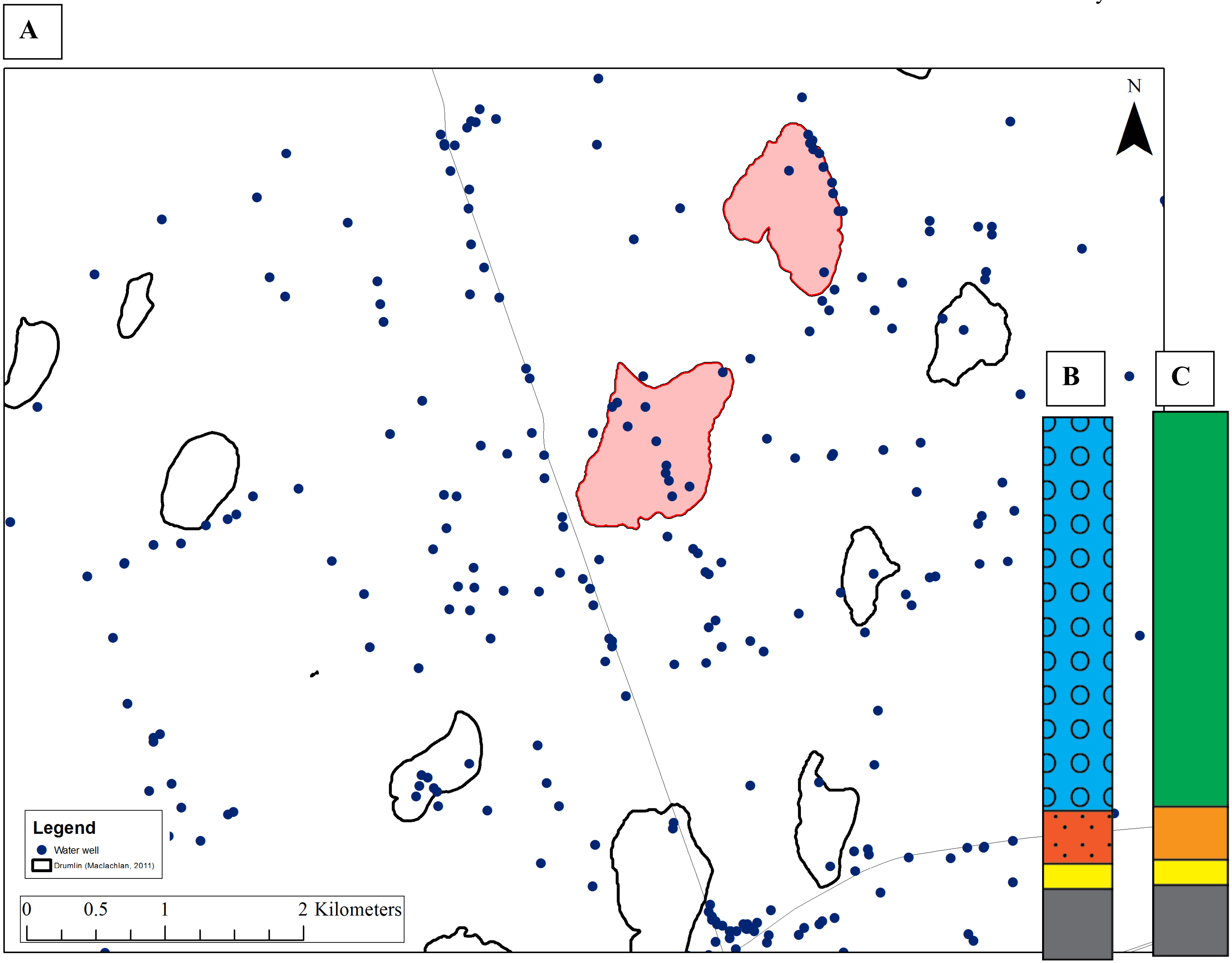
The location of the well is also recorded on the well log. Prior to the availability of GPS, drillers would submit the approximate location of the well and, during well inspection by the MOE, geographic coordinates would be determined and submitted with the final well record. The driller also included a small hand drawn map of the location which typically included a major street or intersection name and the distance from the street to the well or other land marks. These maps are only available on the original record and are a valuable source of information to verify location data. Currently, drillers use handheld GPS devices to record well location coordinates for the records.

Since 2003 well drillers and contractors are required by O.Reg. 372/07 to affix a well tag permanently to the outside of the casing or structure that houses the well. The tag number is then recorded on the well record. This provides a high level of certainty that the well record matches a well. Prior to 2003 there is no certainty that a record belongs to a particular well.

2.2.3 *Identification of studied drumlins*

The first step in analyzing the subsurface stratigraphy of the drumlin field was to import all of the water well records within the study area from the WWIS to ARCGIS. There were over 30,000 wells in the database for the study area (Fig. 2.3). The water well data were then overlain on a shapefile that contained all of the drumlins in the study area as established by Maclachlan and Eyles (2013; n=812; Figs. 2.3, 2.5) using a computational methodology. Maclachlan and Eyles (2013) used a 10 meter DEM (dataset from Ontario Geospatial Data Exchange) to find closed loop contours using GIS software and created polygons that represented drumlins within the boundaries of these closed-loop contours. Landforms with a relief of less than 20 meters were not included in the study and inverted closed contour depressions (i.e. from a lake) were removed. The water wells that were of particular interest for this study were those found on a

Figure 2.5. Drumlin selection and well logs. **(A)** Drumlins were selected based on availability of water well records within the drumlin shape. This figure shows the distribution of drumlins (dark outline) in a portion of the study area as well as the available water well records (blue dots). Drumlins highlighted in red have a high density of wells within the drumlin and have therefore been selected for analysis. The area between the two drumlins also has a high density of wells and was used to construct an inter-drumlin swale cross section. A five meter buffer around the drumlin was also included to establish continuity of the units. **(B)** Example of a borehole log created using driller's descriptions. In this case, the first unit (top) would have been reported as: clay (primary material; depicted by colour) and gravel (secondary material; depicted by symbol). The second unit would have been reported as gravel and sand. The third was sand. The fourth (lowermost) was limestone bedrock. **(C)** Example of an interpreted well log. The first unit (top: clay and gravel) was interpreted as an aquitard with a fine grained matrix with clasts of various sizes and given the appropriate colour code (green). The second unit was interpreted as a medium-coarse grained aquifer (light orange). The third and fourth (lowermost) units were left with the same original colour code they each recorded one material type.


A
N
B
C
Legend
Water well
Drumlin (Maclachlan, 2011)
0 0.5 1 2 Kilometers

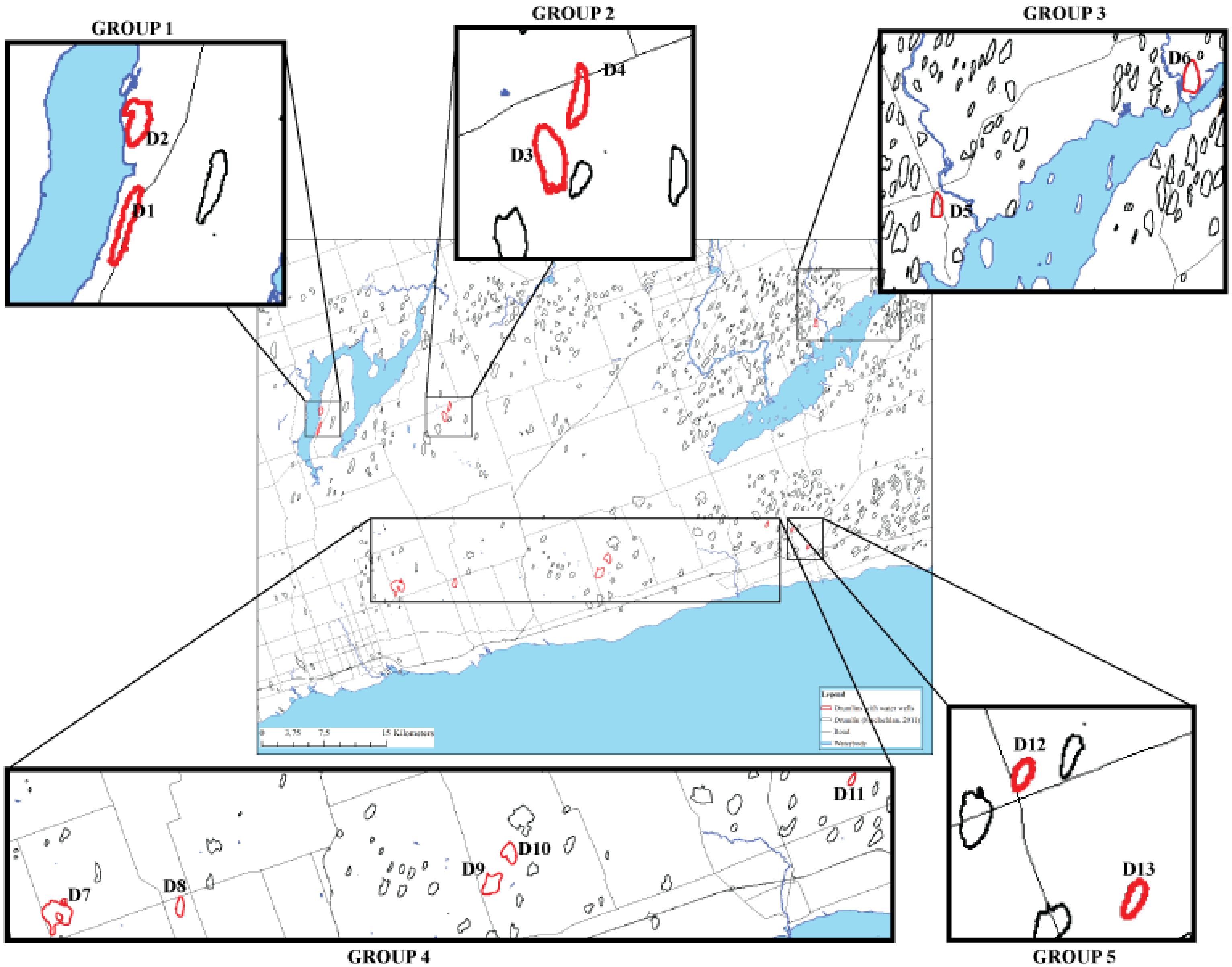
drumlin or within the adjacent drumlin swale and were used to help establish spatial patterns of drumlin and swale stratigraphy.

The drumlin identification data were combined with the WWIS data in ARCGIS to determine which drumlins had a sufficient number of wells to create a cross section through the subsurface stratigraphy (greater than four wells within drumlin boundary by visual inspection) (Fig. 2.5a). Cross sections provide the basis for correlation, stratigraphic interpretation, and visualization of the relationships between each of the subsurface lithologic units identified in the logs. The wells considered for inclusion in the drumlin cross sections included a 5 meter buffer outside the drumlin "edge" to capture any additional wells within close proximity of the drumlin form. Swales (areas of low elevation) were also identified between drumlins and cross sections were plotted through swales adjacent to studied drumlins (Fig. 2.5a). Ground surface elevation data were obtained using a DEM (GTA 2002 DEM) and were checked with that recorded on the water well record (where available) and topographic maps to ensure the DEM-obtained value was reasonable with respect to local topography. In total, thirteen drumlins (D) and associated swales (S) were selected for analysis and each given numbers to facilitate identification (Fig. 2.6). Following examination of the stratigraphy associated with each of these selected drumlins, drumlins were classified into five groups according to similarities in their subsurface characteristics (D1 – 13; Groups 1 – 5; Fig. 2.6).

2.2.4 *Unit descriptions and interpretation*

Subsurface cross sections were created using the data available in the water well records for each of the 13 drumlins and swales selected. The thickness of each subsurface unit encountered during drilling of the well is recorded on the record. This information was combined with the elevation data from the DEM to make cross sections through each of the selected drumlins. This

Figure 2.6. The geographically-determined drumlin groups (1 – 5).


GROUP 1
D2
D1
GROUP 2
D4
D3
GROUP 3
D6
D5
GROUP 4
D7
D8
D9
D10
D11
GROUP 5
D12
D13
15 Kilometers
Legend

study only utilizes data from drumlins identified by Maclachlan and Eyles (2013) and water well records that were available online.

Driller's logs were initially drafted schematically to show the lithology as described by the driller, with the primary material shown as a colour and any other materials with a symbol (logs based on drillers descriptions are presented in Appendix 1). For example, a clay (most common) gravel (other material) description would be depicted as a blue column with small circles for gravel (Fig. 2.5; Appendix 1). There are some discrepancies in the driller's descriptions because the digital copies, in some cases, had reversed the dominant materials recorded by the driller. Also, because drillers are not formally trained to use standard sedimentological terminology when describing lithology, they may record a sandy-clay unit on the record (interpreted by a sedimentologist as clay with some sand) when they were in fact intending to report a clayey-sand (sand with some clay). These initial schematic logs and cross-sections show considerable variability in the sediment types recorded by drillers in wells that were drilled close to one another (e.g. Appendix 1).

A second level of analysis of the driller's logs was therefore carried out to allow more realistic and consistent interpretation of subsurface conditions beneath the selected drumlins and swales. The cross sections presented for each drumlin/swale (Figs. 2.9 – 2.20) provide an interpretation of the original data recorded by the driller, grouping individual units identified on the basis of described material type, into amalgamated units based on grain size, likely genetic origin, and predicted hydrogeological properties. Schematic logs showing interpreted data are colour coded accordingly. Five groups of sediment were identified in this way and include bedrock, clay/silt, silt/sand/clay, sand/gravel, and diamict (Table 1; Fig 2.8).

Table 2.2. Groupings of sediment types reported in water well records. These were created to facilitate interpretation of subsurface materials with respect to hydrostratigraphic characteristics. Units with single descriptors are given a unique colour identifier (e.g. clay, sand). Units with multiple descriptors are lumped into groups according to grain size (e.g. fine-medium grained group is depicted with pink and contains any combination of clay, sand and silt). Fill and organic materials are present at surface only and are not included in these groupings.

	1	2	3	4	5
Description	**Bedrock**	**Clay/Silt** very fine - fine grained	**Silt/Sand/Clay** fine - medium grained	**Sand/Gravel** medium - coarse grained	**Diamict** matrix: fine grained clasts: various sizes
Aquitard/ Aquifer	Aquifer	Aquitard	Aquitard	Aquifer	Aquitard (leaky ?)
Included descriptors	LIMESTONE SHALE SHALE LIMESTONE LIMESTONE SHALE	SILT SAND SILT CLAY SILT CLAY SAND CLAY SILT CLAY SILT	CLAY SAND CLAY SAND SILT CLAY SILT SAND SAND SILT SAND SILT CLAY SAND CLAY	GRAVEL SAND SAND GRAVEL GRAVEL SAND	CLAY GRAVEL CLAY GRAVEL SAND CLAY GRAVEL SILT CLAY SAND GRAVEL GRAVEL CLAY GRAVEL CLAY SAND SILT GRVL GRAVEL SAND CLAY GRAVEL SILT SAND CLAY GRAVEL SAND GRAVEL CLAY SAND GRAVEL SILT SAND SILT GRAVEL HARDPAN

The first group (bedrock) includes all of the bedrock descriptors and is considered a potential aquifer unit. The second (clay/silt) and third (sand/silt/clay) groups contain very fine to fine grained sediment descriptors including silts, clays and fine sands and are considered as aquitard units. These sediments were probably deposited in lacustrine or deltaic conditions (Benn and Evans 2014). The fourth group (sand/gravel) is medium to coarse-grained and is also considered to form a potential aquifer unit. Such coarse-grained sediments are interpreted to record fluvial/glaciofluvial conditions (Benn and Evans 2014). The fifth group (diamict) contains descriptors that indicate very poor sediment sorting and because of the presence of fine-grained matrix materials is considered as an aquitard or leaky-aquitard. These poorly sorted sediments are interpreted as subglacial deposits (i.e. till; Benn and Evans 2014). Interpretation of the original driller's records was necessary to facilitate reconstruction of the depositional history of the drumlins and to allow differentiation of coarse-grained (aquifer) units and fine-grained (aquitard) units, an important step when attempting to identify the hydrostratigraphic characteristics of subsurface materials.

2.3 RESULTS

2.3.1 *General Observations*

All drumlins selected for analysis in the study area had diamicton mapped as the primary surficial material by the Ontario Geological Survey (OGS; OGS 2010; Fig. 2.7). Half of the drumlins analysed (D1 - D4, D7, D8, D12) have surficial sandy units mapped on their flanks (Fig. 2.7). The remainder have a variety of materials in the inter-drumlin swale including clay, fill, sand, and organic material. Depth to bedrock (i.e. surficial sediment thickness) varies across the study area but is similar for groups of drumlins. The bedrock surface elevation decreases from north to south towards Lake Ontario but has similar values from west to east. The drumlins

Figure 2.7. Surficial geology of the study area as mapped by the OGS (2010). Drumlins (black shapes) are predominantly diamict. Sands and gravels are noted in the adjacent swales.

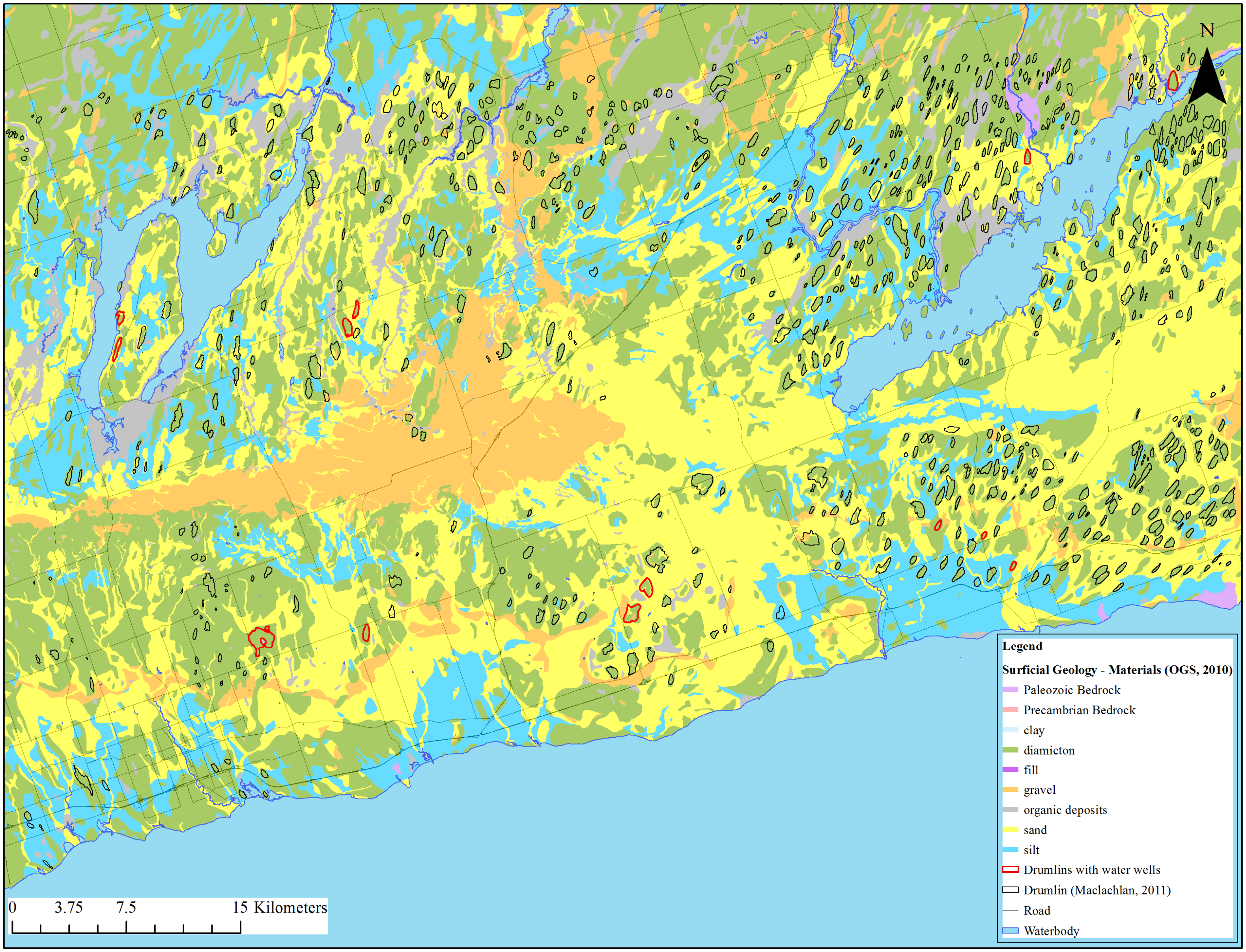

N
Legend
Surficial Geology - Materials (OGS, 2010)
Paleozoic Bedrock
Precambrian Bedrock
clay
diamicton
fill
gravel
organic deposits
sand
silt
Drumlins with water wells
Drumlin (Maclachlan, 2011)
Road
Waterbody
0 3.75 7.5 15 Kilometers

Figure 2.8. Master legend applies to figures 2.9 – 2.20.

MASTER LEGEND

Drumlin and Cross Section Location Maps

Road
190 Contour and elevation (m.a.s.l.)
Drumlin boundary
Water well
Water body
A A' Cross section deliniation

Surficial Material (OGS, 2010)

Sand
Diamicton
Organic Deposits
Fill
Silt
Gravel

Drumlin/Swale Stratigraphic Interpretation

Group 1 - Aquifer
Bedrock

Group 2 - Aquitard
Silt/sand, Silt/clay, Silt/Clay/Sand, Silt
Clay

Group 3 - Aquitard
Clay/sand, Clay/Sand/Silt

Group 4 - Aquifer
Gravel/Sand
Gravel
Sand

Group 5 - Aquitard
Clay/gravel, Clay/gravel/sand, Clay/gravel/silt
Hardpan

selected for study also vary with respect to surficial sediment thickness (20 m to 100 m), and the number and subsurface depth of aquifers that can be identified. These variable characteristics allowed five geographically-controlled groupings of drumlins to be discriminated (Fig. 2.6).

2.3.2 *Drumlin Group 1*

Two drumlins (D1 and D2) and an adjacent swale (S1) are located on Scugog Island near the north-western corner of the study area (Fig. 2.9) and comprise drumlin Group 1. The surficial geology in the area around the drumlins and in the swale is mapped as diamict, with sand, silt and organic deposits (OGS 2010; Fig. 2.9). Depth to bedrock is approximately 80 meters below the ground surface (185 – 195 m.a.s.l.; Fig. 2.10). Both the drumlins and the swale show the presence of two aquifer units separated by a thick diamict package.

D1 is 1600 meters long and 200 meters wide with twenty meters of relief to the north and five meters of relief to the south (Fig. 2.9). D2, located north of D1, is approximately 900 meters long and 500 meters wide (Fig. 2.9) and has 20 meters of relief to both north and south. From east to west, D1 and D2 both have 20 meters of relief. Both drumlins are oriented approximately parallel to the shore of Lake Scugog (Fig. 2.9). 63 drilled wells are located on the two drumlins (Fig. 2.9). S1 is an west-east cross section through the swale adjacent to both drumlins (S1; BB' Fig. 2.9)

Four wells in D1 encounter bedrock at 195 m.a.s.l. (80 m.b.g.l; Fig. 2.10a) but no wells were drilled to bedrock on D2 (Fig. 2.10c). Bedrock beneath S1 is only encountered in two wells at the easternmost end of the section at an elevation of 185 m.a.sl. Immediately overlying bedrock in this group is a thin (<5m) layer of sand and gravel at 200 m.a.s.l (Fig. 2.10); this unit is considered to be a basal bedrock aquifer. The unit is continuous across D1 and S1.

Figure 2.9. Group 1 drumlins: Surficial geology and contour map for drumlins D1 and D2 and cross sections A-A', B-B', C-C', D-D' (black lines). See Fig. 6 for location in study area.

GROUP 1

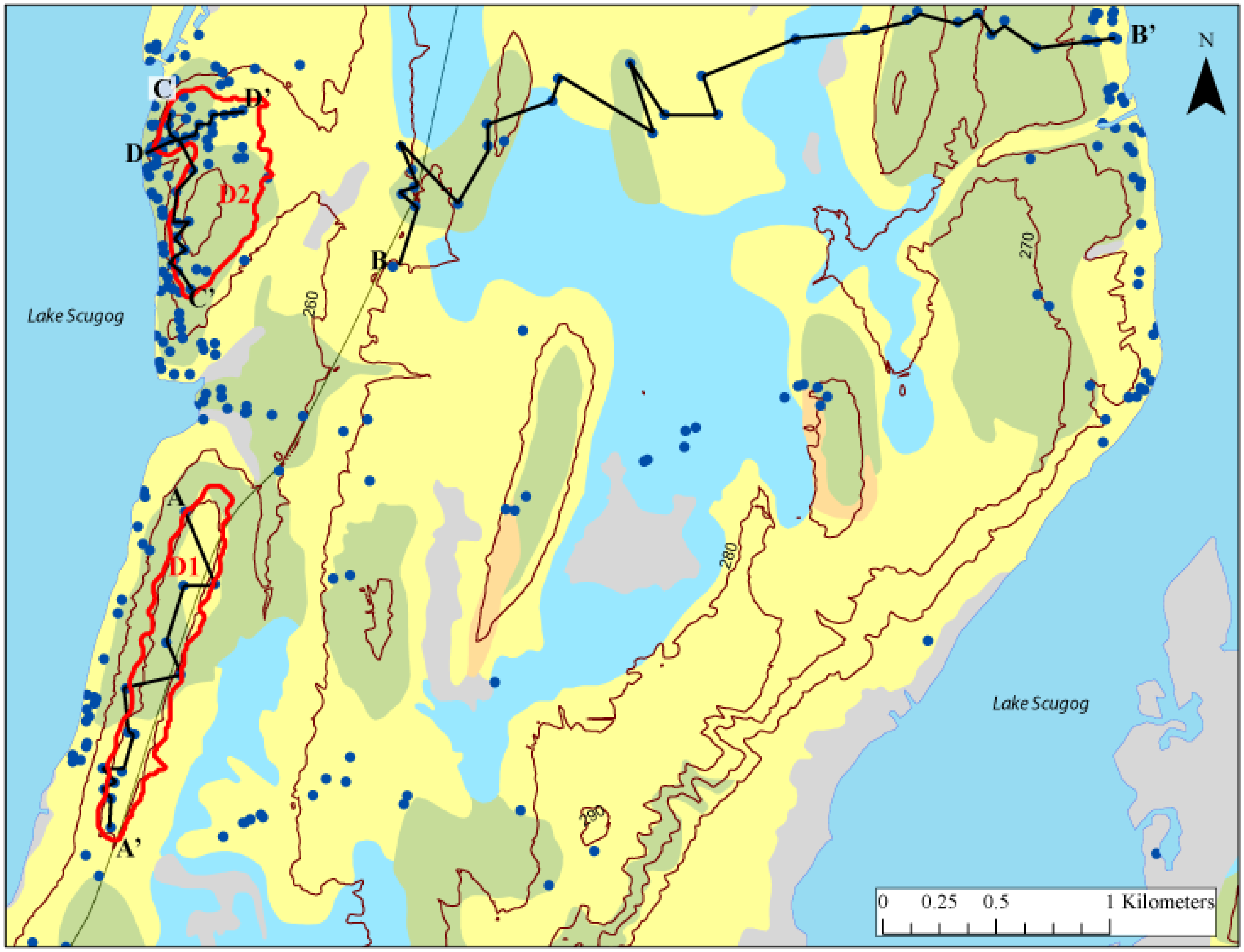
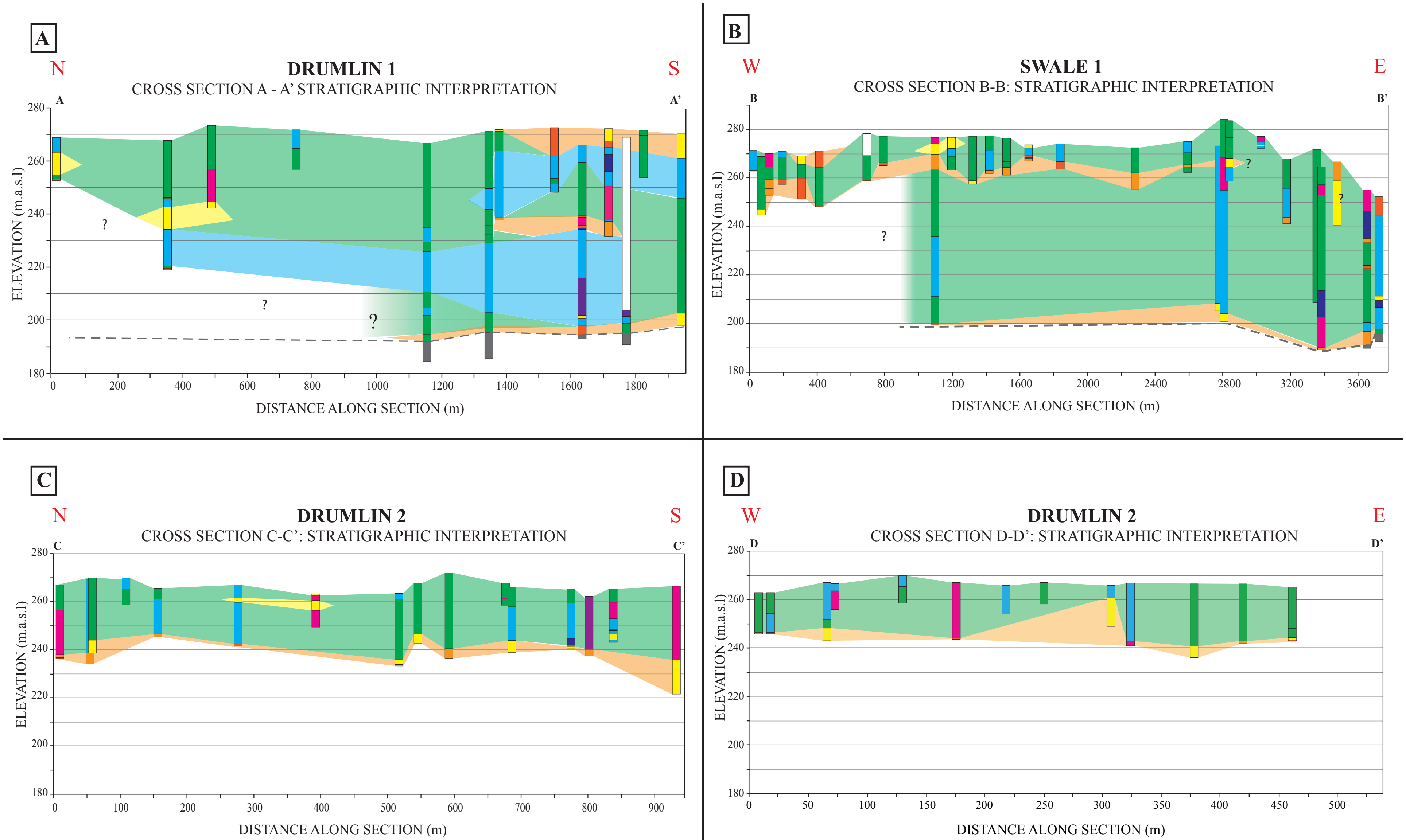

C
D'
D
D2
B
B'
C'
N
Lake Scugog
260
270
A
D1
A'
280
290
Lake Scugog
0 0.25 0.5 1 Kilometers

Figure 2.10. Cross sections through Group 1 drumlins (D1 and D2) and swale (S1). See Figs 2 6 and 2.9 for location, Fig.2.8 for colour codes. (A) Cross section A-A' (drumlin 1). (B) Cross section B-B' (Swale 1). (C) Cross section C-C' (Drumlin 2). (D) Cross section D-D' (Drumlin 2)


A
N
DRUMLIN 1
S
CROSS SECTION A - A' STRATIGRAPHIC INTERPRETATION
A
A'
ELEVATION (m.a.s.l)
180
200
220
240
260
280
?
?
?
0
200
400
600
800
1000
1200
1400
1600
1800
DISTANCE ALONG SECTION (m)
B
W
SWALE 1
E
CROSS SECTION B-B: STRATIGRAPHIC INTERPRETATION
B
B'
ELEVATION (m.a.s.l)
180
200
220
240
260
280
?
?
?
0
400
800
1200
1600
2000
2400
2800
3200
3600
DISTANCE ALONG SECTION (m)
C
N
DRUMLIN 2
S
CROSS SECTION C-C': STRATIGRAPHIC INTERPRETATION
C
C'
ELEVATION (m.a.s.l)
180
200
220
240
260
280
0
100
200
300
400
500
600
700
800
900
DISTANCE ALONG SECTION (m)
D
W
DRUMLIN 2
E
CROSS SECTION D-D': STRATIGRAPHIC INTERPRETATION
D
D'
ELEVATION (m.a.s.l)
180
200
220
240
260
280
0
50
100
150
200
250
300
350
400
450
500
DISTANCE ALONG SECTION (m)

Overlying the basal bedrock aquifer is a thick (30 – 60 m) diamict of variable texture (descriptions include clay-gravel, clay, clay-sand; Fig. 2.10). Examination of water well records compiled on cross sections D1 (A-A') and S1 (B-B') suggest this diamict is continuous from north to south and east to west.

