QUATERNARY LANDFORM AND SEDIMENT ANALYSIS OF THE ALLISTON AREA (SOUTHERN SIMCOE COUNTY), ONTARIO, CANADA

QUATERNARY LANDFORM AND SEDIMENT ANALYSIS OF THE ALLISTON AREA (SOUTHERN SIMCOE COUNTY), ONTARIO, CANADA

By

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A Thesis

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ABSTRACT

Urban expansion and agricultural growth are placing significant stresses on existing groundwater reserves hosted within Quaternary sediments in southern Ontario. Preserving the quality and quantity of groundwater resources requires a detailed knowledge of the three-dimensional distribution of subsurface geologic units. In this study, integrated analysis of surficial sediment exposures, geophysical and remotely-sensed data, and fully-cored boreholes in the Alliston region of southern Ontario has allowed for the identification of landform-sediment associations, or landsystems, which can be used to predict the nature of subsurface sediment types and to assist with the reconstruction of paleoenvironmental change in the region. The landsystems identified in the Alliston region can also be used as a foundation for the development of a stratigraphic framework for hydrogeological investigations.

Nine landsystems were identified in the study area and include: i) bedrock escarpment, ii) gravel bench, iii) V-shaped valleys and fills, iv) streamlined uplands, v) low-relief uplands, vi) upland plains and scarps, vii) erosional amphitheatres, viii) hummocky terrain, and ix) lowland plains. These landsystems record the changing distribution of glacial, ice-marginal, glaciofluvial, glaciolacustrine, and post-glacial depositional systems that affected the region during the late Quaternary. The landsystems analysis approach provides a useful framework for discerning the spatiotemporal relationship of a complex suite of depositional systems. Analysis of the distribution and internal composition of landsystems in the study area has allowed the development of a preliminary risk assessment map for aquifer vulnerability in the region.

Detailed analysis of 56 outcrop exposures in cutbanks along the Nottawasaga River within the former Lake Algonquin plain has led to the identification of six lithofacies associations (FA 1–6) that present a detailed record of environmental change during the deglacial period. The stratigraphy is floored by the Late Wisconsin Newmarket Till (FA 1) which is locally overlain by ice-proximal debris flows (FA 2). These glacial sediments are overlain by glaciolacustrine silt rhythmites (FA 3) that pass upwards into deltaic sand (FA 4) and channelized fluviodeltaic sand and gravel (FA 5). Lying above the fluvial deposits and capping the succession are widespread sand and silt rhythmites (FA 6), which coarsen up-section. These six facies associations provide a record of changing environmental conditions that existed during deglaciation of the region and give valuable insights into the nature of the evolution of glacial lakes Schomberg, Algonquin, and Nipissing. The deglacial environmental changes described from southern Simcoe County may be valuable analogues for the interpretation of regional-scale events that occurred in extensive lake basins in other formerly glaciated regions.

Qualitative observations of groundwater discharge from sediment facies at outcrop faces along the Nottawasaga River have yielded important data on the internal heterogeneity of subsurface units. These data can be used to identify possible preferential groundwater flow pathways through both aquifer and aquitard units in the region. Understanding the geometry and interconnectedness of these subsurface sediments is essential for planning future water supply for growing urban communities and agricultural irrigation needs in the region and for the prediction of contaminant migration pathways.

ACKNOWLEDGEMENTS

Carolyn and Andy, you've been the best supervisors, mentors, and friends a young student could ask for. Anywhere I might end up looking at rocks (or 'dirt') in the future, it will always be both of you that I have to thank for helping me develop an eye for reading the landscape, deconstructing and understanding the complicated mess of sediments that make up 'typical' glacial successions (even though I've come to learn there really is no such thing), and to question everything - including myself. A big thank you goes to Carolyn for taking the risk on hiring me as an undergrad in the first place and for creating a consistently stress-free work environment where I'm never afraid to ask questions, or to be wrong. Learning from and working with everyone in the glacial lab – Jess, John, Kelsey, Stacey, Paul, Rodrigo, Leslea, Prateek has been a privilege – one that generally kept a smile on my face throughout, even during the early mornings, late nights, wind, rain, sleet and snow. Any time things did get rough, I was able to escape back home to an amazing and supportive group friends and family. Thanks to field assistance from Angela Hanson and Shane Stratton (sorry for working you both so hard). Funding support, data analysis, and encouragement from the Ontario Geological Survey are very gratefully appreciated – this project has been an unbelievable opportunity for me to be able to work with great people and such a broad range of data sets.

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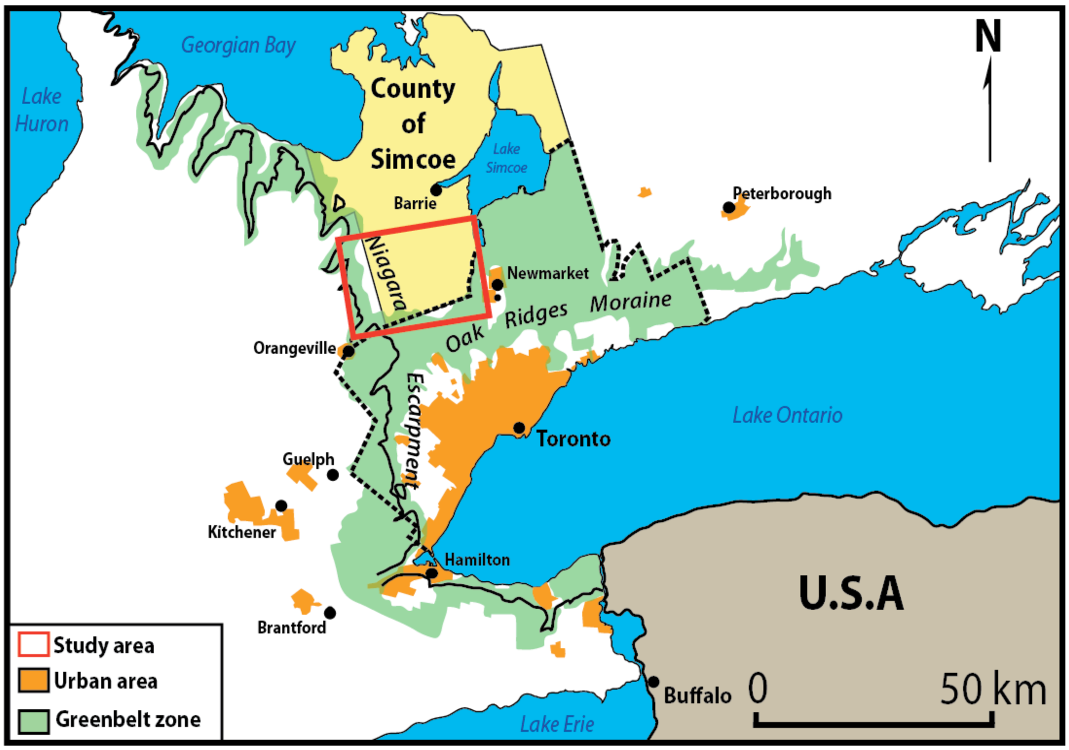
CHAPTER 1: INTRODUCTION

Southern Ontario is projected to experience rapid and dramatic population growth in the near future (Ministry of Public Infrastructure and Renewal, 2006). Expansion will be concentrated along the margins of existing urban areas, and in these areas new infrastructure is required to supply clean drinking water to the growing population. Nearly one third of Ontario's current population relies on groundwater for drinking, and the projected increase in population will force many urban centres to locate and develop new groundwater resources in order to meet future demands.

The southern part of the County of Simcoe, Ontario (herein referred to as southern Simcoe County) is situated immediately north of the Greater Toronto Area (GTA) and lies along the boundaries of two prominent Greenbelt zones, the Niagara Escarpment to the west, and the Oak Ridges Moraine to the south (Figure 1.1). The area has been identified as one of Ontario's *Places to Grow* (Ministry of Public Infrastructure and Renewal, 2006) and will see large increases in population by 2030. Currently, the majority of the population in the region is reliant on groundwater as a source of drinking water. The importance of understanding the nature and characteristics of groundwater systems in southern Ontario was highlighted following the Walkerton tragedy in 2001. Since that time, Quaternary research in southern Ontario has focused on developing a comprehensive understanding of the sediments that host the groundwater system, with particular emphasis on identifying the source, flow pathways and major seals for groundwater resources (Bajc et al., 2011).

Figure 1.1: Location of the County of Simcoe in central Ontario. Niagara Escarpment and Oak Ridges Moraine greenbelt zones shown in green, urban areas in orange, Greater Toronto area (GTA) shown in dashed line.



Georgian Bay
Lake Huron
County of Simcoe
Lake Simcoe
Barrie
Peterborough
Niagara
Newmarket
Oak Ridges Moraine
Orangeville
Escarpment
Lake Ontario
Toronto
Guelph
Kitchener
Hamilton
Brantford
U.S.A
Buffalo
0
50 km
Lake Erie
N
Study area
Urban area
Greenbelt zone

In response to these demands, in 2002 the Ontario Geological Survey (OGS) initiated a series of regional-scale three-dimensional (3D) mapping programs in southern Ontario. The aims of these programs are to: i) map the bedrock geology and topography; ii) characterize the Quaternary stratigraphic framework; iii) assess the groundwater resource potential, and identify any possible groundwater – surface water interactions (Bajc et al., 2011). As part of this 3D mapping program, the surficial geology of the Alliston area (National Topographic series (NTS) map 031/D04), which includes southern Simcoe County was mapped during the summers of 2010 and 2011 (Chapter 2; Appendix B), and detailed analysis of outcrop exposures along modern river valleys was undertaken during the summers of 2011 and 2012 (Chapter 3).

The data obtained in these 3D mapping investigations form a robust framework for groundwater applications, and also provide valuable insights into the nature of paleoenvironmental changes that occurred during and following the last major glacial episode in southern Ontario. The landscape in the study area was shaped by the complex interactions of glacial, fluvial, and glaciolacustrine processes (Chapman and Putnam, 1984; Sharpe et al., 2002; Bajc et al., 2012). The data presented in this thesis help to identify the principal processes responsible for the formation of landforms and associated sedimentary units and to constrain the boundaries between the depositional systems in which they formed.

This thesis presents a summary of investigations into the nature of Quaternary-age landforms and surficial deposits in the southern Simcoe County region of Ontario and is intended to complement and supplement the 3D mapping program initiated by the OGS in 2010 (Figure 1.1). The thesis is organized into four chapters: 1) Introduction; 2)

Landsystems analysis of surficial deposits in the southern Simcoe County (Alliston) region of Ontario; 3) Paleoenvironmental analysis and hydrogeologic significance of Late Wisconsin and Holocene glaciolacustrine deposits, southern Simcoe County, Ontario; and 4) Conclusions.

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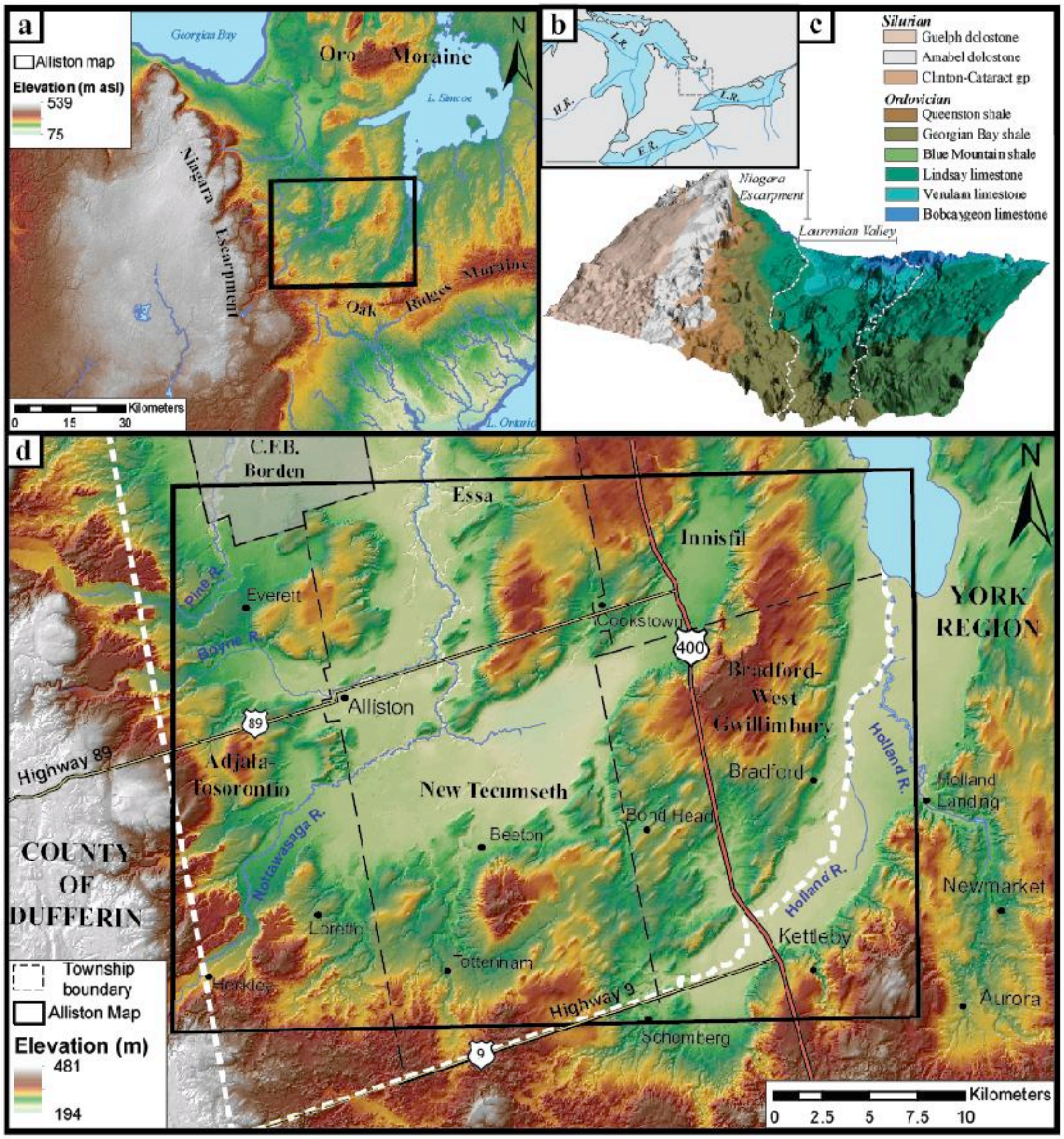
CHAPTER 2: LANDSTYSTEMS ANALYSIS OF SURFICIAL DEPOSITS IN THE SOUTHERN SIMCOE COUNTY (ALLISTON) REGION OF ONTARIO

2.1 INTRODUCTION

Recent groundwater investigations in the southern part of Simcoe County, Ontario (Figure 1.1) have highlighted the need for a better understanding of the Quaternary stratigraphic framework of the region (Sharpe et al., 2002; Bajc & Rainsford, 2010). Quaternary sediment thickness in the region can exceed 200m (Gao et al., 2006) and the majority of the rapidly growing population is reliant on local potable groundwater resources extracted from aquifers hosted within thick and heterogenous sediment successions. A three-dimensional (3D) mapping program involving the analysis of subsurface sediments obtained from 17 fully-cored boreholes (Figure 2.1a) was initiated by the Ontario Geological Survey (OGS) in 2010 (Bajc & Rainsford, 2010; Bajc & Rainsford, 2011; Mulligan, 2011; Bajc et al., 2012). To complement and supplement this subsurface investigation, a study of surficial sediments and landforms was undertaken in the Alliston area of southern Simcoe County (Figure 2.1d; Appendix B) in order to better constrain the nature, distribution, and origin of surficial and shallow subsurface sediment units (Mulligan, 2011; Bajc et al., 2012; Mulligan & Bajc, 2012). The results of this detailed study of the Alliston map area (and immediately adjacent regions) are reported here. The integration of field-based sediment mapping, and digital topographic data, with borehole data collected by the OGS has the potential to more accurately constrain the 3D geometry and interconnectivity of surficial deposits within the study area and to enhance the interpretation of late Quaternary paleoenvironmental conditions. Landforms and near-surface sediment successions exposed in the Alliston map area provide a detailed record of environmental change during the Wisconsin Episode and hold important clues for the interpretation of regional events that affected southern Ontario (Barnett, 1992; Karrow et al., 2000; Sharpe et al., 2004). The sediments and landforms in the

Figure 2.1: a) location of study area (black box) in southern Ontario; b) ancestral drainage of Great Lakes basins, after Spencer (1890), L.R. = Laurentian River, H.R. = Huronian River, E.R. = Erigan River; c) regional bedrock geology draped onto 2.5-D surface showing bedrock topography viewed from the southeast, approximate extent of Laurentian Valley marked with white dashed line, geology from Armstrong and Carter (2010); d) Digital Elevation model (DEM) and geography of southern Simcoe County (white dashed line), Alliston map sheet (black rectangle) and surrounding study area.


a
Alliston map
Elevation (m asl)
539
75
Georgian Bay
Oro Moraine
L. Simcoe
Niagara Escarpment
Oak Ridges Moraine
Kilometers
0 15 30
L. Ontario
b
c
Silurian
Guelph dolostone
Amabel dolostone
Clinton-Cataract gp
Ordovician
Queenston shale
Georgian Bay shale
Blue Mountain shale
Lindsay limestone
Verulam limestone
Bobcaygeon limestone
Niagara Escarpment
Laurentian Valley
d
C.F.B. Borden
Essa
Innisfil
YORK REGION
Everett
Pine R.
Boyne R.
Cookstown
400
Bradford-West Gwillimbury
Alliston
89
Highway 89
Adjala-Tosorontio
New Tecumseth
Bradford
Holland R.
Holland Landing
Bond Head
Beeton
COUNTY OF DUFFERIN
Nottawasaga R.
Newmarket
Loretto
Kettleby
Tottenham
Township boundary
Alliston Map
Highway 9
Aurora
Schomberg
9
Elevation (m)
481
194
Kilometers
0 2.5 5 7.5 10

Alliston map area record the conditions beneath the southern margin of the Laurentide Ice Sheet (LIS) and provide insight into the retreat behaviour of the ice margin during the early deglacial period. The area was affected by the development, growth and drainage of a succession of ice-marginal and post-glacial lakes in which extensive blankets of sand-rich and fine-grained sediment were deposited (Deane, 1950; Bajc et al., 2012). Similar large lakes covered many other areas of central and eastern Canada at the end of the last glaciation (Teller, 2001). Understanding the nature of the evolution of these former lake basins holds important clues to help establish their sensitivity to environmental changes in the past, and to predict their response to projected future climate change.

This chapter provides a description and interpretation of Quaternary sediments and associated landforms within the Alliston map area through a detailed landsystems analysis. The characteristics of the sediment-landform assemblages are used to constrain the spatial and temporal relationships of changing environmental conditions at the end of the last glacial episode. These characteristics can also help to identify local zones of environmental sensitivity, potential aquifer recharge, and areas particularly vulnerable to contaminant leakage into regionally significant aquifers.