Overlying this diamict is a continuous, thin (<10 m) sand and gravel unit which is frequently encountered around 240 m.a.sl. beneath the drumlins and 260 m.a.s.l. beneath the swale. The unit is mappable in both drumlins from north to south, and west to east through the adjacent swale (S1; Fig. 2.10b). This coarse-grained unit is interpreted here as the upper aquifer.

The upper aquifer is overlain by another thick (10 – 30 m) variably textured diamict (described as clay with sand and gravel, clay with gravel and silt, clay with gravel or clay; Fig. 2.10) which is considered to function as an aquitard. Cross section AA', BB', CC' and DD' show this upper diamict as a continuous unit from east to west and north to south (Fig. 2.10c).

S1 has seven wells that penetrate a small drumlin at the eastern end of the section. These well records indicate that the upper sand and gravel unit (aquifer) is present at a similar depth through the swale to the west, the small drumlin, and into the swale to the east (Fig. 2.10b).

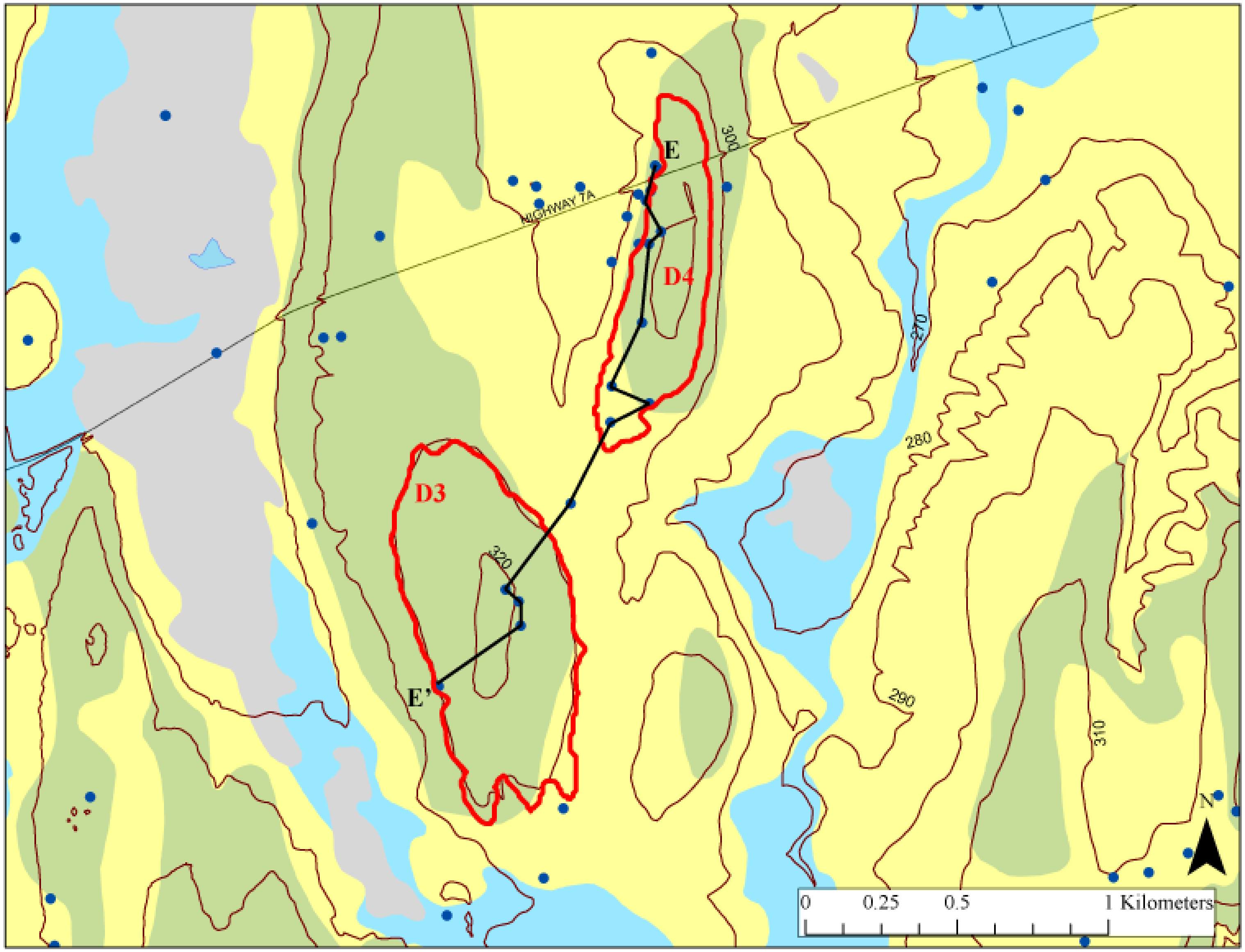
Analysis of the available water well data suggest there are two coarse-grained units that serve as aquifers in Group 1 drumlins: an upper aquifer which is typically penetrated between 240 and 260 m.a.s.l. and an aquifer immediately above or in the bedrock surface at 195 m.a.s.l. (Fig. 2.10). Each aquifer is overlain by a thick diamict unit which likely acts as an aquitard and the aquifers can therefore be considered to be confined.

2.3.3 *Drumlin Group 2*

Drumlin Group 2 consists of two drumlins (D3 and D4; section EE'; Fig. 14) located east of Lake Scugog and north of the ORM (Fig. 2.11). Group 2 drumlins show similar characteristics

Figure 2.11. Group 2 drumlins: Surficial geology and contour map for drumlins D3 and D4 and cross section E-E'. See Fig. 2.6 for location in study area; Fig. 2.8 for colour codes.

GROUP 2


E
D4
D3
E'
HIGHWAY 7A
300
320
270
280
290
310
N
0 0.25 0.5 1 Kilometers

to those in Group 1 with two distinct aquifer units; however, the maximum ground surface (330 m.a.s.l) is significantly higher in Group 2 than Group 1 (280 m.a.s.l.) and the lower bedrock aquifer is not well represented by the records available (Fig. 2.12).

The surficial geology of drumlins D3 and D4 is mapped as diamict with sand, silt and organic deposits in the adjacent swales (Fig. 2.12). Section E-E' passes through the western flank of D4 and traverses D3 from north to south (Fig. 2.12). 14 wells were used to create section E-E' however none of them penetrate bedrock; this indicates a maximum overburden thickness of at least 80 meters (Fig. 2.12).

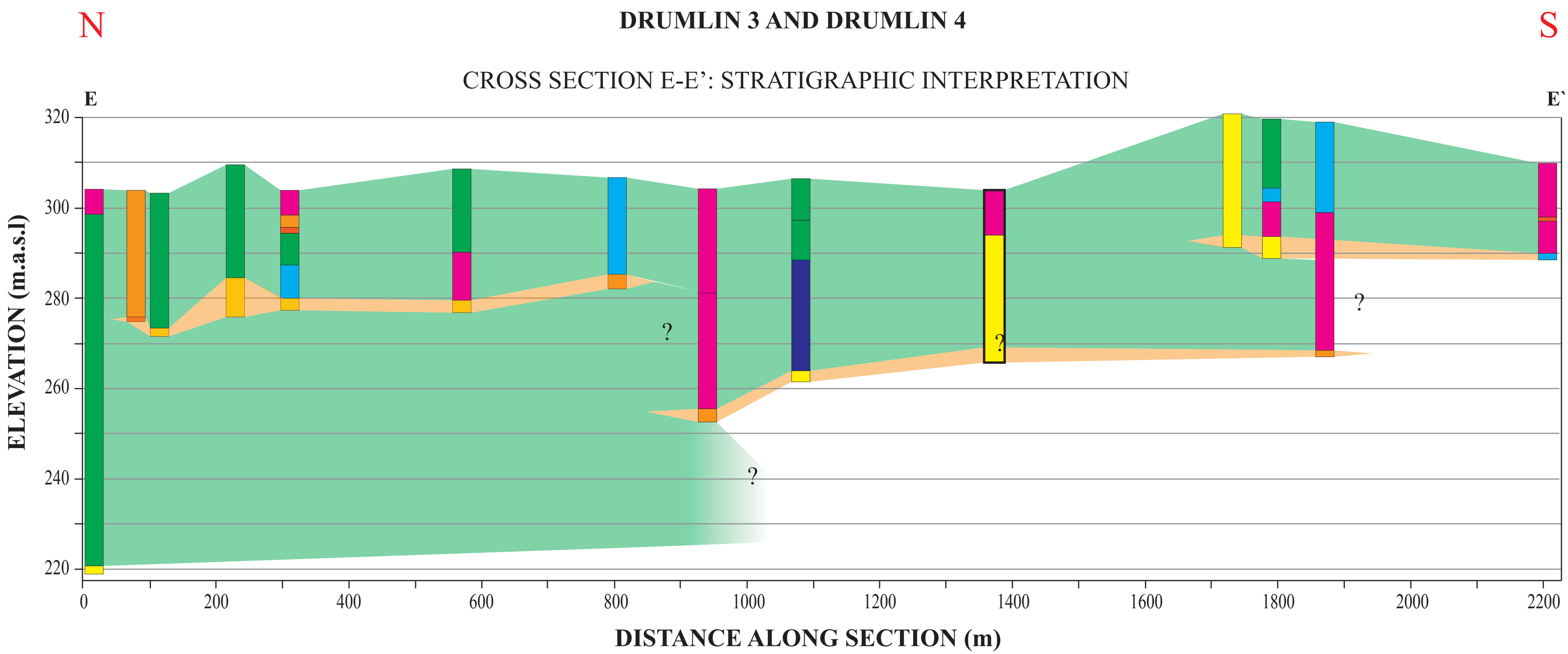
One well record at D4 indicates the presence of a thin (<2m) sand unit at depth (220 m.a.s.l.). Bedrock is encountered between 200 and 180 m.a.s.l. in adjacent drumlin groups (Groups 1 and 3) and so this unit is considered a basal sand, likely close to the bedrock surface. This unit is overlain by a thick diamict sequence (>30 m; Fig. 2.12).

Well records also indicate the presence of a thin (<5 m) sand and gravel unit within diamict that is encountered at between 305 m.a.s.l. and 265 m.a.s.l. (Fig. 2.12). It is not clear if these coarse-grained sediments actually form two distinct units (one between 255 and 270 m.a.s.l. and one between 295 and 285 m.a.s.l.; Fig. 2.12) or one laterally discontinuous unit. This unit of coarse-grained material is interpreted as an upper aquifer.

Overlying the upper aquifer is a thick (20 – 40 m) variably textured (descriptions include clay-sand, clay-gravel, clay and gravel) diamict unit (Fig. 2.12). This unit is continuous across the section and is interpreted as an aquitard.

Group 2 drumlins thus show the presence of a discontinuous upper aquifer unit overlain by a thick diamict. The elevation of the upper aquifer unit is slightly higher than in Group 1 drumlins and the upper diamict is thicker.

Figure 2.12. Cross Sections through Group 2 drumlins (D3 and D4). See Figs 2.6 and 2.9 for location, Fig.2.8 for colour codes.


N
S
DRUMLIN 3 AND DRUMLIN 4
CROSS SECTION E-E': STRATIGRAPHIC INTERPRETATION
E
E`
320
300
280
260
240
220
ELEVATION (m.a.s.l)
?
?
?
?
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
DISTANCE ALONG SECTION (m)

2.3.4 *Drumlin Group 3*

Drumlin Group 3 consists of two drumlins (D5: FF' and D6: GG', HH') and one swale (S2; II') located on the northern shore of Rice Lake (Fig. 2.13). The surficial geology of the drumlins is mapped as diamict with sands and organic deposits in the adjacent swales (Fig. 2.13). Maximum ground surface elevation at these drumlins is 240 m.a.s.l. and overburden thickness reaches 60 meters in the drumlins and declines to 20 meters in the swale (S1; Fig. 2.14d). Drumlins of Group 3 are penetrated by wells that intersect the lower bedrock aquifer and at D6 an upper aquifer can be identified at approximately 210 m.a.s.l.; an upper aquifer cannot be clearly identified at D5 (Fig. 2.14a).

D5 is 975 meters long and 360 meters wide (Fig. 16) and shows 45 meters of relief (elevation 190 to 235 m.a.s.l.; Fig. 2.14a). D6 is 1300 meters long and 650 meters wide (Fig. 2.14b,c) and has a relief of 50 meters (ground surface elevation from 190 to 240 m.a.s.l.; Fig.14b, c). The long axes of D5 and D6 lie parallel to previous estimations of local ice flow directions (northeast – southwest; Boyce and Eyles 1991).

16 of 19 wells were utilized on D5 to create cross section FF' which is oriented along the long axis of the drumlin from north (F) to south (F') (Fig. 2.14a). 37 wells of 76 were selected on D6 to create two perpendicular sections through the subsurface. Well record selection was based on the spatial distribution and the continuity of record (i.e. records to bedrock were favored for a more complete understanding of the stratigraphy). Cross section GG' is oriented north-west to south-east approximately parallel to the long axis of the drumlin.

The bedrock surface beneath drumlins D5 and D6 is variable (relief may be up to 20 m; Fig. 2.14a,b,c) and several wells show evidence of a thin (less than 1 m) gravel unit overlying bedrock; the bedrock and overlying sediment are interpreted to form a basal bedrock aquifer.

Figure 2.13. Group 3 drumlins: Surficial geology and contour map for drumlins D5 and D6 (cross sections FF', GG', HH') and Swale 2 (cross section II'). See Fig. 2.6 for location in study area, Fig. 2.8 for colour codes.

GROUP 3

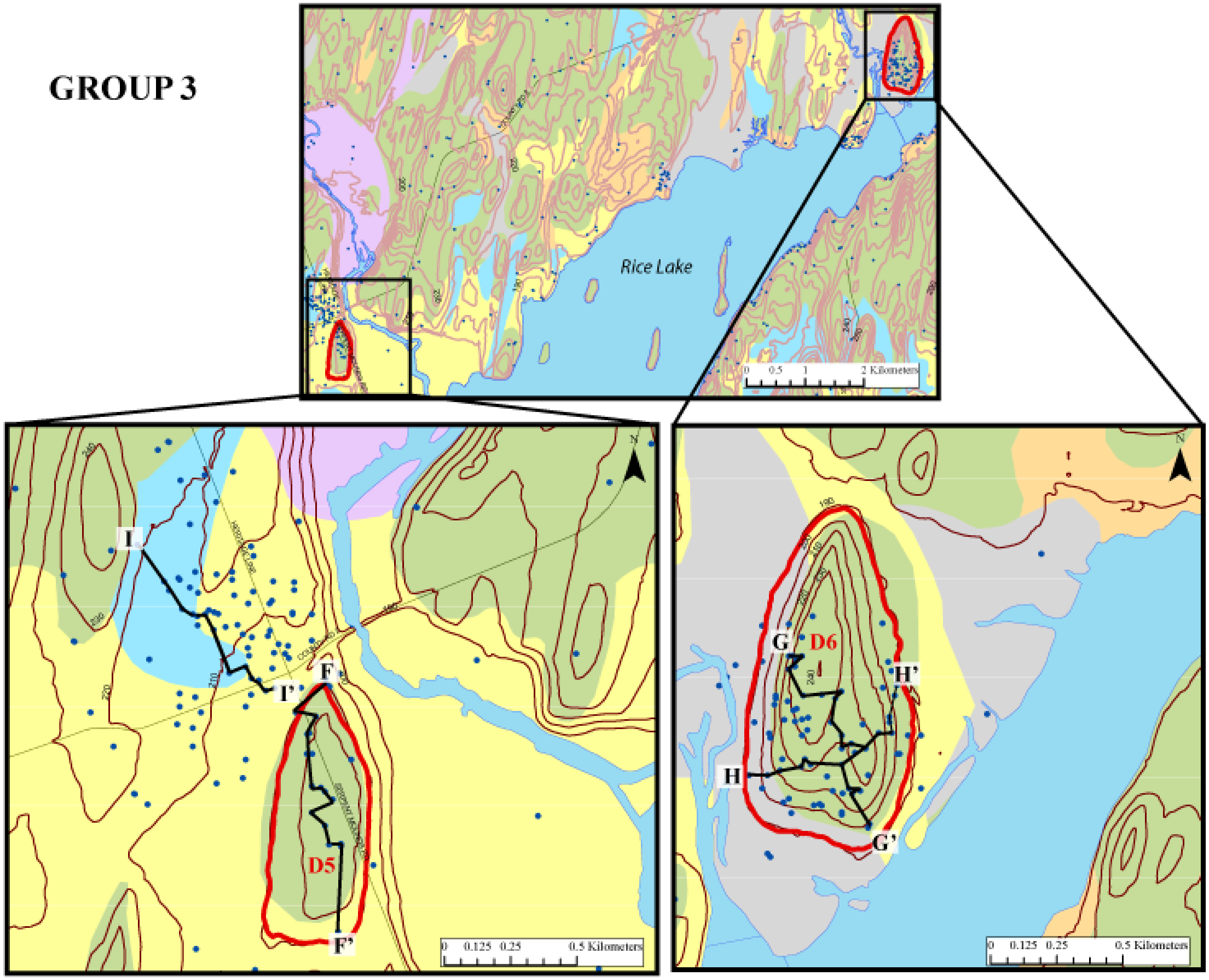
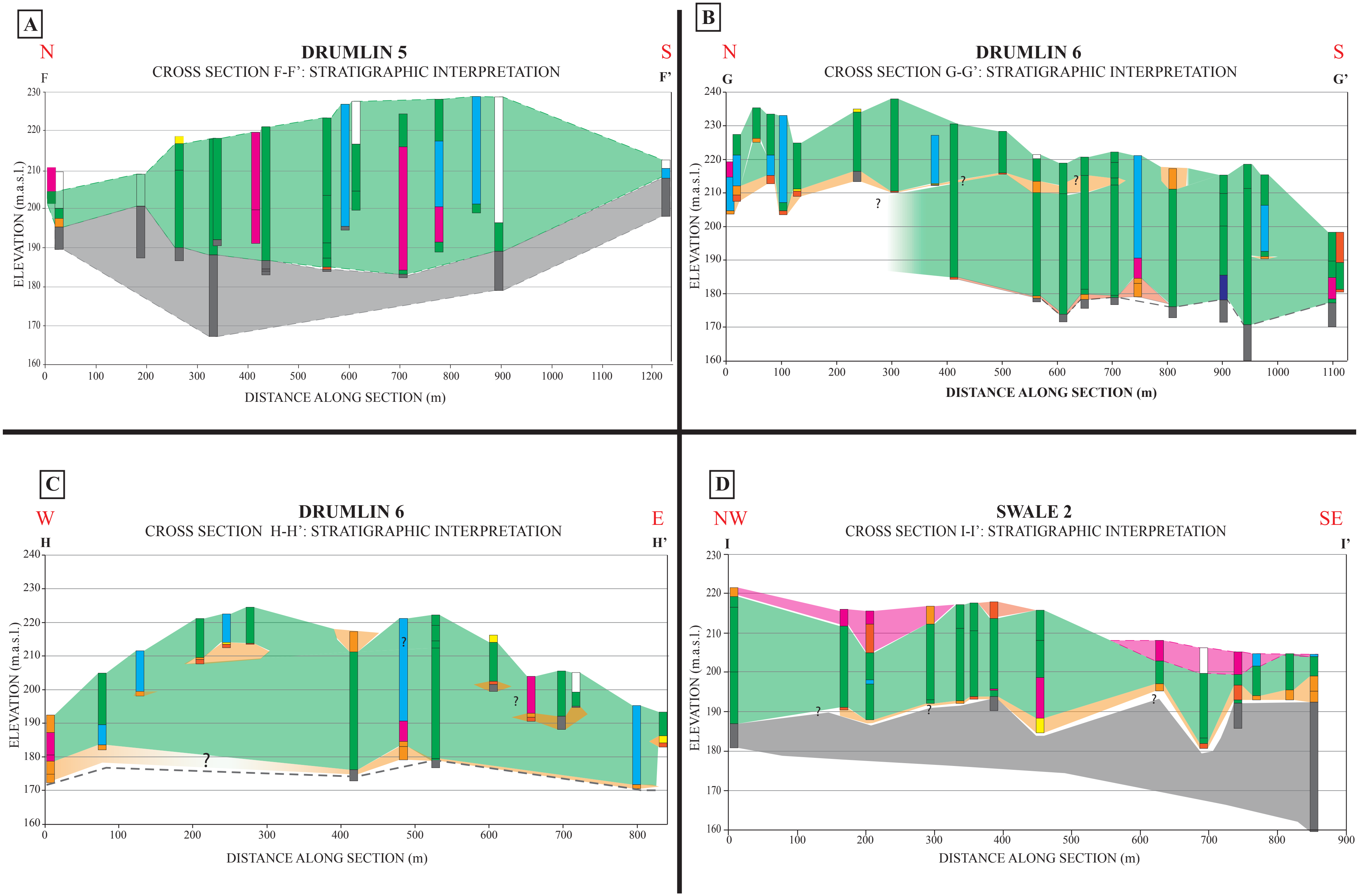

Rice Lake
0 0.5 1 2 Kilometers
I
I'
F
F'
D5
0 0.125 0.25 0.5 Kilometers
N
G
G'
H
H'
D6
0 0.125 0.25 0.5 Kilometers
N

Figure 2.14. Cross Sections through Group 3 drumlins (D5 and D6) and swale 2 (S2). See Figs. 2.6, 2.13 for location in study area, Fig. 2.8 for colour codes. (A) Cross section FF' (drumlin 5). (B) Cross section GG' (drumlin 6). (C) Cross section HH' (drumlin 6). (D) Cross section II' (swale 2).


A
N
DRUMLIN 5
CROSS SECTION F-F': STRATIGRAPHIC INTERPRETATION
S
F
F'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
B
N
DRUMLIN 6
CROSS SECTION G-G': STRATIGRAPHIC INTERPRETATION
S
G
G'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
C
W
DRUMLIN 6
CROSS SECTION H-H': STRATIGRAPHIC INTERPRETATION
E
H
H'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
D
NW
SWALE 2
CROSS SECTION I-I': STRATIGRAPHIC INTERPRETATION
SE
I
I'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)

Each well penetrates a thick diamict unit overlying bedrock with variable textures recorded (descriptions ranging from clay with gravel or stones, sandy clay or clay with no clasts). This unit is continuous across sections GG' (Fig.2.14b) and HH' (Fig. 2.14c).

There is no upper aquifer identified at D5 but a thin (<5m) sand and gravel unit is encountered between 205 and 215 m.a.s.l. below D6 (GG'; Fig. 2.14b), possibly outcropping on the southern flank of the drumlin. This coarse-grained (upper aquifer) unit is not recorded at consistent elevations in wells included in section HH' that runs west to east across D6 (Fig.2.14c) and may be discontinuous.

Section II' was constructed through a swale to the north of D5 (Fig. 2.14a). This section utilizes 14 wells and many other wells in the area were analyzed to confirm the stratigraphy identified in this area (Fig. 2.14d). Bedrock elevation is variable (183 to 193 m.a.s.l.) and, together with an overlying sand and gravel unit, is considered to form a continuous basal aquifer. This basal aquifer in the swale is overlain by a thick (30 m) diamict unit (descriptions include clay-gravel, sand-clay) which is in turn overlain by a thin (<10 m), discontinuous, sand and clay unit with some gravel (Fig. 2.14d).

The drumlins of Group 3 show differing stratigraphies from Groups 1 and 2 and from each other. Both drumlins appear to have a continuous basal bedrock aquifer but only wells in D6 penetrate a discontinuous upper aquifer within the thick diamict package that overlies bedrock.

2.3.5 *Drumlin Group 4*

Drumlin Group 4 consists of 5 drumlins (D7, D8, D9, D10, D11) and 3 swales located along a 45 km transect from near Oshawa in the west to Coburg in the east, south of the ORM (Figs.2.15, 2.16).

Figure 2.15. Group 4 drumlins: Surficial geology and contour map for drumlins D8 and D9 (cross section JJ', LL') and Swale 3 and 4 (cross section KK', MM'). See Fig. 2.6 for location in study area, Fig. 2.8 for colour codes.

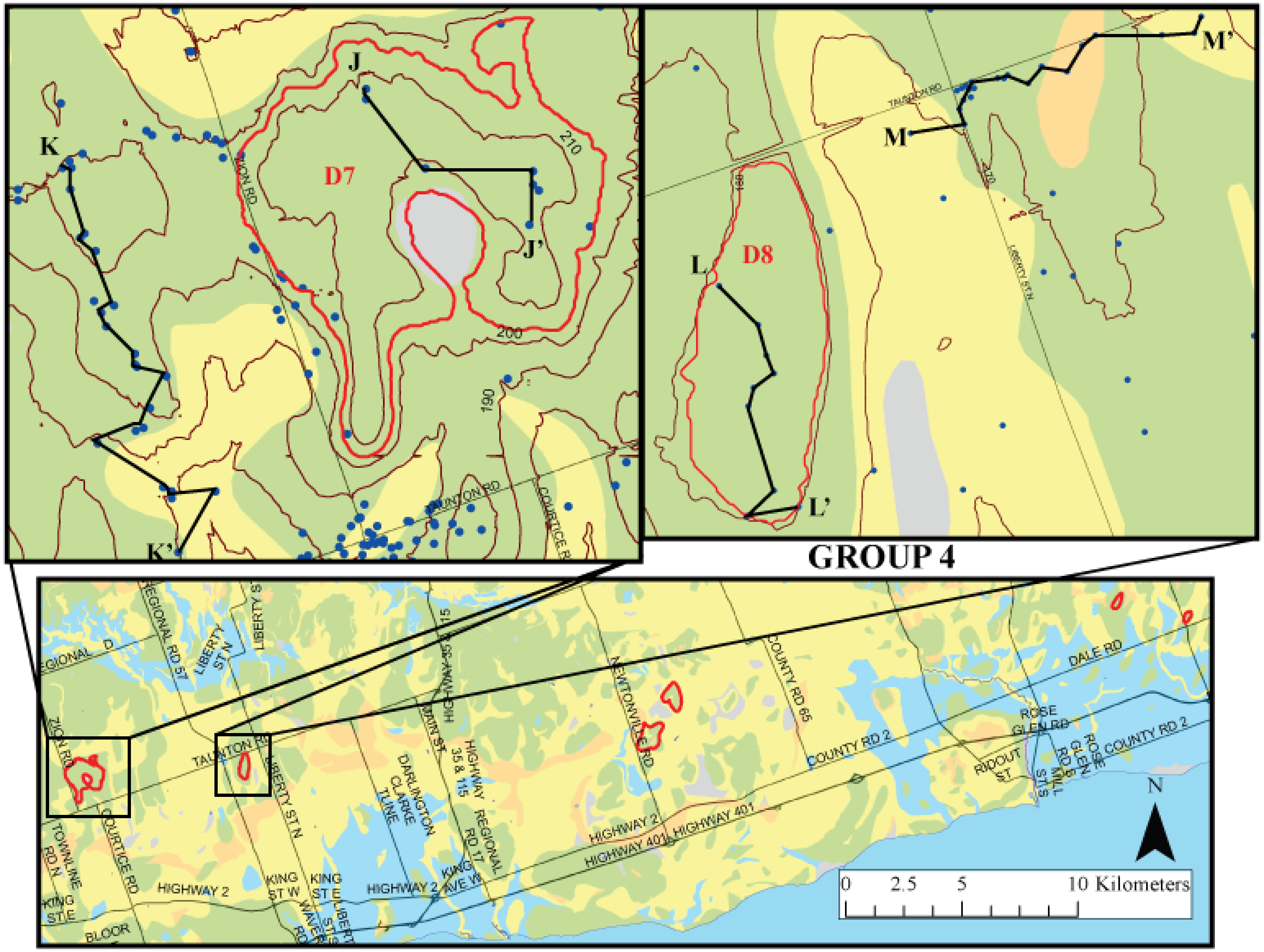
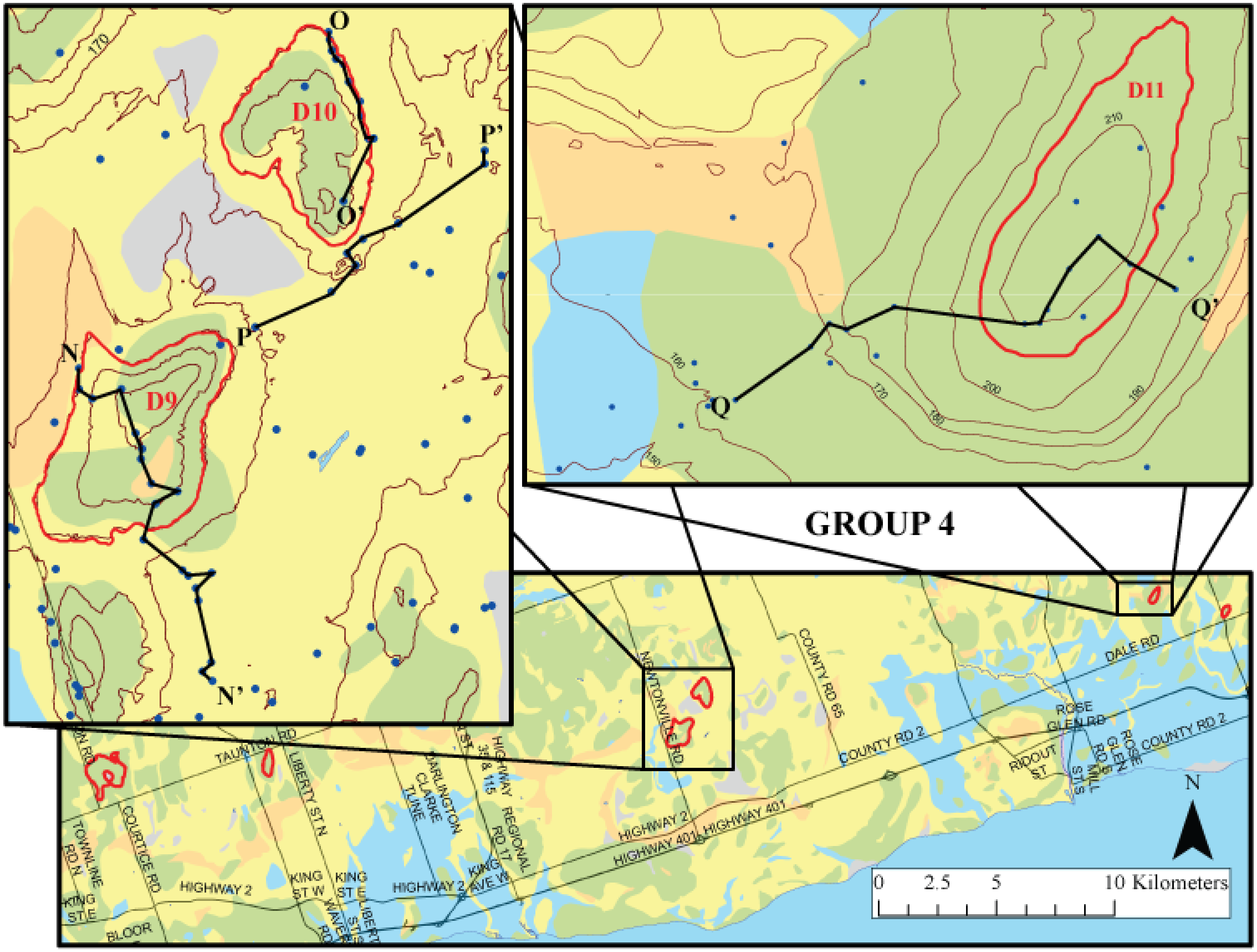

J
J'
K
K'
D7
L
L'
D8
M
M'
GROUP 4
N
0 2.5 5 10 Kilometers

Figure 2.16. Group 4 drumlins: Surficial geology and contour map for drumlins D9, D10 and D11 (cross section NN', OO', QQ") and Swale 5 (PP'). See Fig. 2.6 for location in study area, Fig. 2.8 for colour codes.


GROUP 4
D9
D10
D11
N
N'
O
O'
P
P'
Q
Q'
0 2.5 5 10 Kilometers
N
HIGHWAY 2
HIGHWAY 401
COUNTY RD 2
DALE RD
COUNTY RD 65
TAUNTON RD
LIBERTY ST N
COURTICE RD
TOWNLINE RD N
BLOOR
RIDOUT ST
ROSE GLEN RD

Many of the wells penetrating drumlins in this group indicate the presence of a basal bedrock aquifer (Figs.2.15, 2.16). All of the drumlins in this group, with the exception of D10, suggest the presence of an upper aquifer, overlain by a variably textured diamict, which may be exposed at ground surface in inter-drumlin swales. The upper aquifer appears to decrease in elevation from west (180 m.a.s.l. average top of aquifer) to east (160 m.a.s.l average; Figs.2.15, 2.16).

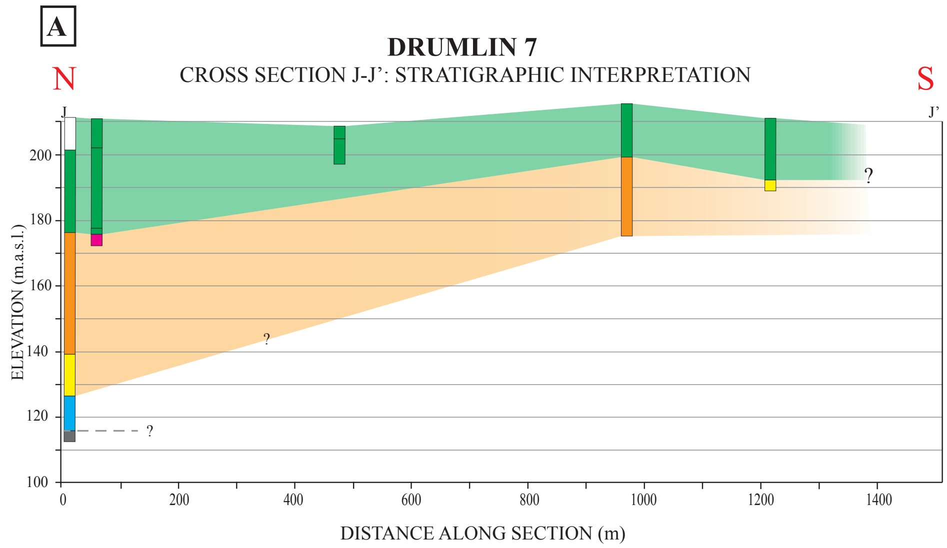
Drumlin size is variable with lengths between 750 m (D11; Fig. 2.16) and 1900 m (D7; Fig. 2.15) and widths of 300 m (D11; Fig. 2.16) to 1500 m (D7; Fig. 2.15). Drumlin relief is between 20 and 30 meters. Each drumlin long axis is oriented parallel to local ice flow direction (northeast to southwest; Boyce and Eyles 1991). Drumlin 9 is located south of the high water level mark of post-glacial Lake Iroquois (Fig. 2.16). The surficial geology at each drumlin is mapped as diamict with sands and gravels at surface in the surrounding swales (Figs.2.15, 2.16)

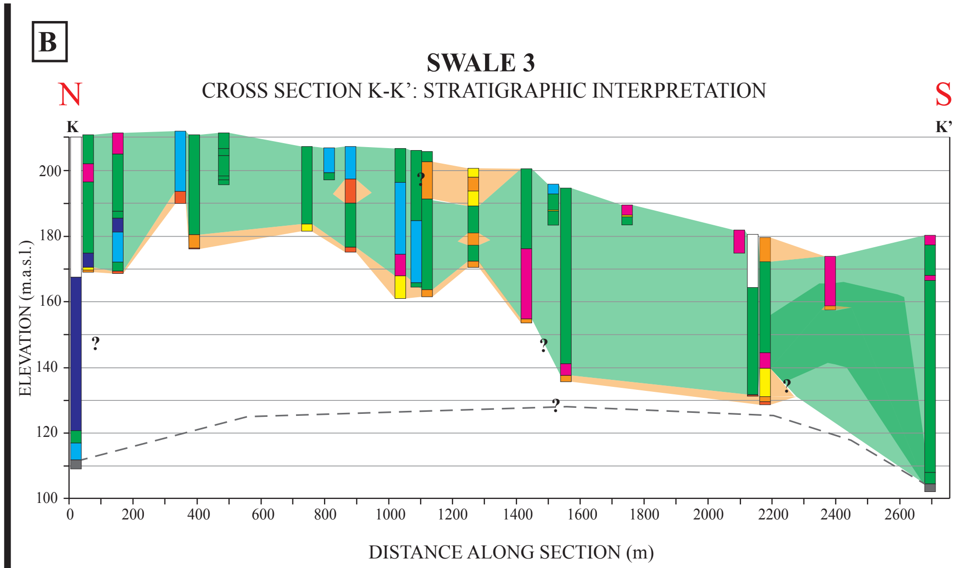
The average elevation of bedrock across this group is 110 m.a.s.l. (number of bedrock wells = 19/105). Drumlins 7 and 8 overlie the Blue Mountain Formation and the remainder of drumlins in Group 4 overlie the Lindsay Formation. There is no evidence of significant fluctuations in bedrock elevation (Figs. 2.17, 2.18).

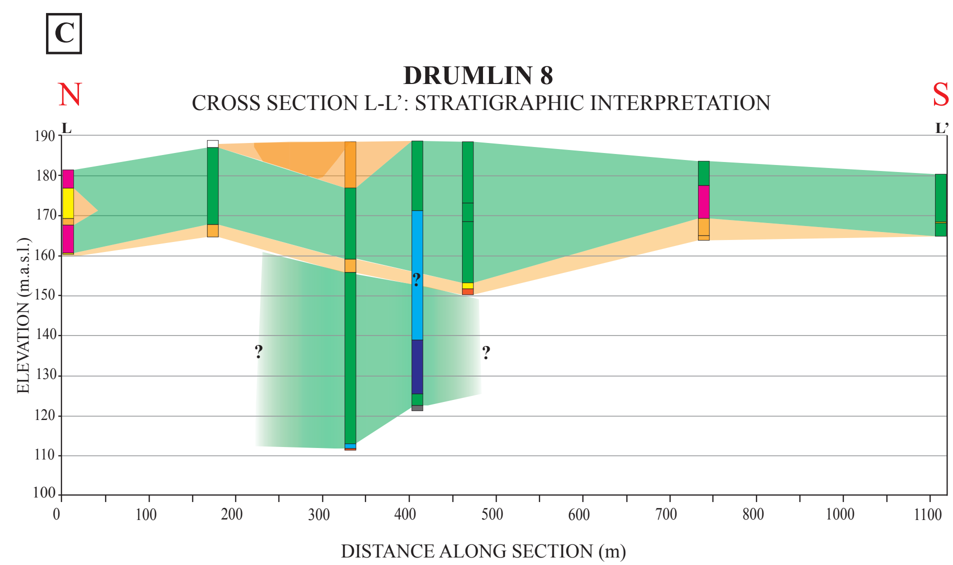
Overlying bedrock at D10 and 11 is a thin (<10 m; Fig. 2.18b,d), discontinuous sand and gravel unit, interpreted here as a basal aquifer. Elsewhere, a 20 – 80 meter thick diamict package with variable texture (descriptors include clay-gravel, sand-clay, hardpan, silt-clay) directly overlies bedrock (Figs. 2.17, 2.18).

A reasonably thick (5 to 20 m) sand and gravel unit is frequently encountered at elevations of between 140 and 160 m.a.s.l. at D7, S3, D8, S4, D9, S5, and D11 (Figs. 2.17, 2.18). This unit appears to be continuous between drumlins and adjacent swales and is interpreted here as an upper aquifer.

Figure 2.17. Cross Sections through Group 4 drumlins (D7, D8) and swales 3 and 4 (S3; S4). See Figs. 2.6, 2.15 for location in study area; Fig. 2.8 for colour codes. (A) Cross section JJ' (drumlin 7). (B) Cross section KK' (swale 3). (C) Cross section LL' (drumlin 8). (D) Cross section MM' (swale 4).


A
DRUMLIN 7
CROSS SECTION J-J': STRATIGRAPHIC INTERPRETATION
N
S
J
J'
ELEVATION (m.a.s.l.)
100
120
140
160
180
200
0
200
400
600
800
1000
1200
1400
DISTANCE ALONG SECTION (m)
?


B
SWALE 3
CROSS SECTION K-K': STRATIGRAPHIC INTERPRETATION
N
S
K
K'
ELEVATION (m.a.s.l.)
100
120
140
160
180
200
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
DISTANCE ALONG SECTION (m)
?


C
DRUMLIN 8
CROSS SECTION L-L': STRATIGRAPHIC INTERPRETATION
N
S
L
L'
ELEVATION (m.a.s.l.)
100
110
120
130
140
150
160
170
180
190
0
100
200
300
400
500
600
700
800
1000
1100
DISTANCE ALONG SECTION (m)
?

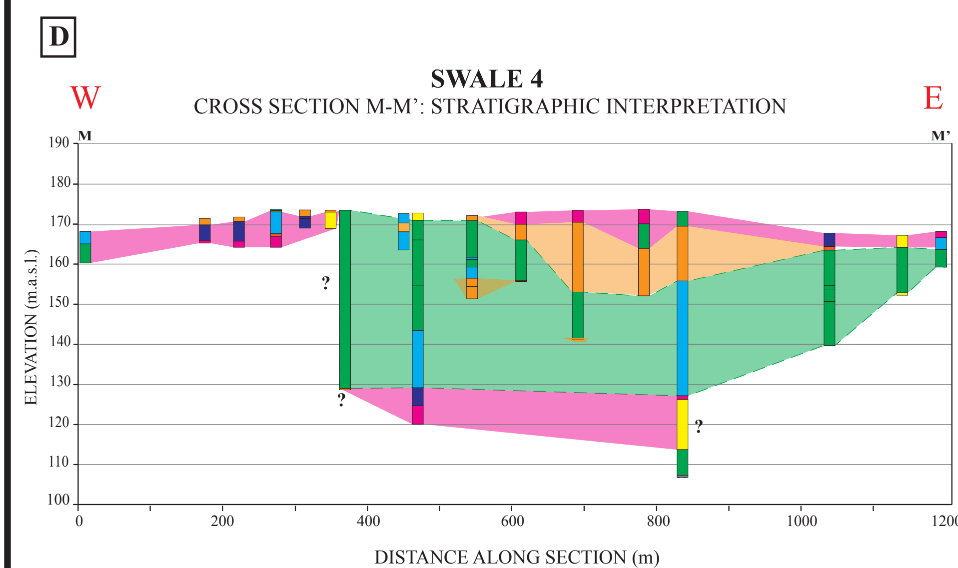
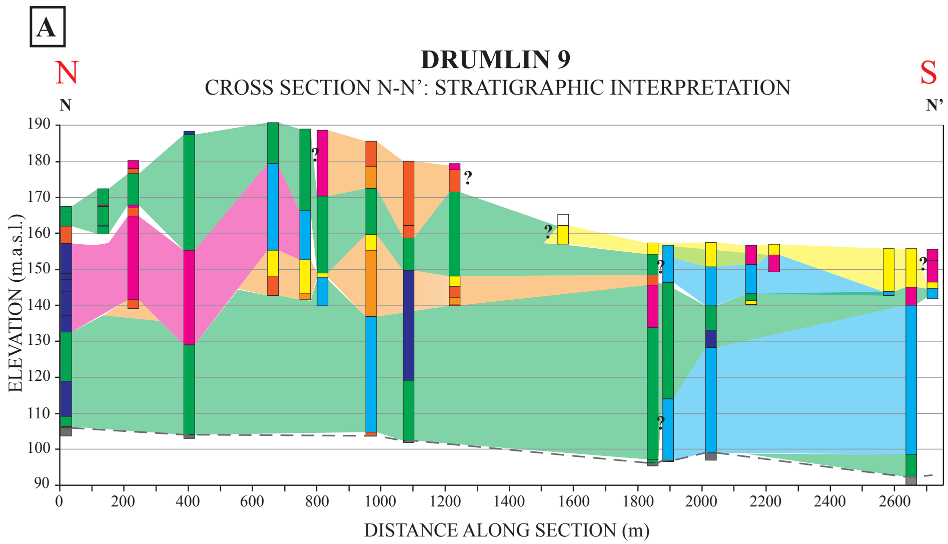
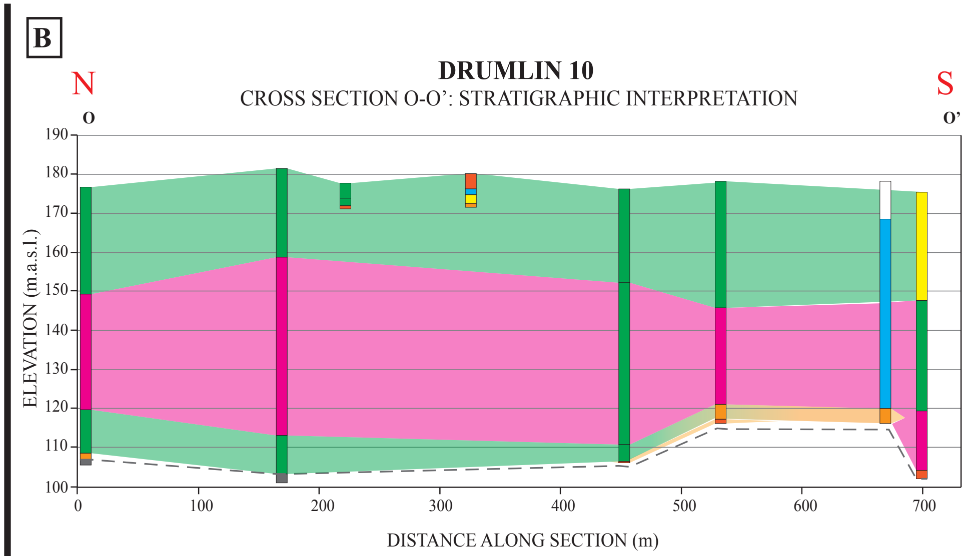
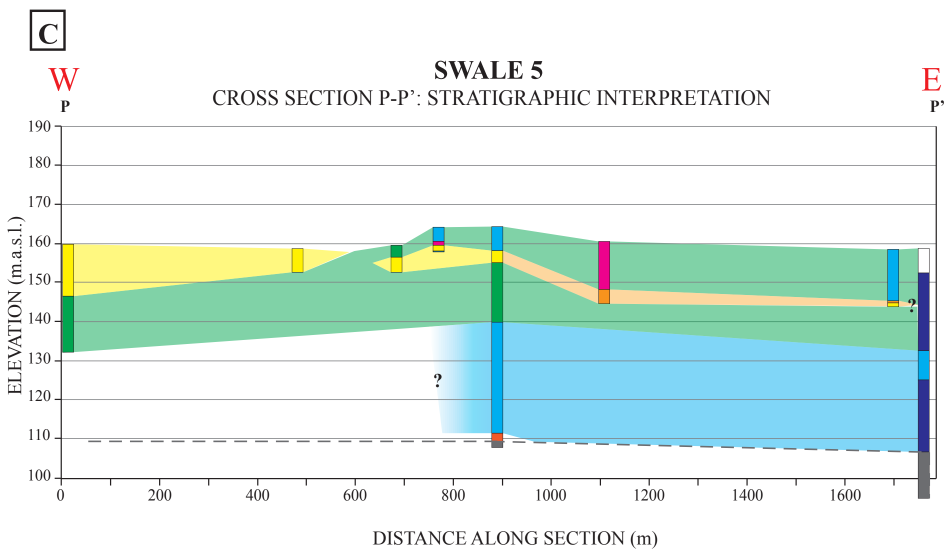
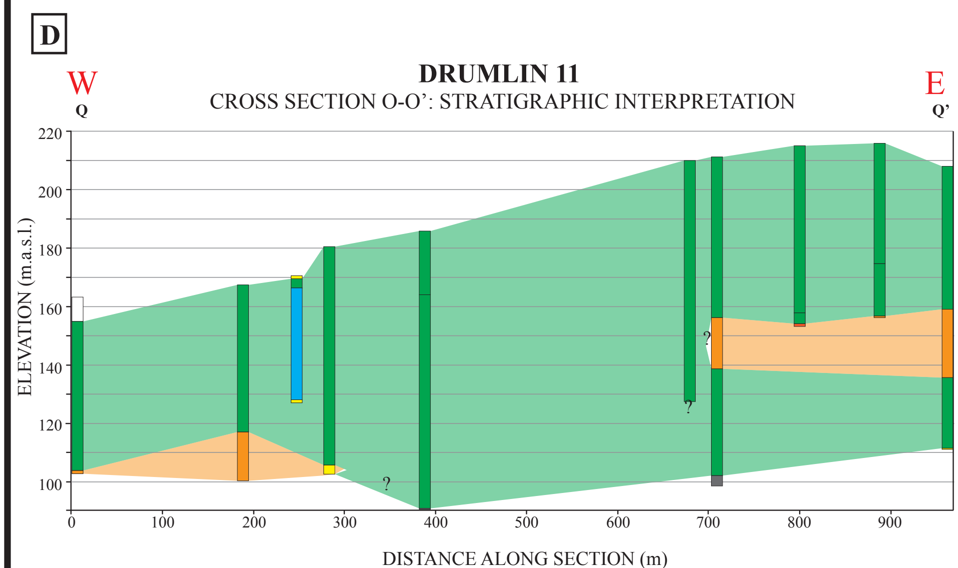

D
SWALE 4
CROSS SECTION M-M': STRATIGRAPHIC INTERPRETATION
W
E
M
M'
ELEVATION (m.a.s.l.)
100
110
120
130
140
150
160
170
180
190
0
200
400
600
800
1000
1200
DISTANCE ALONG SECTION (m)
?

Figure 2.18. Cross Sections through Group 4 drumlins (D9, D10, D11) and Swale 5 (S5). See Figs. 2.6, 2.16 for location in study area, Fig. 2.8 for colour codes. (A) Cross section NN' (drumlin 9). (B) Cross section OO' (drumlin 10). (C) Cross section PP' (swale 5). (D) Cross section QQ' (drumlin 11).


A
N
S
DRUMLIN 9
CROSS SECTION N-N': STRATIGRAPHIC INTERPRETATION
N
N'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)


B
N
S
DRUMLIN 10
CROSS SECTION O-O': STRATIGRAPHIC INTERPRETATION
O
O'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)


C
W
E
SWALE 5
CROSS SECTION P-P': STRATIGRAPHIC INTERPRETATION
P
P'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)


D
W
E
DRUMLIN 11
CROSS SECTION O-O': STRATIGRAPHIC INTERPRETATION
Q
Q'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)

All of the drumlins within Group 4 exhibit a sand and gravel unit (upper aquifer) between 140 and 180 m.a.s.l (with the exception of D10) which appears to be laterally continuous for at least 4500 m in a west to east direction (Fig. 2.17, 2.18). D10, D9, S4, and S5, also show evidence of a sand and gravel unit at ground surface. This coarse-medium grained unit is probably related to shoreline incision and deposition of sands related to post-glacial Lake Iroquois (Karrow 1981).

2.3.6 *Drumlin Group 5*

Drumlin Group 5 occurs in the eastern portion of the study area and consists of two drumlins (D12 and D13) and one swale (S6) adjacent to D13 (Fig. 2.19). The surficial deposits are mapped as diamict with clays and sands in the inter-drumlin swales (Fig. 2.19). The drumlins in Group 5 do not show the presence of an upper aquifer unit at the same elevation as Group 4 drumlins as their ground surface elevations are significantly lower. Both D12 and D13 drumlins occur south of the Lake Iroquois maximum water level shoreline (Karrow 1981).

D12 is 300 meters long and 525 meters wide (Fig. 2.19). D11 is 250 meters wide and 600 meters long (Fig.2.19). They both exhibit at least 30 meters of relief. Between the two drumlins there are 48 drilled wells (Fig. 2.19). Bedrock is found between 80 and 110 m.a.s.l. beneath Group 5 drumlins and cross-sections (RR', SS', TT' and WW'; Fig. 2.20) show between10 and 30 meters of relief on the bedrock surface.

Immediately overlying bedrock is a thin (<5m), discontinuous sand and gravel unit interpreted here as a basal aquifer. Elsewhere, a thick package of variably textured diamict (up to 50 meters; Fig.2.20) overlies bedrock and this unit likely behaves as an aquitard.

Overlying the diamict unit at D12 is a 10 – 20 meter thick unit of poorly sorted sand and gravel. This unit may reflect an episode of shoreline incision, reworking of diamict, and associated deposition of sands during high water conditions associated with post-glacial Lake Iroquois (Karrow 1981).

Figure 2.19. Group 5 drumlins: Surficial geology and contour map for drumlins D12 and D13 (cross sections RR', SS', TT') and swale 6 (WW'). See Fig. 2.6 for location in study area, Fig. 2.8 for colour codes.

GROUP 5

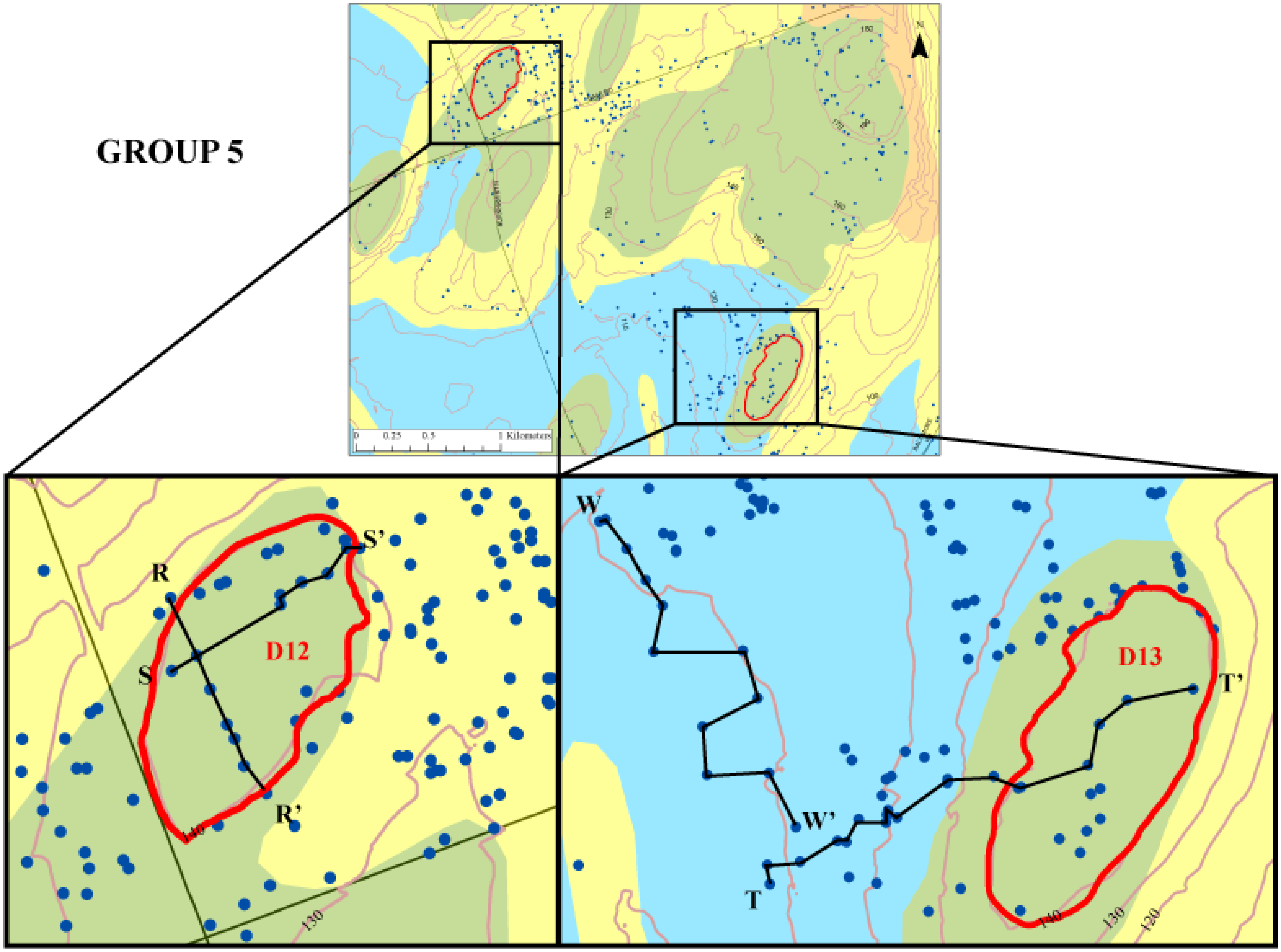
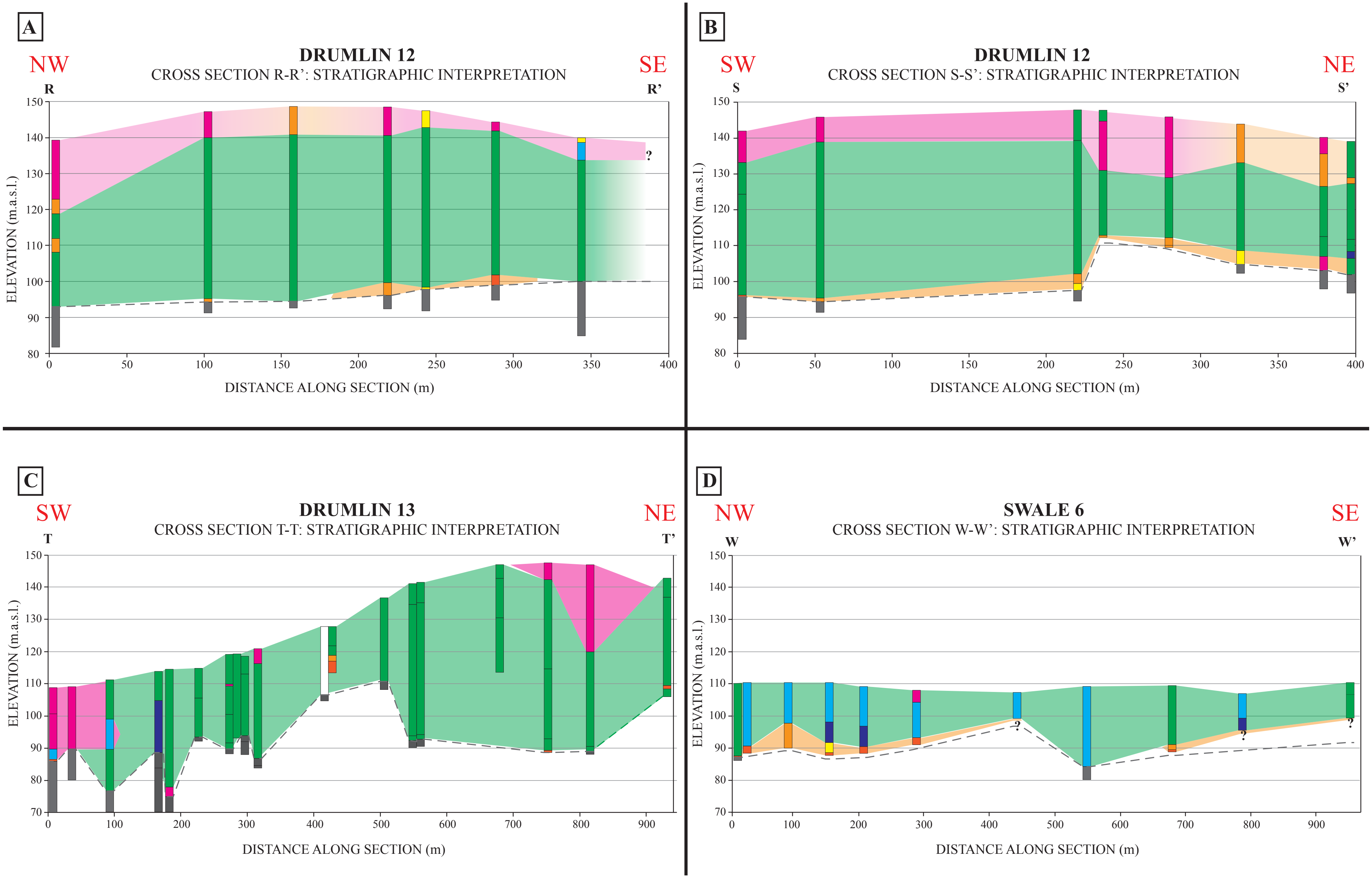


Figure 2.20. Cross Sections through Group 5 drumlins (D12, D13) and Swale 6 (S6). See Figs. 2.6, 2.19 for location in study area, Fig. 2.8 for colour codes. (A) Cross section RR' (drumlin 12). (B) Cross section SS' (drumlin 12). (C) Cross section TT' (drumlin 13). (D) Cross section WW' (swale 6).


A
NW
DRUMLIN 12
CROSS SECTION R-R': STRATIGRAPHIC INTERPRETATION
SE
R
R'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
B
SW
DRUMLIN 12
CROSS SECTION S-S': STRATIGRAPHIC INTERPRETATION
NE
S
S'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
C
SW
DRUMLIN 13
CROSS SECTION T-T: STRATIGRAPHIC INTERPRETATION
NE
T
T'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
D
NW
SWALE 6
CROSS SECTION W-W': STRATIGRAPHIC INTERPRETATION
SE
W
W'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)

2.4 DISCUSSION

2.4.1 *Stratigraphy of the PDF*

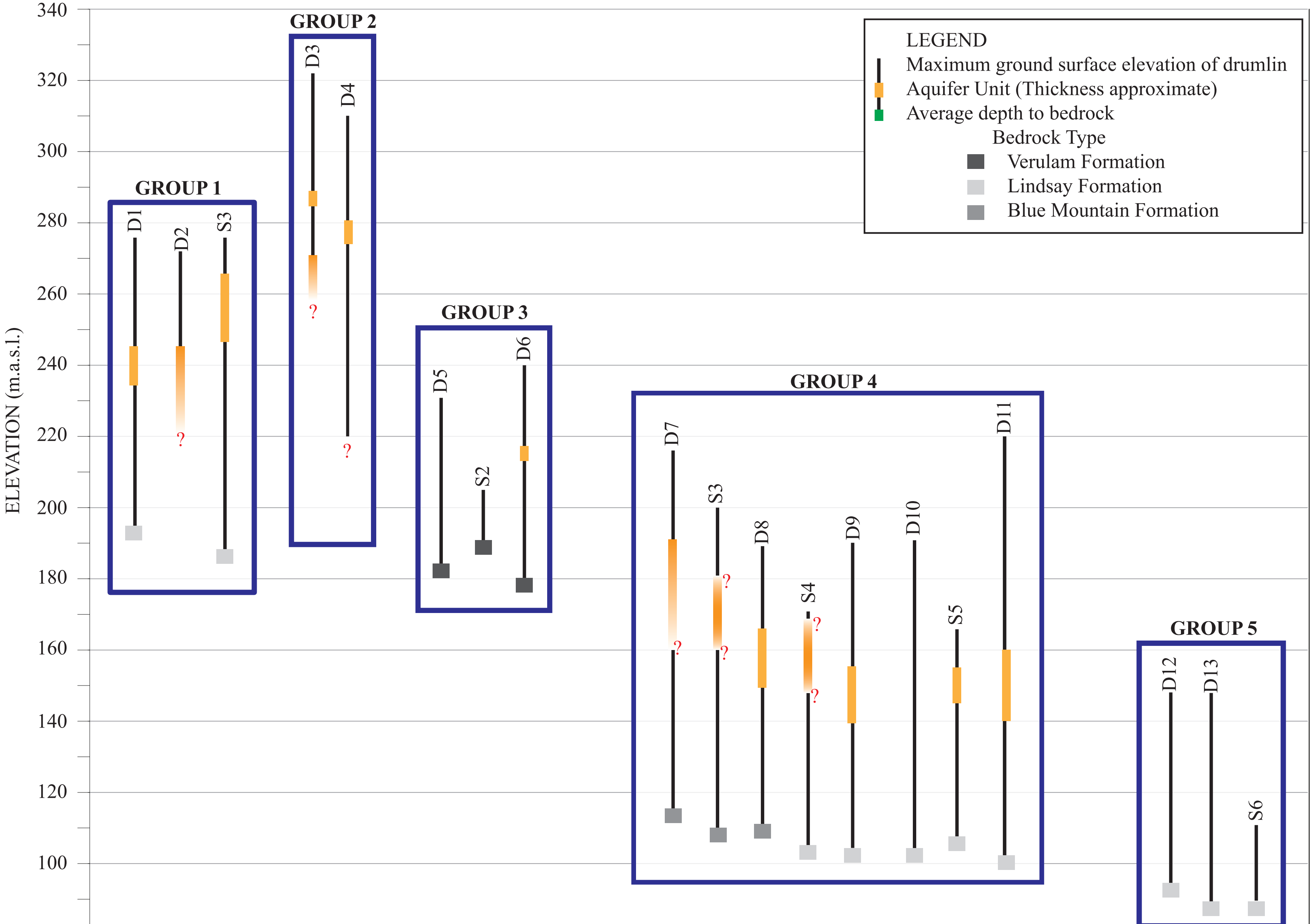
There are obvious patterns that can be identified in the basic drumlin stratigraphy across the study area; these patterns are summarized and visualized in Fig. 2.21 and relate to general changes in bedrock (type and elevation) and the geographic distribution of drumlins, north and south of the ORM, and west to east across the study area.

North of the ORM, ground surface elevation fluctuates significantly (between 280 m.a.s.l. in the west near Lake Scugog, to 330 m.a.s.l. in the center of the area and to 240 m.a.s.l. near Rice Lake; Fig.2.21). As a consequence, there is considerable variation in the overburden thickness. Maximum overburden thickness (north of the ORM) was observed in the drumlins of Group 2 at over 110 meters (Fig. 2.21). South of the ORM, ground surface elevation ranges between 220 and 170 m.a.s.l. (Fig.2.21) and overburden thickness varies between approximately 100 meters beneath drumlins and 60 meters beneath the swales.

The stratigraphy in most of the drumlins consists of bedrock overlain by a sand and gravel unit (basal aquifer), a diamict sequence (lower aquitard), a sand and gravel unit (upper aquifer), and a diamict sequence (upper aquitard). This sequence is replicated in the adjacent swales, however, the upper aquitard is generally absent (removed by fluvial/shoreline erosion) or is much thinner.

Groups of drumlins that lie north of the ORM (Groups 1, 2 and 3; Fig. 2.21) show relatively consistent bedrock elevation from west to east of between 175 and 200 m.a.s.l. Group 4 shows bedrock at relatively constant elevations from west to east of between 100 and 115 m.a.s.l. (Fig.2.21). Group 5 drumlins are associated with slightly lower bedrock elevations of between 95 and 85 m.a.s.l.