2.2 GEOLOGIC BACKGROUND

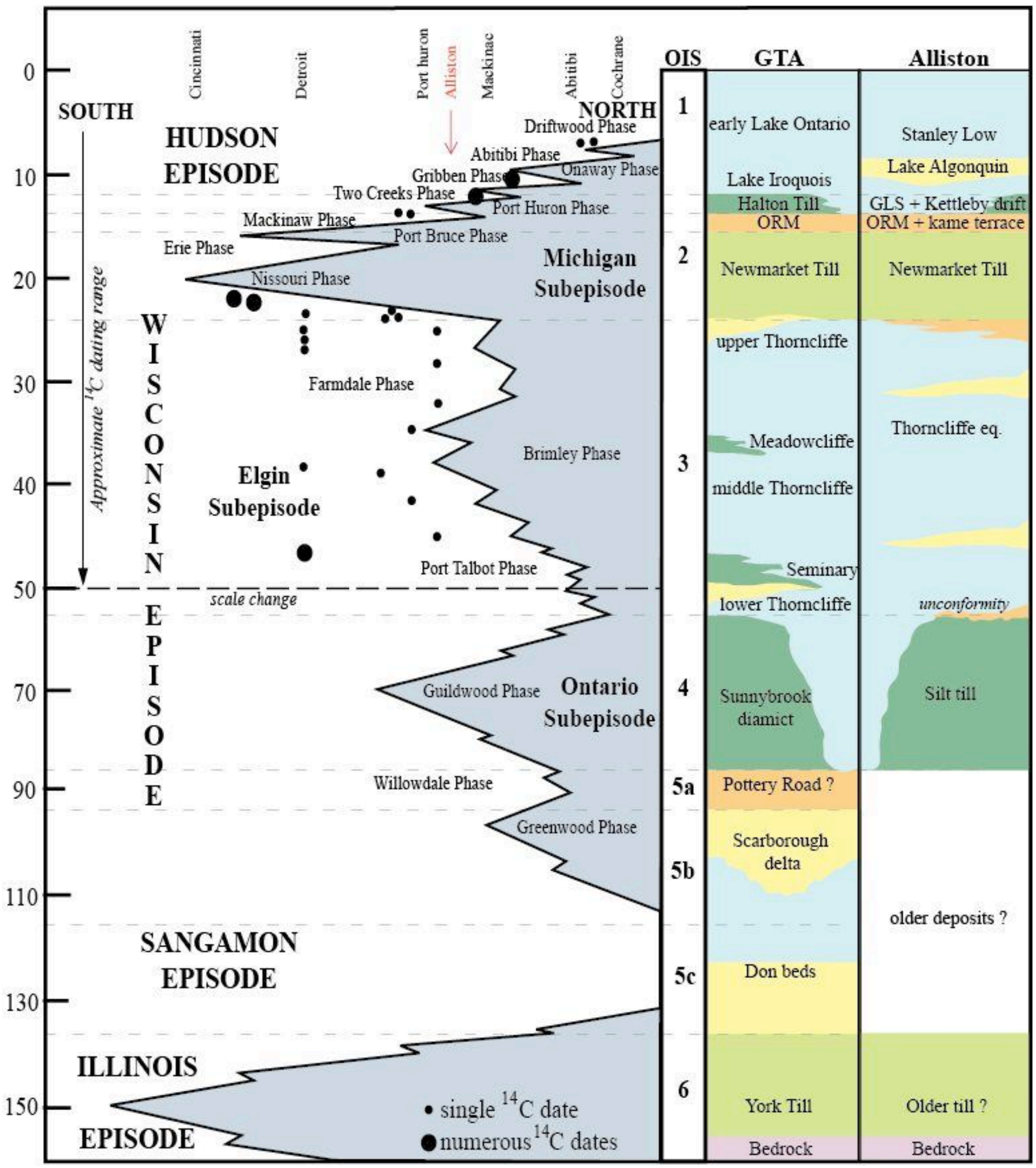
The southern Simcoe County region is underlain by a succession of Paleozoic limestone, shale, and dolostone that covers the Precambrian basement (Armstrong & Carter, 2010; Figure 2.1c). A broad, southeast-trending bedrock low beneath the study area is interpreted to mark the position of (interconnected?) bedrock valleys that may record erosion of a pre-glacial fluvial system (Laurentian River; Spencer, 1890; Eyles et al., 1985; Figure 2.1b, c). However, due to the thickness of the overlying Quaternary sedimentary succession, the bedrock valley is poorly-defined (Gao, 2011). Under-cutting of soft shale that underlies younger, more resistant dolostones created the Niagara Escarpment, a prominent bedrock cuesta that borders the study area to the west (Straw, 1968; Figure 2.1). Valleys cut into the face of the escarpment likely predate, but had their forms enhanced by, Quaternary fluvial and glacial erosion (Straw, 1968).

2.2.1 Quaternary Depositional History

The irregular bedrock topography of the southern Simcoe County region is overlain by a thick (> 200m) succession of Quaternary sediments. The surface topography is characterized by broad, streamlined upland areas (220-350m asl) separated by narrow, flat-lying lowland areas (195-225m asl), bordered by higher ground of the Oak Ridges moraine to the south and the Niagara Escarpment to the west (Figure 2.1). These physiographic features record conditions during the last major glaciation and subsequent deglaciation events.

The last major advances of the Laurentide Ice Sheet (LIS) occurred during the Wisconsin Episode (110 – 10 ka BP) and erased much of the pre-Quaternary sediment record in southern Ontario. Most of our understanding of Wisconsinan environmental conditions is derived from data obtained from sediment exposures at the Scarborough Bluffs and Don Valley Brickyards in Toronto (Karrow, 1967; Eyles & Eyles, 1983; Eyles & Clarke, 1988; Figure 2.2). Many of the major sediment groups identified near Toronto have been tentatively identified in boreholes and from geophysical investigations as far north as the Oak Ridges Moraine and into the southern Simcoe County area (Eyles et al., 1985; Barnett et al., 1998; Sharpe et al., 2004). Recent sediment drilling in southern

Figure 2.2: time vs. distance diagram of the glacial and non-glacial record for southern Ontario showing major stratigraphic units identified in exposures in the Greater Toronto Region (GTA) and potentially correlative units in the Alliston map area; OIS = Oxygen Isotope Stage. Modified from Karrow et al. (2000). Alliston area stratigraphy modified from Bajc and Rainsford (2011); Mulligan (2011), Bajc et al. (2012), Bajc and Mulligan (2013).

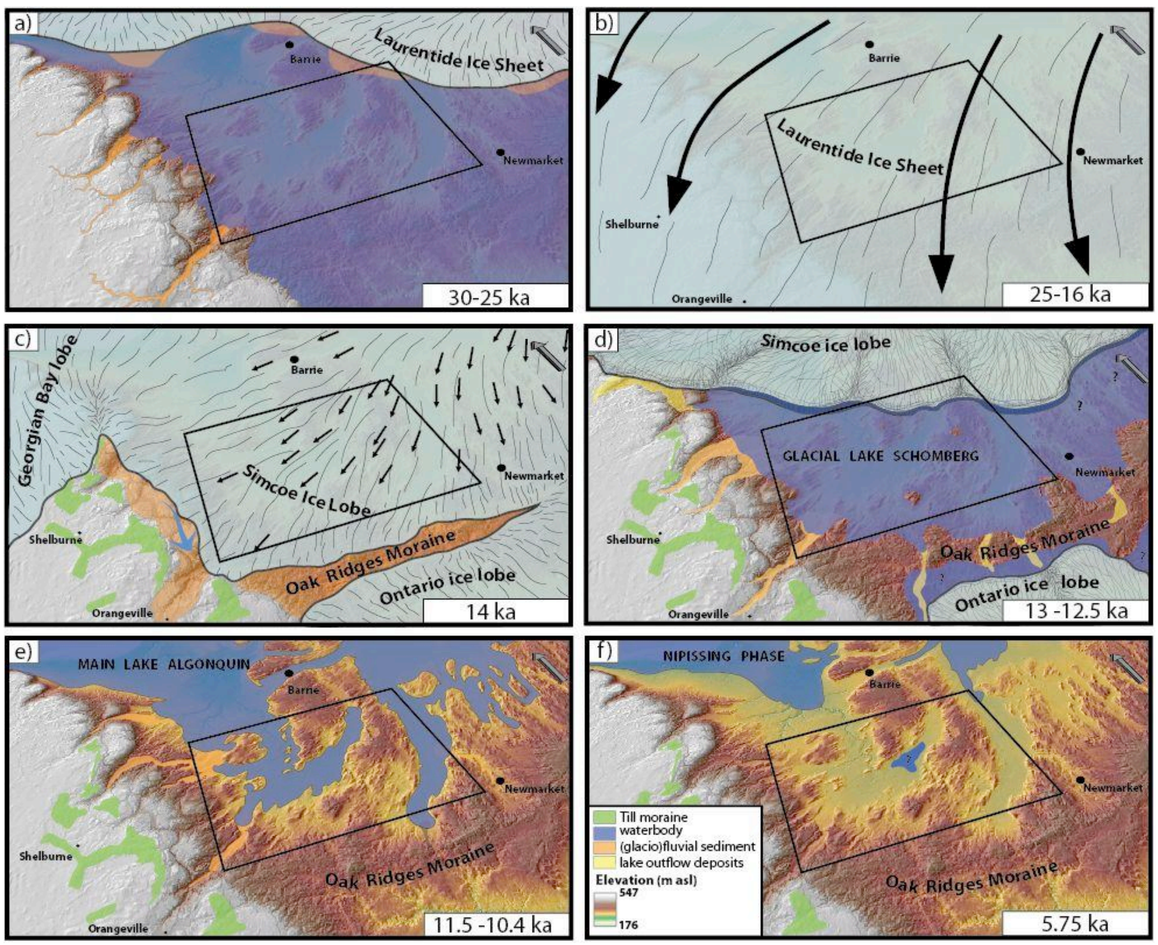

Cincinnati
Detroit
Port huron
Alliston
Mackinac
Abitibi
Cochrane
OIS
GTA
Alliston
SOUTH
NORTH
HUDSON EPISODE
Driftwood Phase
Abitibi Phase
Onaway Phase
Gribben Phase
Two Creeks Phase
Port Huron Phase
Mackinaw Phase
Port Bruce Phase
Erie Phase
Nissouri Phase
Michigan Subepisode
Approximate 14C dating range
WISCONSIN EPISODE
Farmdale Phase
Brimley Phase
Elgin Subepisode
Port Talbot Phase
scale change
Guildwood Phase
Ontario Subepisode
Willowdale Phase
Greenwood Phase
SANGAMON EPISODE
ILLINOIS EPISODE
single 14C date
numerous 14C dates
0
10
20
30
40
50
70
90
110
130
150
1
2
3
4
5a
5b
5c
6
early Lake Ontario
Lake Iroquois
Halton Till
ORM
Newmarket Till
upper Thorncliffe
Meadowcliffe
middle Thorncliffe
Seminary
lower Thorncliffe
Sunnybrook diamict
Pottery Road ?
Scarborough delta
Don beds
York Till
Bedrock
Stanley Low
Lake Algonquin
GLS + Kettleby drift
ORM + kame terrace
Newmarket Till
Thorncliffe eq.
unconformity
Silt till
older deposits ?
Older till ?
Bedrock

Simcoe County by the OGS (Bajc & Rainsford, 2011; Bajc et al., 2012) has identified thick successions of glaciolacustrine and glacial sediments that pre-date late Wisconsin ice advances and may be correlative with similar units to the south (Figure 2.2).

During the latest phases of the Wisconsin Episode (<25 ka), the LIS advanced across the study area and deposited the regionally extensive Newmarket Till (Gwyn, 1972; Figures 2.2, 2.3b). The Newmarket Till has a drumlinized upper surface that produces a highly variable surface topography (Sharpe et al., 2011; Mulligan et al., 2013). It caps a thick succession of older, predominantly fine-grained glaciolacustrine sediments in upland areas (Bajc et al., 2012) and underlies up to 70m of deglacial glaciolacustrine sediments in lowland areas (Bajc & Rainsford, 2011; Figure 2.3g).

The LIS reached its maximum southward extent by 18-20 ka covering all of southern Ontario and reaching into the northern United States before retreat and thinning of the ice sheet formed distinct lobes in the Great Lakes region (Barnett, 1992; Figure 2.3c). During the Mackinaw phase (14-13 ka; Figure 2.2), of interstadial ice marginal recession (Karrow et al., 2000), meltwater was ponded between the Simcoe lobe in the north, the Ontario lobe in the south, and the Niagara Escarpment in the west, allowing the deposition of thick successions of interbedded sand, silt and gravel-rich deposits that now comprise the Oak Ridges Moraine (Howard et al., 1996; Barnett et al., 1998; Figure 2.3c). Along the western margin of the Simcoe ice lobe, meltwater was channeled between the retreating ice margin and the Niagara Escarpment, forming an extensive kame terrace system that stretches from east of Shelburne southward to Orangeville (Sibul & Choo-Ying, 1971; Figure 2.3c). The margins of the Simcoe ice lobe (Figure

Figure 2.3: Paleogeography of central Ontario and map area (black rectangle) during a) early phases of late Wisconsin ice advance; b) maximum late Wisconsin ice extent; c) early phases of ice retreat; d) development of glacial Lake Schomberg; e) evolution of glacial Lake Algonquin,; f) transgression of Lake Nipissing.


a)
Laurentide Ice Sheet
Barrie
Newmarket
30-25 ka
b)
Barrie
Laurentide Ice Sheet
Newmarket
Shelburne
Orangeville
25-16 ka
c)
Georgian Bay lobe
Barrie
Simcoe Ice Lobe
Newmarket
Shelburne
Oak Ridges Moraine
Ontario ice lobe
Orangeville
14 ka
d)
Simcoe ice lobe
GLACIAL LAKE SCHOMBERG
Newmarket
Shelburne
Oak Ridges Moraine
Ontario ice lobe
Orangeville
13 -12.5 ka
e)
MAIN LAKE ALGONQUIN
Barrie
Newmarket
Shelburne
Oak Ridges Moraine
Orangeville
11.5 -10.4 ka
f)
NIPISSING PHASE
Barrie
Newmarket
Till moraine
waterbody
(glacio)fluvial sediment
lake outflow deposits
Elevation (m asl)
547
176
Oak Ridges Moraine
5.75 ka

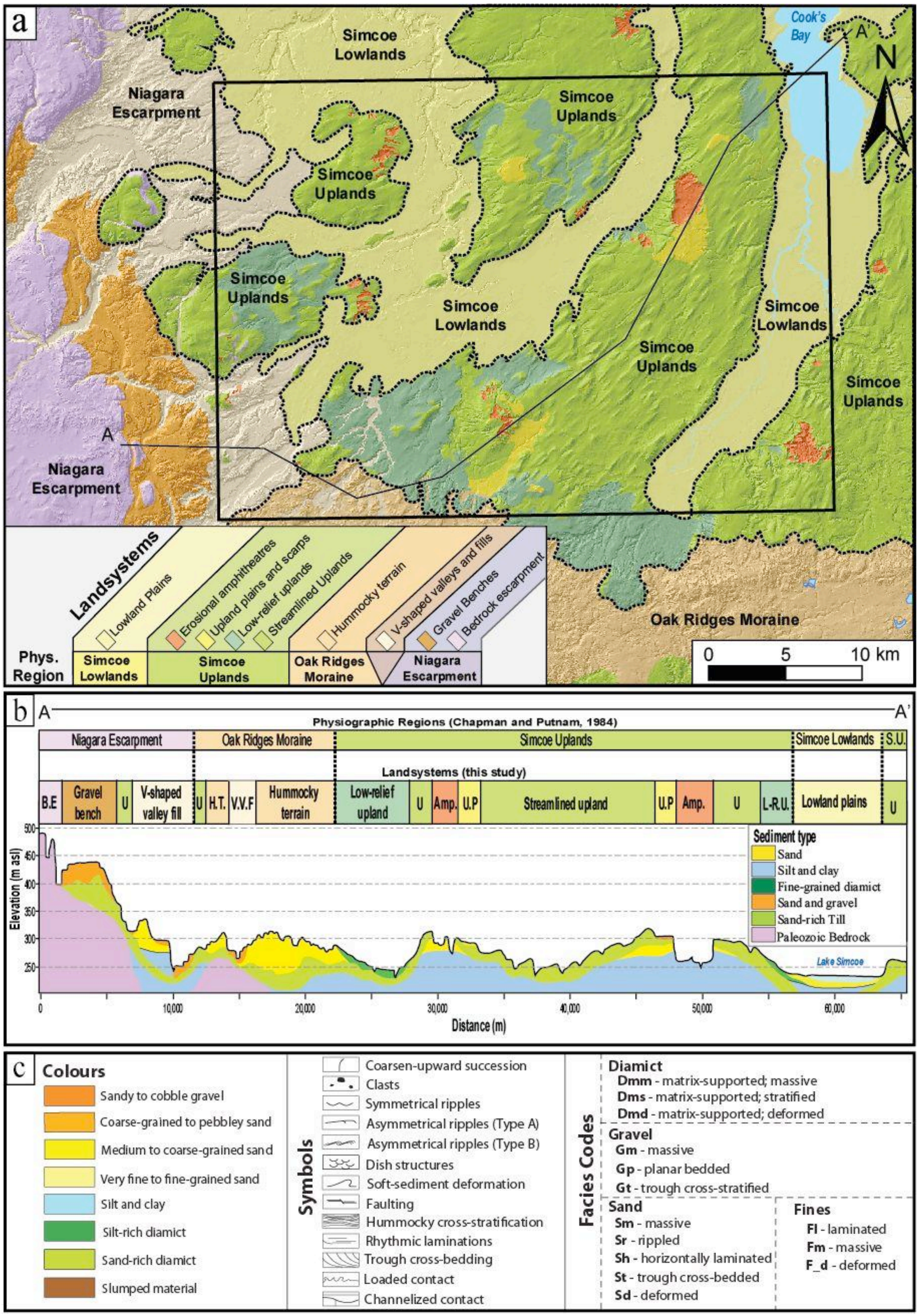
2.3c) were fairly stable during the Port Huron phase (Figure 2.2), except for minor, localized re-advances of the ice front within topographic lows. Fine-grained diamict (Kettleby diamict) locally overlies glaciolacustrine sediments and may record a re-advance of ice during or following the Port Huron phase (Gwyn, 1972; Russell & Dumas, 1997).

Following the Port Huron phase, further retreat of the Simcoe ice margin diverted meltwater to the east, into newly exposed low-lying areas in southern Simcoe County, where a series of ice-marginal lakes developed (Figures 2.2, 2.3d-f). Glacial lakes Schomberg (13-12.5 ka), Algonquin (12.5-10.5 ka) and Nipissing (6-4 ka) inundated low-lying areas in the region and deposited thick successions of glaciolacustrine sediments above the Newmarket Till (Deane, 1950; Chapman & Putnam, 1984; Chapter 3; Figure 2.3g). Although the major depositional events to affect southern Ontario during the late Quaternary are reasonably well known, the detailed spatial and temporal relationships between regional and local environmental changes and resultant sediment successions and landforms is still poorly understood.

2.3 PHYSIOGRAPHIC REGIONS AND LANDSYSTEMS

The southern Simcoe County region can be divided into four broad physiographic regions based on surface morphology and surficial sediment cover (Chapman and Putnam, 1984; Figure 2.4). These physiographic regions are the Niagara Escarpment (includes the Horseshoe Moraines of Chapman and Putnam, 1984), the Oak Ridges Moraine, the Simcoe Uplands (includes the Schomberg Clay Plain of Chapman and Putnam, 1984), and the Simcoe Lowlands (Figure 2.4). These physiographic regions can

Figure 2.4: a) Physiographic regions (outlined by dashed lines) within the Alliston map sheet (black rectangle) and surrounding area, draped onto 5m hillshade relief map. Each region is composed of one or more landsystems (see bottom left for legend). Note that V-shaped valleys and fills occupy two physiographic regions; location of cross-sectional profile A-A' shown in black; b) idealized cross-sectional profile showing physiographic regions (upper bar), landsystems (lower bar), topography and principal surficial sediment types. Abbreviations: S.U.= Simcoe Uplands landsystem; B.E.=bedrock escarpment landsystem; U= streamlined upland landsystem; H.T.= hummocky terrain landsystem; V.V.F.=V-shaped valley and fill landsystem; Amp=Amphitheatres; U.P.=Upland plains and scarps landsystem; L-R.U.= Low-relief uplands landsystem. Profile constructed from OGS borehole records and surficial sediment exposures (See AppendixA, B); c) colour, symbol key and facies codes for figures in this paper.



a
Simcoe Lowlands
Niagara Escarpment
Simcoe Uplands
Cook's Bay
A'
N
Simcoe Uplands
Simcoe Uplands
Simcoe Lowlands
Simcoe Lowlands
Simcoe Uplands
Simcoe Uplands
A
Niagara Escarpment
Oak Ridges Moraine
0 5 10 km
Landsystems
Lowland Plains
Erosional amphitheatres
Upland plains and scarps
Low-relief uplands
Streamlined Uplands
Hummocky terrain
V-shaped valleys and fills
Gravel Benches
Bedrock escarpment
Phys. Region
Simcoe Lowlands
Simcoe Uplands
Oak Ridges Moraine
Niagara Escarpment
b
A
A'
Physiographic Regions (Chapman and Putnam, 1984)
Niagara Escarpment
Oak Ridges Moraine
Simcoe Uplands
Simcoe Lowlands
S.U.
Landsystems (this study)
B.E
Gravel bench
U
V-shaped valley fill
U
H.T.
V.V.F
Hummocky terrain
Low-relief upland
U
Amp.
U.P
Streamlined upland
U.P
Amp.
U
L-R.U.
Lowland plains
U
Elevation (m asl)
500
450
400
350
300
250
Sediment type
Sand
Silt and clay
Fine-grained diamict
Sand and gravel
Sand-rich Till
Paleozoic Bedrock
Lake Simcoe
0
10,000
20,000
30,000
40,000
50,000
60,000
Distance (m)
c
Colours
Sandy to cobble gravel
Coarse-grained to pebbley sand
Medium to coarse-grained sand
Very fine to fine-grained sand
Silt and clay
Silt-rich diamict
Sand-rich diamict
Slumped material
Symbols
Coarsen-upward succession
Clasts
Symmetrical ripples
Asymmetrical ripples (Type A)
Asymmetrical ripples (Type B)
Dish structures
Soft-sediment deformation
Faulting
Hummocky cross-stratification
Rhythmic laminations
Trough cross-bedding
Loaded contact
Channelized contact
Facies Codes
Diamict
Dmm - matrix-supported; massive
Dms - matrix-supported; stratified
Dmd - matrix-supported; deformed
Gravel
Gm - massive
Gp - planar bedded
Gt - trough cross-stratified
Sand
Sm - massive
Sr - rippled
Sh - horizontally laminated
St - trough cross-bedded
Sd - deformed
Fines
Fl - laminated
Fm - massive
F_d - deformed

be further subdivided into landsystems (after Fookes et al., 1975; Eyles, 1983; Evans & Twigg, 2002; Hambrey and Ehrmann, 2004), based on the distribution of landform assemblages and genetically-related sediment types. The Niagara Escarpment (section 2.3.1) includes the bedrock escarpment landsystem, gravel benches landsystem, and V-shaped valleys and fills landsystem (Figure 2.4). The Simcoe Uplands (section 2.3.2) contains the streamlined uplands landsystem, low-relief uplands landsystem, and upland plains and scarps landsystem (Figure 2.4). The Oak Ridges Moraine (section 2.3.3) is comprised of the hummocky terrain landsystem and also contains components of the V-shaped valleys and fills landsystem (Figure 2.4). The Simcoe Lowlands (section 2.3.4) comprises the lowland plains landsystem (Figure 2.4).

Individual landsystems identified in this study (Figure 2.4) are geographic areas containing sediments and landforms that can be attributed to formation in a particular depositional setting or environment. Landsystems analysis is an appropriate approach to use as it builds on the physiographic studies of past workers by fully integrating geomorphological and sedimentological data. This provides an effective framework for understanding the spatial and temporal relationships between major sediment-landform assemblages across broad regions as well as the prediction of the internal composition of the landforms (Spedding & Evans, 2002). This methodology has traditionally been used to describe modern glacial systems (Eyles, 1983; Evans et al., 2009), but can also be used to describe formerly glaciated basins (Kehew et al., 2012). Each of the landsystems identified in the study area will be described and interpreted below. It is important to note that some landsystems can be identified in more than one physiographic region and will be described in the context of the region in which they are most extensive.

2.3.1 NIAGARA ESCARPMENT

2.3.1.1 Bedrock Escarpment Landsystem

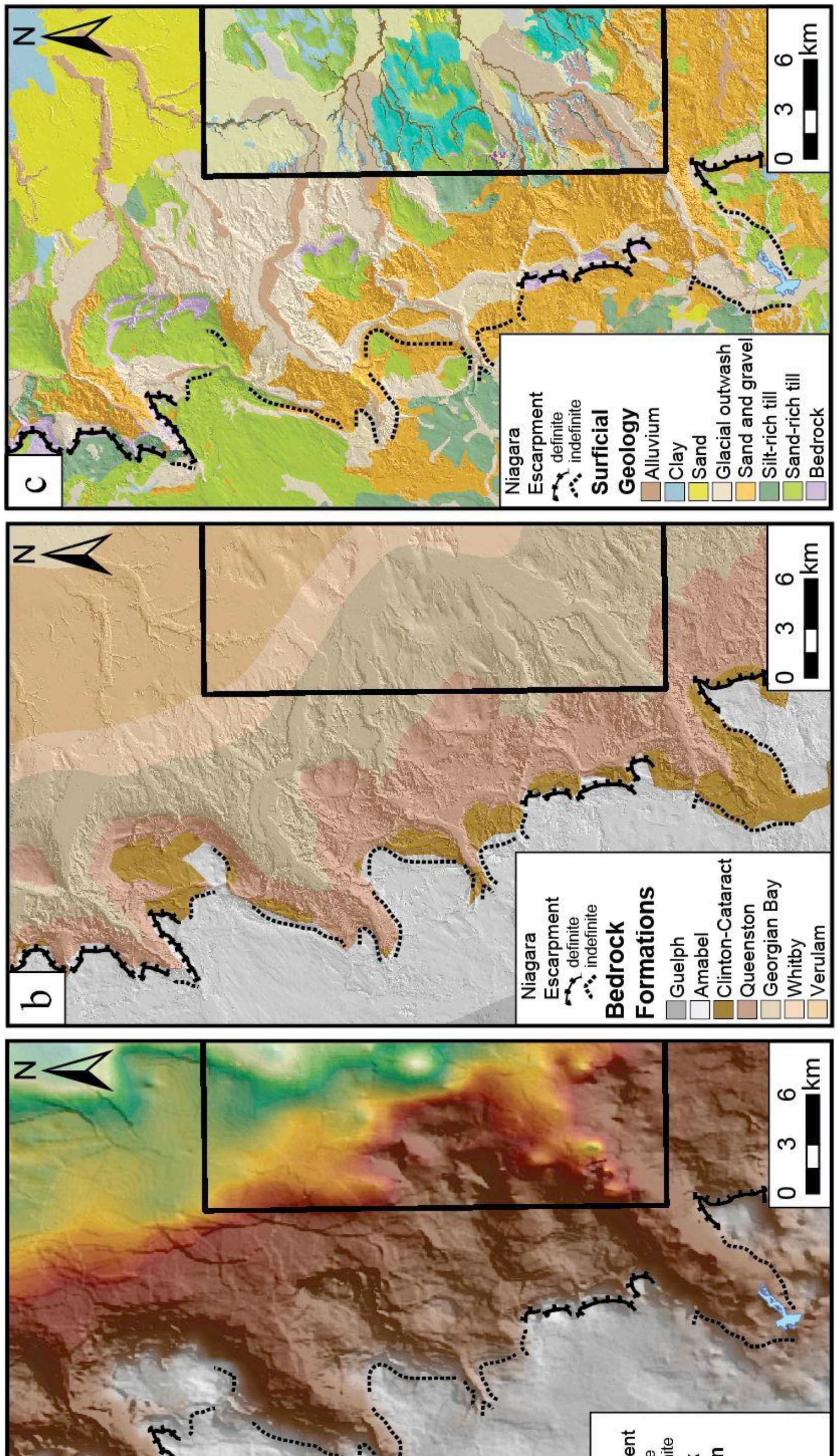
Bedrock outcrops are observed in areas of thin drift on high ground between large northeast-trending valleys cut into the Niagara Escarpment along the western boundary of the map area (Figure 2.5a), and beneath Late Wisconsin deposits exposed along valley walls (Figure 2.5c; Appendix B). Bedrock valleys are also commonly expressed as surface valley features (Figures 2.1 and 2.5a). Several bedrock outliers occur along the face of Niagara Escarpment (Figure 2.5c), separated by valleys up to 225m deep that are partially infilled with sand and gravel deposits.

Bedrock outcrops in the Alliston area expose light to dark grey shale with fossiliferous, fine-grained crystalline limestone beds (Georgian Bay Formation; Figure 2.5d) and reddish-brown shale with minor blue-green limestone beds (Queenston Formation; Figure 2.5e; Armstrong and Carter, 2010). To the west of the study area, exposures of grey dolostone (Amabel Formation; Armstrong & Carter, 2010) are observed in steep escarpment faces that trend northward (Figure 2.5f). The shale-rich Georgian Bay and Queenston formations are often highly weathered and fissile where they are exposed at surface.

Interpretation

The bedrock exposures along the western border of the study area form part of the Niagara Escarpment, a regionally extensive bedrock feature that stretches north-south across the southern Ontario peninsula. Outcrops of Georgian Bay and Queenston shale at the base of the escarpment area are extensively smoothed and rounded

Figure 2.5: Bedrock escarpment landsystem. a) Bedrock topography of the Niagara Escarpment area draped onto shaded relief map of bedrock surface (Gao, et al., 2006); b) bedrock geology of Niagara Escarpment area (after Armstrong and Carter, 2010) draped over shaded relief map of modern topography; c) simplified surficial geology of Niagara Escarpment area (OGS, 2003) showing location of bedrock outcrops (purple). See Appendix A for colour key for area inside Alliston map (black rectangle).


a
N
0 3 6 km
Niagara Escarpment
definite
indefinite
Bedrock elevation (m asl)
536
56
b
N
0 3 6 km
Niagara Escarpment
definite
indefinite
Bedrock Formations
Guelph
Amabel
Clinton-Cataract
Queenston
Georgian Bay
Whitby
Verulam
c
N
0 3 6 km
Niagara Escarpment
definite
indefinite
Surficial Geology
Alluvium
Clay
Sand
Glacial outwash
Sand and gravel
Silt-rich till
Sand-rich till
Bedrock

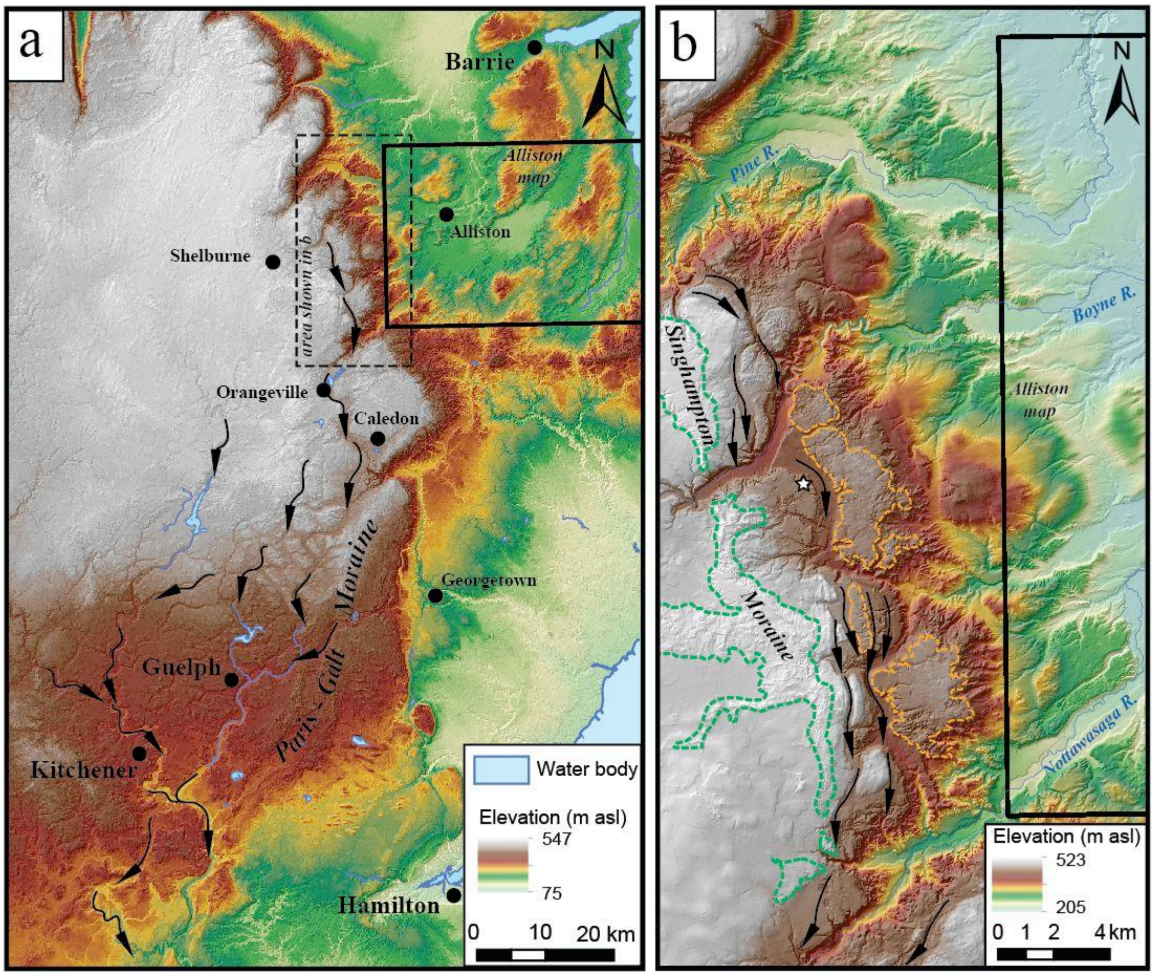
(Figures 2.5b, c), likely reflecting modification by glacial erosion processes. More resistant dolostones of

the Amabel Formation form the main face of the Niagara Escarpment (Figure 2.5b), and promontories separating re-entrant valleys (Figures 2.5a,c).

2.3.1.2 Gravel bench landsystem

Along the base of the Niagara Escarpment, thick accumulations of coarse-grained sand and gravel are observed between Shelburne and Orangeville (Figure 2.6a). The coarse-grained deposits form a flat bench averaging 2-4km wide that contains frequent closed depressions (up to100m wide and 10m deep) and is dissected by a network of north-south trending channels on its upper surface (Figure 2.6b). The entire system appears to grade toward the south, with a decrease in elevation from approximately 445m asl in the north, to 415m asl in the south (Figure 2.6b). The channels are relatively straight, with a nearly north-south orientation, and have flat bases up to 1km wide that lie between 5 and 10 m below the bench surface, generally decreasing in elevation toward the south (Figure 2.6). The channels can be traced from the gravel bench along the western edge of the study area, south past Orangeville, and into a major braided outwash system in the Guelph and Cambridge areas further south (Karrow, 1967; Straw, 1988; Figure 2.6a). Several pits are currently extracting gravel aggregate from this area. Exposures in pit sections cut into the flat upper surface of the bench reveal sand and cobble-rich gravel successions up to 8m thick (Figure 2.7). Clasts are well-rounded and, in places, average clast size is up to 5-10cm in diameter. A relatively high concentration of far-travelled lithologies is observed (Figure 2.7c), and paleocurrent indicators show a south to south-southeast paleoflow direction (Figure 2.7b, d). Coarse-grained gravel facies are either massive, planar or

Figure 2.6: Gravel bench landsystem. a) Major meltwater pathways during the early deglacial period (black arrows); location of Figure 2.6b shown by black dashed line; Alliston map area shown by black box. b) topography of Niagara Escarpment region, showing gravel bench landsystem (orange dashed line), Singhampton moraine (green dashed line), and major meltwater pathways (black arrows); direction of flow inferred from surface gradient and paleocurrent indicators observed in outcrops (see Figure 2.8; white star shows location). Note preferred north-south orientation of meltwater pathways that appear to be truncated by deeper (younger) northeast-trending valleys now occupied by the Pine, Boyne and Nottawasaga rivers. See Figure 2.5c for surficial geology.



a
Barrie
Alliston map
Alliston
Shelburne
area shown in b
Orangeville
Caledon
Georgetown
Paris - Galt Moraine
Guelph
Kitchener
Hamilton
Water body
Elevation (m asl)
547
75
0 10 20 km
b
Pine R.
Boyne R.
Singhampton
Alliston map
Moraine
Nottawasaga R.
Elevation (m asl)
523
205
0 1 2 4 km

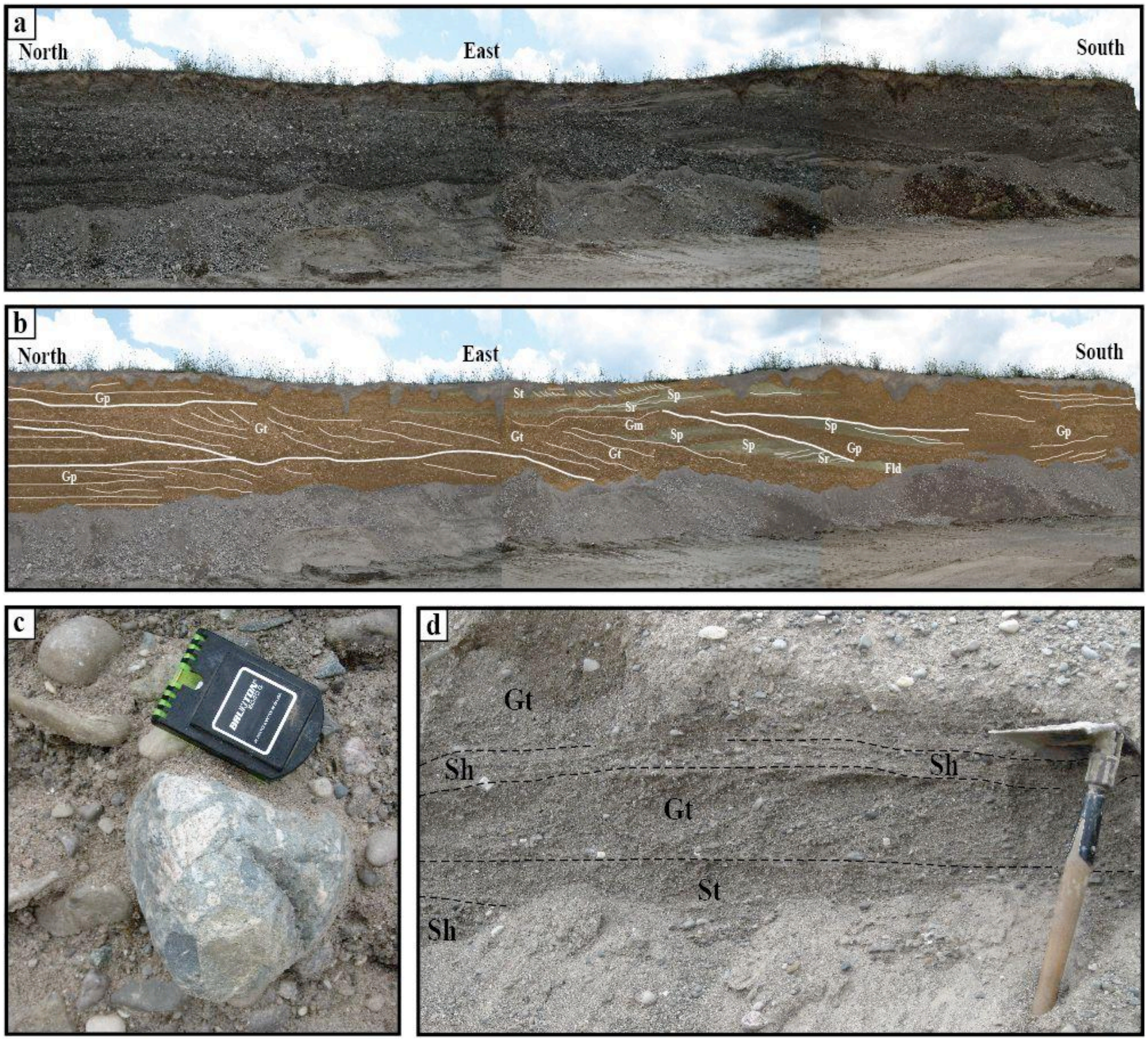
trough cross-bedded with channelized truncationtruncation horizons 4-7m deep and up to 20m across (Figure 2.7b, d).