Figure 2.21. Visual representation of the stratigraphy of each drumlin and swale investigated (D1-D13, S1 – S6) showing the maximum ground surface elevation (average), average elevation of upper aquifer unit (orange), and average depth to bedrock (bedrock type indicated by colour coded square). See Fig. 2.6 for location of drumlin Groups 1 – 5.



LEGEND
Maximum ground surface elevation of drumlin
Aquifer Unit (Thickness approximate)
Average depth to bedrock
Bedrock Type
Verulam Formation
Lindsay Formation
Blue Mountain Formation
GROUP 1
GROUP 2
GROUP 3
GROUP 4
GROUP 5
D1
D2
S3
D3
D4
D5
S2
D6
D7
S3
D8
S4
D9
D10
S5
D11
D12
D13
S6
ELEVATION (m.a.s.l.)
340
320
300
280
260
240
220
200
180
160
140
120
100
80

Overall, bedrock elevation decreases from north to south; this finding is consistent with known bedrock elevation trends in the area (Liberty 1969). It is likely that the bedrock elevation changes are due largely to differential erosion of the bedrock surface during the Tertiary and Quaternary which caused the development of north-south oriented valleys and channels (Eyles et al. 1985; Eyles et al. 1993; Eyles et al. 1997), including the bedrock low in which Rice Lake now sits. This may also account for the undulating nature of the bedrock surface across the study area, particularly in a west-east direction. Post-glacial differential uplift seems to have had little effect as average bedrock elevations change little from west to east across the area.

All of the drumlins exhibit the presence of a lower till unit overlying bedrock/basal sands and gravels. In groups 1 – 3, this unit is 40 to 80 meters thick and is identified in both north-south and east-west oriented sections. In groups 4 and 5, the unit is up to 60 meters thick. The lower till unit, across all groups, is likely a Northern/Newmarket Till equivalent.

North of the ORM, from west to east, drumlin Groups 1 and 2 show a similar stratigraphy. Drumlins in this group all show the presence of an upper aquifer unit. The elevation of this upper aquifer is variable between the two groups. Additionally, D6 in Group 3 shows the presence of an upper aquifer, however, it is at a much lower elevation than that found in Groups 1 and 2. South of the ORM, drumlins in Group 4 exhibit a similar stratigraphy as those in groups 1 and 2, however, all units occur at a much lower elevation. An upper aquifer can be clearly identified in all of the drumlins and swales (with the exception of D10). It appears to decrease in elevation from north to south in a similar manner to the average bedrock and ground surface elevation. This unit is likely an Oak Ridges Moraine complex/Mackinaw sands equivalent (Meriano and Eyles 2008).

Overlying this sand and gravel aquifer is another till unit which is found across all drumlin groups and ranges from 10 to 30 meters in thickness. The upper diamict unit noted in the drumlin sections in Groups 1, 2 and 3 was likely deposited by the Simcoe Lobe during the late Port Huron stade and is a late phase Northern/Newmarket Till equivalent (Duckworth 1979, Boyce and Eyles 1991, Meriano and Eyles 2009, and OGS 2010). This till appears to be regionally extensive, north of the ORM, and occurs in the study area as the upper drumlin surface. It appears to have been eroded in places and is quite thin or absent in the inter-drumlin swales (Figs. 2.14 b,c). South of the ORM, in Groups 4 and 5, the upper till unit is likely a Halton Till equivalent, deposited by the northwestward flowing Ontario ice lobe during the Port Huron stade (Meriano and Eyles 2008).

Drumlins and swales in Group 5 and D9, S4 and S5 in Group 4 show evidence of a fine grained sand and gravel unit draping the upper diamict. These deposits likely formed post-glacially when drumlins in the southern part of the PDF were modified by shoreline incision, diamict reworking and sand deposition in Lake Iroquois (Karrow 1981).

2.4.2 *Drumlin Formation*

There have been many theories put forward to explain the formation of drumlins including erosion and/or deposition by catastrophic subglacial meltwater floods (Shaw 1983; Shaw and Sharpe 1987), subglacial remobilization and deformation of pre-existing sediment (Boulton 1987), and erosion of pre-existing sediment (Boulton and Hindmarsh 1987, Boyce and Eyles 1991; see Chapter 1). Sedimentological analysis of the information provided in water well records does not support the idea of drumlins in the PDF having an extensive ‘core’ of coarse grained (fluvial) material and therefore does not support the hypothesis of drumlin formation by subglacial megafloods (Shaw 1983, Shaw and Sharpe 1987, Shaw and Gilbert 1990, Gilbert and

Shaw 1994). The data presented here also do not support the hypothesis of drumlins having formed as a result of extensive subglacial remobilization or deformation of fine-grained sediment and the streamlining of coarser-grained sediment into drumlins (Boulton and Hindmarsh, 1987; Boyce and Eyles, 1991). There is no evidence, from data presented here, that drumlins in the PDF contain cores of coarse-grained sediment. Drumlins were found, instead, to host a range of sediments which include thick till packages and units of both fine- and coarse-grained sediment which are laterally extensive between drumlin cores and swales. These data support the idea that drumlins have formed by erosion of pre-existing sediment, most of which was previously-deposited till. During this process, some of the older material located in the swales would have been remoulded and may form some of the diamict found near the surface.

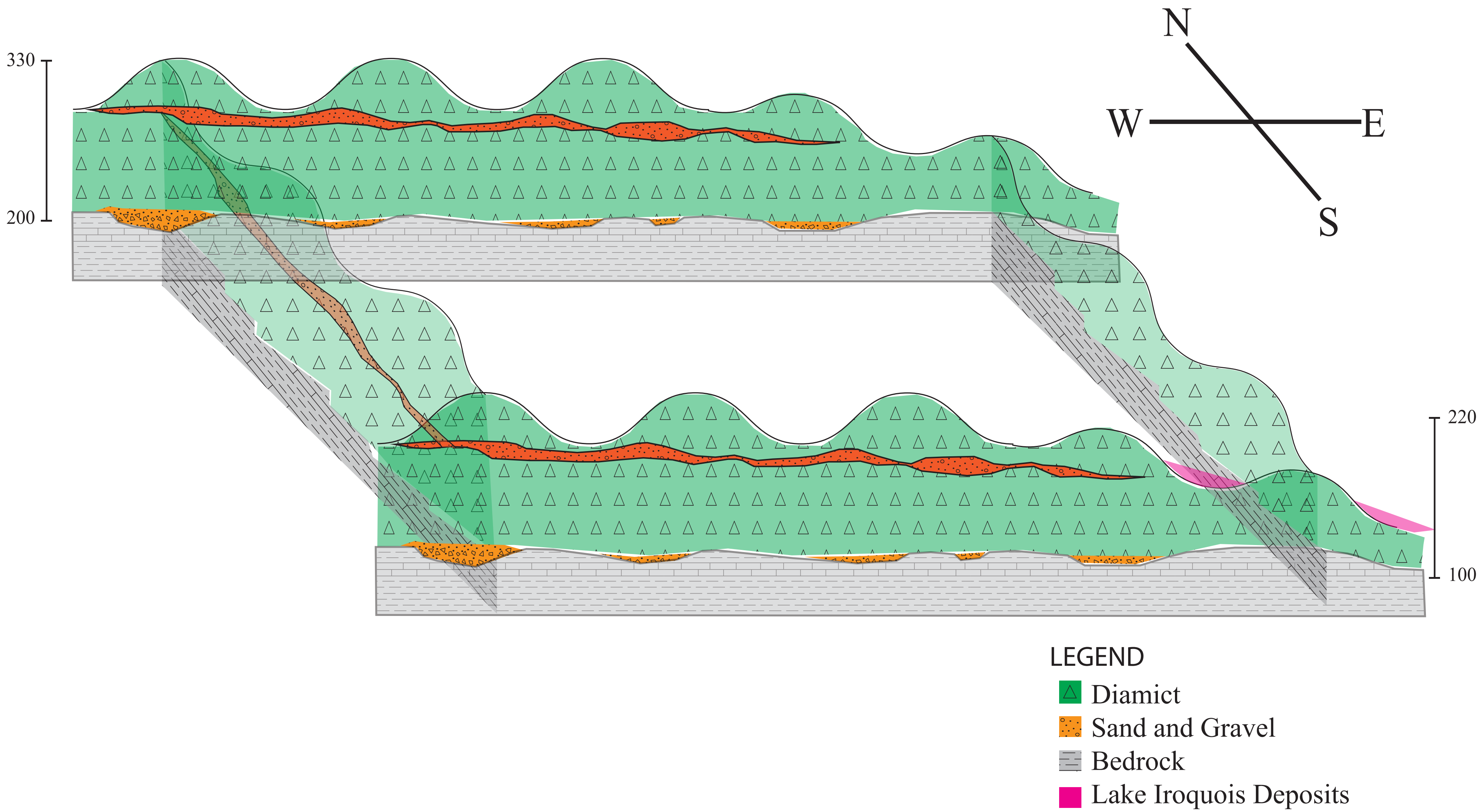
The stratigraphic analysis presented here indicates that two till units can often be identified, separated by a discontinuous sand and gravel unit (upper aquifer). It is therefore possible that drumlinization occurred in multiple stages with the lower diamict surface having been drumlinized prior to the deposition of the upper diamict. This could account for the discontinuous nature of the upper sand/gravel unit across the study area, which may be preferentially preserved in low areas (swales) of the previously drumlinized surface. Unfortunately, the spatial resolution of the available water well data is not sufficient to be able to confirm this possibility. However, evidence from the Pickering region of southern Ontario, using seismic and closely-spaced borehole data through a thick till succession, suggests that drumlins do exist, and can be identified, on the buried surface of older tills (Boyce and Eyles 2000).

2.4.3 *Hydrogeological Implications*

The subsurface data presented here indicate that two aquifers exist below the PDF that serve to provide communities in the region with potable water. These consist of a regionally continuous basal bedrock aquifer, hosted in the upper fractured part of the bedrock surface and overlying coarse-grained sands and gravel, and an upper aquifer is formed by discontinuous units of sand and gravel within overlying packages of diamict (till) (Fig. 2.22). Bedrock underlying the study area consists of relatively fine-grained limestones and shales of the Verulam, Lindsay or Blue Mountain formations. The productivity of bedrock aquifers in this region is therefore dependent on the development of secondary porosity in these rocks through fracturing or dissolution processes (Fetter 2001). The Verulam Formation and Lindsay formations have relatively high water yields (Singer et al. 2003) and are presumed to be extensively fractured. However, the Blue Mountain Formation generally has a poor yield (Singer et al. 2003) and likely has limited development of secondary porosity. The basal bedrock aquifer is enhanced in many areas by the presence of a discontinuous coarse-grained sand and gravel unit overlying bedrock. This permeable unit may be a potential target for future development of groundwater resources; however, due to its discontinuity, the productivity of this unit is unpredictable.

The Northern/Newmarket Till overlying bedrock has been subject to extensive studies of its hydrogeologic behaviour (Gerber and Howard 1996; Boyce and Eyles 2000; Gerber and Howard 2000). The regionally-extensive till is described as a thick, sandy silt to silty sand deformation till (Gerber and Howard 1996; Meriano and Eyles 2008; Boyce and Eyles 2000) with an average textural composition of 15% clay, 47% silt and 38% sand (Boyce and Eyles 2000). The till matrix is considered to contain enough clay content to classify it as having a low hydraulic conductivity (10^{-9} to 10^{-4} cm/s; Fetter 2001).

Figure 2.22. Fence diagram showing idealized section through the study area within the PDF. The succession in the northern part of the study area has a higher elevation (330 to 200 m.a.s.l.) to that in the south (220 to 100 m.a.s.l.) The stratigraphy in both the north and south of the area shows a discontinuous basal sand and gravel unit overlying an irregular bedrock surface (grey and light orange). This is overlain by a thick diamict sequence (green). A discontinuous medium to coarse grained unit is depicted beneath the drumlins representing the upper aquifer (dark orange). Note that the upper aquifer cuts out to the east. Note also the presence of finer grained material (pink) in drumlin lows to the east – this represents sediment deposited during post-glacial reworking of drumlins in Lake Iroquois.


330
200
220
100
N
W
E
S
LEGEND
Diamict
Sand and Gravel
Bedrock
Lake Iroquois Deposits

The Northern/Newmarket Till was therefore thought to function well as an aquitard and to restrict recharge to underlying aquifers and protect aquifers from surface contaminants (Boyce 1998). However, more recent studies have indicated that this till unit actually functions as a “leaky” aquitard due to the presence of discontinuous permeable zones within the till created by boulder pavements, interbeds of glaciofluvial and glaciolacustrine sediments, and fractures (Gerber and Howard 1996; Gerber and Howard 2000; Boyce and Eyles 2000). These features increase the secondary hydraulic conductivity of the till and in some cases may host enough groundwater to allow them to be used as domestic water supplies (Stephenson et al. 1988). However, these coarse-grained elements are not generally large enough to host municipal groundwater supplies. Infiltration of water through the Northern/Newmarket Till is thought to be the primary source of recharge to underlying aquifers (Gerber and Howard 2000). The Halton Till, which lies at surface south of the ORM, has also been studied extensively (Karrow 1967; Gerber and Howard 2000) and has been found to have hydraulic conductivities ranging between 2×10^{-7} and 2×10^{-3} cm/s (Meriano and Eyles 2009). However, the function of the Halton Till as an aquitard is compromised as a result of weathering and extensive fracturing of the diamict and the unit is also considered to be ‘leaky’ (Rowe and Booker 1990). Any development of water resources in the PDF, in areas underlain by diamict equivalent to the Northern/Newmarket Till or Halton Till, should take into account these properties which could allow not only recharge, but also infiltration of contaminants into aquifers hosted in or below these supposedly ‘low permeabilty’ sediments.

In the study area of the PDF the upper aquifer unit, is tentatively identified as a Mackinaw Interstadial or Oak Ridges Moraine Complex equivalent, which forms a well-known regional aquifer (Meriano and Eyles 2008). The yield of this unit will be dependent on thickness, continuity, and heterogeneity of the aquifer sediments and in areas where it is close to the ground surface, may be particularly vulnerable to anthropogenic influences.

2.5 CONCLUSIONS

This study investigated the subsurface geology, stratigraphy and hydrogeologic characteristics of 13 drumlins within the PDF using subsurface data available from water well records hosted in the WWIS. Analysis of these water well data has provided new insight into geological conditions beneath the PDF and has allowed inferences to be made regarding drumlin genesis in this region. Drumlin stratigraphy appears to be fairly consistent with a thick package of diamictite (till) overlying an undulating bedrock surface draped by a discontinuous unit of coarse-grained sands and gravel which serves as a basal aquifer (Fig. 2.22). A discontinuous horizon of sands and gravels also occurs within the diamict package and this unit functions as an upper aquifer. The discontinuous nature of this upper sand and gravel unit may be due to it having been deposited on a drumlinized till surface during interstadial (Mackinaw) conditions. These data do not support previous work in the PDF which interpreted drumlins as the product of subglacial megafloods (Shaw 1987; Shaw and Sharpe 1987; Shaw and Gilbert 1990; Gilbert and Shaw 1994) or of extensive subglacial sediment deformation (Boulton and Hindmarsh 1987; Boyce and Eyles 1991). The lateral continuity of stratigraphic units and the presence of thick diamict and limited thicknesses of sand and gravel beneath the drumlins suggest that they formed as erosional features carved from older pre-existing sediments.

Additional hydrogeologic information is required to assess the viability of either the lower or upper aquifer units for long-term sustainable water supply, although the data presented here may be used to guide groundwater exploration efforts. There is considerable interest in developing communal groundwater resources for growing communities in the PDF to ensure the better management of water quantity and quality in the future. Although the basal bedrock aquifer identified here would appear to be the most likely candidate for further aquifer development, targeted pumping tests and water quality investigations are certainly required.

This study has demonstrated the utility of the careful use of water well data to provide subsurface information in areas where outcrops and sediment exposures are lacking. However, determining the precise meaning of the sediment descriptions given in driller's logs is difficult and the interpretations presented here are solely those of the author.

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CHAPTER 3:

THE HIAWATHA FIRST NATION RESERVE:

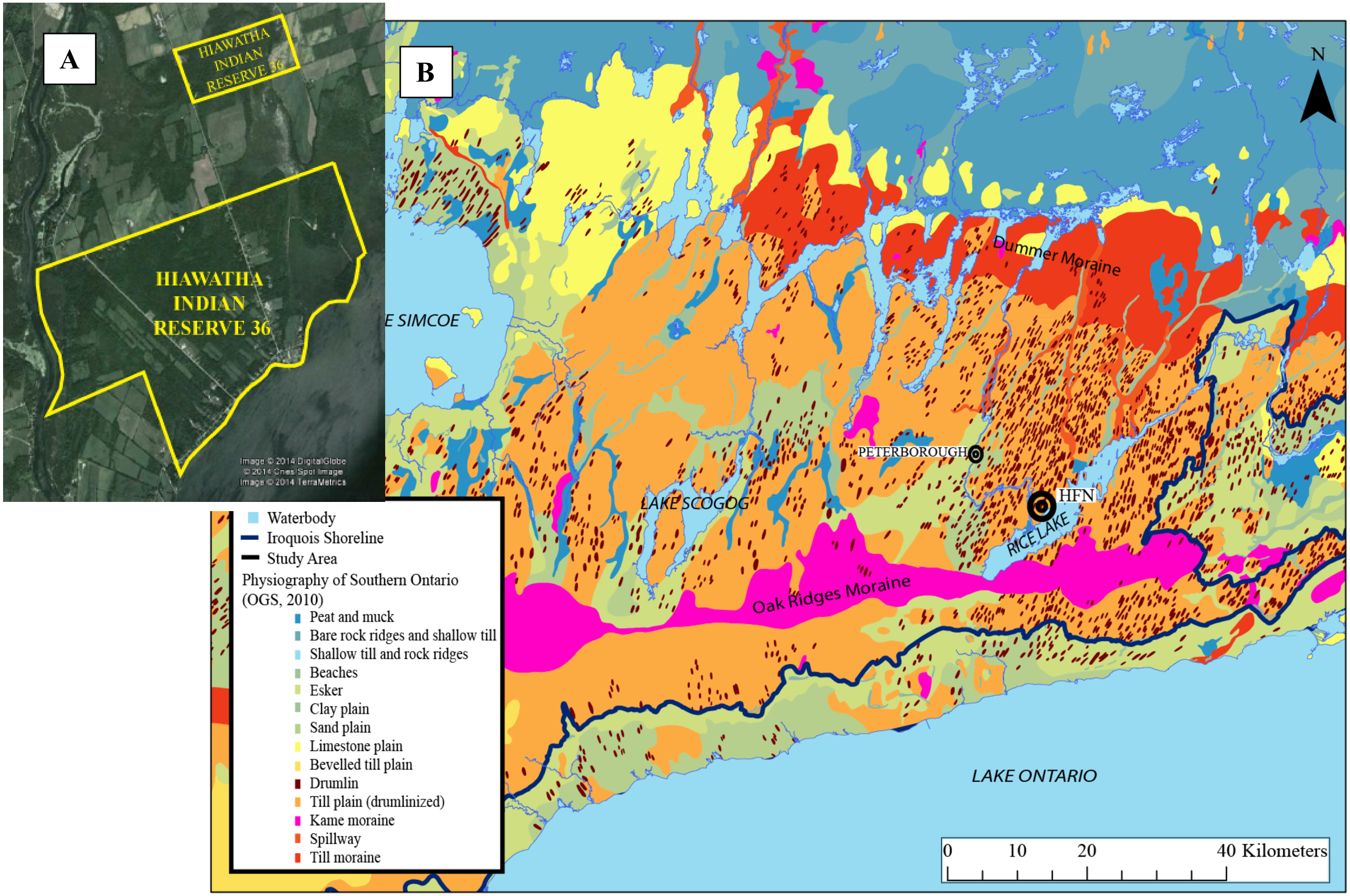
DEVELOPING GROUNDWATER SUPPLIES IN DRUMLINIZED TERRAIN

3.1 INTRODUCTION

The Hiawatha First Nation (HFN) is a First Nation community located on the northern shore of Rice Lake (Fig. 3.1) in the Peterborough Drumlin Field (Fig. 3.1). The community is located on a Reserve that covers approximately 800 hectares of a large drumlin (termed here a mega-drumlin; Rose and Letzer 1977) and extends from Kent's Bay Road to the northern shore of Rice Lake. Due to changes in regulations regarding Indian Status (from 1985 Bill C-31) the community has experienced a significant growth of population which is expected to continue. In 2005, the population of the HFN was estimated to be 189 people and the 2031 projected population was originally set at 328 people (FNES 2009). However, by 2013, the actual population living on the Reserve was 370. The HFN also has seasonal trailer parks and summer cottages which bring an estimated additional 400 people to the Reserve during the summer months. There are 160 year-round residences and 33 seasonal cottages on the HFN Reserve for a combined total housing of 193 units.

At this time, the band offices and facility buildings utilize a decentralized drinking water system (AANDC 2010). Individuals in the community rely on individual wells (dug, bored and drilled – 84%), a local spring (5%), Rice Lake (8%), or purchase bottled water for their potable water supply. Oakridge Environmental (ORE) conducted hydrogeological studies of the HFN Reserve between 1998 and 2007 in response to concerns about the long-term sustainability of the groundwater supply. They identified several water quality and water quantity concerns related to the current private wells and the decentralized drinking water systems that result in a widespread perception amongst residents of inadequate and possibly unsafe water supply on the Reserve (ORE 2009).

Figure 3.1. (A) Google Earth image of the Hiawatha First Nations Reserve (HFN; www.hiawathafirstnation.com/map_hiawatha.pdf). Reserve boundaries highlighted in yellow. Rice Lake lies to the south, the Otonabee Rive to the west. (B) The physiography of Southern Ontario (OGS 2010). HFN Reserve denoted by yellow star. Note that the HFN lies in a drumlinized till plain that forms part of the Peterborough Drumlin Field (PDF).



A
HIAWATHA INDIAN RESERVE 36
HIAWATHA INDIAN RESERVE 36
Image © 2014 DigitalGlobe
© 2014 Cnes/Spot Image
Image © 2014 TerraMetrics
B
N
E SIMCOE
Dummer Moraine
PETERBOROUGH
HFN
RICE LAKE
LAKE SCOGOG
Oak Ridges Moraine
LAKE ONTARIO
0 10 20 40 Kilometers
Waterbody
Iroquois Shoreline
Study Area
Physiography of Southern Ontario (OGS, 2010)
Peat and muck
Bare rock ridges and shallow till
Shallow till and rock ridges
Beaches
Esker
Clay plain
Sand plain
Limestone plain
Bevelled till plain
Drumlin
Till plain (drumlinized)
Kame moraine
Spillway
Till moraine

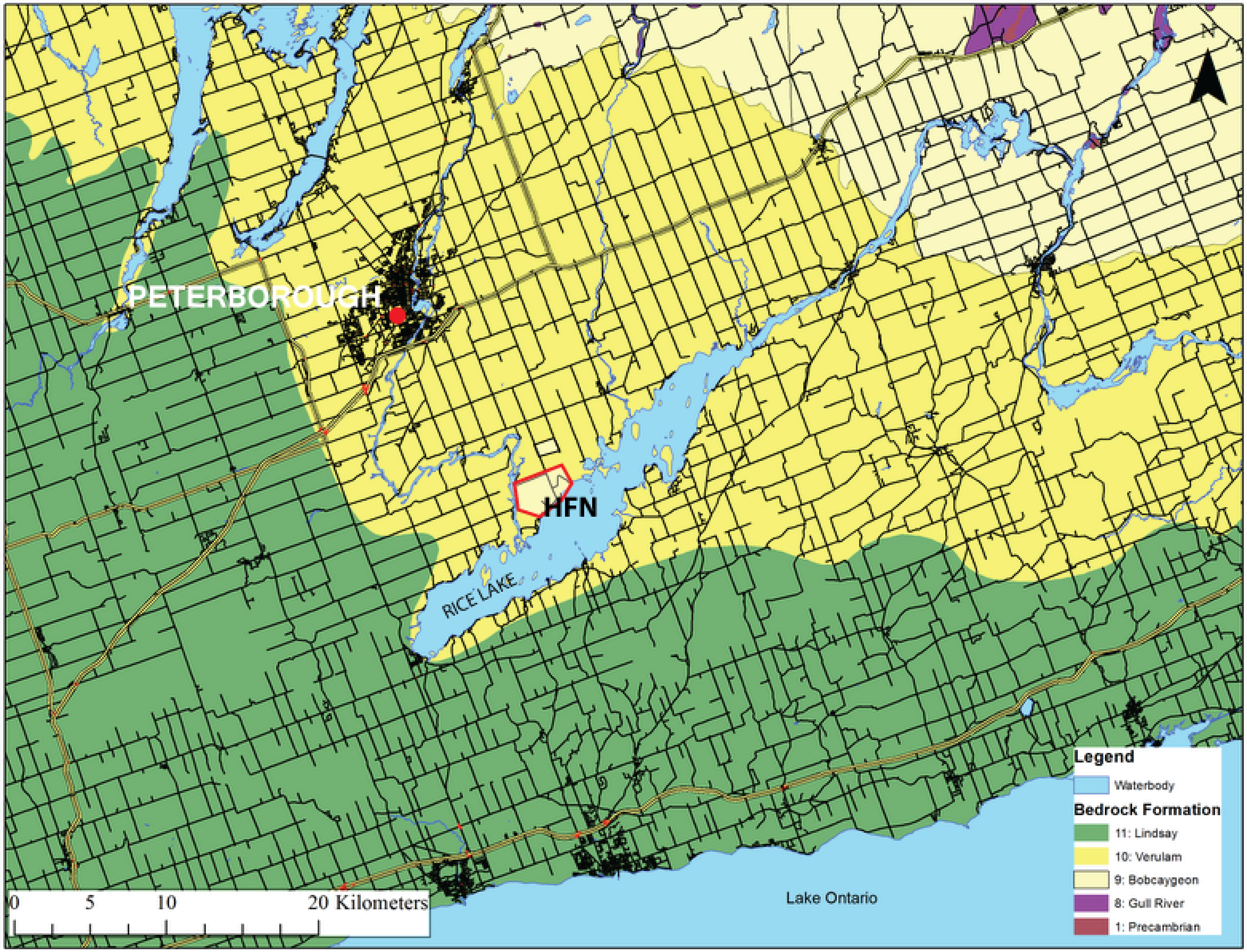
To accommodate the predicted increase of population and concerns related to drinking water supplies on the HFN Reserve, the community commissioned an updated assessment of their existing water resources (both water quantity and water quality) in 2012 to identify how to properly develop and protect groundwater resources in the future.

Regional studies of drumlins within the Peterborough Drumlin Field (see Chapter 2) indicate that there should be two aquifers present on the HFN Reserve. The first is a permeable zone located within the drumlinized Quaternary sediments and is typically encountered at elevations above those of the local inter-drumlin (swale) ground surface. The second aquifer is found at depth and consists of either permeable sediments lying directly above bedrock or the upper fractured bedrock itself. Although there is a reasonable understanding of the regional hydrostratigraphic framework within the PDF (Boyce and Eyles 1991, Gerber and Howard 1996, Gerber and Howard 2000, Gerber et al. 2001, Meriano and Eyles 2009) there is little detailed sedimentological or hydrogeologic data available to inform groundwater resource development on the HFN Reserve. The objective of this chapter is to report the findings of an investigation of the aquifers supplying the HFN Reserve in order to enhance the understanding of the internal sedimentological composition of the drumlin on which the Reserve is located, and to better manage future groundwater needs. The findings of this study will have implications for the development and management of groundwater resources in other communities located on similar drumlin fields.

3.2 SITE DESCRIPTION

The HFN Reserve is underlain by Paleozoic aged rocks of the Verulam Formation, formed in a shallow marine depositional environment, which lie on top of the Precambrian basement rock (Karrow 1967, Sanford 1995, Singer et al. 2003; Fig. 3.2).

Figure 3.2. Bedrock beneath the Hiawatha First Nation Reserve (HFN; yellow box) consists of Paleozoic-aged limestone and shales of the Verulam Formation. The Lindsay Formation underlies the area to the south-west (green), and the Bobcaygeon Formation lies to the north-east.


PETERBOROUGH
HFN
RICE LAKE
Lake Ontario
Legend
Waterbody
Bedrock Formation
11: Lindsay
10: Verulam
9: Bobcaygeon
8: Gull River
1: Precambrian
0 5 10 20 Kilometers

The 32 - 65 m thick Verulam formation is part of the Simcoe Group and consists of limestone with interbeds of shale (Singer et al. 2003). The elevation of the bedrock surface undulates slightly between 170 and 180 m.a.s.l. below the Reserve and the upper fractured portion hosts an aquifer utilized by numerous private wells on the Reserve.

Bedrock is overlain by late Quaternary-age sediment with thicknesses of between 10 m and 70 m (Fig. 3.3). Regionally, the subsurface sediment stratigraphy is composed of late Wisconsin diamict (Newmarket/Northern Till) with interbeds of outwash silt, sand and gravel (Karrow, 1984, Boyce and Eyles 1991, Sharpe et al. 1996, Logan et al. 2001). These materials overlie fine-grained, predominantly glaciolacustrine, sediments (Karrow 1967, Boyce and Eyles 1991, Logan et al. 2001). The late Wisconsin diamict and interbedded sediments are ascribed to deposition during an advance of the Simcoe lobe of the Laurentide Ice Sheet. This event led to the formation of the 5000 km^2 Peterborough Drumlin field which contains upwards of 3000 drumlins (Boyce and Eyles 1991, Maclachlan and Eyles 2013). At least some of the drumlins appear to have formed during a final readvance of the ice lobe sometime after 13,000 y.B.P. as it thrust southward and overrode the eastern portion of the Oak Ridges Moraine (Boyce and Eyles, 1991). The site on which the HFN Reserve is located has also been affected by postglacial high lake levels associated with Lake Iroquois (c. 12,500 y.B.P.; Sonnenburg et al. 2012) and the early formation of Rice Lake. Water levels in Rice Lake have fluctuated considerably (±9 meters) during the Holocene as a result of post-glacial isostatic uplift of lake outlets (±30 meters around Rice Lake), climate changes, and most recently by anthropogenic activity (Yu and McAndrews 1994, Anderson et al. 2012, Sonnenburg et al. 2012). Changing water levels in Rice Lake have caused the development of shoreline features and the deposition of organic materials in the southern portions of the HFN Reserve (Fig. 3.4).

Figure 3.3. Drift thickness in the area of the HFN Reserve (red box; values shown by contours in metres and colour shading in meters above sea level; OGS 2010). Between 10 and 70 meters of Quaternary aged sediments overlie bedrock below the Reserve. Drift thickness is greatest at the centre of the Reserve and identifies the form of a mega-drumlin.