Interpretation

The coarse-grained cobble-rich facies within the gravel bench landsystem indicate deposition in a high-energy fluvial environment with high large amounts of bedload, proximal to the sediment source (Heinz et al., 2003). Large closed depressions in the surface of the benches are interpreted as kettle holes that record the melting of buried ice blocks (e.g. Evans et al., 2009, Livingstone et al., 2010). The presence of kettle holes in the surface of the gravel benches suggests they were sourced from a retreating ice margin, and the relative abundance of far travelled lithologies compared to locally-derived carbonate rocks suggests sediment supply was from an ice lobe that advanced into the area from Precambrian terrain to the north and northeast.

Currently, there is no physiographic feature that would confine a meltwater system at high elevations along the base of the Niagara Escarpment (Figures 2.1, 2.6). The deposition of a thick succession of fluvial gravels at this location requires the presence of a former ice margin along the eastern boundary of the landsystem (Figure 2.3c). The coarse-grained facies, southward gradient of the bench surface, presence of abundant kettle holes, abundance of far-travelled lithologies, and the physiographic location of this landsystem suggest that these gravel deposits were laid down in an extensive kame terrace system fed by meltwaters draining from the retreating Simcoe (and Georgian Bay?) ice lobe(s) to the north and east (Sibul & Choo-Ying, 1971). Changing ice marginal positions, rates of meltwater supply, and fluctuating water levels in the Huron

Figure 2.7: Sediments exposed in gravel bench landsystem. a) photomosaic of exposure through the eastern side of a gravel pit extracting from the gravel bench landsystem (Figs. 2.4, 2.6). Section is 8m high; b) annotated photomosaic of Figure 2.7a. 3m thick packages of trough cross-bedded gravel (Gt) with forsets dipping south to southwest, and minor rippled (Sr), planar-laminated (Sp), or deformed (Fld) fine-to coarse-grained sand,incise downward into planar-bedded gravels (Gp). The succession is capped by planar bedded gravel (Gp) and minor amounts of fine-to coarse-grained sand. c) Precambrian (Gowganda Formation) clasts exposed in pit sections, compass is10cm long; d) trough cross-bedded coarse sand/pebble gravel (St/Gt) and interbedded horizontally bedded gravelly sand (Sh) exposed near the surface in northwest corner of gravel pit. Paleoflow was right to left (south-southwest).


a
North
East
South
b
North
East
South
Gp
Gt
St
Sr
Sp
Gm
Sp
Gt
Sp
Sp
Gp
Sr
Fld
Gp
c
d
Gt
Sh
Sh
Gt
St
Sh

and Erie basins at this time (Barnett, 1992) would cause major changes in regional base levels that may have resulted in the subsequent incision of the shallow, north-south-trending channels into the surface of the kame terraces.

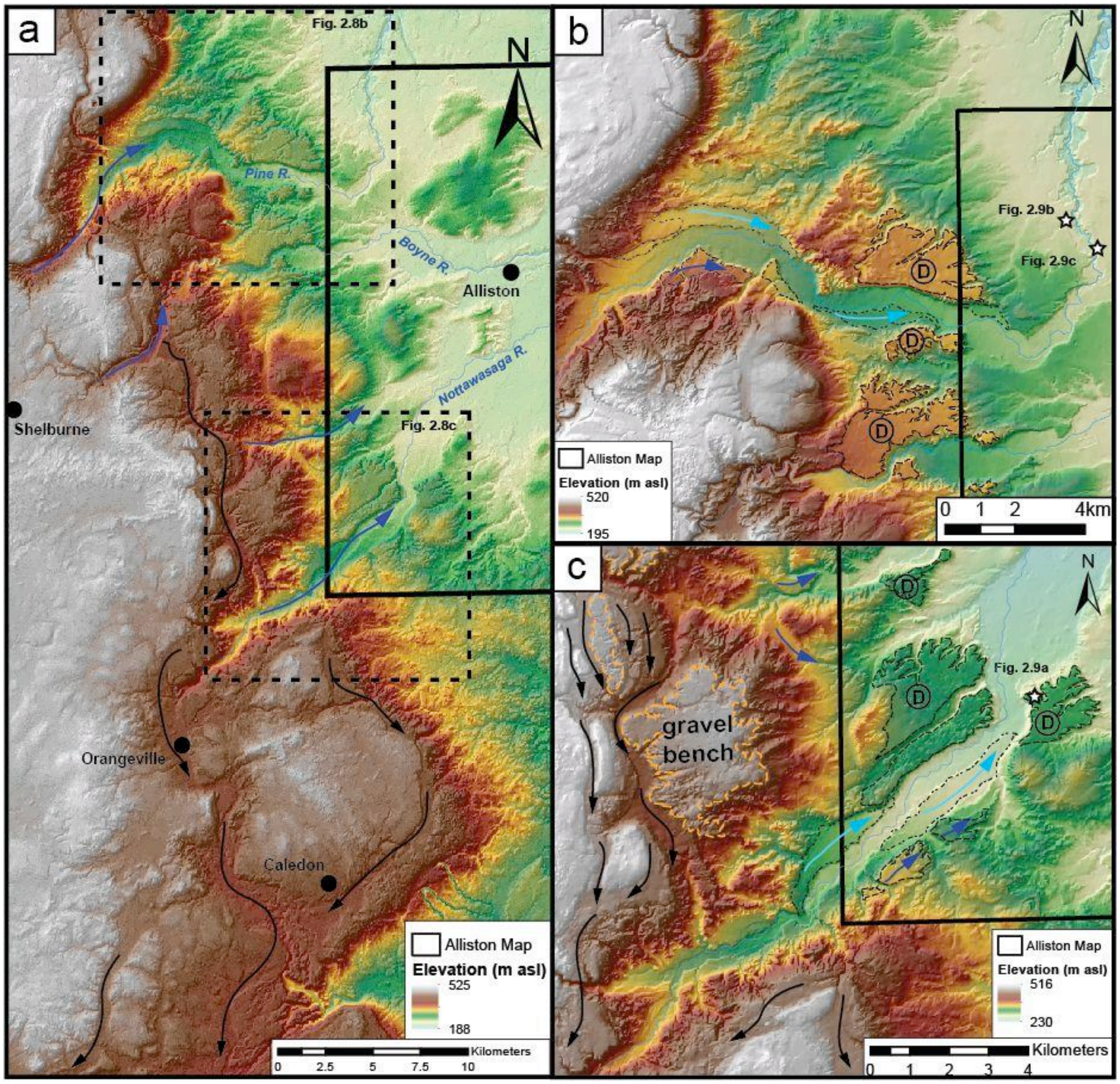
2.3.1.3 V-shaped Valleys and fills landsystem

Along the southern and western border of the study area, a network of deep channels can be observed cross-cutting the bedrock escarpment and gravel bench landsystems (Figure 2.8). The valleys trend toward the northeast, and are currently occupied by misfit streams (Figure 2.8). These channels often have V-shape cross-sectional profiles and can exceed 150m in depth from the valley shoulders (up to 450m asl) to the base (down to 240m asl; Figure 2.8b,c). Paleozoic bedrock is often exposed along the walls of the larger channels (Figure 2.5c; Appendix B).

Valley walls commonly show well-developed lateral terraces extending from the valley heads in the southwest to the mouths in the northeast (Figure 2.8b,c). Two sets of terraces are notably well-developed and continuous along long stretches of the V-shaped valleys. An upper set grades to 290-300m asl (dark blue arrows, Figure 2.8b,c) and a lower set grades to 225-235m asl (light blue arrows, Figure 2.8b,c) where it merges into the lowland plains landsystem to the east. At the mouths of the larger valleys sit large, flat-topped lobate features that rise 60-80m above the flat valley floors (Figure 2.8b,c). Their upper surfaces lie at similar elevations, between 290-305m asl, and mark the end of the upper terrace set. These flat, lobate features are marked by numerous closed depressions and their outer margins are heavily dissected.

Sediment outcrops up to 20m high within valley walls expose dominantly coarse-grained sand and gravel, with minor amounts of silt and clay. Coarse-grained sand and

Figure 2.8: V-shaped valleys and fills landsystem a) DEM showing topography of Niagara Escarpment in the study area. Northeast-trending valleys (blue arrows) cross-cut channels in the gravel bench landsystem (black arrows). Locations of figures 2.8b,c shown in dashed lines; b) surface topography of the Pine River Valley and (c) Nottawasaga Valley areas. An upper set of lateral terraces (dark blue arrow) grades down to flat, lobate features (D) with closed depressions in the upper surface. A lower set of terraces (light blue arrows) grades to the surface of lowland areas. Locations of borehole SS-11-04 and photos in Figure 2.9 shown with white stars.



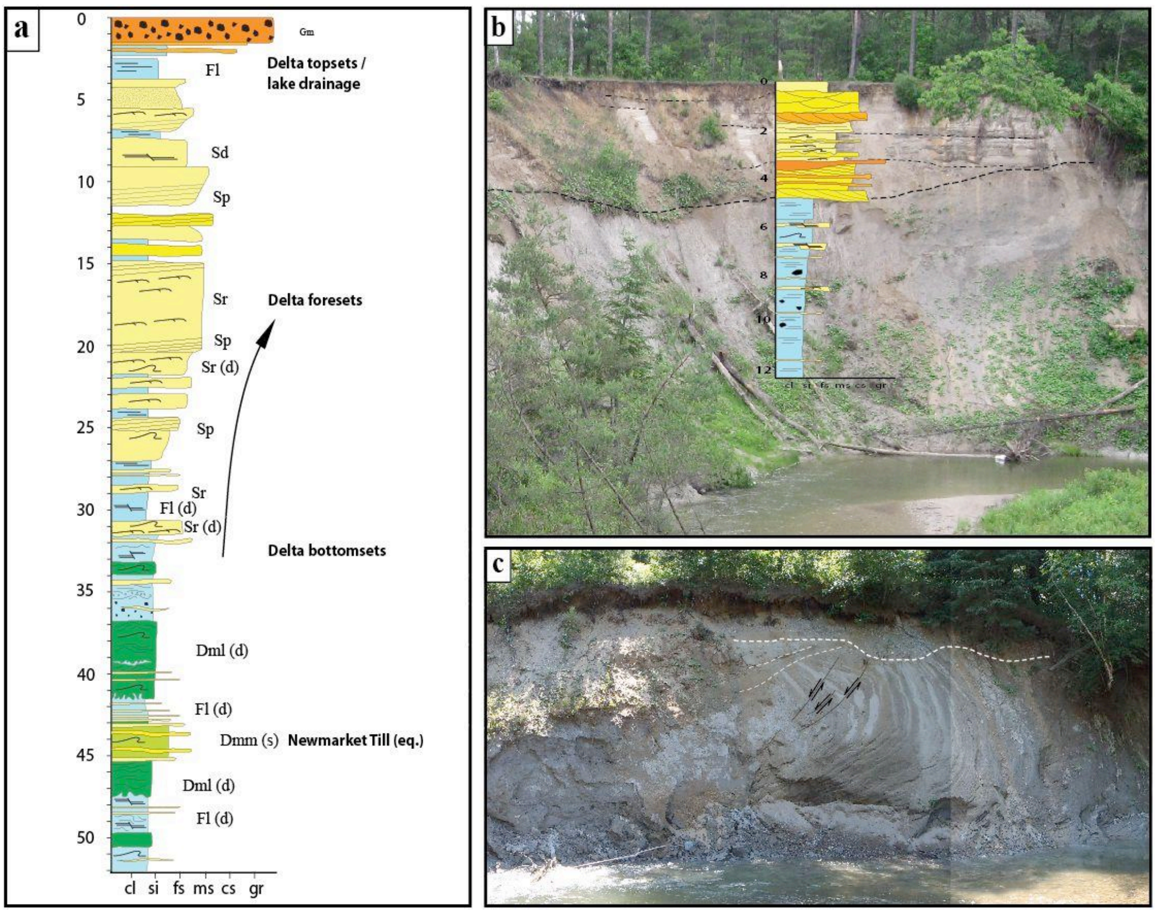
a
Fig. 2.8b
N
Pine R.
Boyne R.
Alliston
Nottawasaga R.
Shelburne
Fig. 2.8c
Orangeville
Caledon
Alliston Map
Elevation (m asl)
525
188
Kilometers
0 2.5 5 7.5 10
b
N
Fig. 2.9b
Fig. 2.9c
D
D
D
D
Alliston Map
Elevation (m asl)
520
195
0 1 2 4km
c
N
D
D
D
Fig. 2.9a
gravel bench
Alliston Map
Elevation (m asl)
516
230
Kilometers
0 1 2 3 4

gravel facies are typically trough cross-bedded or planar bedded, while finer-grained sand and silt facies typically display asymmetrical ripple forms and small-scale deformation features. Paleocurrent indicators typically record flow parallel to the valley axes toward the northeast.

Thick successions of predominantly fine-grained material are observed near the mouths of the valleys. Borehole SS-11-04 was drilled through the upper surface of one of the lobate features (Figure 2.8c) and exposes a 40m-thick coarsening-upward succession of silt rhythmites passing upward into sand and gravel (Figure 2.9a). The succession is floored by a 14m thick unit of interbedded sand- and silt-rich diamict. Diamict facies range from massive to stratified or laminated, with varying clast content. The diamict is interbedded with, and overlain by silt and clay rhythmites that are occasionally deformed and contain silt and clay intraclasts, as well as very fine-grained sand interbeds that increase in thickness and frequency up-section (Figure 2.9a). Rhythmites grade upwards into rippled (Type-A climbing pattern) and planar-laminated (possibly hummocky cross stratified?) fine to medium-grained sand with thin silt interbeds and intraclasts. Sand – rich facies form a unit up to 20m thick and are overlain by pebbly and gravelly sand observed both in the borehole and surrounding outcrops. Correlative successions of gravelly coarse-grained sand overlying finer-grained sand and silt are observed in road cuts along the flanks of the lobate feature penetrated by borehole SS-11-04 (Figure 2.8c; Appendix B).

Sand-Similar coarsening-upward successions to that recorded in Borehole SS-11-04 (Figure 2.8c) are observed in outcrops exposed along the Pine River, near the base of the northernmost lobate feature (Figures 2.8b, 2.9). In this area, thick silt and clay

Figure 2.9: Sediments of V-shaped valleys and fills. a) sediment log and paleoenvironmental interpretation of upper part of borehole SS-11-04 (Figure 2.8c for location; Appendix A). See Figure 2.4c for colour and symbol key. Top of borehole collared at 292m asl, numbers record depth from ground surface in meters; b) annotated photo of large cutbank exposure along the Pine River (Figure 2.12b for location). Cross-bedded sand and gravel with northward paleoflow indicators overlie laminated and deformed silts and clays. Sand-rich diamict, interpreted as Newmarket Till, is exposed at river level 50m downstream and 150m upstream of the section (Appendix B); c) Deformed unit of silt and clay rhythmites (dark coloured beds) with interbedded fine-grained sand (pale coloured beds) truncated by pebbly to cobble-rich gravel (heavy white dashed line). See Figure 2.8b for section location. Several large faults are observed in this section.


a
b
c
Gm
Fl
Delta topsets /
lake drainage
Sd
Sp
Sr
Delta foresets
Sp
Sr (d)
Sp
Sr
Fl (d)
Sr (d)
Delta bottomsets
Dml (d)
Fl (d)
Dmm (s)
Newmarket Till (eq.)
Dml (d)
Fl (d)
0
5
10
15
20
25
30
35
40
45
50
cl si fs ms cs gr

rhythmite successions overlie a structureless sand-rich diamict. Locally, the silt and clay rhythmites are highly deformed and faulted (Figure 2.9c). The rhythmites exposed along the Pine River grade upwards into fine- and medium-grained sand displaying Type-A climbing ripples, planar laminations and silt and clay intraclasts and silt rip-up breccias. Sand facies in this area are truncated by planar tabular and trough cross-bedded, coarse-grained pebbly sand and gravel (Figure 2.9b). Paleocurrent indicators within the coarse-grained facies record flow directions to the northeast and north-northwest.

Interpretation

V-shaped cross-sectional profiles suggest a fluvial origin for the valleys identified within this landsystem (Montgomery, 2002). This interpretation is supported by the abundance of trough and planar tabular cross-bedding observed within sand and gravel facies within the valley fills, which record deposition in shallow, fast-moving fluvial systems (Eynon & Walker, 1974). Paleocurrent indicators and surface gradients of lateral terraces along the upper reaches of valleys suggest that water was channeled northeastward, down through re-entrant valleys along the Niagara Escarpment (Figure 2.8).

The two sets of well-developed terraces grading to 300m and 230m respectively are interpreted to record the delivery of fluvial sediments into relatively stable and persistent water bodies in the southern Simcoe County area. The upper set of terraces terminates at large, lobate features that occupy the mouths of the re-entrants ('D', Figure 2.8). The morphological characteristics of these features are consistent with those of river-dominated deltas (Bhattacharya, 2010) and suggest a fluviodeltaic depositional origin.

The upper surface elevation of the deltas (‘D’; Figure 2.8b, c) may be used to infer a water plane elevation of between 290 to 300m asl.

Gradational coarsening-upward successions of silt and clay rhythmites passing upward into rippled sand and gravel observed within borehole SS-11-04 and in cutbank exposures along the Pine River (Figure 2.9) are interpreted to record progradation of a delta into a standing water body (Kelly & Martini, 1986; Bhattacharya, 2010). High sedimentation rates are suggested by the presence of climbing ripples (Jopling & Walker, 1968) and may have contributed to the instability along the delta front. Silt interbeds within the sand-rich facies record quiet water conditions related to delta lobe migration, seasonal ice cover, or water level fluctuations (Breckenridge et al., 2004). Silt intraclasts and rip-up breccias within the sand and underlying silt-rich facies record the erosion and re-sedimentation of underlying fine-grained facies via density underflows entering the former lake (Harrison, 1975).

Interbedded diamicts at the base of the succession in SS-11-04 (Figure 2.9a) probably record subaqueous debris flows related to instability of sediments deposited along the valley margins (Bennett et al., 2002) and may be associated with local ice-margin fluctuations. The massive sand-rich diamict exposed at the base of the succession along the Pine River is interpreted here to be correlative with the Newmarket Till and suggests that ice may have been present in the region during the development of these delta bodies (Appendix B). The abundance of large-scale deformation features within the silt and clay rhythmites overlying the diamict likely reflects instability along the delta front and diamict surface, resulting in slumping and re-working during delta progradation (Winsemann et al., 2007). The overall succession of silt, sand and gravel overlying diamict identified within the delta bodies is interpreted to record sediment delivery into a stable, standing water body during early phases of deglaciation.

The morphology and stratigraphic position of the V-shaped valleys and fills landsystem records the routing of fast-flowing (glacio)fluvial systems towards low-lying areas in southern Simcoe County during the early phases of ice retreat. Coarsening-upward successions observed within lobate deltaic features occupying the mouths of the V-shaped valleys reflect high rates of sediment supply and the progradation of small deltas into a lake with a stable water plane at elevations of around 300m asl (Figure 2.3d). Lateral terraces below the elevation of the upper surfaces of the deltas record lowering base levels following drainage of the lake.