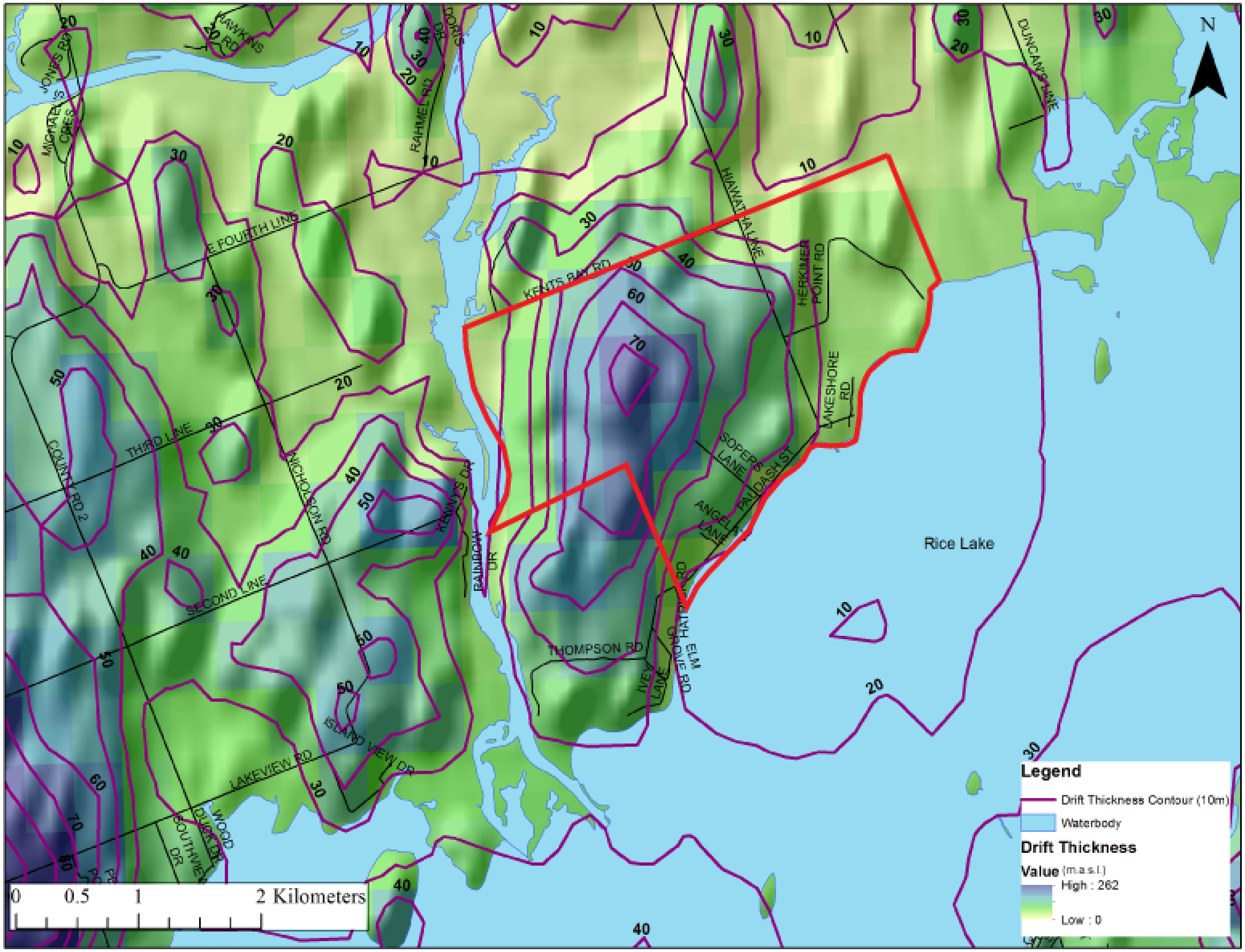
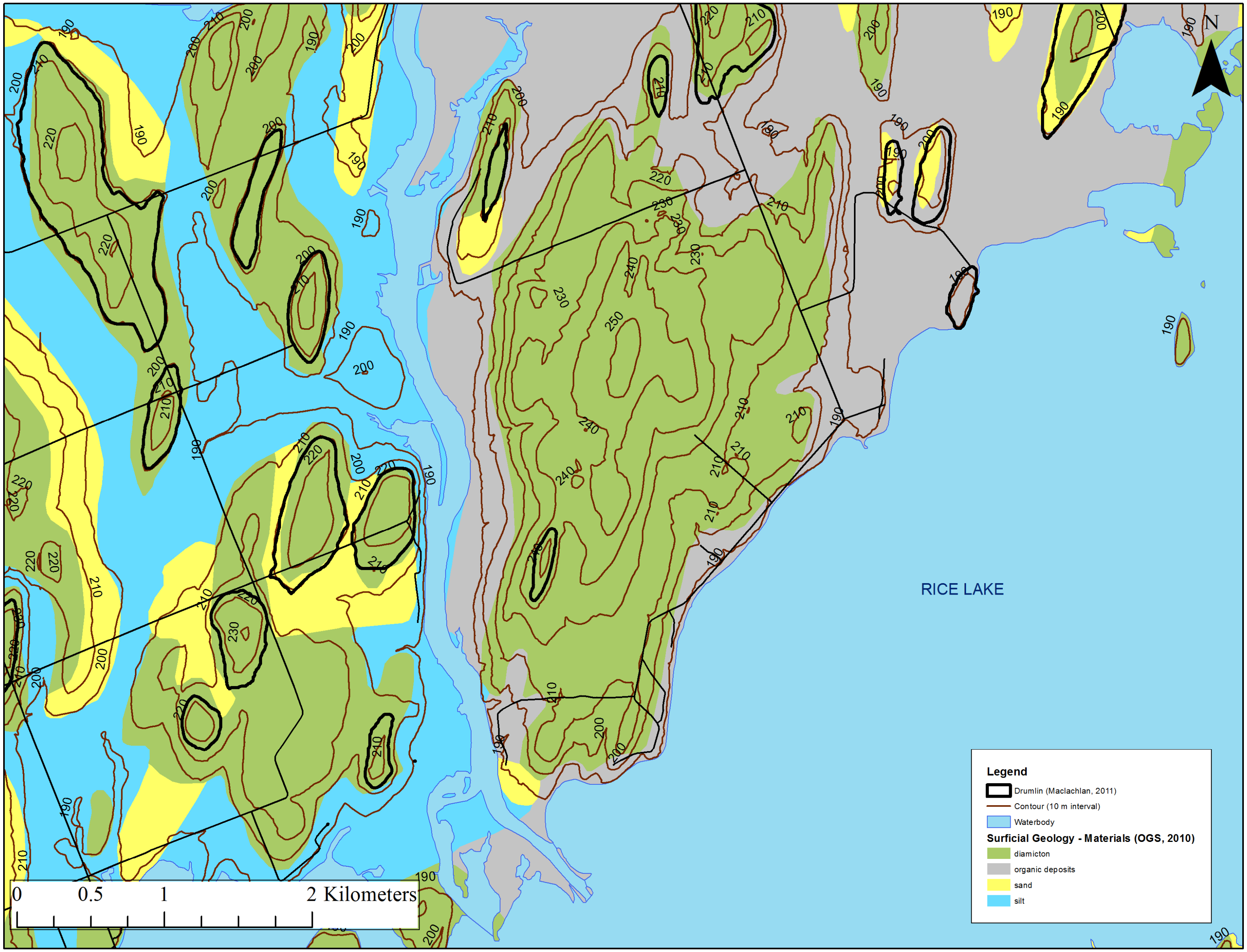

N
Rice Lake
Legend
Drift Thickness Contour (10m)
Waterbody
Drift Thickness
Value (m.a.s.l.)
High : 262
Low : 0
0 0.5 1 2 Kilometers
FOURTH LINE
THIRD LINE
SECOND LINE
LAKEVIEW RD
THOMPSON RD
KENTS BAY RD
HIAWATHA LINE
HERKIMER POINT RD
LAKESHORE RD
COUNTY RD 2
NICHOLSON RD
ISLAND VIEW DR
RAINBOW DR
PAUDASH ST
DUNCAN LINE
RAHME RD

Figure 3.4. Surficial geology of the HFN Reserve (red box) and surrounding area (map data from OGS, 2010). The area is predominately mapped as diamict (green) on the local highs (drumlins). The low areas (swales and/or fluvial valleys) are underlain organic material (grey), sand (yellow) and silt (blue).



N
RICE LAKE
0 0.5 1 2 Kilometers
Legend
Drumlin (Maclachlan, 2011)
Contour (10 m interval)
Waterbody
Surficial Geology - Materials (OGS, 2010)
diamicton
organic deposits
sand
silt

The majority of the surficial sediments on the HFN Reserve are mapped as the Newmarket Till (OGS 2010). The ground surface topography suggests that the Reserve is located on a large drumlin with a length of 2 kms, width of 1 km and height of 60 m. This landform has the characteristic asymmetric shape of a drumlin and has the dimensions of a 'mega-drumlin' (Fig. 3.5; Rose and Letzer, 1977); it is too large to be recognized by the computerized identification system used by Maclachlan (2011) to delineate drumlins on DEM imagery in the PDF and is identified here by visual inspection of DEM data and field observations.

3.2.1 Groundwater Exploration Study – Oakridge Environmental Ltd

In 1998, the Hiawatha First Nation contracted Oakridge Environmental Ltd. (Oakridge) to conduct a study of their groundwater resources. The expectation was to determine the feasibility of a communal (centralized) water supply system for the entire HFN Reserve to replace the existing private wells and decentralized systems. The initial objective of the project was to explore the community's groundwater resources to identify an aquifer capable of meeting the calculated water supply demand on the Reserve (estimated at 5.6 L/s; Oakridge 1998). The water quality within the aquifer would also be determined. Following the identification of a viable aquifer and the development of a communal (centralized) system, it was hoped that recommendations would be made for basic wellhead protection requirements.

Stage 1 of the project began in 1998 when Oakridge performed a background review of water well records for wells located on and around the Reserve. Oakridge (1998) concluded that it was unlikely that a single production well would be sufficient to supply the growing needs of the Reserve as there were few to no private wells with a high enough capacity (based on aquifer thickness and yield as noted in water well records) that could meet the projected water supply demand. They therefore concluded that exploration should begin for location(s) suitable for development of a communal well field consisting of 3 to 4 wells that could run individually or in tandem to meet demand.

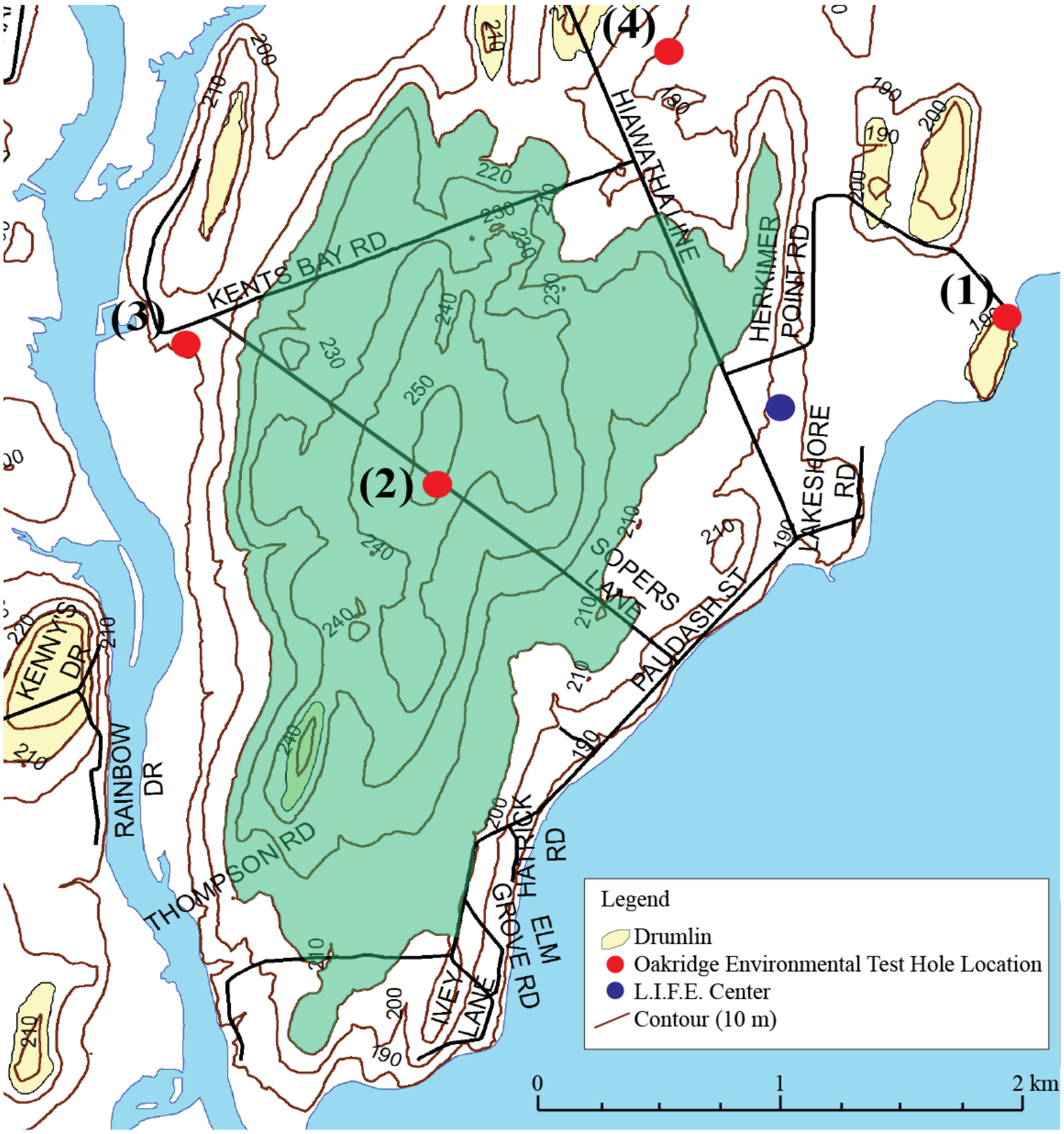
Stage 2 of the Oakridge project (2001) began with field inspections and the construction of the first two test wells at Herkimer Point road (TW-1and TW-2, Fig. 3.5 labelled (1)). The wells are completed in limestone bedrock which was encountered at 166 m.a.s.l (50.5 meters below ground level). The overburden material reportedly consists of "gravel-clay, water producing gravel seams and hard clay" according to Oakridge drilling records (Oakridge 2001). A 24 hour pumping test at Test Well 1 (TW-1) found that the sustainable pumping rate of the well is 1.5 L/s. During the test, Test Well 2 (TW-2), located about 120 m away from TW-1, experienced a high level of interference from the pumping of TW-1; this demonstrates that the two wells cannot be pumped simultaneously to achieve a significantly higher yield.

In 2005, Stage 2b, a community-wide random survey and sampling program was completed (Oakridge 2005). Questionnaires were distributed to each residence within the HFN Reserve that asked residents about household wells, including its depth, construction, observed/tested water quantity, observed/tested water quality, and if any water treatment is used. Out of 175 residences visited, 108 responses were received. This survey found that there is a general perception of poor water quality, there are water quantity issues, and that it would be advisable to upgrade several of the wells to meet current Ontario Reg. 903 standards (notably with respect to separation from onsite septic systems; Oakridge 2005). They found that high yield wells (wells that produce greater than or equal to 3.15 L/s) are "quite rare" (Oakridge 2005). During Stage 2b, Oakridge also performed a more detailed review of hydrogeological conditions on the Reserve by constructing subsurface cross sections on and around the Reserve from water well records. They identified a granular zone that appears to drape the bedrock and/or an upper fractured bedrock surface that has a variable thickness (0 to 7 meters; Oakridge 2005). They also identified "discontinuous" upper aquifers of variable thickness. Due to the assumed discontinuity and unpredictability of the upper aquifers, the basal aquifer was identified as the zone most likely to be productive, reliable and consistent to locate as a possible water source.

Based on their interpretation of the subsurface geology, Oakridge chose three locations as suitable sites for further exploration and eleven new test wells were drilled during Stage 3 of the project. The locations included (1) Herkimer Point development, (2) two wells at Soper's Lane in the Public Works Yard, (3) three wells at Kent's Bay Road near the Otonabee River, (4) five wells in an area just outside of the Reserve boundary along Hiawatha Line called the "Discovery Zone" and (5) one well drilled in a smaller land parcel along Hiawatha Line that is owned by the Reserve (Fig. 3.5 – locations labelled 1 to 4; 5 not shown; Oakridge 2007). Four of the test wells at the Discovery Zone underwent a 4-hour pumping test and water quality was tested at each well prior to the pumping test. Oakridge concluded that the Discovery Zone (concession 10, lot 7) could be the site for a viable communal well field, providing 4 to 5 L/s, and the wells at Herkimer point could be used as a supplementary or backup supply (recommended for 1.5 L/s; Oakridge 2009). At both sites, groundwater is considered to be under the direct influence of surface water (GUDI), despite evidence of a reasonably thick (10 m at the Discovery Zone and 20 m at Herkimer Point) low permeability diamict overlying the aquifer.

Stage 4 of the Oakridge project was completed in 2010, and involved further exploration of groundwater resources at the Discovery Zone and additional aquifer testing. Four more test wells were drilled and the basal aquifer located at or close to the bedrock surface (shale with overlying basal gravel) was found to be quite extensive, although probably discontinuous (Oakridge 2011a).

Figure 3.5. The HFN Reserve is located on a mega-drumlin (approximate outline depicted in green) within the PDF. Ovoid contoured areas identified in yellow are drumlins as identified by Maclachlan (2011). Locations of the test holes drilled by Oakridge Environmental (red dots): (1) Herkimer Point, (2) Soper's Lane, (3) Kent's Bay Road, (4) The Discovery Zone. The L.I.F.E. Center campus noted by blue dot.



(1)
(2)
(3)
(4)
KENTS BAY RD
HIAWATHA LANE
HERKIMER POINT RD
LAKESHORE RD
SOPERS LANE
PAUDASH ST
THOMPSON RD
RAINBOW DR
KENNY'S DR
HATRICK RD
ELM GROVE RD
IVEY LANE
Legend
Drumlin
Oakridge Environmental Test Hole Location
L.I.F.E. Center
Contour (10 m)
0
1
2 km

A final project completed by Oakridge was the testing of the two wells on Soper's Lane at the Works Yard (Fig. 3.5; location (3); Oakridge 2011b), both completed in an upper aquifer (named the "intermediate aquifer" by Oakridge) that was found between 27.7 and 31 m.b.g.l. below a clay-rich diamict. This aquifer was tested via a 24 hour pumping test of W-1 (Fig. 3.5 – location (3)) and private wells were utilized for monitoring purposes. Water quality data were obtained and elevated nitrate was observed (average 4 mg/L). Following this test, a new well was constructed at the Works Yard (TW-2; Fig. 3.5 – location (3)). TW-2 was drilled with the intention of serving the 6-plex building exclusively as previous attempts to construct a reliable water supply for this building were unsuccessful (these wells were all located in bedrock on the 6-plex property). Oakridge (2011b) concluded that the aquifer located here is not widespread, based on analysis of well records in the vicinity and pumping test and monitoring well observations, and therefore was not large enough to host a centralized (communal) water system. It is, however, sufficient to supply the 6-plex and works yard. They recommended that the Discovery Zone continue to be the focus of additional study.

To date (August 2014), the proposed centralized system has not been completed as the projected cost ($12 million) is beyond the financial resources of the HFN and the Reserve continues to rely on private wells. As a result, the HFN has decided to further evaluate the potential of using both individual wells and/or decentralized systems to meet their future needs as these would likely be of lower cost. As much of the previous efforts had been to identify conditions for a centralized system source within the Discovery Zone only, the stratigraphy underlying the remainder of the Reserve is not well understood and thus the alternative to Discovery Zone supply could not be adequately evaluated.

In 2012, the HFN Band decided to build a new emergency response (EMS) building at the site of the Hiawatha L.I.F.E. center campus (Fig. 3.5 – blue dot). This site was chosen to further evaluate the potential for small decentralized water system(s). As testing had shown that the capacity of the existing L.I.F.E center well was limited to only meeting the needs of the existing facility, a new water supply was required for the new EMS building. The drilling program for the new water supply well allowed for further exploration of the subsurface stratigraphy on the Reserve; the findings from this most recent phase of investigation are reported here.

3.3 METHODOLOGY

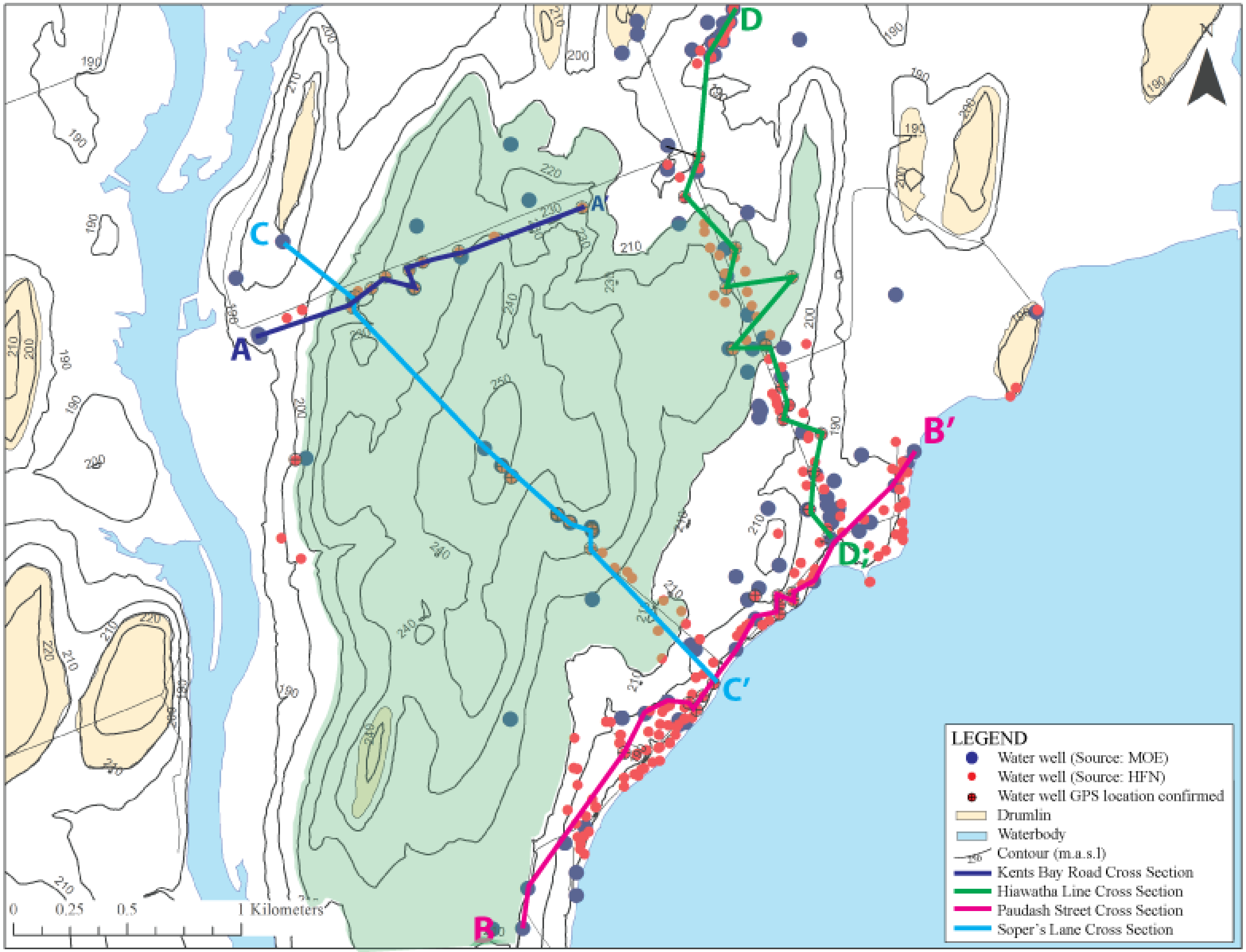
Previous investigations of hydrogeologic conditions focussed on specific sites they considered to offer the greatest potential for communal well field development. As a result, the subsurface conditions of the entire HFN Reserve have not been thoroughly evaluated. To better understand this subsurface stratigraphy an analysis of the available water well record database was completed. This allowed further investigation of the relationships between the aquifer(s) and aquitard(s) located beneath the Reserve, within the mega-drumlin. This analysis will help to inform the Hiawatha First Nation of their water supply options for the future and provide detailed insight into the subsurface stratigraphy of a mega-drumlin within the Peterborough Drumlin Field.

The analysis was carried out in several stages. The first was an analysis of well records contained within the Water Well Information System (WWIS), an online database of drinking water wells in Ontario. These data were used to develop cross sections that provided information on the subsurface continuity of stratigraphic units encountered during water well drilling. As the WWIS often lacks reliable location data for individual wells, a second stage of this study involved a survey and door-to-door inspection of all of the wells located on the Reserve to correctly establish the location and elevation of each well. The third stage involved sedimentological analysis (using standard sedimentological logging techniques recording sediment type, structures, unit thickness, the nature of unit contacts, and grain size; Eyles et al. 1983) and interpretation of drill core data obtained when a cored hole and three test holes were drilled at the Hiawatha L.I.F.E. centre. These wells were drilled to establish the nature of the aquifer(s) on the property and to determine the location of a new production well. The fourth stage of this study was a pumping test designed to establish the continuity and raw water quality of the aquifer located at the L.I.F.E. center and further inform the hydrostratigraphy of the area. Field investigations of springs, streams and sediment exposures on the HFN Reserve were also conducted.

3.3.1 *Water well database*

Under the Ontario Water Resources Act, all wells drilled in Ontario are required to have a well record submitted to the Ministry of the Environment (MOE). A scanned copy of the original record is made available to the public online, via the MOE website, and displayed using an interactive map (http://www.ontario.ca/environment-and-energy/map-well-record-data). Each record includes information about the well, including the overburden material as encountered and recorded by the driller. Location of the well and depths/thicknesses of materials are also recorded. To establish a basic understanding of the stratigraphy on the HFN Reserve, all of the water wells found within the Reserve boundaries were analyzed (Fig. 3.6). First, the easting and northings for each well were imported into ARCGIS and a DEM was used to establish the ground surface elevation for each well.

Figure 3.6. Water wells within and around the HFN Reserve (blue dots – records from WWIS; red dots – records from HFN). Location of subsurface cross sections constructed from water well records shown by solid coloured lines.


A
A′
B
B′
C
C′
D
D′
0 0.25 0.5 1 Kilometers
LEGEND
Water well (Source: MOE)
Water well (Source: HFN)
Water well GPS location confirmed
Drumlin
Waterbody
Contour (m.a.s.l)
Kents Bay Road Cross Section
Hiawatha Line Cross Section
Paudash Street Cross Section
Soper's Lane Cross Section

The ground surface elevation and record of materials encountered during drilling were used to create four cross sections: A-A' (Kent's Bay Road), B-B' (Hiawatha Line), C-C' (Paudash Street) and D-D' (Soper's Lane) (Fig. 3.6). These four sections were analyzed using the same methods as those outlined in Chapter 2 and give a reasonable representation of the sediment stratigraphy underlying the Reserve.

3.3.2 *HFN Water Well Survey*

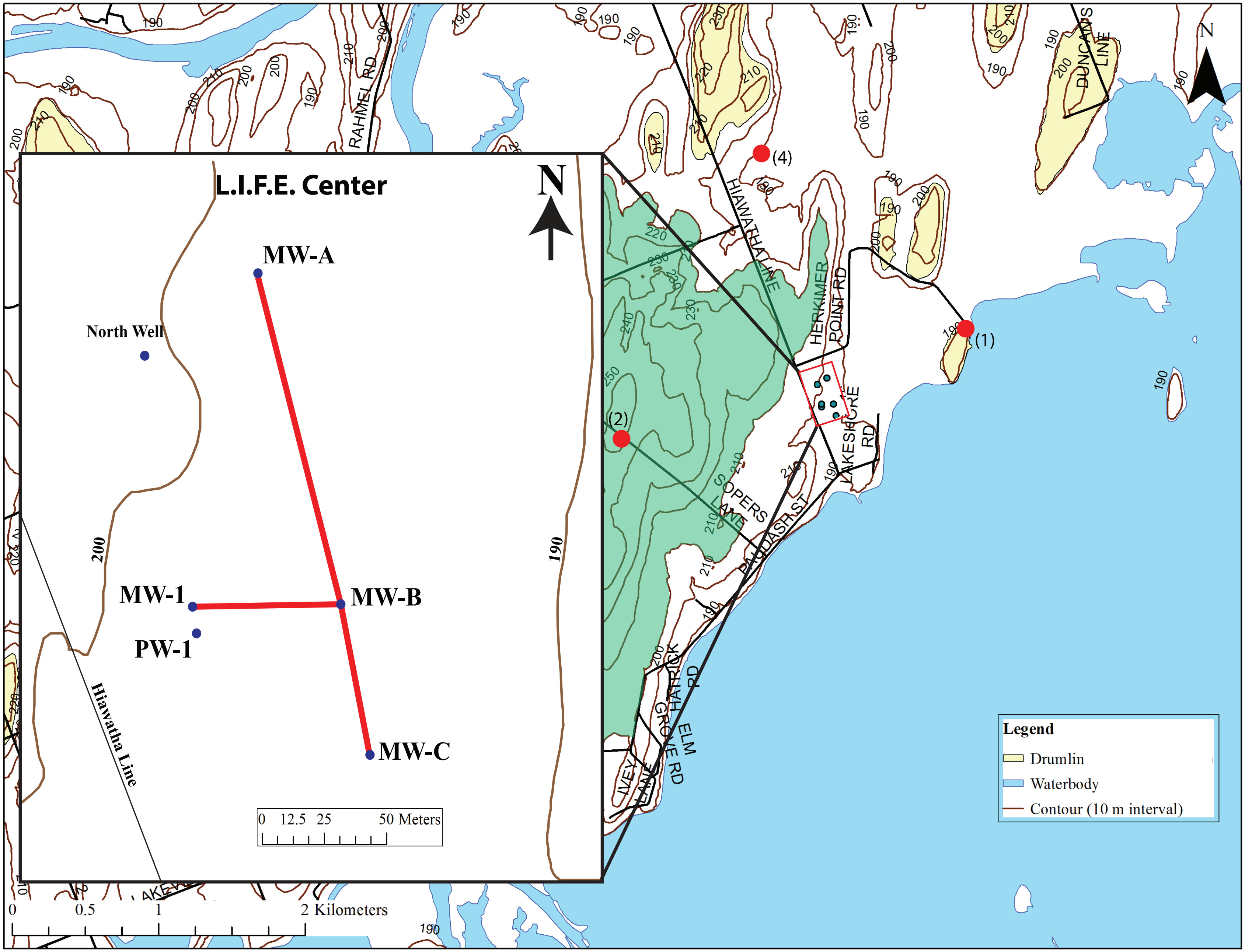
Since 2003, all water wells drilled in Ontario are required to have a well tag affixed and the number recorded on the well record that is submitted to the WWIS. However, prior to 2003, there are no means to confirm that a well matches a well record or that the location of said well is accurate. As a consequence, it is not always possible to have confidence in the accuracy of interpretations made from older subsurface data that may be poorly located. To help alleviate some of this uncertainty, the HFN confirmed well locations and created an inventory of the GPS location and elevations of all of their wells (using a Garmin Montana 650 handheld GPS unit), the type of well, the condition of the well, and its proximity to a septic system.

To confirm the accuracy of the elevations recorded by the HFN, elevations extracted from a DEM in ARGGIS were compared to the elevations recorded by the HFN for each well. It was found that thirteen of the 43 records had an elevation difference greater than 5 meters. The largest difference was 54.5 meters. Where the elevations were greater than 5 meters difference (above or below the DEM value), the DEM value was used as it is considered to be more accurate.

3.3.3 *Drilling program*

The Hiawatha First Nation has a property on Hiawatha Line that hosts their essential services buildings (Fig. 3.7). The primary building, called the L.I.F.E. Center, is a child care centre and provides health and social services and is served by a well completed in sand and gravel 22.9 meters below ground level (Fig. 3.7 – “PW-1”). There is also a bedrock well on the property that is not in use due to its low yield (Fig. 3.7 – “north well”). To establish the stratigraphy underlying the property and provide recommendations for the location of the new well, a drilling program was completed in the fall of 2012 and spring of 2013. This involved a video survey and geophysical logging of the “north” well (Fig. 3.7), completion of a mud-rotary cored borehole and geophysical logging of the hole, drilling of three observation monitoring wells MW-1, MW-A and MW-C; Fig. 3.7), and creation of a test production well (MW-B; Fig. 3.7). A pumping test and water quality analysis were also performed on the new test production well. The results of this drilling program were used to further enhance the understanding of the stratigraphy on the HFN Reserve and as a supplement to any further development of a centralized drinking water system.

Figure 3.7. The location of production (PW-1 and PW-2) and monitoring wells (MW-1, MW-A and MW-C; blue dots) drilled at the L.I.F.E. center.


L.I.F.E. Center
N
MW-A
North Well
MW-1
PW-1
MW-B
MW-C
200
190
Hiawatha Line
0 12.5 25 50 Meters
(1)
(2)
(4)
HIAWATHA LINE
HERKIMER POINT RD
LAKESHORE RD
SOPERS LANE
PAUDASH ST
HATRICK RD
GROVE RD
ELM RD
IVEY LANE
RAHMEL RD
DUNCANS LINE
0 0.5 1 2 Kilometers
Legend
Drumlin
Waterbody
Contour (10 m interval)

3.4 RESULTS

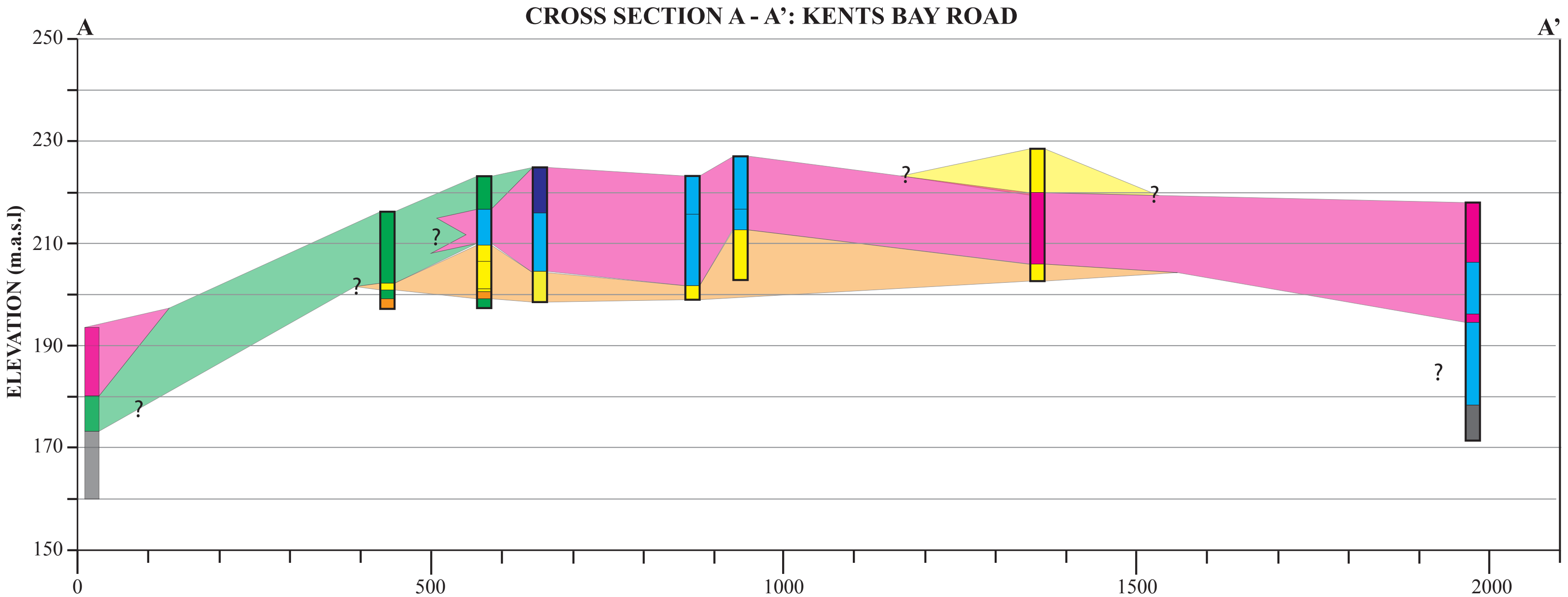
There are 117 wells within the bounds of the Reserve according to the MOE database. Of these 117 wells, 56 are drilled to bedrock. The Hiawatha First Nation survey of wells identified 7 bored wells, 157 drilled wells, and 46 dug wells for a total of 210 wells on the Reserve. 43 of these wells have a matched record of materials penetrated during drilling, location and elevation.

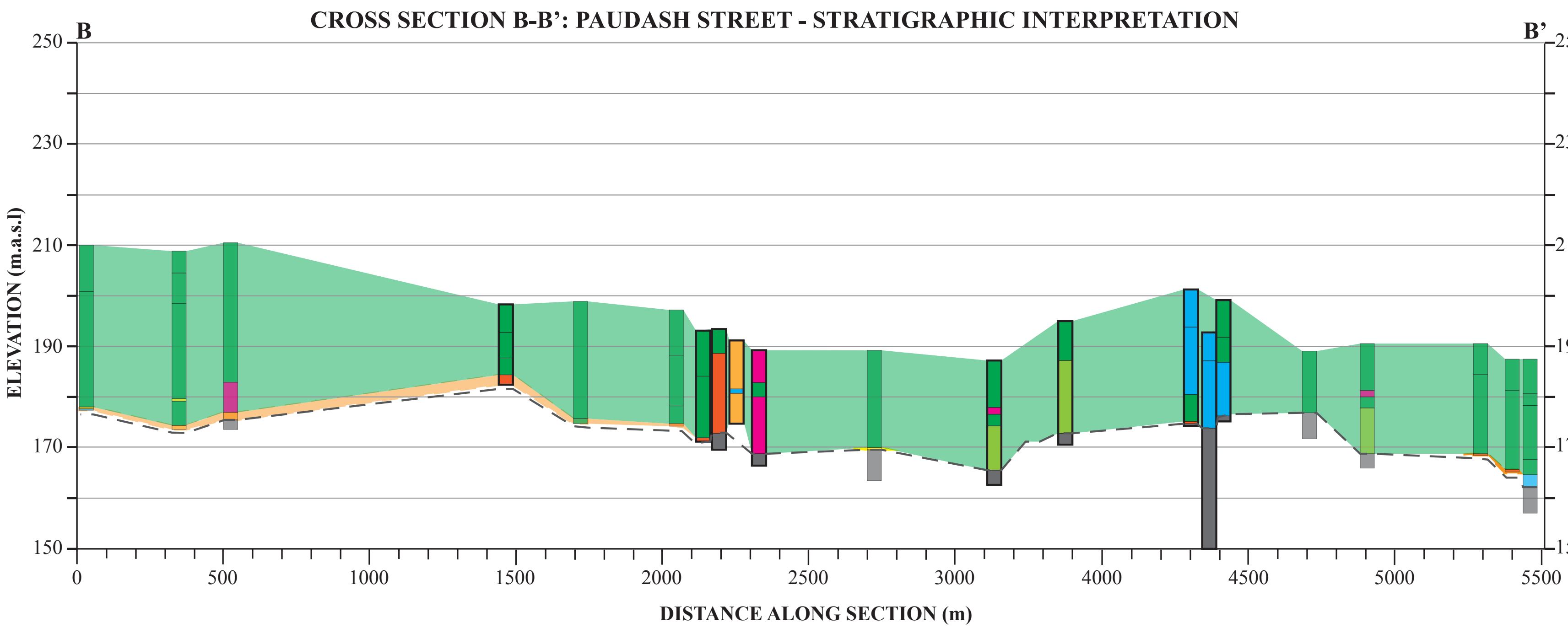
Utilizing records from both the WWIS and the HFN survey, four cross sections of the subsurface geology underling the HFN Reserve were developed: A-A' (Kent's Bay Road), B-B' (Paudash Street), C-C' (Soper's Lane), and D-D' (Hiawatha Line) (see Fig. 3.6 for locations). On each cross section presented, the borehole logs outlined in a thicker black line have a confirmed location and elevation.

3.4.1 *Cross Section A-A': Kent's Bay Road*

Cross section A-A' is 2 kilometers in length and runs west to east along Kent's Bay Road (Fig. 3.8). The section begins near the Otonabee River in the east where ground surface elevation is 190 m.a.s.l.; the ground surface increases in elevation as it crosses the mega-drumlin to the west (average 225 m.a.s.l.; Fig. 3.8) and overburden thickness ranges from 20 to 50 meters. Bedrock was penetrated at approximately 175 m.a.s.l. and is overlain by diamict of variable texture. A relatively thick (5 – 15 m) sand unit is penetrated between 200 and 215 m.a.s.l. and appears to be laterally continuous for at least 1.5 kilometers (Fig. 3.8). It is not clear if this unit outcrops at ground surface or is truncated by overlying diamict which is approximately 20 meters thick at the center of the section (Fig. 3.8). The surface sand unit identified in one well may represent a localized accumulation of fluvial or aeolian sediment.

Figure 3.8. (a) East-west cross section A – A' along Kent's Bay Road in the north of the HFN Reserve. (b) East-west cross Section B-B' along Paudash Street along the southern margin of the Reserve (see Fig. 3.6 for location of cross sections). Note the predominance of diamict/ fine-grained sediment and the presence of a sand-rich (aquifer) unit at between 200 and 210 m.a.s.l. in the north (A-A') and the thinning of diamict and significance of wells that penetrate bedrock to obtain water in the south (B-B').


CROSS SECTION A - A': KENTS BAY ROAD
A
A'
ELEVATION (m.a.s.l)
250
230
210
190
170
150
0
500
1000
1500
2000
?


CROSS SECTION B-B': PAUDASH STREET - STRATIGRAPHIC INTERPRETATION
B
B'
ELEVATION (m.a.s.l)
250
230
210
190
170
150
0
500
1000
1500
2000
2500
3000
4000
4500
5000
5500
DISTANCE ALONG SECTION (m)

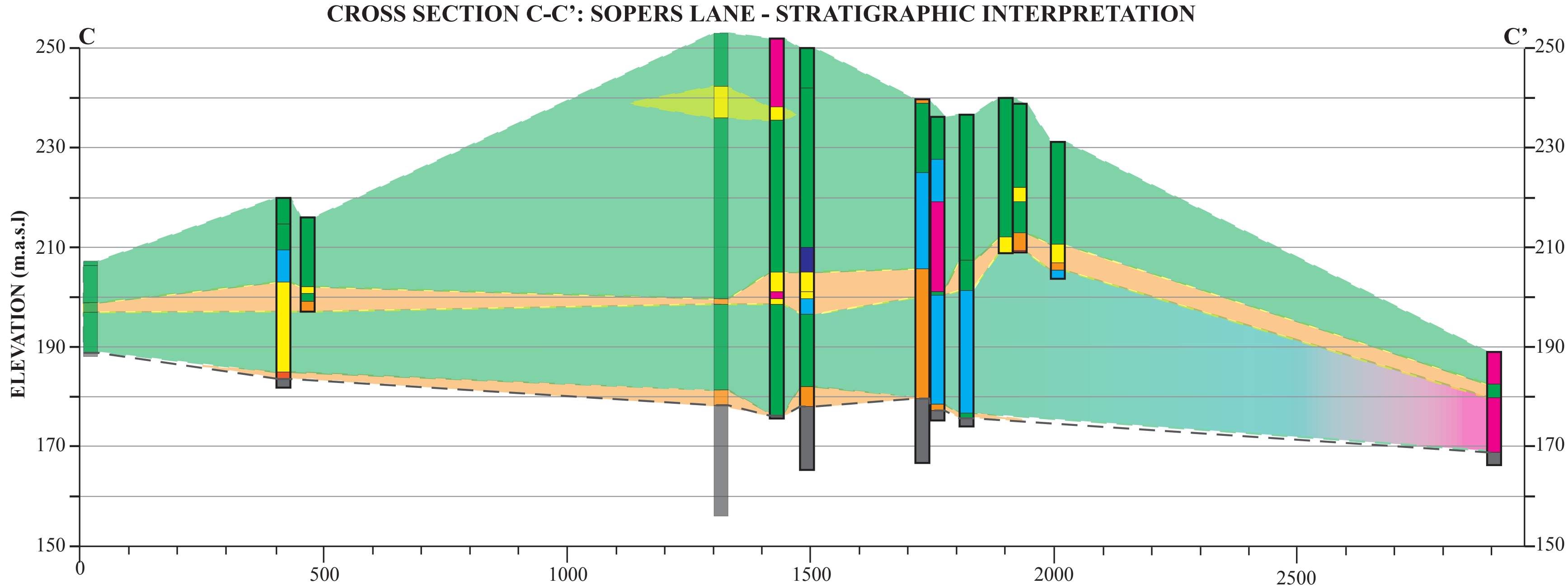
3.4.2 *Cross Section B-B': Paudash Street*

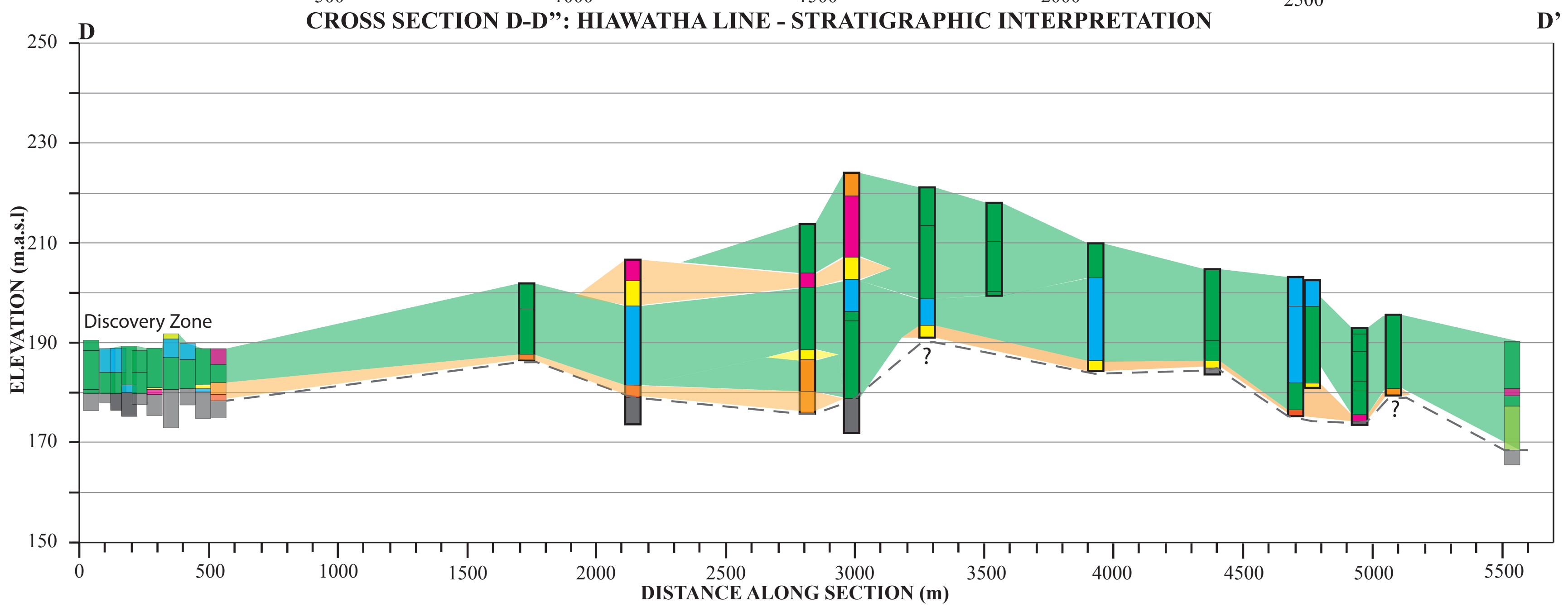
Cross Section C-C' (Paudash Street) runs west to east along the northern shore of Rice Lake in the southern part of the Reserve (Fig. 3.8). The ground surface elevation ranges between 210 m.a.s.l. (B) and 195 m.a.s.l (B') and bedrock is encountered between 165 and 175 m.a.s.l.; overburden thickness varies between 20 and 30 meters (Fig. 3.8). The subsurface stratigraphy is dominated by clay-rich to sand-rich diamict. Most wells are completed in bedrock or in a sand/gravel unit (<5 m thick) immediately overlying the bedrock surface (Fig. 3.8).

3.4.3 *Cross Section C-C': Soper's Lane*

Cross section C-C' (Soper's Lane) runs north to south across the west-central part of the mega-drumlin (Fig. 3.9). Ground surface elevation ranges from 255 m.a.s.l. in the centre of the section to 190 m.a.s.l. in the south and overburden thickness ranges from 20 meters to 70 meters (Fig. 3.9). Well records indicate that the bedrock surface also slopes towards the south (from 190 m.a.s.l at C to 170 m.a.s.l. at C'; Fig. 3.9), which is consistent with the bedrock slope towards Rice Lake as reported in the literature (Liberty 1969; Russell et al. 2003). Overlying bedrock is a thin (<5 meters thick; Fig. 3.9) basal sand and gravel unit which serves as an aquifer for many wells. This is overlain by 20 – 30 meters of variably textured diamict (clay – to sand-rich; Fig. 3.9) and a thin (<10 m) continuous sand and gravel unit which is penetrated between 190 and 205 m.a.s.l. This coarse-grained (aquifer) unit is overlain by another diamict package (20 to 50 meters thick) which includes isolated sand rafts (Fig. 3.9).

Figure 3.9. (a) Northeast-southwest cross section C-C’ along Soper’s Lane on the western side of the HFN Reserve (b) North-south cross section D-D’ along Hiawatha Line towards the eastern side of the Reserve. Note that wells either penetrate an aquifer in or immediately overlying bedrock or a laterally continuous sand and gravel unit within diamict at approximately 200 m.a.s.l. (see Fig. 3.6 for cross section locations).


CROSS SECTION C-C': SOPERS LANE - STRATIGRAPHIC INTERPRETATION
C
C'
ELEVATION (m.a.s.l)
250
230
210
190
170
150
0
500
1000
1500
2000
2500


CROSS SECTION D-D": HIAWATHA LINE - STRATIGRAPHIC INTERPRETATION
D
D'
ELEVATION (m.a.s.l)
Discovery Zone
?
?
250
230
210
190
170
150
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
DISTANCE ALONG SECTION (m)

3.4.4 *Cross Section D-D': Hiawatha Line*

Cross Section D-D' runs north to south along Hiawatha Line and is 5.5 kilometers in length, depicting the stratigraphy in the eastern half of the mega-drumlin (Fig. 3.9). The ground surface topography along Hiawatha Line is undulating and ranges in elevation from 190 m.a.s.l. at the "Discovery Zone" in the north and near Rice Lake in the south (D'), to 220 m.a.s.l.in the central portion of the section; bedrock lies at 180 m.a.s.l in the area of the "Discovery Zone" and decreases in elevation towards Rice Lake (168 m.a.s.l; Fig. 3.9). This part of the mega-drumlin consists predominantly of diamict (10 to 40 meters thick) with clay- to sand-rich matrix texture (Fig. 3.9). Most water wells are supplied by a sand and gravel unit (less than 5 meters thick) that appears to overlie bedrock or by wells that penetrate the bedrock surface (Fig. 3.9). There is also an upper, 5 to 10 meter thick, coarse-grained unit at approximately 200 m.a.s.l. that extends for at least one kilometer in the northern part of the section (Fig. 3.9). This occurs at the same elevation as the laterally extensive sand and gravel unit identified in cross sections A-A' and C-C' (Fig. 3.9).

3.4.5 *Wells at the L.I.F.E. Center*

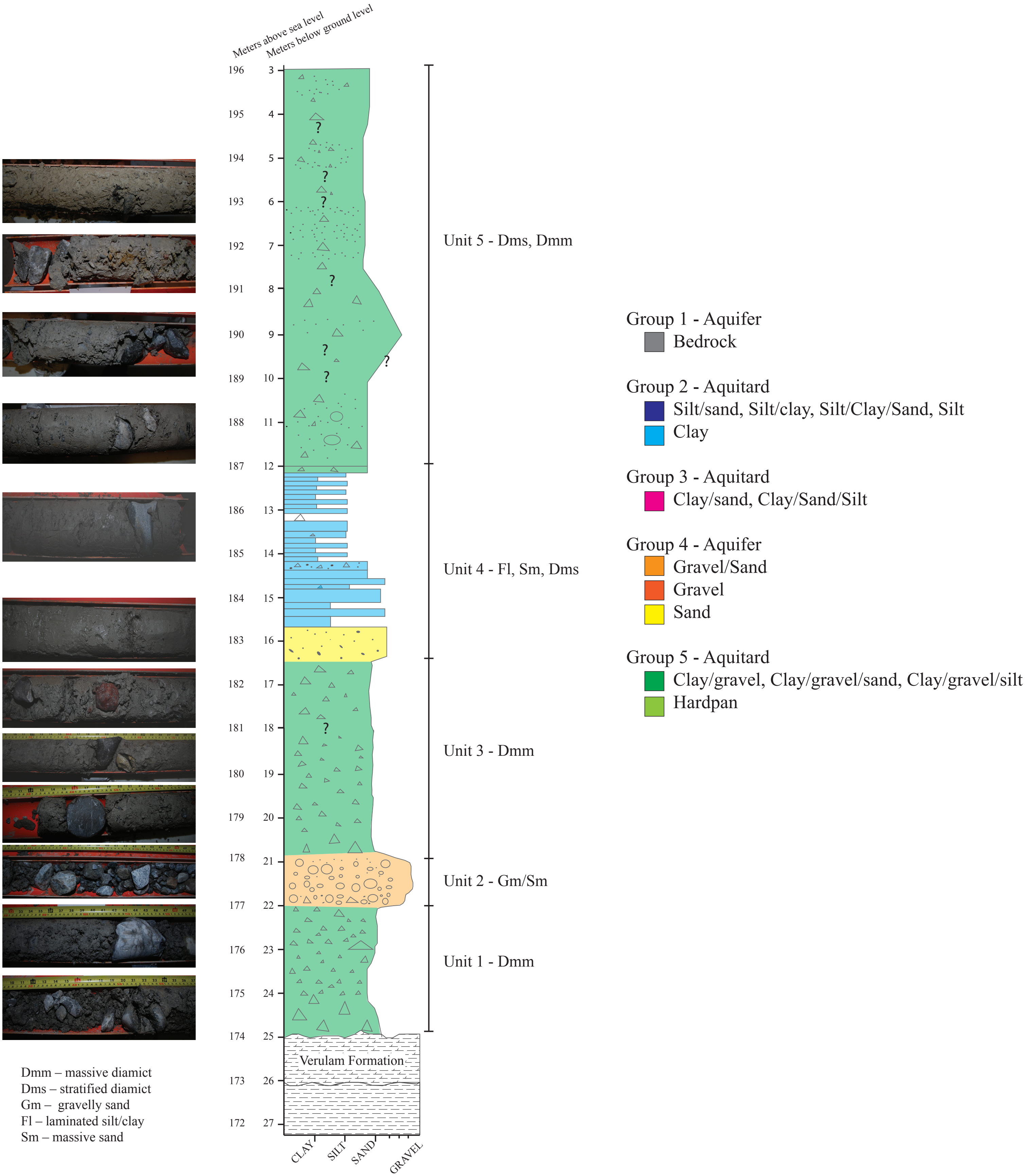
The proposed construction of a new EMS building and wells on the L.I.F.E. centre campus in 2012 required a program of drilling to establish the extent, continuity and productivity of the aquifer underlying the centre as well to as test the raw water quality of this aquifer. A fully cored borehole (MW-1; Fig. 3.10) was drilled to establish the nature of the underlying sediment stratigraphy and several monitoring wells (MW-A, MW-B, MW-C; Fig. 3.11) were also constructed.

MW1: Fully cored borehole

A cored borehole (MW1, Fig. 3.10) was drilled using mud rotary, using drilling mud as a circulating fluid, in November 2012. The well was drilled to 26.8 m.b.g.l. (172.2 m.a.s.l) into limestone bedrock which was encountered at 174 m.a.s.l. (25 m.b.g.l.); the surface of the bedrock was fractured to a depth of 0.9 m.

Immediately overlying the bedrock surface are 3 meters of massive clast-rich diamict with a sandy matrix (Dmm, Unit 1; Fig. 3.10). Clasts are angular and include both Precambrian gneisses and granites and Paleozoic lithologies (limestones and shale). This lowermost diamict unit passes upwards into a 1 m thick unit (Unit 2; Fig. 3.10) of gravelly sand/sandy gravel (Gm, Sm) with sub-rounded clasts, between 1 and 7 cm diameter, which are of mixed lithology. This relatively coarse-grained unit is overlain by 5.5 m of massive sand-rich diamict (Dmm) containing clasts up to 10 cm diameter, some of which were striated (Unit 3; Fig. 3.10). A 3.75 m thick fining-upwards unit (Unit 4; Fig. 3.10) of thinly bedded fine-grained sands, silts and clays with occasional diamict horizons (Fl, Sm, Dms) overlies the diamict. The fine-grained sand horizons within this unit were water saturated. The uppermost unit cored in this well (Unit 5; 196 m.a.s.l. to 187 m.a.s.l; Fig. 3.10) consists of massive to crudely stratified sandy to silty-sand diamict with variable clast content (Dmm, Dms; Fig. 3.10). Rounded to sub-rounded clasts are up to 10 cm diameter, of mixed lithologies (granites and limestones/shales), and some are striated. Poor core recovery affected more sand-rich zones of the diamict and the upper 3 m of the core were not recovered.

Figure 3.10. Sedimentological log through fully cored borehole MW-1 located on the L.I.F.E. center property (See Fig. 3.7 for location). Photographs to left of log are representative of the facies types encountered. Diamict predominates in this borehole, although five distinct sedimentary units can be identified (Units 1 - 5) above bedrock.


Meters above sea level
Meters below ground level
196 3
195 4
194 5
193 6
192 7
191 8
190 9
189 10
188 11
187 12
186 13
185 14
184 15
183 16
182 17
181 18
180 19
179 20
178 21
177 22
176 23
175 24
174 25
173 26
172 27
Unit 5 - Dms, Dmm
Unit 4 - Fl, Sm, Dms
Unit 3 - Dmm
Unit 2 - Gm/Sm
Unit 1 - Dmm
Verulam Formation
CLAY
SILT
SAND
GRAVEL
Dmm – massive diamict
Dms – stratified diamict
Gm – gravelly sand
Fl – laminated silt/clay
Sm – massive sand
Group 1 - Aquifer
Bedrock
Group 2 - Aquitard
Silt/sand, Silt/clay, Silt/Clay/Sand, Silt
Clay
Group 3 - Aquitard
Clay/sand, Clay/Sand/Silt
Group 4 - Aquifer
Gravel/Sand
Gravel
Sand
Group 5 - Aquitard
Clay/gravel, Clay/gravel/sand, Clay/gravel/silt
Hardpan

Following the completion of coring, a monitoring well was installed in the hole that is screened from 20.6 to 26.7 m.b.g.l. (178.4 m.a.s.l. to 172.3 m.a.s.l). The screened interval straddles diamict (Units 1 and 3), basal sand and gravel (Unit 2), fractured rock (174.7 to 173.1 m.a.s.l.), and terminates in bedrock (173.1 to 172.2 m.a.s.l.).

Monitoring Well A (MW-A)

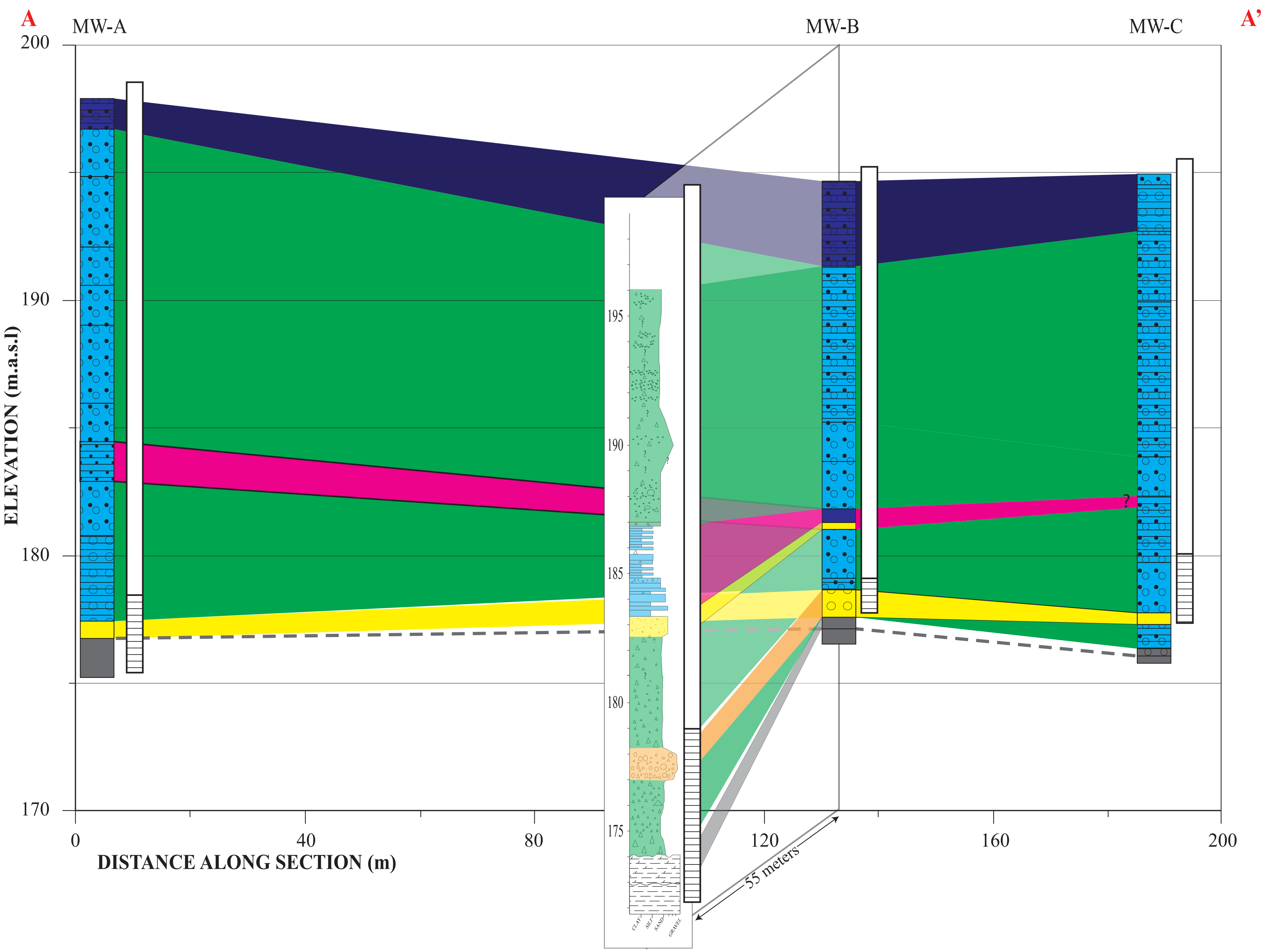
Monitoring Well A (MW-A) was drilled to 175.2 m.a.s.l. (24.1 m total depth) using air rotary (compressed air and water as circulating fluids) on the northern side of the L.I.F.E. center building (Fig. 3.11). The hole terminates in limestone bedrock which was encountered at 176.8 masl (22.6 mbgl, Fig. 3.11). This well is screened from 178.3 to 175.3 m.a.s.l.

At this location, a fine sand layer (>1 m thick) immediately overlies bedrock. Above this unit, silt- and clay-rich diamict transitions upwards into a 5m thick unit of sand-rich diamict. A 1 meter section of fine-grained, sand- and clay-rich sediment overlies the diamict and may be equivalent to Unit 4 identified in MW-1 (Fig. 3.11). The stratigraphy is capped by a 12 m thick unit of sand-rich diamict and a thin (<2 m) veneer of silty-clay diamict (Fig. 3.11). All diamict units contain clasts of both local (Paleozoic) and far-travelled (Shield – granites and gneiss) lithologies.

Monitoring Well B (MW-B)

Monitoring well B (MW-B) was drilled by air-rotary and to 176.5 m.a.s.l. (19.4 m total depth), terminating in limestone bedrock which is fractured between 177.6 and 177.1 m.a.s.l. (Fig. 3.11). Overlying bedrock is a thin (<2 m) sand and gravel unit (equivalent to Unit 3 of MW-1?; Fig. 3.11). This coarse-grained unit is overlain by 4 m of sand-rich diamict and a fining upwards succession (>2 m) of sands to silty-clays (Unit 4 equivalent?; Fig. 3.11).

Figure 3.11. Fence diagram showing the relationship of sedimentary units identified in the cored borehole (MW-1) to those recorded in monitoring wells at the L.I.F.E. Center. See Fig.3.7 for location of wells.


A
MW-A
MW-B
MW-C
A'
200
190
180
170
ELEVATION (m.a.s.l)
0
40
80
120
160
200
DISTANCE ALONG SECTION (m)
195
190
185
180
175
CLAY
SILT
SAND
GRAVEL
55 meters
?

A 10 m thick unit of sand rich, silty-clay diamict overlies the fining upwards succession and 3 m of silty-clay rich diamict caps the stratigraphy (Fig. 3.11).

After drilling, this well was converted to a production well and has become the primary production well for the new facility. The well has stainless steel casing and well screen, surrounded in silica sand, with cement sealant to ground surface. The screened interval straddles the lowest sandy diamict, fine sand with clasts, and fractured bedrock (179 – 177.2 m.a.s.l; Fig. 3.11).

Grain Size Analysis of sediments from MW-B

To enable design of the well screen, grain size analysis was performed on grab samples acquired during the drilling of MW-B and focussed on the aquifer unit that overlies bedrock as this was thought to offer the most potential for further development (Fig. 10). Three sediment samples were air-dried (48 hours) and sieved and the data are presented in Table 3.1 (method as per Sterrett 2008).

Table 3.1 Results of grain size analysis performed on samples acquired during drilling of MW-B.

	Sample 1	**Sample 2**	**Sample 3**
Grain Size	16.7 - 17.2 m.b.g.l.	17.2 - 18.2 m.b.g.l.	18.3 to 18.4 m.b.g.l.
Boulders - Pebbles	10%	11%	6%
Coarse sand	12%	13%	7%
Medium sand	23%	25%	11%
Fine sand	33%	33%	29%
Very fine sand	8%	9%	18%
Silt -Clay	13%	10%	30%

Overall, the grain size analysis indicates that this unit consists of poorly-sorted fine to very fine sand with silt, clay and clasts. This unit is likely to have low hydraulic conductivity because of the high silt and clay content (from 10^{-6} to 10^{-4} cm/s for silt, sandy silts, clayey sands and till; Fetter 2001).

Monitoring Well C (MW-C)

Monitoring Well C (MW-C; Fig. 3.11) was drilled via air-rotary with water and air as circulating fluid. The hole was drilled to 175.8 m.a.s.l. (20 m.b.g.l) and is terminated in limestone bedrock.

Solid bedrock was encountered at 176.1 m.a.s.l. and is overlain by 1 meter of fractured bedrock intermixed with diamict. Overlying the fractured unit is a thin (<2 m) sandy diamict with clasts of varying lithologies (equivalent to Unit 1?; Fig.3.11) which is overlain by <1 m of clean sand (equivalent to Unit 2?; Fig. 3.11). An 18 m thick silty-clay to sandy-clay rich diamict with clasts of varying size and lithologies overlies the sandy unit.

3.4.6 *Hydrogeological data*

Pumping tests are frequently performed on aquifer units as they can reliably provide a plethora of information about the aquifer and the nature of the aquitard (if present). Common aquifer characteristics that can be determined include hydraulic conductivity, specific storage, or transmissivity (Fetter 2001). The confining capabilities of the aquitard can also be established. This information directly relates to the nature and properties of the aquifer and aquitard sediments. Water quality data can provide additional valuable information.

Pumping Test (MW-B)

On March 6, 2013 a pumping test was performed using Monitoring Well B (MW-B). The test was designed to determine the capacity of the new well and the aquifer in which it was completed and involved pumping MW-B at 11.5 L/min (the estimated required yield of the facility) for 8 hours (the typical daily operating period). The pumping rate was observed to decline to 10.1 L/min during the test due to performance characteristics of the well pump. As a result, all data has been corrected to account for this decline using standardized techniques (Fetter 2001).