2.3.2 SIMCOE UPLANDS

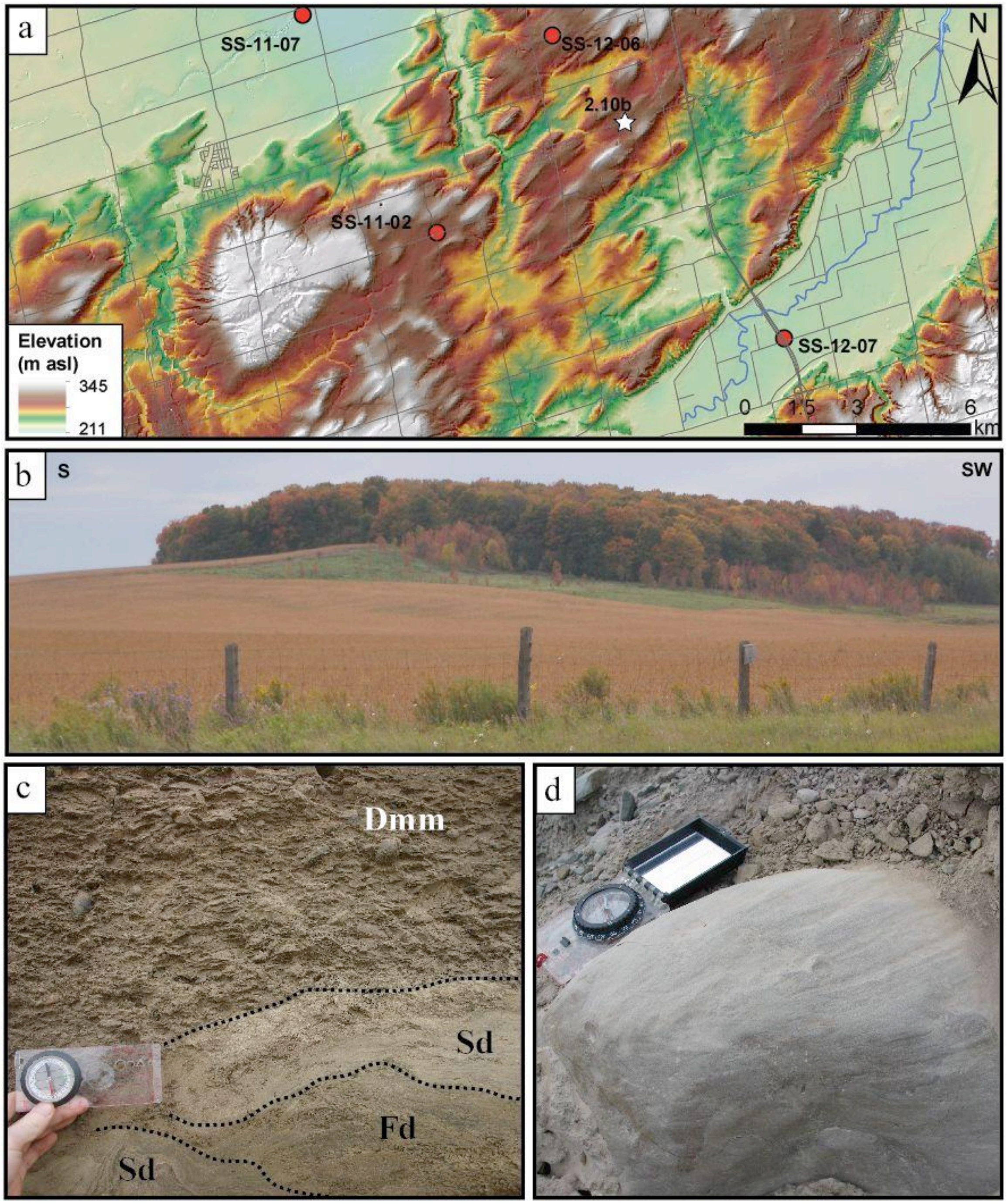
In the southern Simcoe County region, the physiographic region identified as the Simcoe Uplands is characterized by the streamlined uplands landsystem, the low relief uplands landsystem, the uplands plains and scarps landsystem, and erosional amphitheatres (Figure 2.4).

2.3.2.1 Streamlined Uplands Landsystem

Uplands within the study area are characterized by streamlined and undulating terrain that lies between 220 and 360m asl (Figure 2.10a). Surficial sediment cover on upland areas is typically structureless, over-consolidated diamict, overlain by widespread fine-grained (and localized coarse-grained) stratified deposits with occasional fine-grained diamict interbeds (Appendix B). Streamlined ridges of diamict crop out locally in other physiographic regions, suggesting the diamict extends beneath much of the study area (Figures 2.4; Appendix B).

The long axis orientation of the streamlined ridges ranges from 270 degrees in the western parts of the study area to 210 degrees in the southeast (Figures 2.1 2.10a, Appendix B). 166 ridges are mapped in the study area and form the southwestern extension of a larger cluster of similar landforms that lie to the north and east (Deane, 1950; Chapman & Putnam, 1984; Sharpe et al., 2002). The morphology of the ridges varies greatly across the study area, but they range from approximately 400m to 1500m in length, are up to 350m wide and rise 10-20m above the surrounding undulating topography (Figures 2.1, 2.10). The streamlined surface topography is best developed within the central part of the study area, where topographic variations of more than 40m over distances less than three kilometers are not uncommon (Figure 2.10a). In the north and northwestern parts of the upland areas, the size and frequency of streamlined ridges decreases dramatically and the topography shows only gentle undulation with little variation in elevation. Upland areas are typically capped by light brown to grey, poorly sorted and highly consolidated silt to sand-rich diamict. The matrix is generally structureless and occasionally shows well-developed fissility (Figure 2.10c). Thin, discontinuous, and deformed lenses or interbeds of sorted sediments (<1m thick) are observed within the diamict, which can reach thicknesses of up to 30m (Borehole SS-12-02; Appendix A) but is generally between 6-12m thick (Figure 2.4b). Clasts comprise approximately 5-10% of the diamict volume and consist primarily of locally-derived Paleozoic lithologies. Paleozoic clasts are typically less than 1m in diameter, with an average of 2-7 cm, but bedrock rafts as large as 4m in diameter have been observed. Clasts often show a preferred sub-horizontal, long-axis orientation between 270-230 degrees and are ornamented with striae showing similar directional trends (Figure 2.10d).

Figure 2.10: Streamlined uplands landsystem. a) DEM showing topography of central streamlined upland landsystem. Note strong northeast-southwest orientation of streamlined ridge features. White star shows location of Figure 2.10b. Location of OGS boreholes shown in red; b) streamlined ridge west of Bradford, view to the south-southwest; c) well-developed matrix fissility in sand-rich diamict (Newmarket Till) exposed in a pit west of Cookstown (Figures 2.12, 2.13 for location). Note that underlying sand (Sd) and fine-grained sediment (Fd) are highly deformed; d) large (50cm) striated and faceted clast within sand-rich diamict (Newmarket Till) facies exposed in a gravel pit, Adjala twp. Clast long axis and striae oriented to the southwest.


a
SS-11-07
SS-12-06
N
2.10b
SS-11-02
SS-12-07
Elevation
(m asl)
345
211
0
1.5
3
6
km
b
S
SW
c
Dmm
Sd
Fd
Sd
d

Many clasts are faceted with smoothed ends pointing to the northeast and flattened tops or bases (Figure 2.10d). Occasionally, large clasts are concentrated along sub-horizontal planes, often associated with sand or silt interbeds in an outcrop exposure.

Interpretation

The characteristics of the diamict unit associated with the streamlined upland landsystem are consistent with a subglacial origin for the unit (Boulton & Deynoux, 1981; Evans et al., 2006; Benn & Evans, 2010). Interbeds and clast horizons likely record the presence of subglaciofluvial systems draining meltwater toward the former ice margin (Meriano & Eyles, 2009). Streamlined ridges on the diamict surface are interpreted as drumlins, a landform attributed either to subglacial sediment deformation (Boyce & Eyles, 1991; Stokes & Clark, 2002; Benn & Evans, 2010, Maclachlan & Eyles, 2013), or erosion by large catastrophic subglacial meltwater sheetflows (Shaw, 1983; Shaw & Sharpe, 1987; Brennand & Shaw, 1994; Sharpe et al., 2004). The streamlined diamict ridges observed in the study area have very similar size and form to drumlins reported elsewhere in southern Ontario (Chapman & Putnam, 1984; Boyce & Eyles, 1991; Maclachlan & Eyles, 2013). Drumlins composed of till are commonly used as indicators of former ice flow directions (Chapman & Putnam, 1984). Drumlin long axis orientation, clast fabric, and striae orientations within the till unit found within the streamlined upland landsystem, suggest ice flow from the north and northeast. Changes in orientations across the study area (from 210 degrees in the southeast to 270 degrees in the west; Figure 2.1) likely record a fanning out of the ice as it entered the study are from the northeast.

Similar diamict units are found within other landsystems in the map area and suggest that the diamict forms a regionally extensive till sheet that underlies and predates most other surficial sediment groups. The physical characteristics, stratigraphic position, and ice flow indicators suggest that the till is correlative with the Newmarket Till (Gwyn, 1972; Russell & Dumas, 1997). The Newmarket Till records the advance of the Laurentide Ice Sheet (LIS) into the region from the northeast during the late Wisconsinan (Figures 2.2, 2.3b).

2.3.2.2 Low-Relief Uplands Landsystem

Low-relief uplands show a subdued, low-relief topography compared to the adjacent streamlined upland and hummocky terrain landsystems (Figure 2.4). Elongated ridges with long axes oriented northeast-southwest show gentle relief (<5m), compared to drumlins mapped within the streamlined uplands landsystem. Low-relief uplands are most commonly observed flanking high ground of the Niagara Escarpment to the west, or the Oak Ridges Moraine to the south (Figure 2.4). The spatial extent of this landsystem (Figure 2.4) is consistent with areas previously mapped as Kettleby Till (Russell & Dumas, 1997) and it is not observed at elevations above 295m asl.

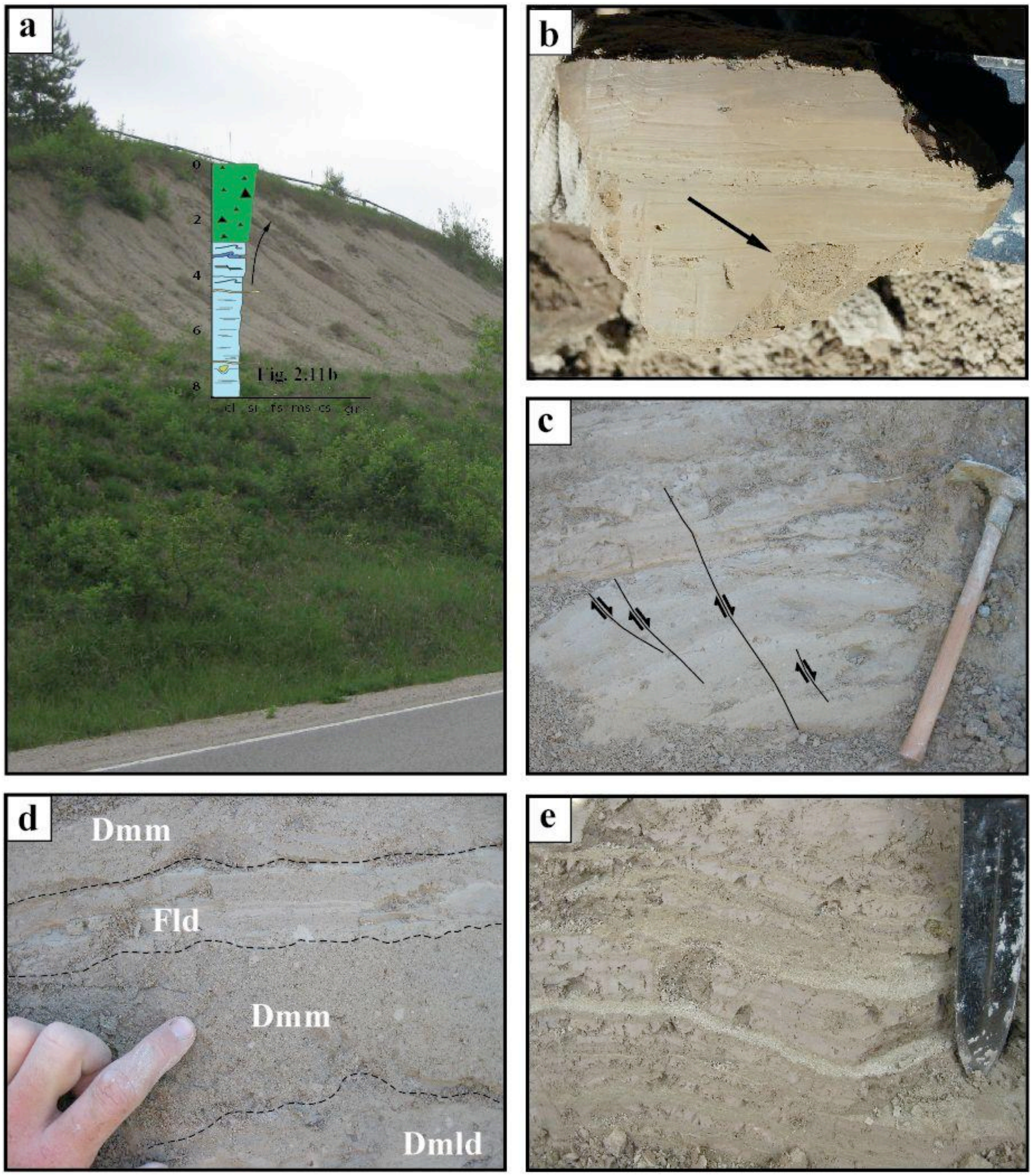
The sediments associated with this landsystem are characterized by a silt-rich and stone-poor diamict assemblage associated with fine-grained stratified deposits (unit 7b, Appendix B). The diamict has variable characteristics and ranges from massive, dark brown, stone-poor facies to rhythmically interbedded sand, silt, and clay with thin clast-rich diamict interbeds (Figure 2.11). Individual diamict beds and clast-rich facies are often contained within packages of undisturbed silt and clays (Figure 2.11d,e). Massive diamict facies are most common in the southwest of the study area, west of Tottenham (Figure 2.1; Appendix B) and form the thickest successions observed within the low-relief uplands landsystem, reaching thicknesses of up to 10m.

The fine-grained diamict assemblages either directly overlie coarser-grained and more clast-rich diamict similar to that observed in the streamlined uplands landsystem (interpreted here as Newmarket Till), or rest above or within fine-grained sediment packages (Figure 2.11). Laminated silts, clays and fine-grained sands underlying the fine-grained diamict commonly show extensive soft sediment deformation features including folds and faults (Figure 2.11). However, in many places beneath the surface of the low-relief uplands landsystem silt and clay rhythmites that are laterally equivalent to the fine-grained diamict assemblage are undisturbed (Appendix B).

Interpretation

The interbedding of a wide range of facies types within the low-relief uplands landsystem (previously mapped as Kettleby till; Gwyn, 1972; Russell & Dumas, 1997) suggests that several different processes may have contributed to the development of this landsystem (Eyles & Eyles, 2010). The subdued relief of the low-relief uplands landsystem likely records blanketing of the surface of streamlined uplands terrain by widespread glaciolacustrine deposits. Elongated forms punctuating the generally subdued relief may record the position of large drumlins on the surface of the underlying coarser-grained diamict that have been partially buried (Figures 2.4, 2.11; Appendix B). The fine-grained nature of sediments in the low-relief uplands landsystem and its restricted spatial distribution to areas below 295m asl in elevation suggest an origin associated with low energy glaciolacustrine depositional environments. The confinement of diamict beds and clast-rich facies within packages of undisturbed silt and clays (Figure 2.11d,e), and the presence of undisturbed clay drapes within diamict packages are interpreted to record a subaqueous depositional environment. Subaqueous downslope resedimentation processes

Figure 2.11: Sediments exposed in low-relief uplands landsystem. a) lithofacies log and photo of laminated to deformed silts and clays passing upwards into fine-grained diamict (stratigraphic reference section of the Kettleby Till, White, 1975) exposed in a road cut near Kettleby (Figure 2.1); stratigraphic position of sediments shown in Figures 2.11b marked; b) undisturbed lower rhythmites beneath upper diamict. Very fine laminae and colour banding with small-scale deformation (dewatering?) structures and a rip-up clast of sand-rich diamict (Newmarket Till? arrowed); c) normally faulted and deformed interbedded silt and fine-grained sand south of Kettleby. Grub hoe is 1m long; d) interbedded diamict (Dmm) and laminated sediments with small-scale faulting and syn- and post-depositional deformation structures (Fld); e) laminated silt and interbedded fine- to medium-grained sand within low-relief upland sediments.


a
0
2
4
6
8
Fig. 2.11b
cl si fs ms cs gr
b
c
d
Dmm
Fld
Dmm
Dmld
e

may have also played an important role in the deposition of low-relief uplands sediments where they overlie the irregular surface of the underlying sand-rich diamict (Bennett et al., 2002; Eyles & Eyles, 2010). The association of massive fine-grained diamict facies with underlying highly deformed glaciolacustrine sediments (Figure 2.11a), is reported from successions containing deformation tills (glacitectonites) and may record (minor) re-advance(s) of an ice front over ponded ice-marginal or previously deposited glaciolacustrine sediments (White, 1975; Evans et al., 2006; Maclachlan & Eyles, 2011).

The distribution and facies characteristics of the low-relief uplands landsystem are interpreted to record sedimentation by glaciolacustrine and gravitational processes operating in low energy lacustrine environments at (or near) a retreating ice margin (e.g. Figure 2.3c). The presence of localized massive fine-grained diamict facies interpreted as subglacial deformation tills probably records fluctuations of the ice front within pre-existing lows on the underlying till sheet during overall ice retreat from the basin.

2.3.2.3 Uplands Plains and Scarps Landsystem

Widespread stratified sediments lie directly above the surface of the streamlined uplands across the study area, typically partially in-filling the swales between drumlins with a low relief topographic surface (Appendix B). Sediments are dominantly fine-grained, but localized coarse-grained facies are observed beneath flat plains at high elevations and near the base of steep slopes on the streamlined diamict surface.

Localized flat-lying plains found at elevations between 300m and 307m asl are topographically distinct from the surrounding streamlined uplands landsystem (Figure 2.12). The largest of the flat plains is located northeast of Bradford and is bordered to the east by two parallel, north-trending scarps 2-3m high at 302 and 308m asl. A second flat-lying plain feature is located west of Cookstown, has a flat upper surface at 300-302m asl, and is bordered by scarps on the southern and western rim (Figures 2.12, 2.13). Several other prominent scarps are visible within upland regions across the map area, lying between 250 and 305m asl (Figure 2.12a). The scarps can reach heights of up to 8m and the highest concentration of these features is found on uplands to the west of the present Lake Simcoe shoreline along Cook's Bay, at around 300m asl (Figure 2.12a). Isolated scarps are also observed along the flanks of drumlins at around 300m asl.

Sediment exposures through the uplands plains reveal fine-grained facies composed of massive to rhythmically-laminated light grey silt and clayey silt lying above the diamict of the streamlined uplands (Newmarket Till, Appendix B). The rhythmites form couplets of variable thicknesses, reaching up to 10cm, and often contain thin (>0.5cm) very fine-grained sand stringers. Clasts are infrequent but, where present, are usually observed in the massive facies whereas the rhythmites are typically clast-free. Clasts up to 1m in diameter are observed, however most are less than 1cm. Successions of fine-grained sediments lying above sand-rich diamict on streamlined uplands are thickest (up to 9m, SS-11-02, Appendix A) in lows on the till sheet. Uplands plains areas are also characterized by coarse-grained facies up to 10m thick that locally erode into underlying Newmarket Till (Figure 2.14b). Coarse-grained facies are observed along the base of scarps along the flanks of drumlins on the uplands plains landsystem, often forming isolated packages of gravels and sands less than 2-3m thick, at elevations of around 300m asl (Figure 2.12a). Along the margins of the uplands plain landsystem east of Cookstown (Figure 2.12a), coarse-grained pebbly sand and gravel lie directly above up to 4m of Newmarket Till (Appendix B). In other areas it appears that the till has been deposition. Pit exposures reveal up to 6m of trough cross-bedded sand and gravel

Figure 2.12: Upland plains and scarps landsystem. a) surface topography of eastern half of map area. Contours for 250m, 300m (bold), and 350m shown in black. Locations of Figs. 2.12b,c and 2.13 shown; b) medium to coarse-grained sand (Sh, Sr) erosively overlying structureless sand-rich diamict (Dmm, Newmarket Till). Diamict rip-up clasts (arrowed) up to 5cm diameter present in lower portion of sand. Shovel handle is 50cm long; c) annotated photo of section east of Kettleby exposing 2-3m of sand and gravel; beds dip to the southeast, possibly recording beach development in glacial Lake Schomberg; location of photo in 2.12d shown in black rectangle; d) rippled (Sr) and horizontally laminated (Sh) medium-fine to coarse-grained pebbley sand.

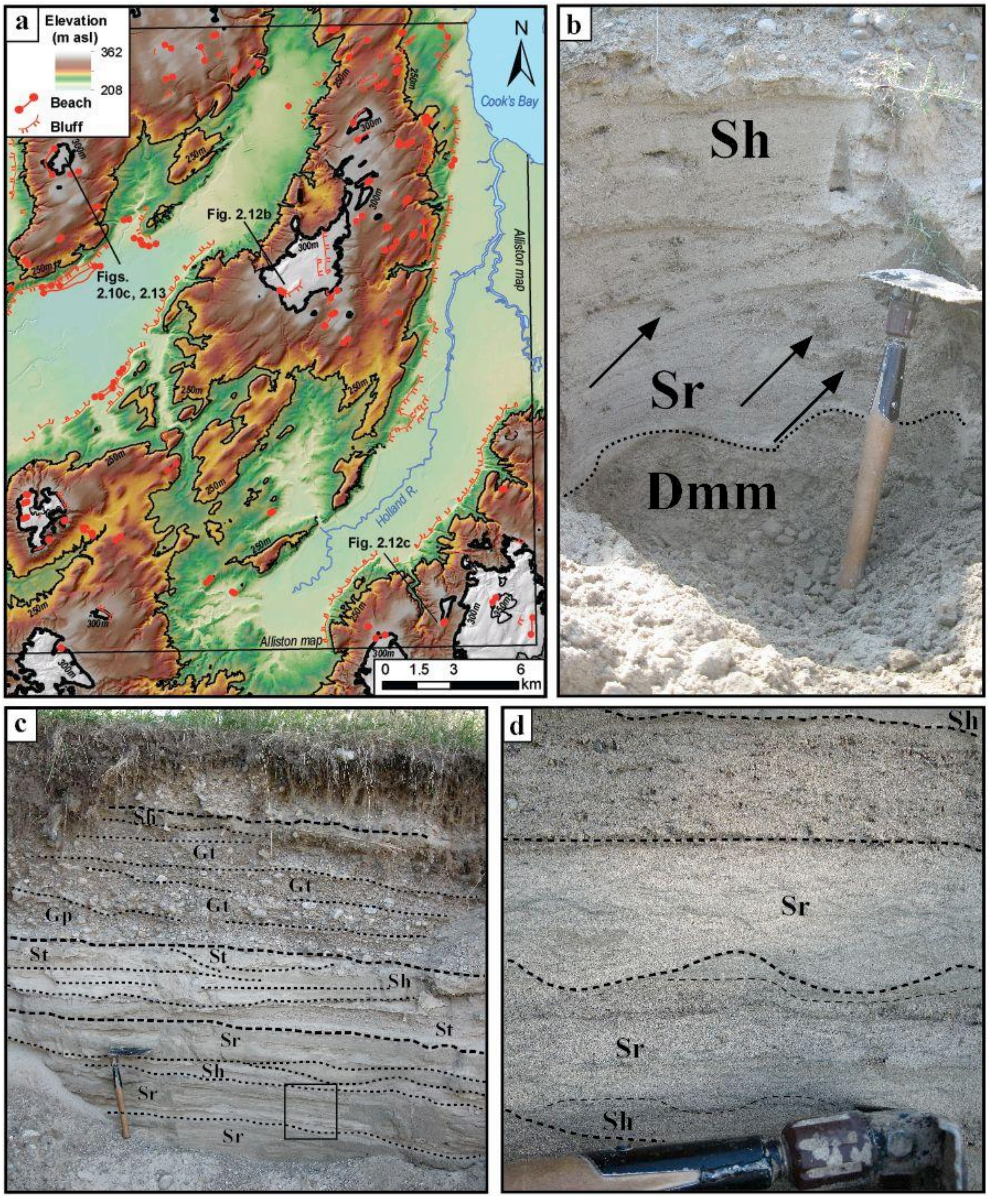
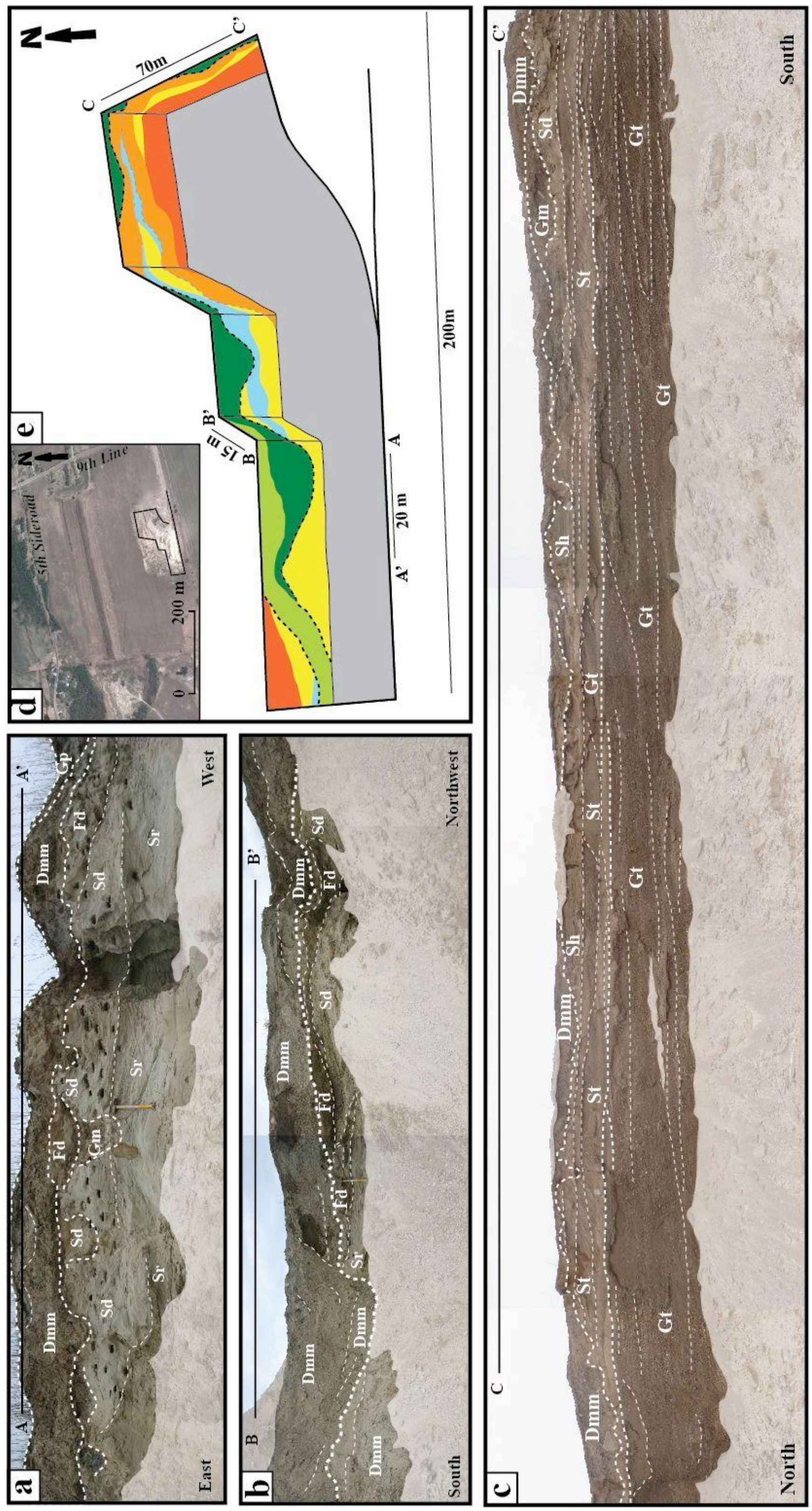

a
Elevation
(m asl)
362
208
Beach
Bluff
N
Cook's Bay
Fig. 2.12b
Figs.
2.10c, 2.13
Alliston map
Holland R.
Fig. 2.12c
0 1.5 3 6
km
b
Sh
Sr
Dmm
c
Sh
Gt
Gt
Gt
Gp
St
St
Sh
St
Sr
Sh
Sr
Sr
d
Sh
Sr
Sr
Sh

Figure 2.13: Photomosaics of exposures along the south (A-A'), west (B-B'), and east (C-C') faces of a gravel pit extracting from an upland plain landsystem west of Cookstown. See Figure 2.4cfor facies codes, Figure 2.12a for location; a) type-A and –B rippled fine-grained sand (Sr) grading up into highly deformed sand (Sd) unconformably overlain by massive to crudely stratified silt-rich diamict (Dmm). Planar-bedded gravels (Gp) truncate the upper units in the west; b) rippled (Sr) and deformed (Sd, Fd) fine-grained sand and minor silt unconformably overlain by silt-rich diamict and fissile, massive, sand-rich diamict (Dmm, Newmarket Till); c) trough cross-bedded gravels (Gt) passing upwards into pebbley coarse-grained sand (St) overlain by silt-rich diamict (Dmm); d) location of pit (black outline), courtesy of Google Earth; e) distribution of sediment facies within the pit. Dashed line represents upper and lower contact of diamict package attributed to late Wisconsin ice advance (Newmarket Till). Locations of photomosaics marked; sections are approximately 8m high, see Figure 2.4c for colour legend.


a
East
West
A
A'
Dmm
Sd
Sr
Fd
Gm
Gp
b
South
Northwest
B
B'
c
North
C
C'
St
Gt
Sh
d
5th Sideroad
9th Line
0
200 m
N
e
15 m
20 m
70m
200m

uplands plains landsystem and exposed a 12m coarsening-upward succession of silt and clay rhythmites passing upwards into sand and gravel at the surface (Appendix A). The elevation of the upper contact of the rhythmites underlying the pit exposures of coarse-grained sediments lies at 285m asl. Coarse-grained facies of the uplands plains landsystem range from very fine-grained sand to coarse gravel. Medium and coarse-grained sand facies are generally planar-laminated, but occasionally symmetrical ripples, trough cross-bedding, and current ripples are observed (Figure 2.12b,c,d). . Gravel facies types range from planar tabular or trough cross-bedded to massive, open-framework deposits and typically form sub-horizontal units that dip towards adjacent low-lying areas and truncate underlying sediments (Figure 2.12c). In one pit exposure located along the flank of a drumlin northwest of Bradford, medium to coarse-grained sand beds contain sediment intraclasts composed of sand-rich diamict (Figure 2.12b).

Interpretation

The fine-grained facies composed of massive to rhythmically-laminated light grey silt and clayey silt that underlie most of the uplands plains landsystem are interpreted as lacustrine and glaciolacustrine sediments deposited in high level lakes formed on the underlying diamict (Newmarket Till) surface as ice retreated from the area. Scarps that are eroded into the diamict and are commonly associated with localized coarse-grained sand and gravel facies near 300m asl are interpreted as shoreline features that record wave erosion and reworking of sediment along the margins of an aerially extensive lake (Shaetzl et al., 2002). Coarse-grained sediments found along the base of scarps in the upland plains landsystem contain structures that indicate deposition in shallow, wave influenced depositional environments. Symmetrical ripples record the oscillatory motion of waves, and typically form in shallow (5-10m) water depths (Hamblin and Walker, 1979); planar bedding is common in sand and gravels deposited in the swash zone along beachfronts (Pascucci et al., 2008). Sediment intraclasts of sand-rich diamict are interpreted as having been eroded from the underlying Newmarket Till, which probably served as the sediment source for the coarse-grained facies. The absence of Newmarket Till at the surface in parts of the uplands plains landsystem and the presence of steep scarps and coarse-grained, shoreface sediments around the rim of the plain (Figure 2.14a; Bajc & Rainsford, 2011; Appendix B), suggest the till was eroded by wave action.

Sediments exposed in the pits in the interior of the flat plain west of Cookstown underlie a structureless sand-rich diamict interpreted as the Newmarket Till, and suggest they were deposited prior to Late Wisconsin ice advance. Silt and clay rhythmites directly underlying the sand and gravel succession (SS-12-05) indicate sediment deposition into a quiet (deep?) water body that pre-dates ice advance into the region (Van Der Meer & Warren, 1997). The upper contact of the silt lies at 285m asl, indicating the presence of a high elevation water body prior to ice advance in the region.

The series of scarps lying at elevations of between 300 and 250m asl (Figure 2.12a) likely reflect wave erosion and shoreline development during still stands or intense storm events (Schaetzl et al., 2002) as water levels fell during lake drainage. The presence of scarps at several distinct elevations suggests that drainage of the extensive lake was gradual, likely resulting from the exposure of successively lower outlets to the east (Gravenor, 1957) or northwest (Eschman & Karrow, 1985), during ice retreat. The discontinuous, lowermost scarps within the upland plains landsystem, lying between

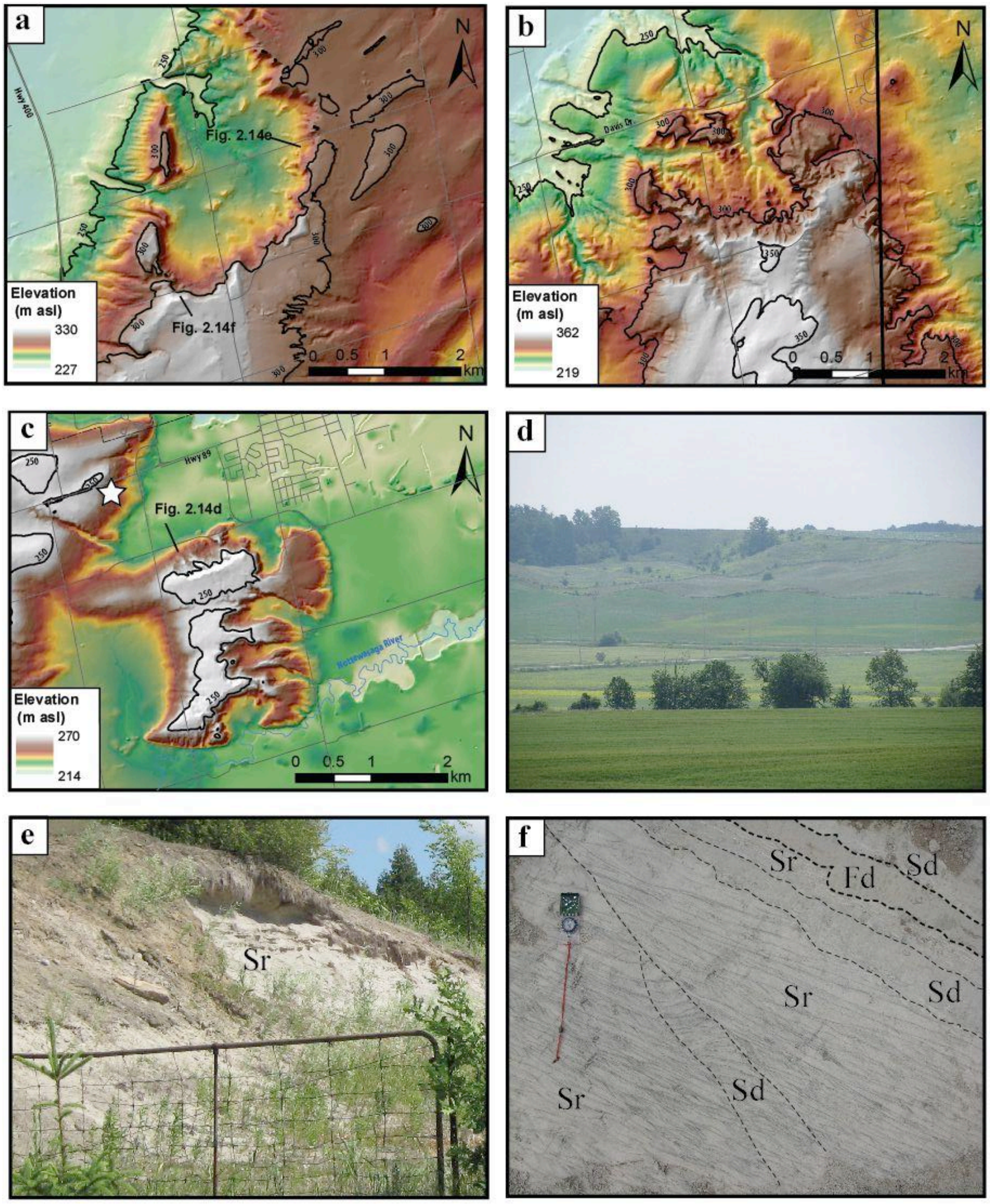
245m and 250m asl north and east of Alliston, may record a stable water plane elevation during later phases of lake drainage (Karrow et al., 1975; Chapter 3).

2.3.2.4 Erosional Amphitheatres

Large, irregular or amphitheatre-shaped erosional forms locally incise into the flanks of the streamlined uplands landsystem (Figure 2.14). These can exceed 4km in diameter and reach depths of 60m from the crest to the base. Heads of ephemeral streams often occupy the forms. The bases of many of these features are typically flat-lying, at elevations slightly higher than the adjacent lowland plains landsystem (Figure 2.14) and the crests are typically associated with steep slopes on the surface of streamlined uplands. The crest of these features commonly lies between 290-310m asl (Figure 2.14), but they are observed at higher elevations along the western and southern borders of the map area (up to 350m asl), and at lower elevations in northern and central parts of the map (245-265m asl). Although the shape and morphology of the erosional amphitheatre forms varies significantly from one area to another (Figure 2.14), the sedimentary successions exposed within the walls of these features are fairly consistent.

Sediment exposures in the walls of the erosional amphitheatres typically reveal thick packages (up to 15m) of laminated silt and clay passing upward into fine to medium-grained sand lying beneath consolidated sand-rich diamict that forms the streamlined uplands landsystem (Newmarket Till, Figure 2.14e,f). Sand packages are characterized by massive to planar laminated or asymmetrical rippled sand and often display faulting and other deformation features, with fault offsets of up to 1m, but more commonly 5-10cm (Figure 2.14f). Paleocurrent indicators in the sands typically record south to southwest paleoflow directions. Northwest of Bradford, vertically bedded and faulted rippled fine-grained sand and silt rhythmites up to 8m thick are observed beneath

Figure 2.14: Erosional amphitheatres. Topography of amphitheatres, a) north of Bradford; location of 2.14e,f shown with star; b) east of Newmarket (Mulligan, 2011); c) southwest of Alliston; location of photo 2.14d shown in white star; d) highly irregular topography along the northern flank of an amphitheatre; e) 4m of asymmetrically-rippled fine-grained sand (Sr) lying stratigraphically beneath diamict (Newmarket Till) exposed along a driveway in the eastern wall of piping feature north of Bradford ; f) rippled (Sr), deformed, and faulted fine-grained sand (Sd, Fd) exposed in a road cut on the south flank of large amphitheatre north of Bradford (Figure 2.14a for location).


a
N
Fig. 2.14e
Fig. 2.14f
Elevation
(m asl)
330
227
0 0.5 1 2 km
b
N
Elevation
(m asl)
362
219
0 0.5 1 2 km
c
N
Hwy 89
Fig. 2.14d
Nottawasaga River
Elevation
(m asl)
270
214
0 0.5 1 2 km
d
e
Sr
f
Sr
Fd
Sd
Sd
Sr
Sr
Sd

the diamict. The larger erosional forms across the study area are typically floored by laminated to massive silt with occasional clasts (Appendix B).

Sediment successions exposed in the amphitheatre-shaped erosional forms are consistent with those observed beneath the Newmarket Till in boreholes and outcrops throughout the region (Figures 2.4b, 2.13; Appendix A). The thickness of sand bodies, however, appears to be much greater in outcrops exposed in amphitheatres along the flanks of streamlined uplands than in boreholes (Appendix A).

Interpretation

Exposures in amphitheatre-shaped erosional forms display a consistent sedimentary succession across the study area, and suggest that the sediments were deposited during regional-scale events. Gradational vertical facies transitions of silt and clay passing upward into rippled fine to medium-grained sand and minor gravels indicates the progradation of sediment sources into the region and may be related to early phases of ice advance which culminated with the deposition of the Newmarket Till that caps the succession (Bajc et al., 2012).