The static water level at the start of pumping was 194.2 m.a.s.l. (1.7 meters below ground level). Water levels in the pumping well were measured manually and at the end of the test a drawdown of 10.35 meters was observed. Recovery was also measured manually for 60 minutes immediately following the test. At the end of this period the water level in the well had recovered to 190.8 m.a.s.l (5.13 m.b.g.l.). Water levels in monitoring wells MW-1, MW-A and MW-C (Fig. 3.12) were also observed using manual measurements and water level sensors with data-loggers during the test (Fig. 3.12). Observations made from these wells were also corrected for the decline in pumping rate due to pump characteristics. Drawdown was measured at 1.61 meters at MW-1, 0.6 meters at MW-1 and 1.72 at MW-C (Fig. 3.12).

A common method of evaluating pumping test data to characterize the aquifer type involves plotting the data on a log-log plot of time versus drawdown (Freeze and Cherry 1979). The graphed drawdown data can then be curve-matched to type curves for each type of aquifer (confined, leaky and unconfined). The response of an "ideal" (confined) aquifer to pumping was determined by Theis in 1935 (Fetter 2001). Theis went on to develop a "type" curve and graphical method of superposition that can be used to determine aquifer characteristics from pumping test data. Corrected manual and logger data obtained from each monitoring well during the pumping test at PW-2 were plotted and overlain on the ideal Theis type curve (Fig. 3.13). The water level data at each monitoring well fell on the Theis type curve for a confined aquifer with little or no departure from the curve that would have resulted if the aquifer was leaky or unconfined.

Figure 3.12. Pumping test results from monitoring well MW-B (see Fig. 3.7 for location). The well experienced over 10 meters of drawdown over the duration of the 480 minute test. Drawdown of under 2 m was observed at MW1, MW-A and MW-C during the test. These data suggest that drawdown and interference will be widespread as expected in a confined aquifer. For well locations see Fig. 3.7.

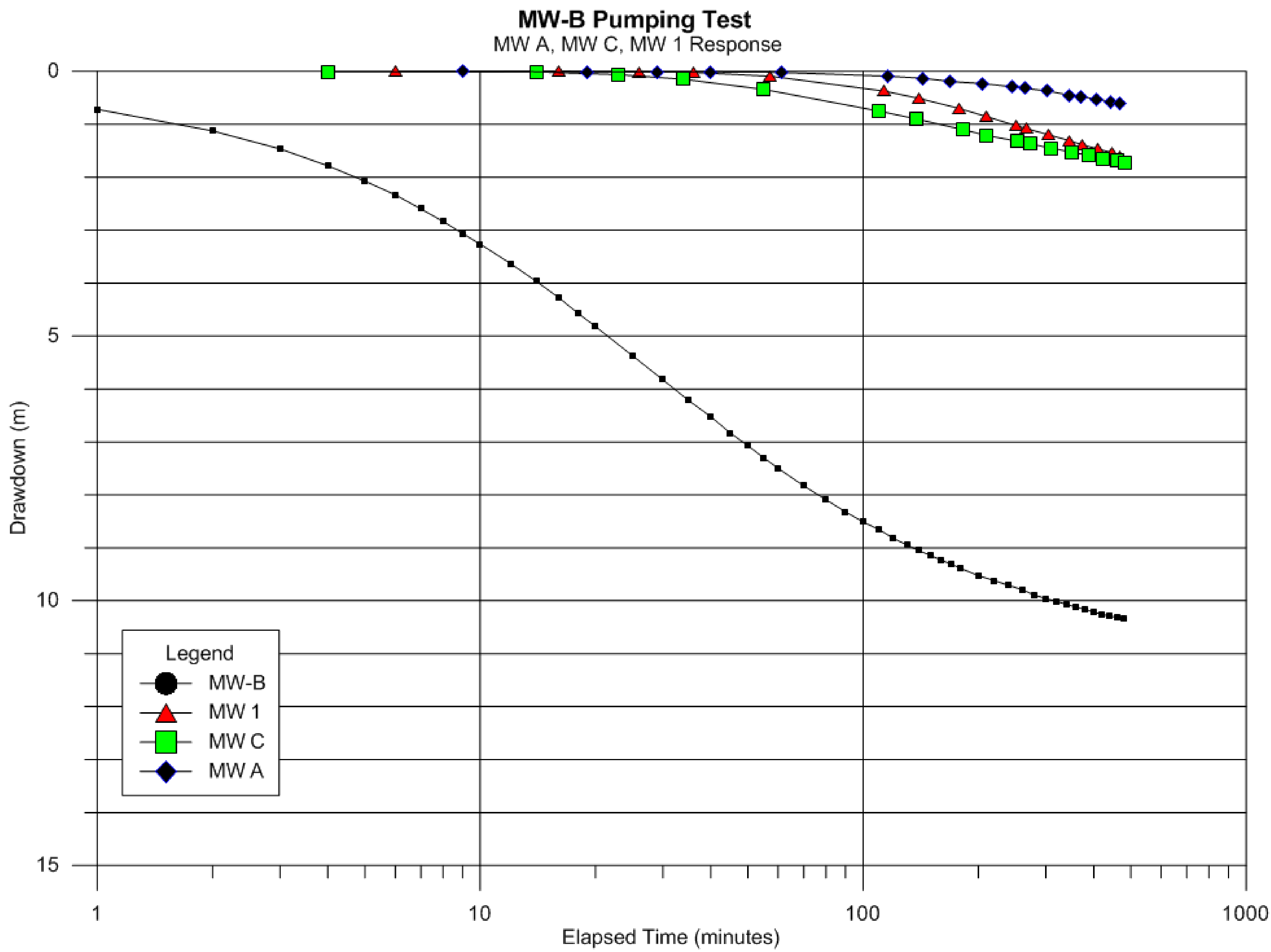
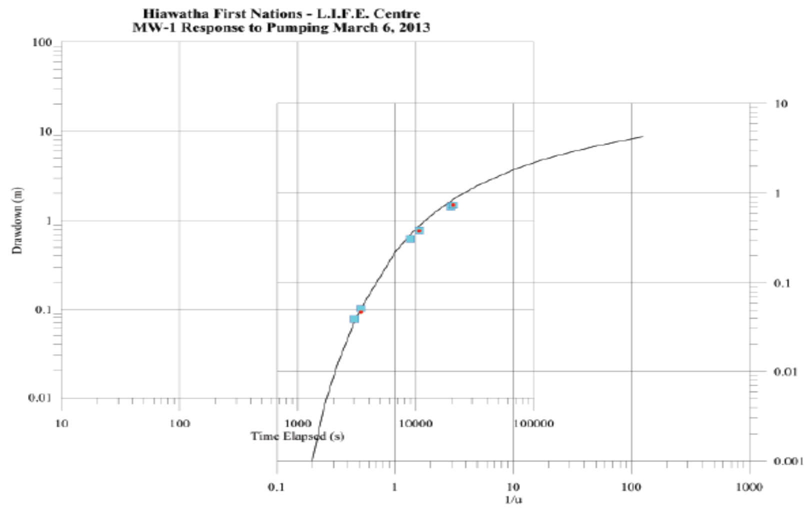
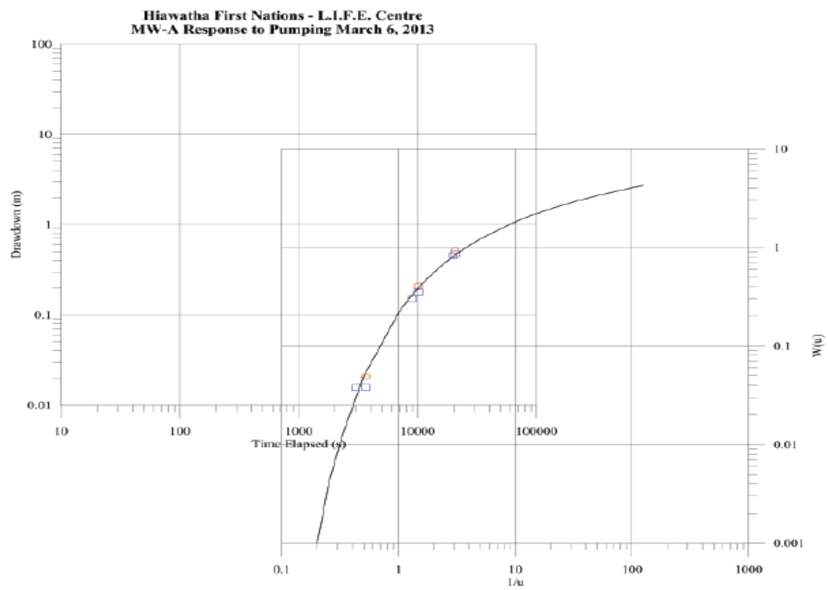

MW-B Pumping Test
MW A, MW C, MW 1 Response
Drawdown (m)
0
5
10
15
Elapsed Time (minutes)
1
10
100
1000
Legend
MW-B
MW 1
MW C
MW A

Figure 3.13. Theis curves showing monitor response to pumping at (a) MW-1, (b) MW-A and (c) MW-C. These curves all match an ideal Theis type curve for a confined aquifer. See Fig. 3.7 for location of wells.

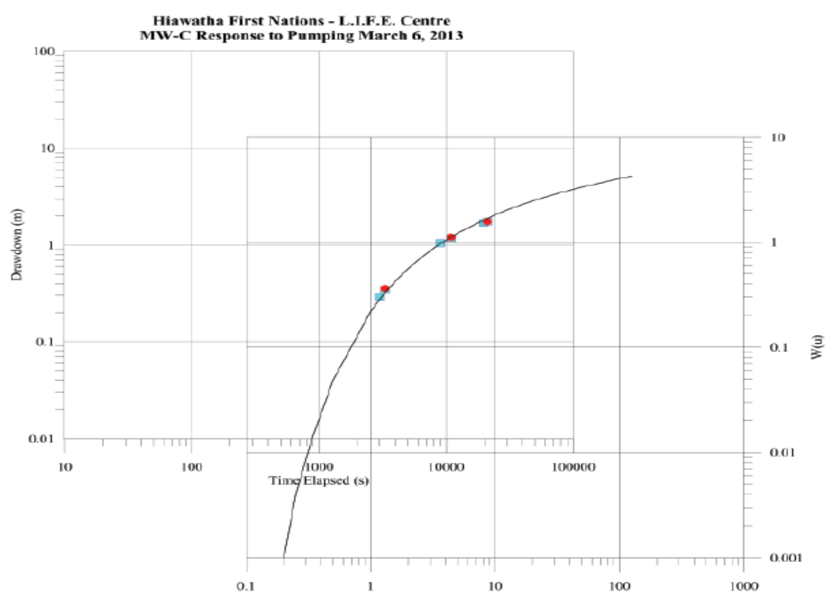
A


Hiawatha First Nations - L.I.F.E. Centre
MW-1 Response to Pumping March 6, 2013
Drawdown (m)
Time Elapsed (s)
W(u)
1/u

B


Hiawatha First Nations - L.I.F.E. Centre
MW-A Response to Pumping March 6, 2013
Drawdown (m)
Time Elapsed (s)
W(u)
1/u

C


Hiawatha First Nations - L.I.F.E. Centre
MW-C Response to Pumping March 6, 2013
Drawdown (m)
Time Elapsed (s)
W(u)
1/u

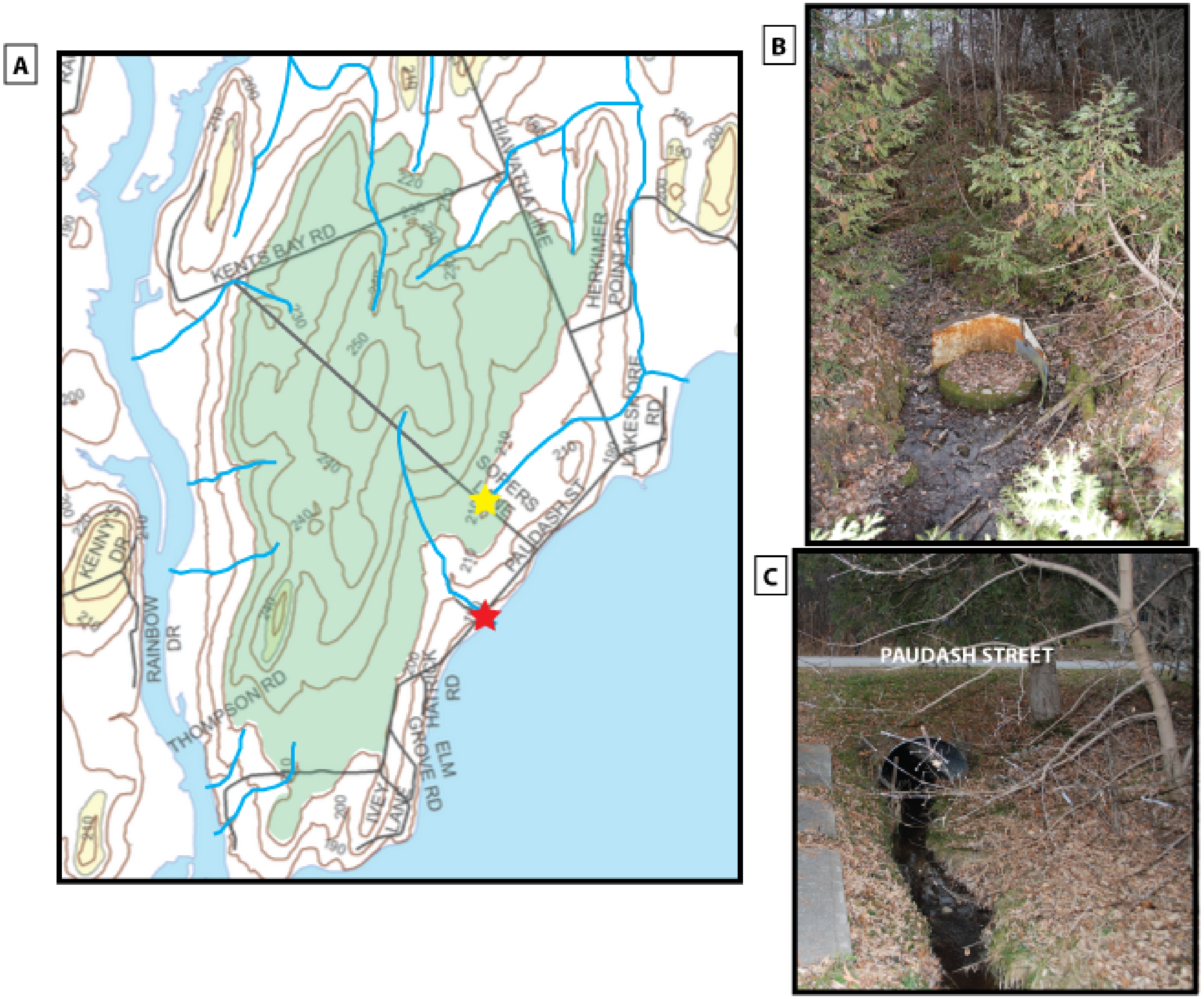
Water Quality Analysis

Of particular interest to this study (from a groundwater protection perspective) are the results of water quality testing where nitrate (NO_3) was analyzed. As nitrate typically does not naturally occur in aquifers and aquitards its presence normally indicates an on-going or historical anthropogenic influence (Robertson et al. 1996). Thus any level of nitrate in an aquifer is cause for concern. The Ontario Drinking Water Standard (health related) for nitrate in Ontario is 10 mg/L. During the pumping test of MW-B at the L.I.F.E center, water quality analyses were performed on water samples taken from the lowermost aquifer at or close to bedrock (average elevation 180 m.a.s.l). Nitrate values obtained from this test were extremely low (<0.1 mg/L; the detection limit for nitrate at Caduceon Environmental Laboratories). This gives evidence that there is little anthropogenic contamination of water in this aquifer (Robertson et al. 1996, Fetter 2001).

3.4.7 *Springs on the HFN Reserve*

Approximately 10% of the homes on the HFN Reserve rely on a 'spring' supply for their potable water (F.N.E.S. 2009). One of the springs can be accessed via Paudash Street West (Fig. 3.14a – red star, b, c). Examination of local maps and field investigations indicate that there are at least two springs/streams on the Reserve that outcrop between 200 and 205 m.a.s.l. and drain into Rice Lake (Fig. 3.14a). There are additional streams around the periphery of the HFN Reserve that appear to be sourced from springs with an average elevation of 215 m.a.s.l. on the western flanks, at 240 m.a.s.l. along the north, and at 205 m.a.s.l on the east (Fig. 3.14a). A water sample taken by ORE from a private residence that uses a spring as its water supply reported nitrate elevations of 9.1 mg/L indicating an anthropogenic influence (Fig. 3.14a – location indicated by yellow star).

Figure 3.14. (a) Map showing the location of springs around the periphery of the mega-drumlin (green shading). Yellow star indicates location of Oakridge sampling location for water quality. Red star indicates location of spring accessible from Paudash Street. (b) A well head in the spring off of Paudash Street (c) spring intersects Paudash St – close to location of sampling point for water quality.


A
B
C
KENTS BAY RD
HIAWATHA LINE
HERKIMER POINT RD
LAKESHORE RD
PAUDASH ST
RAINBOW DR
THOMPSON RD
ELM GROVE RD
PAUDASH STREET

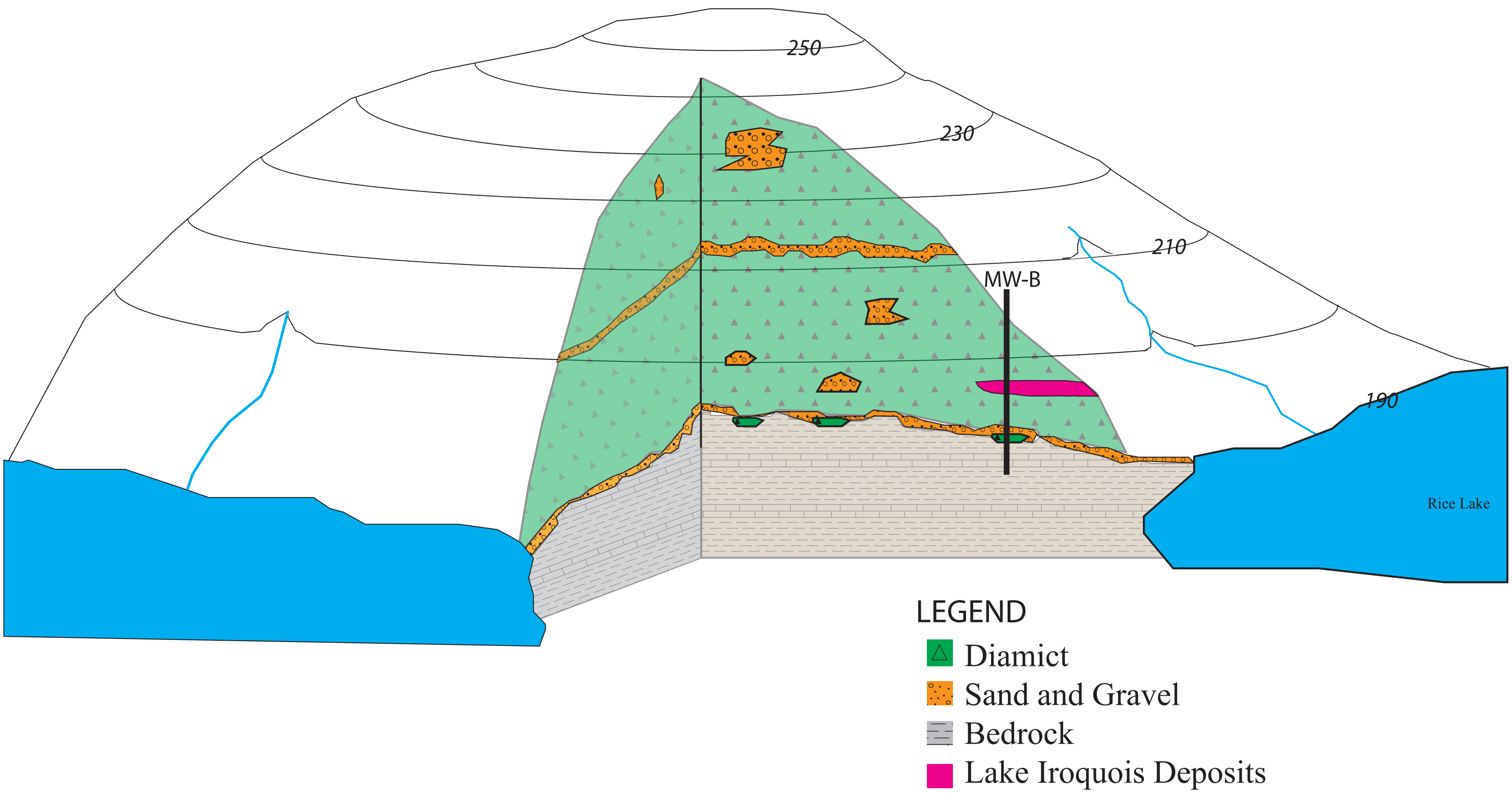
3.5 DISCUSSION

3.5.1 *Stratigraphy at the HFN Reserve*

Bedrock in the area of the HFN Reserve consists of Paleozoic Verulam Formation limestone and shales. Bedrock is observed to have up to 15 meters of relief from west to east and 20 meters of relief from north to south, with the slope trending towards Rice Lake (Fig. 3.15) which is consistent with trends reported in the literature (Liberty 1969; Sanford 1995). Fluctuations in local bedrock elevation may be related to differential erosion of the bedrock surface during the Tertiary/Quaternary, isosatic uplift, and local jointing of the bedrock surface (Eyles et al. 1993, Eyles et al. 1997, Sonnenburg et al. 2012). The upper parts of the bedrock appear to be extensively fractured and discrepancies in the reporting of bedrock elevations in the water well records may result from inaccurate identification of large loosened clasts as bedrock rather than the actual bedrock surface. Bedrock is overlain by a thin (up to 10m) discontinuous veneer of sand and gravel which is likely of fluvial or colluvial origin and, together with the fractured bedrock forms a basal aquifer (Unit 1, 2?; Figs. 3.10, 3.15). This unit seems to function as an effective aquifer despite the low permeability values determined from grain size analysis of these sediments (Table 3.1).

Overlying the basal aquifer and bedrock is a thick (up to 20 m) diamict (termed here the lower diamict). Evidence from the cored hole suggests that this unit may be composed of multiple diamict beds as indicated by the variable textures observed (Units 1 – 3?; Figs. 3.10, 3.15). The diamict contains striated clasts of varying sizes from both local and far travelled sources which is consistent with its origin as a subglacial till (Benn and Evans 2014). This unit is identified here as a Northern/Newmarket Till complex equivalent.

Figure 3.15. Idealized section through the HFN mega-drumlin. Line A – idealized schematic log through stratigraphy along Soper's Lane. Line MW-B idealized schematic log from beneath the L.I.F.E. center. Springs are shown to emanate from the upper aquifer.


250
230
210
190
MW-B
Rice Lake
LEGEND
Diamict
Sand and Gravel
Bedrock
Lake Iroquois Deposits

A significant change in depositional environment is indicated by Unit 4 (Fl, Sm, Dms) which likely records deposition in a subglacial or subaerial glaciolacustrine environment. Unit 4 (Fig, 3.10) may be laterally equivalent to a thin (<10 m) sand and gravel unit recorded in the water well records which is frequently penetrated around 205 m.a.s.l. and forms an upper aquifer on the Reserve. The aquifer appears to be continuous in the subsurface from north to south and east to west, is truncated along the flanks, and is thickest in the center of the mega-drumlin (Fig. 3.15). Several springs around the periphery of the mega-drumlin outcrop between 240 and 210 m.a.s.l. (Figs. 3.14, 3.15) and are likely supplied by the upper aquifer where the unit is truncated and exposed (?) at ground surface. This coarse-grained unit was probably deposited by fluvial/glaciofluvial processes and may indicate deposition during a period of ice retreat; it may be equivalent to the ORM/Mackinaw Interstadial complex (Meriano and Eyles 2008). If it is equivalent to fine-grained sediments of Unit 4, then a spatial transition from fluvial depositional conditions on the north and central parts of the Reserve to lacustrine conditions in the south near Rice Lake, can be demonstrated.

The upper aquifer is capped by an upper diamict unit (Unit 5; Fig. 3.10, 3.15) which is up to 50 meters thick at the center of the mega-drumlin (Fig. 3.15). It has variable texture and incorporates sand rafts and fine grained successions (Fig. 3.15). This diamict unit likely records another episode of ice advance and deposition of till (Benn and Evans 2014) by the Simcoe lobe of the LIS during the Port Huron Stade and is probably equivalent to the late phase Northern/Newmarket Till complex.

3.5.2 *Regional Setting*

The mega-drumlin investigated on the HFN Reserve shows a similar subsurface stratigraphy to other drumlins in the PDF found both north and south of the ORM where the ground surface elevation is greater than 200 m.a.s.l. (Chapter 2). The HFN drumlin was found to consist predominantly of sand-rich diamict with minor amounts of fine grained lacustrine facies, and coarse grained fluvial facies. This stratigraphy was found to be well defined and laterally extensive across the mega-drumlin. The identification of pre-existing stratigraphy in this drumlin provides further support for drumlin formation by erosional processes (Chapter 2) and does not support theories of drumlin formation by subglacial floods (Shaw 1983; Shaw and Sharpe 1987; Shaw and Gilbert 1990; Gilbert and Shaw 1994), subglacial remobilization or extensive deformation of sediment (Boulton 1987; Boulton and Hindmarsh 1987; Boulton et al. 1995; see discussion in Chapter 1).

3.5.3 *Hydrogeological Applications*

The two main aquifers on the HFN Reserve are considered to be (1) the lower aquifer composed of fractured bedrock and basal sand and gravel and (2) the upper aquifer hosted in Quaternary sediments. Hydrogeological data show that these aquifers have different geochemical properties and hydrologic response to pumping tests. The lower aquifer has little to no nitrate and behaves as an ideal confined aquifer as evidenced by the results of pumping at MW-B. The upper aquifer has elevated nitrate levels; there are currently no reliable pumping test data for this aquifer.

The diamict underlying the Reserve, previously identified as the Northern/Newmarket Till, has been studied extensively elsewhere and has been found to behave as a 'leaky' aquitard allowing water to migrate through permeable interbeds in the till sheet (Gerber and Howard 1996; Gerber and Howard 2000, Boyce and Eyles 2000; Gerber et al. 2001; Chapter 2). The presence of nitrate in the upper aquifer (at the Soper's Lane works yard wells and the springs) indicates that on the HFN, the upper section of the diamict is 'leaky', consistent with these observations. However, pumping test data from the HFN Reserve suggests that the lower till behaves as an ideal aquitard to the basal aquifer at this site (Fig. 3.13) and as a result, the basal aquifer has little or no nitrate. The upper diamict, identified as a late phase Northern/Newmarket Till, does not provide the same level of protection to the upper aquifer as it is observed to have elevated nitrate levels. This suggests that the upper diamict package does behave as a leaky aquitard. The difference in aquifer response and observed nitrate levels between the upper and lower aquifer are likely due, therefore, to the thickness and continuity of the aquifer sediments, and the nature of the overlying diamict.

3.6 CONCLUSIONS

The sedimentologic and stratigraphic investigation of materials found within the HFN mega-drumlin has demonstrated that it is composed predominantly of diamict and has a basal bedrock aquifer and an upper (discontinuous) sand and gravel aquifer hosted within the diamict. The overall stratigraphy of the mega-drumlin is consistent with the regional stratigraphy identified beneath drumlins across the PDF (Chapter 2). The continuity of this stratigraphy suggests that it is an erosional feature carved from older pre-existing sediments. The HFN has been attempting to understand and improve their water supply on the Reserve for at least 15 years. Currently, homes and businesses utilize one of four water sources: a basal aquifer, an upper aquifer hosted in Quaternary sediments, a spring source, or Rice Lake (not studied). Data collected during this study indicate that these sources provide a reasonable quantity of water in combination; however, the upper aquifer and surface springs are susceptible to surface contaminants and maintaining water quality has been an issue with these sources. In the long term, given predicted population increases on the Reserve, additional sources of water will need to be sought.

Most of the water quality and water quantity issues identified by residents on the Reserve would be improved by upgrades to wells (increasing efficiency) and the addition of appropriate treatment processes. Due to the disadvantages of high capital cost and low population density, it is recommended here that the Reserve continues to rely on private wells for individual residences or develop small communal type systems where one well serves a small area. The basal bedrock aquifer offers some potential for enhancing water supply to the Reserve, although pumping tests indicate that increasing extraction rates from any of the existing wells may negatively impact the productivity of adjacent wells. Drilling additional wells into bedrock in the southwestern section of the Reserve, at some distance away from existing wells, may offer the most potential for increasing production from this aquifer.

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CHAPTER 4

CONCLUSIONS

4.1 Conclusions

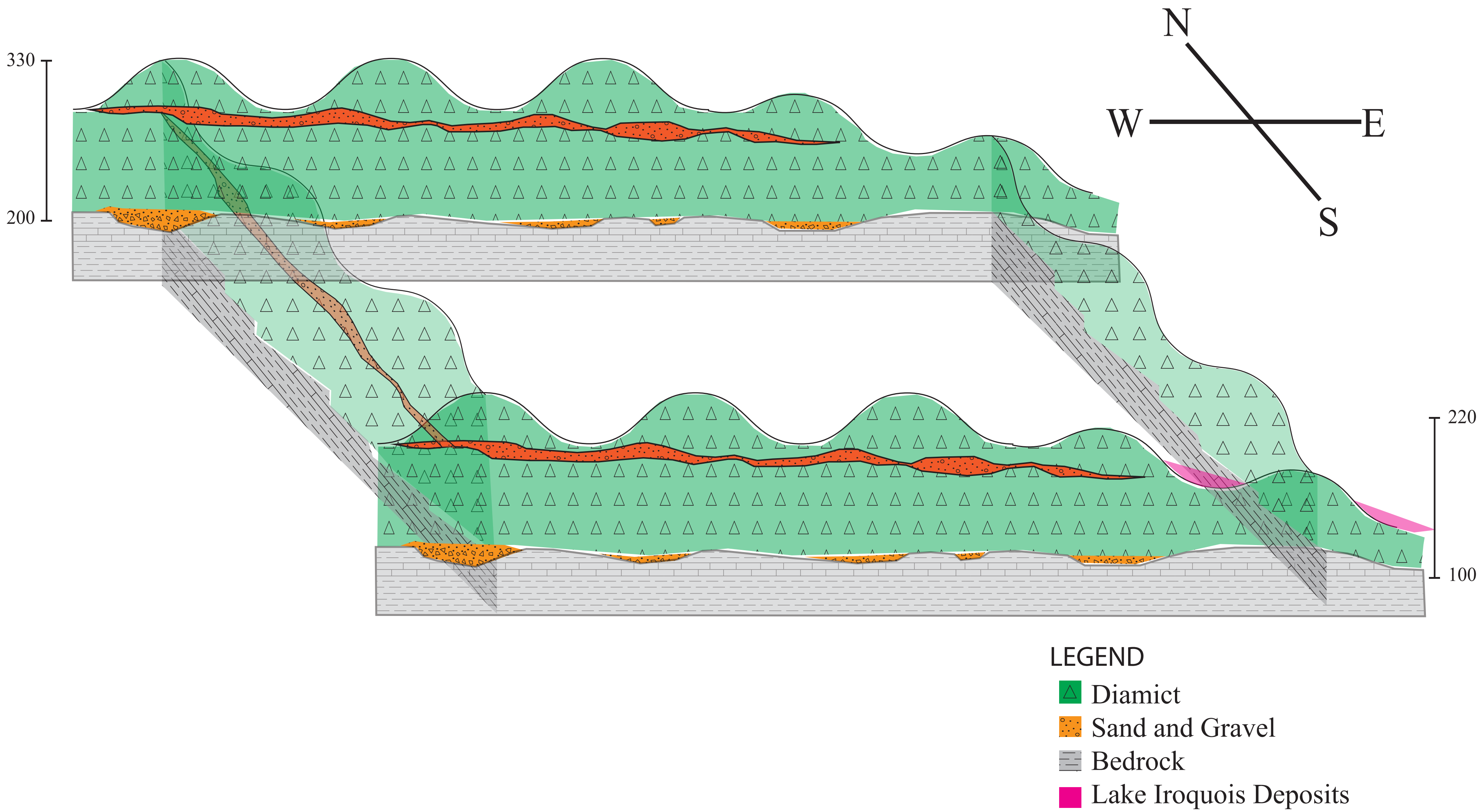
This thesis reports the results of a sedimentological analysis of the Peterborough Drumlin Field from data obtained from water well logs (Chapter 2) and a hydrogeological analysis of a mega-drumlin located within the PDF (Chapter 3) which further enhanced the findings of the sedimentological study.

A moderately consistent subsurface stratigraphy was identified in the drumlins and inter-drumlin swales examined within the PDF (Fig. 4.1), consisting of north-south sloping limestone and shale bedrock draped by a thin veneer of sands and gravels. This is overlain by a thick diamict (till) package, identified as Northern/Newmarket and Halton equivalents, which host discontinuous coarse-grained sand and gravel units (identified as Mackinaw interstadial equivalents). The fact that this stratigraphy can be traced intermittently through the drumlin and into inter-drumlin swales across the entire study area suggests that these drumlins have been carved from pre-existing sediment.