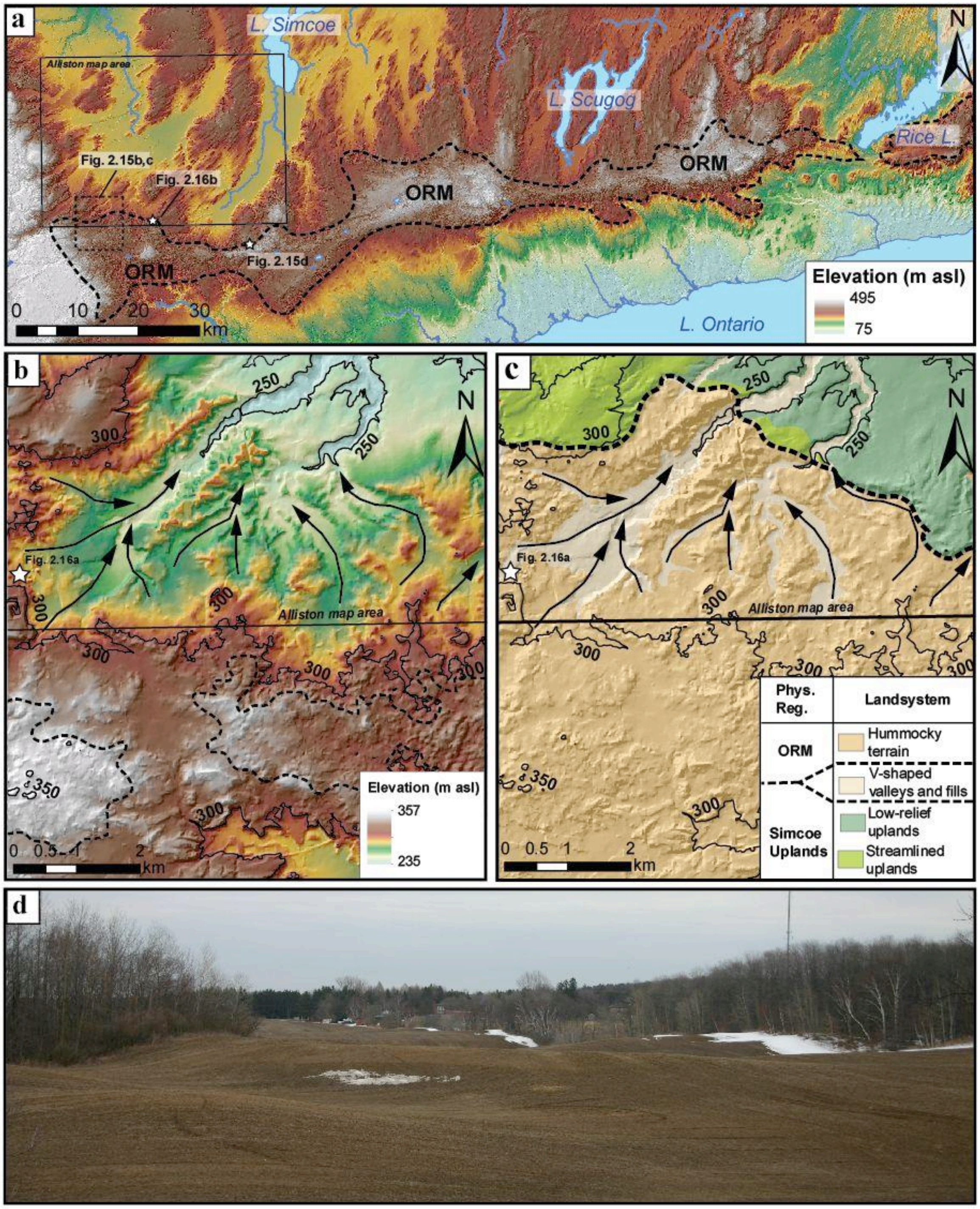
The amphitheatre-shaped forms are interpreted to have been created as a result of headward erosion into the flanks of the streamlined upland landsystem due to groundwater piping following postglacial lake drainage event(s) (Hagerty, 1991a; Barnett, 1997; Bajc & Rainsford, 2010). Groundwater flow beneath uplands would have been concentrated in discrete sand beds within the upper parts of the glaciolacustrine succession beneath the Newmarket Till (Figures 2.4b, 2.13, 2.14; Appendix A). Fine-grained sand units would allow relatively high groundwater flow rates and would be very susceptible to groundwater sapping erosion (Hagerty, 1991a, Fox et al., 2006). Once the diamict (Newmarket Till) was breached by erosion, large volumes of sediment (mostly fine-grained sand) could be excavated from the flanks of the uplands, undercutting the diamict and eventually forming the large piping scars (amphitheatres) observed at present (Hagerty, 1991b; Bajc & Rainsford, 2010; Mulligan, 2011; Figure 2.14). Vertically-bedded fine-grained deposits observed in amphitheatres northwest of Bradford may represent large blocks of sediment that slumped and rotated during erosion of the walls of the piping features (Figure 2.14f). Similar (smaller) erosional features are observed along river valleys in the lowland plains landsystem and have also been attributed to a groundwater piping mechanism (Chapter 3).

2.3.3 OAK RIDGES MORAINE

2.3.3.1 Hummocky Terrain Landsystem

Hummocky terrain that characterizes the southwestern part of the study area typically lies at higher elevations (Figure 2.15a; 290 to 350m asl) than surrounding areas to the north or south. This hummocky terrain forms part of an east-west trending ridge (the Oak Ridges Moraine - ORM; Figures 2.1a, 2.15a) that stretches from Orangeville to Peterborough. The central parts of the hummocky terrain landsystem are dominated by irregular topography that contains abundant closed depressions up to 100m in diameter (Figure 2.15b, c); areas along the northern and southern flanks of the landsystem typically lack closed depressions and the topography is heavily dissected by ephemeral streams that form the headwaters of rivers feeding the modern Lake Huron and Lake Ontario basins (Figure 2.15b). Modern streams occupy a series of deep (up to 50m) valleys dissecting the margins of hummocky areas. The valleys have wide, relatively flat bases, and the heads of some of the larger features appear to have headwaters consistently

Figure 2.15: Hummocky terrain landsystem. a) Regional topography map showing Oak Ridges Moraine physiographic region (outlined by thick dashed line), locations of Figures 2.15b,c (dashed black rectangle), and 2.16b (white star); b) contoured topography (black lines, scale in m asl) of the northwestern part of the Oak Ridges Moraine showing transition from dominantly hummocky terrain (inside dashed lines) to dissected terrain (outside dashed lines). Note the increase in channel size and depth below the 300m contour. Location of Figure 2.16a shown with white star; c) landsystem boundaries in area shown in 2.15b. Boundary between ORM and Simcoe Uplands physiographic regions shown in thick dashed line; note that V-shaped valleys cross this boundary; d) Hummocky terrain landsystem 6km south of the Alliston map sheet (Figure 2.15a for location), looking east from highway 400.

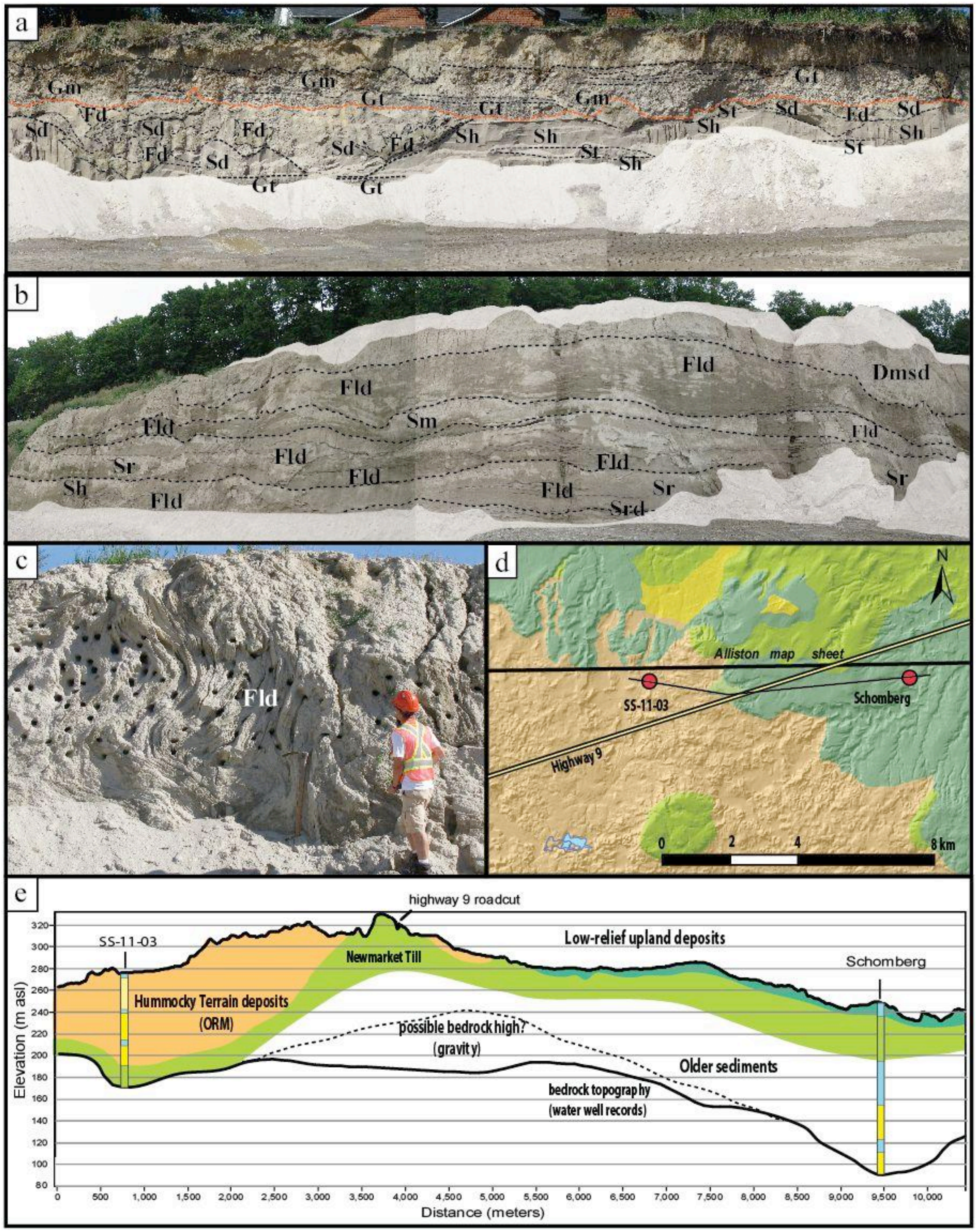

a
L. Simcoe
L. Scugog
Rice L.
Alliston map area
Fig. 2.15b,c
Fig. 2.16b
Fig. 2.15d
ORM
ORM
ORM
L. Ontario
Elevation (m asl)
495
75
0 10 20 30 km
N
b
250
250
300
300
300
300
300
350
Fig. 2.16a
Alliston map area
Elevation (m asl)
357
235
0 0.5 1 2 km
N
c
250
250
300
300
300
300
350
Fig. 2.16a
Alliston map area
Phys. Reg.
Landsystem
ORM
Hummocky terrain
V-shaped valleys and fills
Simcoe Uplands
Low-relief uplands
Streamlined uplands
0 0.5 1 2 km
N
d

around 300m asl (Figure 2.15b). Multiple terrace levels can be observed within some of the valleys (Figure 2.15b, Appendix B). Stream valleys are floored by coarse-grained pebbly to cobble-rich gravel (Figure 2.16c; Appendix B) that displays northeast paleocurrent directional indicators and erosively overlies finer-grained sandy sediment characteristic of most parts of the hummocky landsystem (Figure 2.16a).

Sediments underlying the predominantly hummocky terrain of the ORM are well exposed in road cuts and gravel pits. In these surface exposures, very fine to medium-grained sand and silt, with occasional interbeds of gravel, clay, or silt-rich diamict are common. Sands are massive or crudely graded or contain asymmetrical ripples, deformed horizons, and/or planar laminations (Figure 2.16a,b). Paleocurrent indicators typically show flow directions toward the southwest and northwest. Thick packages (up to 75m) of very well-sorted fine to very fine-grained sand are commonly interbedded with silt, gravel or fine-grained diamict and display continuous, sub-horizontal, but often deformed or undulating bed contacts in outcrop (Figure 2.16b,e). Locally, unit contacts are faulted or intensely folded (Figure 2.16c). Fault offsets reach up to 1-2m and fold limbs and deformation features can exceed 2-3m in amplitude. Interbedded silt-rich diamict facies are often structureless with a well-sorted silt matrix. The diamict is generally clast-poor and dominated by locally derived Paleozoic clasts with average size less than 1cm diameter.

Sediments of the hummocky terrain landsystem were penetrated by borehole SS-11-03 (Figures 2.4, 2.16e; Appendix A) that contained massive diamict (interpreted as the Newmarket Till) overlain by 75m of upward-fining interbedded medium- fine- and very

Figure 2.16: Sediments within hummocky terrain landsystem. a) annotated photomosaic of exposures though V-shaped valley fill sediments within hummocky terrain landsystem (ORM). Exposure reveals coarse-grained cobble-rich gravel (Gm, Gt) erosively overlying horizontally-bedded (Sh), trough cross-bedded (St) or deformed fine- to pebbley coarse-grained sand (Sd, Oak Ridges Moraine sediments) in Adjala twp, section is 7m high; b) Large pit face south of Tottenham exposing 15m of fine-grained glaciolacustrine sediments underlying hummocky areas (see Figure 2.15a for location). Contacts are sharp, undulating and locally deformed; c) highly deformed, laminated fine-grained sediment exposed in the northwest corner of the pit in Adjala twp. d) surficial geology of Alliston (top; Mulligan and Bajc, 2012; see Appendix B) and Bolton (bottom; White, 1975) map sheets with borehole locations and location of cross-sectional profile shown in 2.16e; e) simplified conceptual cross-sectional profile of late Wisconsin stratigraphy based on boreholes (Appendix A) and surficial geological data. Sand-rich diamict at the base of SS-11-03 is interpreted as the Newmarket Till mapped in road cuts 2.5km to the southeast. Note high relief on surface of till sheet; bedrock surface is poorly constrained by water well records. Dashed line represents possible bedrock high, based on high local gravity signature (Bajc and Rainsford, 2011).


a
Gm
Fd
Sd
Gt
St
Sh
b
Fld
Dmsd
Sm
Sr
Sh
Srd
c
Fld
d
Alliston map sheet
SS-11-03
Schomberg
Highway 9
0
2
4
8 km
N
e
highway 9 roadcut
Low-relief upland deposits
SS-11-03
Newmarket Till
Schomberg
Hummocky Terrain deposits
(ORM)
possible bedrock high?
(gravity)
Older sediments
bedrock topography
(water well records)
Elevation (m asl)
Distance (meters)

fine-grained sand with silt (Figure 2.16e; Appendix A). Cored sand packages were characterized by ripples and planar-laminations with abundant deformation features and silt interbeds were planar laminated to massive or highly deformed.

Interpretation

Large hummocks and closed depressions characteristic of the hummocky terrain landsystem are interpreted to record the melting of large ice blocks buried by sediment during deglaciation and are typical features of former ice-marginal areas (Howard et al., 1996; Barnett et al., 1998; Gibbard et al., 2012). The majority of the sand and silt-rich facies observed within this landsystem record deposition in glaciolacustrine environments by density underflows, suspension settling, and minor ice-rafting (Eyles et al., 2005, Bajc & Rainsford, 2011). These processes are active at the mouths of meltwater channels entering a standing water body, often near the base of the former ice margin(s) (Barnett et al., 1998; Winsemann et al., 2007). The wide variety of sedimentary facies identified within the hummocky terrain landsystem suggests high rates of sediment supply and rapid lateral changes in depositional conditions. The abundance of faulting and large-scale deformation features, as well as the highly undulating unit contacts observed within hummocky areas, are likely the combined result of high sedimentation rates, subaqueous debris flows, and the melting of buried ice removing sediment support (Burt 2011; Weaver & Arnaud, 2011).

Valleys observed along the margins of the ORM record fluvial erosion following deposition of the sandy moraine sediments. Truncation of sandy ORM sediments by coarse-grained gravels is interpreted to record a fall in regional base levels and changing gradients following the building of the moraine in the interlobate area in between the

Simcoe and Ontario ice lobes (Barnett et al., 1998; Figure 2.3c). The occurrence of numerous headwater features near 300m asl may record the presence of a former water table (or an elevated water plane) that existed during the early deglacial period (Figure 2.3d; Section 2.3.3.1).

2.3.4 SIMCOE LOWLANDS

The Simcoe Lowlands are a series of contiguous flat-lying valleys, between 4 and15 km wide and 20-30 km long, that separate elements of the broad Simcoe Uplands within the study area. The Simcoe Lowlands physiographic region is made up of a single landsystem, the lowland plains landsystem (Figure 2.4).

2.3.4.1 Lowland Plains Landsystem

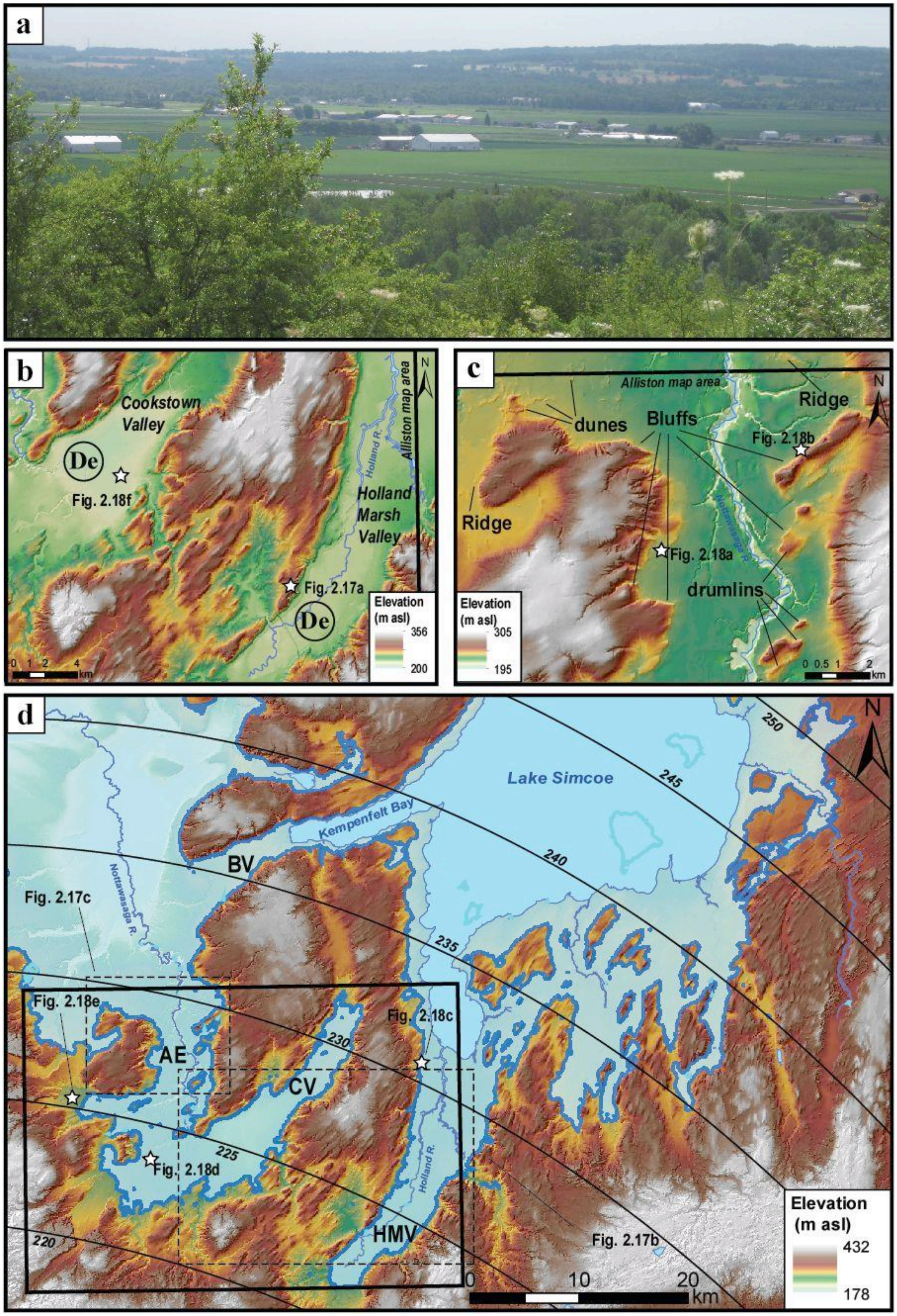
The lowland plains landsystem is characterized by broad, flat-floored valleys with valley floor elevations of between 190m-225m asl (Figure 2.17). The widest individual valley in the study area is the north-south trending Alliston Embayment, which is currently occupied by the Nottawasaga and Pine rivers (Figure 2.1) and extends from the base of the Niagara Escarpment, east to upland areas underlying the Oro moraine (Figure 2.1a). Within the Alliston map area, it reaches a maximum width of 18 km, but broadens to over 40 km to the north (Figure 2.1). The topography of the floor of the Alliston Embayment is relatively flat with a slight northward decrease in elevation towards Georgian Bay and Lake Simcoe (Figures 2.1, 2.17).