This stratigraphy can also be translated into significant hydrogeological units. The bedrock and overlying sands and gravels comprise a basal aquifer. The overlying diamict package functions as a 'leaky' aquitard, providing some level of protection from contamination, while allowing recharge to the sand and gravel units which act as aquifers. Discontinuous coarse grained units within diamict packages make groundwater resource development difficult to predict and may increase the likelihood of contamination of water supplies.

Additional data provided by a detailed investigation of subsurface conditions on the Hiawatha First Nations (HFN) Reserve, located on the northern shores of Rice Lake, allowed for further confirmation of the stratigraphy established elsewhere in the drumlin field.

Figure 4.1 Fence diagram showing idealized section through the study area within the PDF. The succession in the northern part of the study area has a higher elevation (330 to 200 m.a.s.l.) to that in the south (220 to 100 m.a.s.l.) The stratigraphy in both the north and south of the area shows a discontinuous basal sand and gravel unit overlying an irregular bedrock surface (grey and light orange). This is overlain by a thick diamict sequence (green). A discontinuous medium to coarse grained unit is depicted beneath the drumlins representing the upper aquifer (dark orange). Note that the upper aquifer cuts out to the east. Note also the presence of finer grained material (pink) in drumlin lows to the east – this represents sediment deposited during post-glacial reworking of drumlins in Lake Iroquois.

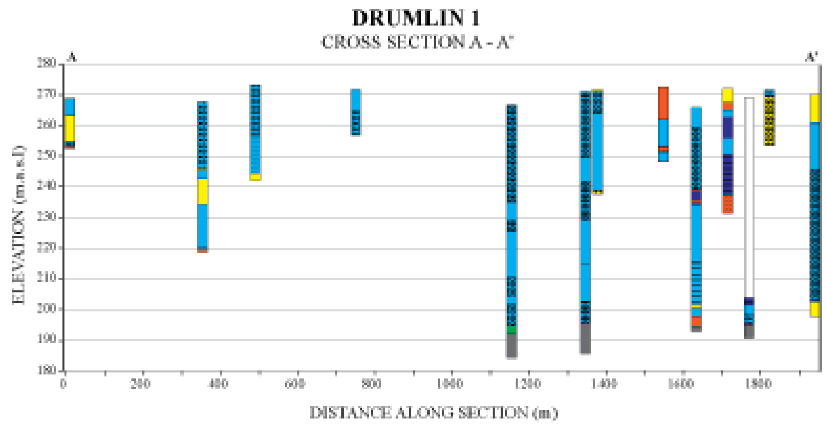

N
W
E
S
330
200
220
100
LEGEND
Diamict
Sand and Gravel
Bedrock
Lake Iroquois Deposits

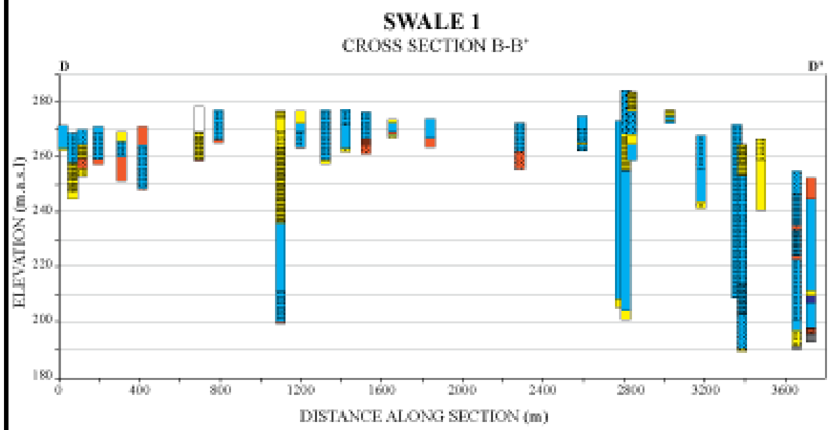
At the HFN, groundwater resources are used almost exclusively for potable water and are accessed by private wells. The research completed for this study was part of a larger project to provide recommendations for a sustainable, safe, drinking water system for the community. Aquifer tests and hydrogeologic analyses conclude that the basal aquifer located here may be a safer, more reliable supply than the upper aquifer hosted in Quaternary sediments. Recommendations are made for the community to upgrade their existing private well system to avoid large capital costs associated with a centralized distribution system.

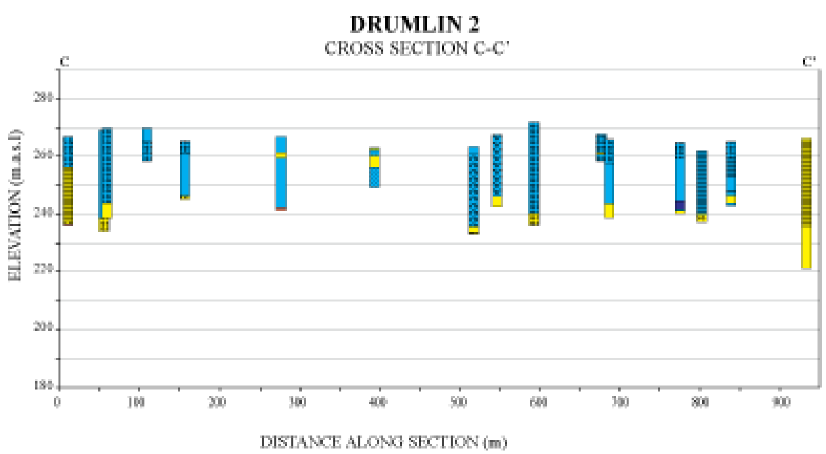
Further research is certainly required to better inform the hydrogeology of the PDF. This study identified that there are two significant aquifer units within the drumlin field. More data are required, however, to accurately establish the lateral continuity and productivity of these aquifers. It would be beneficial to acquire data from fully-cored boreholes that penetrate to bedrock, in multiple locations across the study area, to more accurately delineate the stratigraphy and precisely establish the nature of the basal bedrock aquifer and the characteristics of diamict units underlying the study area (e.g. establish the nature of secondary porosity within bedrock and the form of heterogeneities within the till). These data could be enhanced by integration of other data sources such as downhole geophysics and ground penetrating radar so units can be correlated continuously.

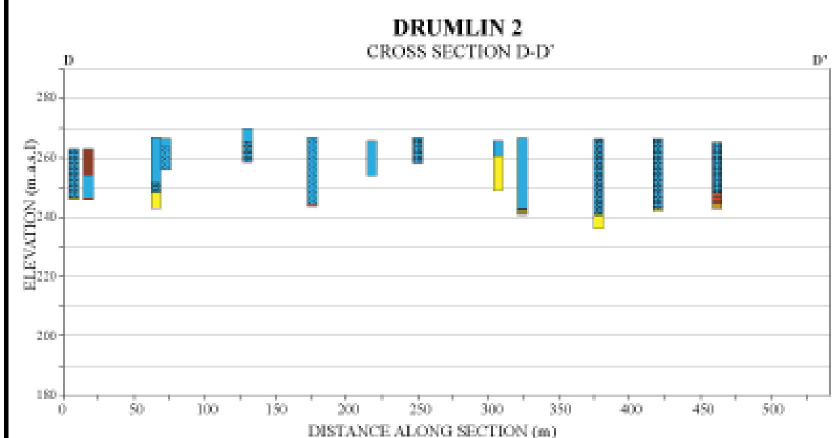
In addition, correctly administered aquifer tests, including water quality analyses, could provide detailed information about the interconnectedness and continuity of permeable units in the subsurface. These hydrogeological test results could be combined with data acquired from fully-cored boreholes to provide a more complete understanding of subsurface conditions beneath the PDF. These data would enable more effective and reliable source water protection plans to be made in areas of recharge and more accurate and reliable development of sustainable drinking water resources in the PDF and in areas of drumlinized terrain elsewhere.

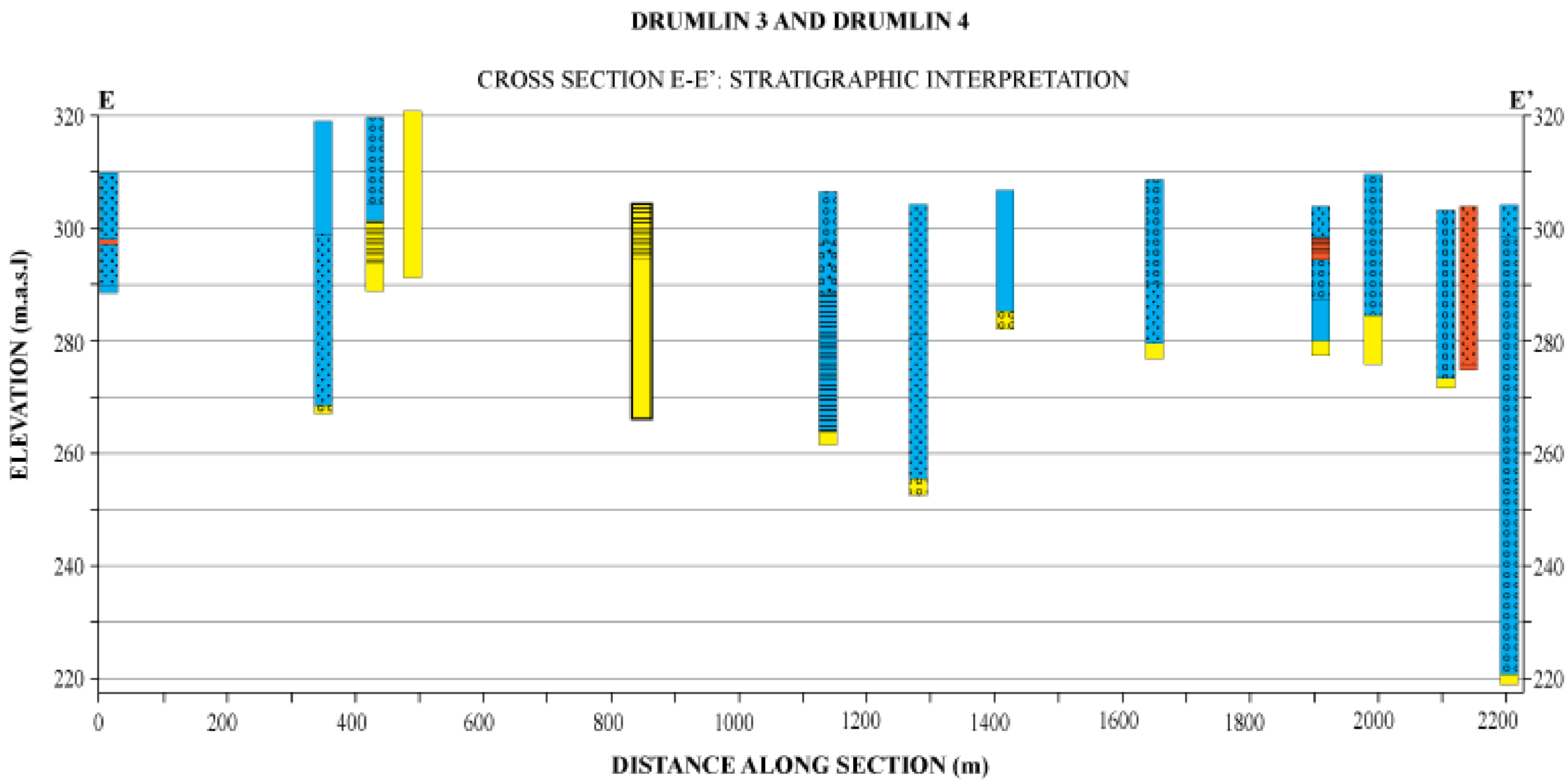
Appendix A

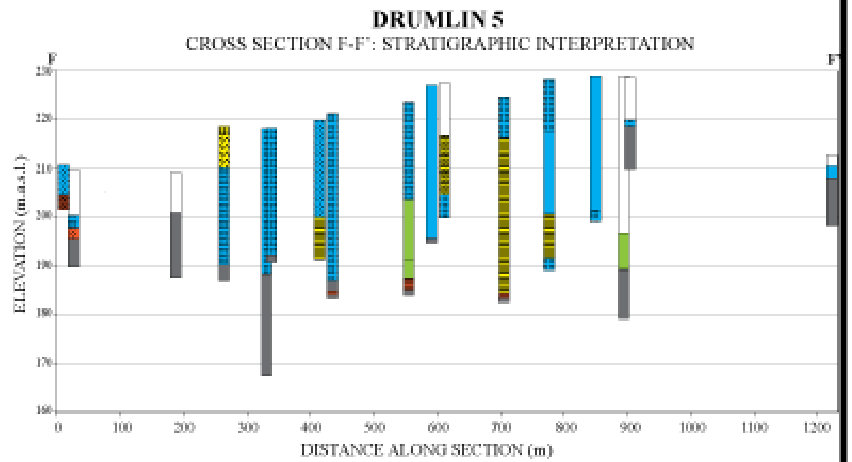

DRUMLIN 1
CROSS SECTION A - A'
A
A'
ELEVATION (m.a.s.l)
DISTANCE ALONG SECTION (m)

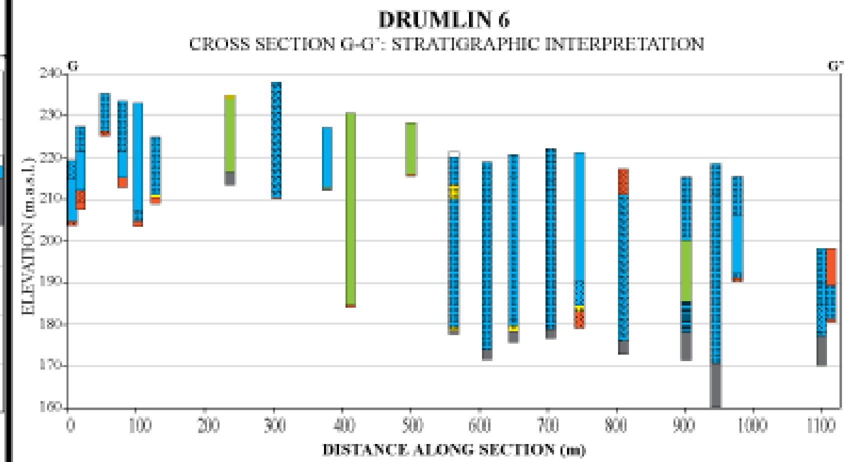

SWALE 1
CROSS SECTION B-B'
D
D'
ELEVATION (m.a.s.l)
DISTANCE ALONG SECTION (m)

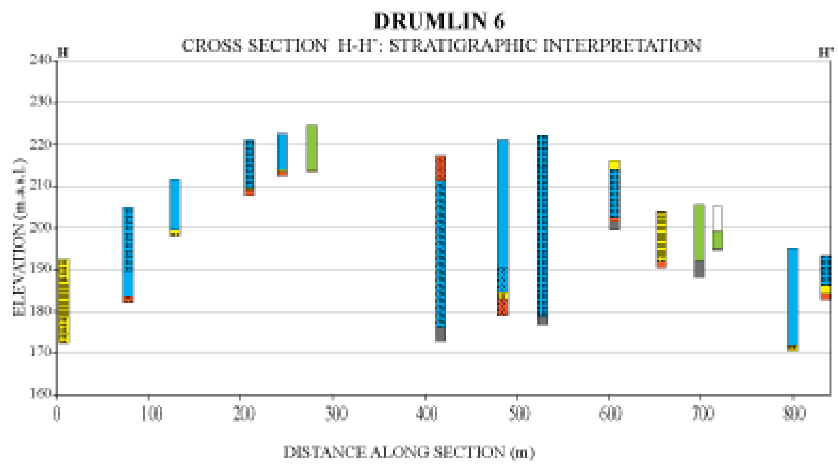

DRUMLIN 2
CROSS SECTION C-C'
C
C'
ELEVATION (m.a.s.l)
DISTANCE ALONG SECTION (m)


DRUMLIN 2
CROSS SECTION D-D'
D
D'
ELEVATION (m.a.s.l)
DISTANCE ALONG SECTION (m)


DRUMLIN 3 AND DRUMLIN 4
CROSS SECTION E-E': STRATIGRAPHIC INTERPRETATION
E
E'
ELEVATION (m.a.s.l)
320
300
280
260
240
220
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
DISTANCE ALONG SECTION (m)


DRUMLIN 5
CROSS SECTION F-F': STRATIGRAPHIC INTERPRETATION
F
F'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200


DRUMLIN 6
CROSS SECTION G-G': STRATIGRAPHIC INTERPRETATION
G
G'
ELEVATION (m.a.s.l.)
240 230 220 210 200 190 180 170 160
0 100 200 300 400 500 600 700 800 900 1000 1100
DISTANCE ALONG SECTION (m)


DRUMLIN 6
CROSS SECTION H-H': STRATIGRAPHIC INTERPRETATION
H
H'
ELEVATION (m.a.s.l.)
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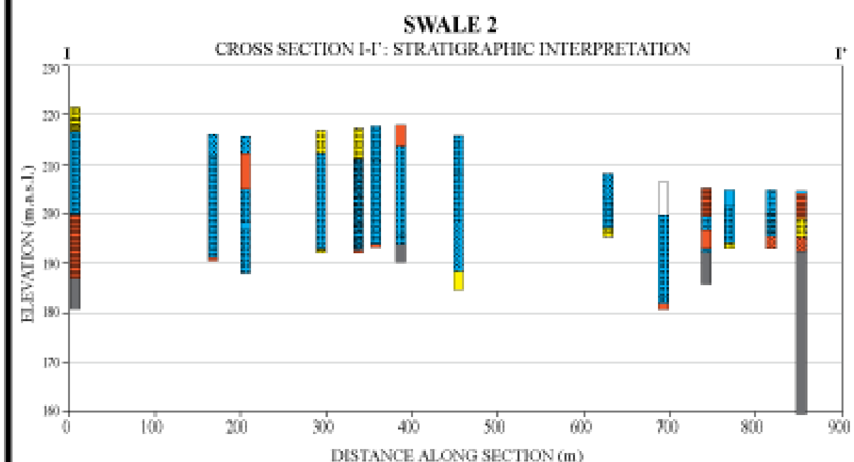
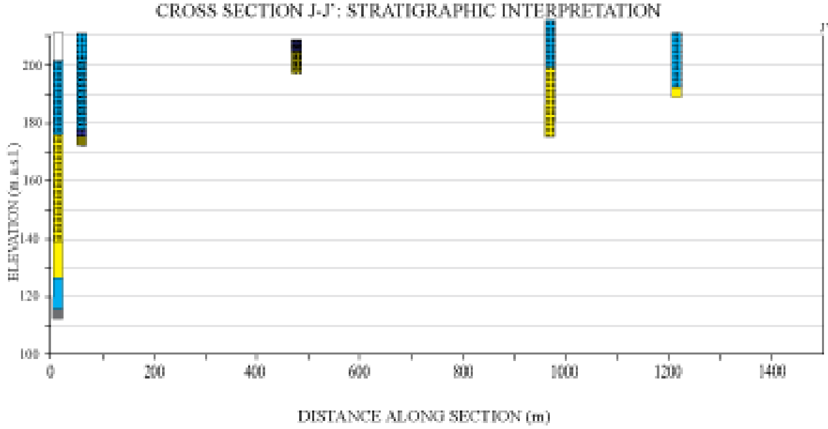
0 100 200 300 400 500 600 700 800
DISTANCE ALONG SECTION (m)


SWALE 2
CROSS SECTION I-I': STRATIGRAPHIC INTERPRETATION
I
I'
ELEVATION (m.a.s.l.)
0 100 200 300 400 500 600 700 800 900
DISTANCE ALONG SECTION (m)

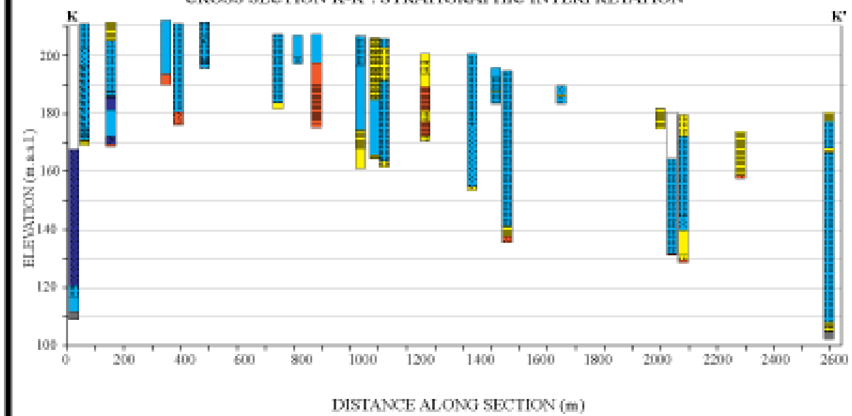
DRUMLIN 7

CROSS SECTION J-J': STRATIGRAPHIC INTERPRETATION



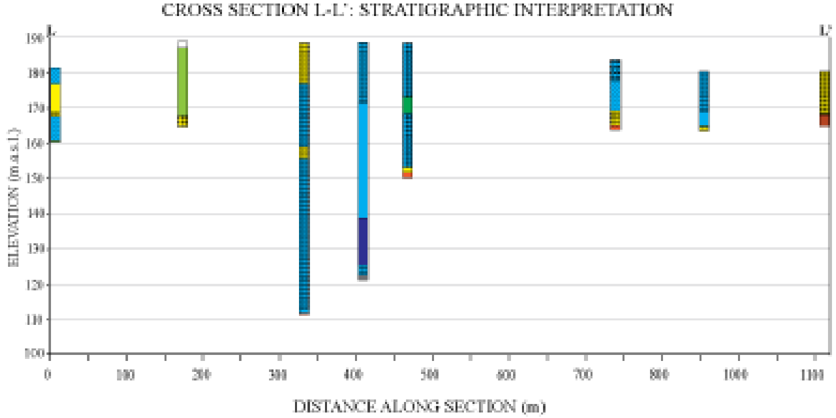
SWALE 3

CROSS SECTION K-K': STRATIGRAPHIC INTERPRETATION



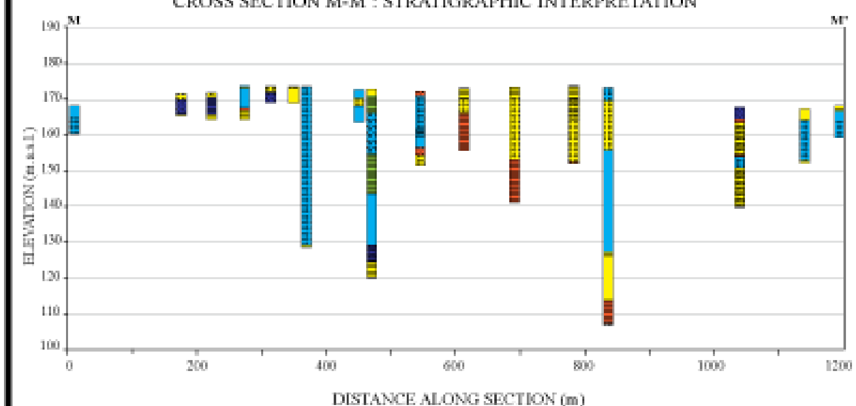
DRUMLIN 8

CROSS SECTION L-L': STRATIGRAPHIC INTERPRETATION



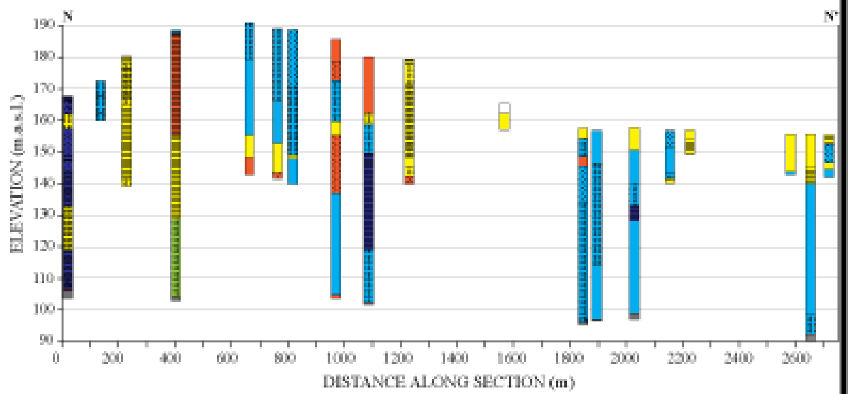
SWALE 4

CROSS SECTION M-M': STRATIGRAPHIC INTERPRETATION



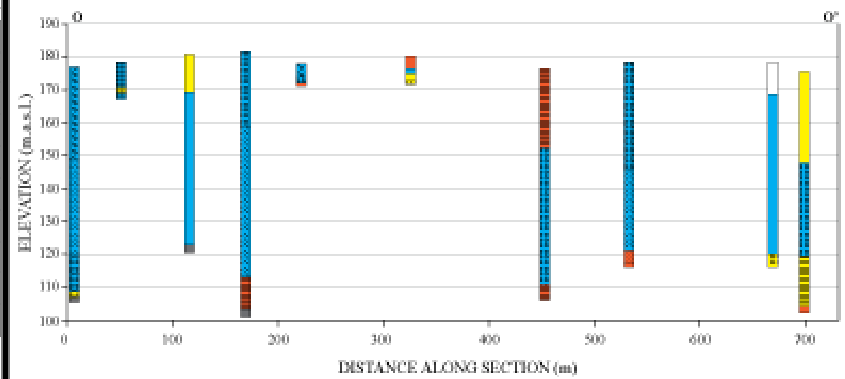
DRUMLIN 9

CROSS SECTION N-N': STRATIGRAPHIC INTERPRETATION



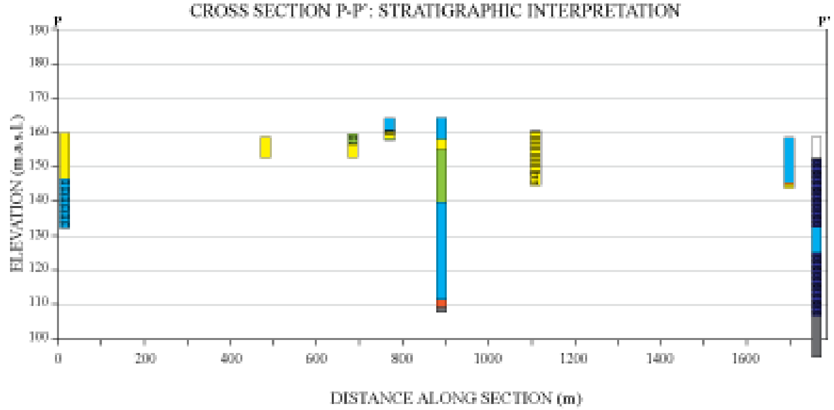
DRUMLIN 10

CROSS SECTION O-O': STRATIGRAPHIC INTERPRETATION



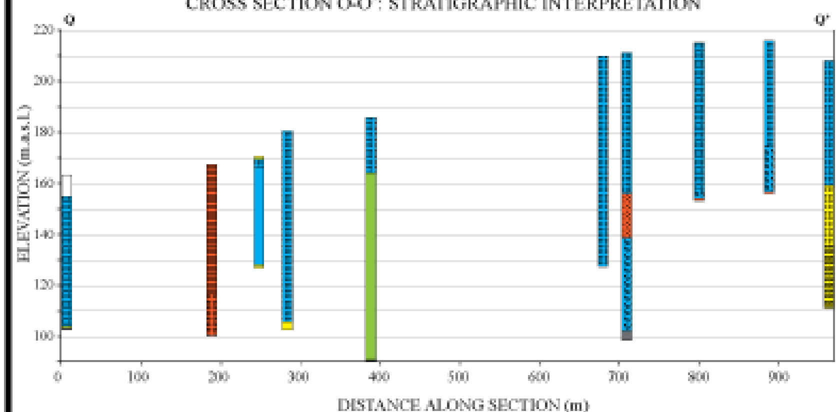
SWALE 5

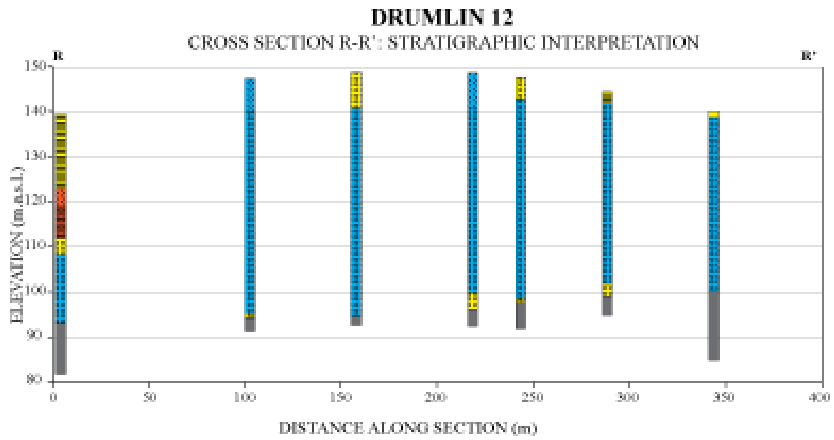
CROSS SECTION P-P': STRATIGRAPHIC INTERPRETATION

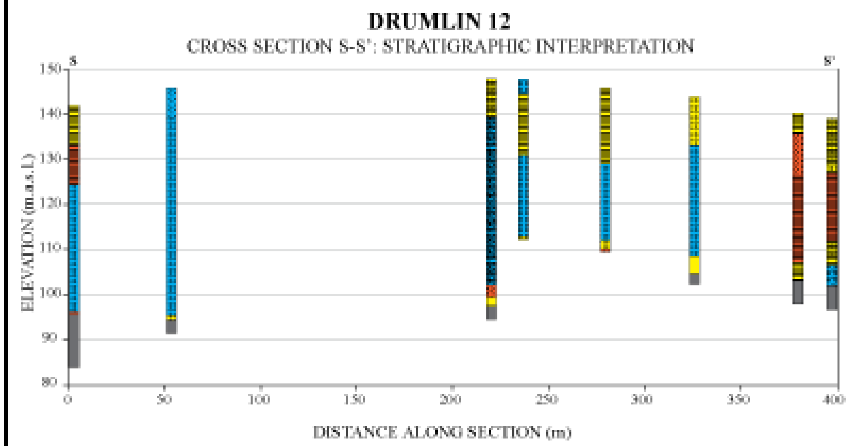


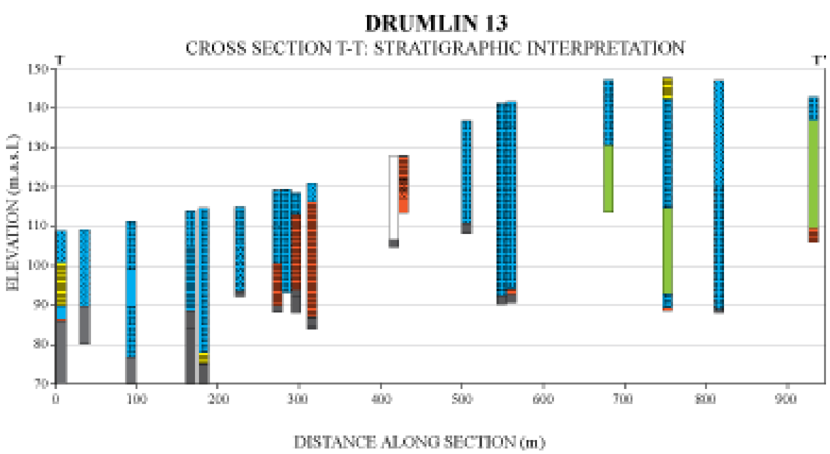
DRUMLIN 11

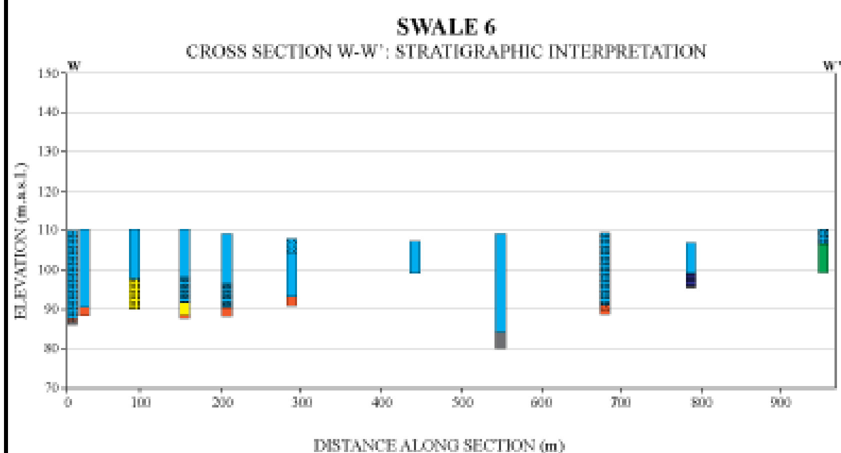
CROSS SECTION Q-Q': STRATIGRAPHIC INTERPRETATION




DRUMLIN 12
CROSS SECTION R-R': STRATIGRAPHIC INTERPRETATION
R
R'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)


DRUMLIN 12
CROSS SECTION S-S': STRATIGRAPHIC INTERPRETATION
S
S'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)


DRUMLIN 13
CROSS SECTION T-T: STRATIGRAPHIC INTERPRETATION
T
T'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)


SWALE 6
CROSS SECTION W-W': STRATIGRAPHIC INTERPRETATION
W
W'
ELEVATION (m.a.s.l.)
DISTANCE ALONG SECTION (m)