Three additional lowland valleys (Barrie (BV), Cookstown (CV), and Holland Marsh (HMV); Figure 2.1a) form part of the lowland plains landsystem in the study area (Figures 2.4a, 2.17). The heads of the Barrie and Holland Marsh valleys likely begin beneath Lake Simcoe (Todd et al., 1998), and the Cookstown Valley appears to originate as a shallow depression in the till plain south of Barrie (Figures 2.1, 2.4a). The floor of the Cookstown Valley lies perpendicular to, and at higher elevations to, the Barrie Valley less than 10 km to the north (Figures 2.1, 2.4, 2.17). Both the Cookstown and Holland Marsh valleys trend south (approximately perpendicular to former ice flow) for as much as 15 km before deflecting to the west, parallel to regional drumlin and striae orientations (Figure 2.10, 2.17). The valleys are flanked by either the sloping surface of the streamlined uplands landsystem (Newmarket Till; Section 2.3.2.1) or the large erosional amphitheatres (Figures 2.4b, 2.16, 2.17; Section 2.3.2.4). The Cookstown and Holland Marsh valleys gradually rise in elevation toward the southwest, and transition into the low-relief uplands (Section 2.3.2.2) and hummocky terrain (Section 2.3.3.1landsystems (Figures 2.1, 2.12a, 2.17).

The rim of the lowland plains landsystem is commonly marked with steep bluffs that lie at the base of upland areas (Figures 2.17b,c, 2.18a,b). These bluffs reach heights of up to 20m and are usually highest and steepest on north- and northwest-facing slopes. A relatively continuous set of bluffs is located directly west of the Lake Simcoe shoreline along Cook's Bay, stretching north to the southern shore of Kempenfelt Bay (Figure 2.17d; Appendix B). The elevation of the base of the bluffs rimming the lowland plains increases towards the northeast (Figure 2.17d). Several broad, low-relief ridges are observed either extending into the plain from the margins of uplands or forming a detached body that typically parallels the base of uplands (Figures 2.17c,d).

The surface elevation of the lowland plains decreases with distance away from the margins adjacent to upland areas (Figures 2.1, 2.17c). Within the map area, the lowest elevations within the lowland plains landsystem are found in broad, shallow surface

Figure 2.17: Lowland plains landsystem. a) View south into the Holland Marsh Valley (Figure 2.17b for location); b) DEM showing shallow depressions (De) in Cookstown and Holland Marsh valley surfaces, Figures 2.17a, 2.18f shown with white stars (Figure 2.17d for location); c) sand dunes, drumlins, and wave-cut scarps rising above the lowland plains, north and east of Alliston. Locations of photos in Figures 2.18a,b shown with white stars (Figure 2.17d for location); d) regional DEM showing proposed extent of a continuous lake body (Main Lake Algonquin, Figure 2.3e). Isobases (solid black lines) show postglacial tilt of the water plane and are constructed from 2^{nd} -order polynomial interpolation of elevation points from the base of shoreline bluffs in the region; elevations in meters above sea level. Position of Barrie (BV, Cookstown (CV), Holland Marsh (HMV) valleys and Alliston Embayment (AE) marked. Alliston map area shown in black rectangle, location of Figures 2.18c,d,e shown with white stars.



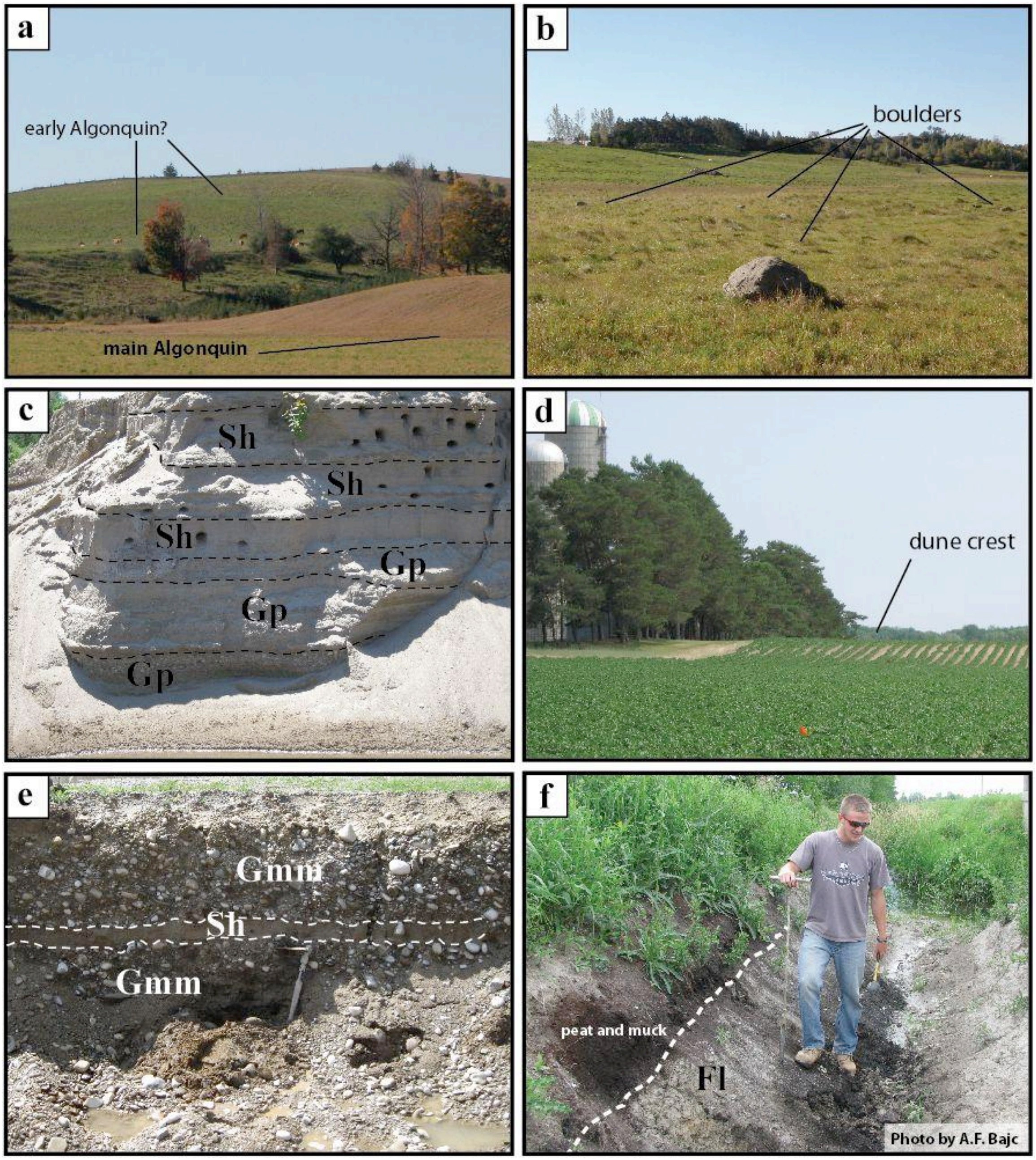
a
b
Cookstown Valley
De
Fig. 2.18f
Holland R.
Alliston map area
Holland Marsh Valley
Fig. 2.17a
De
Elevation (m asl)
356
200
0 1 2 4 km
c
Alliston map area
Ridge
dunes
Bluffs
Fig. 2.18b
Ridge
Fig. 2.18a
Nottawasaga R.
drumlins
Elevation (m asl)
305
195
0 0.5 1 2 km
d
Lake Simcoe
Kempenfelt Bay
250
245
240
235
230
225
220
BV
Fig. 2.17c
Nottawasaga R.
Fig. 2.18e
AE
Fig. 2.18c
CV
Fig. 2.18d
Holland R.
HMV
Fig. 2.17b
0 10 20 km
Elevation (m asl)
432
178

depressions within the central parts of the Cookstown and Holland Marsh valleys ('De'; Figure 2.17b). Northeast of Everett and south of Alliston, a cluster of small, irregular-shaped hills rise above the flat plain by up to 15m (Figures 2.1, 2.17c). Several streamlined hills with similar morphologies to drumlins breach the surface of the lowlands along the eastern margins of the Alliston embayment (Figure 2.17c).

The sediments exposed at surface throughout the lowland plains landsystem are generally very fine- to fine-grained sands (Appendix B). Coarser-grained gravel and sandy gravel facies equivalents are observed near the mouths of V-shaped valley landsystems that cut into the Niagara Escarpment in the west, locally along the flanks of streamlined uplands, and near the mouths of rivers or streams that dissect the surface of uplands (Appendix B). In the southern part of the study area, where the Holland River enters the lowland plains in the Holland Marsh Valley, a broad, low relief plain of medium to coarse-grained sand lies at elevations slightly (2-3m) higher than the lowlands surface and grades to finer-grained sand and silt toward the north (Figure 2.17b; Appendix B).

Sediments found proximal to uplands are composed of medium-grained sand to gravel, and the coarsest sediments are found in the uppermost parts of ridges attached to upland areas (Figure 2.17c). Exposures through these sediments reveal planar laminated to trough cross-bedded sand and gravel with occasional symmetrical ripples and deformed horizons (Figure 2.18c). Accumulations of large boulders can be found at the surface near the break in slope between streamlined uplands and lowland plains (Figure 2.18b). Large, irregular-shaped ridges rise above the floor of the lowland plains in the Alliston Embayment (Figure 2.17).

Figure 2.18: a) large wave-cut bluffs from main (and early?) stage of Lake Algonquin or late glacial Lake Schomberg, northeast of Alliston (see Figure 2.17c for location); b) lag boulders near the base of a large shoreline bluff (see Figure 2.17c for location); c) planar bedded gravels (Gp) overlain by horizontally bedded sands (Sh) exposed near the base of uplands (Figure 2.17d for location); d) low relief dune rising above the flat lowland plain 4km south of Alliston; e) massive cobble-rich gravel (Gmm) and sand (Sh) where the Boyne River valley meets the lowlands (Figure 2.17d for location); f) 0.5m of peat overlying fossiliferous silt (Fl) along the rim of the depression in the Cookstown Valley (Figure 2.17 for location).


a
early Algonquin?
main Algonquin
b
boulders
c
Sh
Sh
Sh
Gp
Gp
Gp
d
dune crest
e
Gmm
Sh
Gmm
f
peat and muck
Fl
Photo by A.F. Bajc

Finer-grained facies of massive to rhythmically laminated silt and clay with minor very fine-grained sand interbeds are observed in low-lying depressions on the surface of the lowlands plain landsystem within the Holland Marsh and Cookstown valleys (Figure 2.17b). Peat and muck deposits often overlie these fine-grained facies and form an extensive surface cover in the Holland Marsh valley (over 40km^2; Appendix B). Radiocarbon dating of organic material recovered from sediments within lowland plains suggests the sediments were deposited between approximately 12.5 and 8.2 ka BP (Bajc & Mulligan, 2013; Appendix A).The lowland plains landsystem is underlain at depth by thick successions (up to 75m, Bajc & Rainsford, 2011; Appendix A) of finely laminated sediment. Sand-rich diamict (interpreted as the Newmarket Till) is often observed at the base of the fine-grained succession in outcrops and in OGS boreholes drilled through the lowland plains landsystem (Figure 2.4b; Chapter 3; Appendix A).

Boreholes SS-12-03, -07, and -08 were drilled into the Barrie, Cookstown, and Holland Marsh Valleys, respectively, and reveal thick fining-upward successions of sediment floored by cobble-rich gravel at the base. Gravels pass upward into sand and glaciolacustrine silt, sand, and clay toward the ground surface. Sand-rich diamict facies (interpreted as the Newmarket Till) were recovered beneath the gravel unit in SS-12-03 and above the gravel unit in SS-12-08 (Appendix A). Gravel in SS-12-07 lies directly on the Paleozoic bedrock surface.

Interpretation

Large bluffs rimming the lowland plains landsystem are interpreted to record wave erosion in extensive glaciolacustrine basins (Schaetzl et al., 2002). The continuity of the lower set of bluffs suggests the presence of a single, aerially extensive water body with a water surface elevation of approximately 230m asl (Figure 2.17d). Changes in the elevation of the base of bluffs from the southwest to the northeast of the study area record differential uplift following lake drainage and retreat of ice from the region (Finamore, 1985; Teller, 2001). Boulders observed at the base of large bluffs near the margins of lowland areas, (Figure 2.18b) are interpreted as lag deposits and record erosion of diamict comprising the streamlined uplands (Newmarket Till) by wave erosion in deglacial lake(s) (Chapman & Putnam, 1984; Bajc & Rainsford, 2010). Ridges of coarse-grained sand or gravel extending into lowland areas from the flanks of uplands are laterally correlative with the continuous, lower set of bluffs and record longshore drift and spit progradation into the former lake basin (Krist & Schaetzl, 2001), with sediment derived from erosion of the Newmarket Till (Figure 2.12b).

The flat-lying surface topography of the lowlands plains landsystem marks the extent of the former basin floor. Gradational lateral facies changes from gravels along the margins of the lowlands to silt and fine-grained sand in low-lying, central areas (Appendix B) record increasing water depths towards the central parts of the former basin. Peat deposits formed in poorly-drained depressions on the former lake floor following lake drainage. Irregular-shaped ridges observed in the northern lowland areas are interpreted as eolian dunes recording re-working of the sand-rich lake floor deposits following drainage of the lake(s) that occupied the lowlands (Arbogast et al., 2002). The elevation of the bluffs, direction of differential uplift, and stratigraphic position and age of the sediments of the lowland plains landsystem suggests that these features record the evolution of glacial Lake Algonquin (12.5 – 10.5 ka BP; Deane, 1950; Karrow, 1975; Finamore, 1985; Lewis et al., 2005).

The presence of Newmarket Till at the base of the glaciolacustrine succession identified in boreholes drilled through the lowland plains landsystem and drumlinization of sediments along the margins of the valleys indicates direct contact with active glacial ice during the Late Wisconsin glacial period (O'Cofaigh, 1996; Chapter 3). Valley long axes and ice flow directional indicators (drumlin and striae orientations), suggest a relationship between former ice flow and valley orientation.

2.4 PALEOENVIRONMENTAL RECONSTRUCTION

Integration of high-resolution datasets from the analysis of sedimentary successions exposed in natural and man-made outcrops, and from fully-cored OGS boreholes, allows a detailed reconstruction of changing environmental conditions that affected the southern Simcoe region during the late Quaternary to be made. However, due to the thickness of Quaternary sedimentary successions within the region, the surficial sediments likely only record the latest phases of glaciation. The following reconstructions of major paleoenvironmental changes are based on the landsystems analysis of landforms and surficial sediment exposures and will therefore focus primarily on events of the last glacial and deglacial episodes to affect the region although brief descriptions of earlier events are included. Preliminary interpretations of the older sediment record revealed in the OGS boreholes are provided by Bajc et al. (2012) and Bajc & Mulligan (2013, Appendix A). Detailed paleoenvironmental interpretation of these older sediments will be the focus of a later report.

2.4.1 Pre-Wisconsinan

The only outcrops of Paleozoic bedrock strata within the study area are concentrated in a narrow band along the western part of the map area. Outcrops are interpreted to form parts of large bedrock promontories that separate re-entrant valleys in the bedrock escarpment landsystem (Figure 2.5; Straw, 1968). The bedrock escarpment forms part of the Niagara Escarpment, which stretches from Manitoulin Island in the north, to the Niagara peninsula in the south. It borders the western margins of the map area and its initial formation is believed to pre-date Quaternary glaciations (Straw, 1968). Northeast-trending valleys that dissect the north-trending face of the escarpment are interpreted as re-entrant valleys carved by fluvial systems that formed the headwaters of the pre-glacial Laurentian River system (Spencer, 1890; Straw, 1968). The consistent northeast trend of re-entrant valleys along the length of the Niagara Escarpment is aligned parallel to major regional joint and fracture networks in southern Ontario, suggesting a possible structural control on their development (Eyles et al., 1993; Boyce & Morris, 2002). Boreholes drilled within valleys along the Niagara Escarpment frequently intersect pre-late Wisconsinan sediments (SS-11-04; Appendix A), suggesting the valleys were carved prior to Wisconsinan glaciation (Bajc & Rainsford, 2011; Burt & Dodge, 2011). Quaternary glaciation likely played a large part in enhancing the form of the re-entrant valleys as well as smoothing the topography of the soft shale-rich units that lie at the base of the escarpment (Figure 2.5; Eyles, 2012).

2.4.2Wisconsin Episode glaciolacustrine conditions

The lowermost sediment units observed in surficial exposures are found in erosional amphitheatres (Section 2.3.2.4) and beneath upland plains and scarps Ssection 2.3.2.3). These sediments form the upper part of a glaciolacustrine and glaciofluvial succession that underlies the streamlined uplands landsystem, and indicate the presence of a large and extensive lake prior to Wisconsin ice advance (Figures 2.3a,, 2.4b, 2.14; Appendix A). Radiocarbon dating of organic material recovered from sand bodies within the dominantly fine-grained succession beneath the streamlined uplands landsystem has produced dates ranging between >49 and 29.5ka BP (Figure 2.4b; Appendix A). Based on these dates and the stratigraphic position of these deposits beneath a diamict interpreted as the Late Wisconsinan Newmarket Till, the glaciolacustrine deposits within the map area are tentatively assigned as an equivalent to the Thorncliffe Formation, observed at the Scarborough Bluffs (Karrow, 1967; Eyles & Eyles, 1983; Bajc & Mulligan, 2013; Figure 2.2). The Thorncliffe Formation has been mapped as far north as the Oak Ridges Moraine (Sharpe et al., 2011), but the exact spatial relationship and continuity of these deposits from the Alliston map area to the Oak Ridges Moraine and Scarborough Bluff areas requires further investigation.

Within the study area, the glaciolacustrine deposits exposed in amphitheatres (Section 2.3.2.4; Figures 2.4b, 2.14), beneath upland plains and scarps (Section 2.3.2.3; Figures 2.4b, 2.13), and underlying the till beneath streamlined uplands (Section 2.3.2.1) are interpreted to record the inundation of the study area by an aerially extensive lake followed by progradation of coarse-grained sediments ahead of the advancing ice front of the LIS sometime after 29.5 ka BP(Figure 2.3a).

2.4.3 Glacial conditions – formation of the Newmarket Till

A sand-rich diamict interpreted as a subglacial till overlies the thick glaciolacustrine succession described above and forms the dominant surface cover in the streamlined uplands landsystem (Section 2.3.2.1) (Figures 2.4, 2.10; Appendix B). The diamict is correlated with the regionally extensive Newmarket Till (Gwyn, 1972) based on its physical characteristics, stratigraphic position, and ice flow directional indicators (Figure 2.10), and records the advance of ice over the study area during the last glacial episode (Michigan Subepisode, Figure 2.3b). Observations of the surface topography of the till plain, the presence of till in the flanks of streamlined uplands, and correlation with till outcrops exposed at the base of lowland plains and valley infill successions (Figure 2.3g, 2.4; Appendix B), suggest that the Newmarket Till has a highly variable surface topography within the map area. Draping of Newmarket Till onto pre-existing topography, including lows on the upper surface of underlying glaciolacustrine (Thorncliffe equivalent?) deposits, has been suggested in the Aurora area (Sharpe et al., 2011). Correlation of surficial exposures of Newmarket Till in the streamlined uplands landsystem with the upper surface of diamict units recovered from boreholes in lowland plains infill successions suggests topographic variations of up to 175m over distances less than 3km. (Figure 2.4b).

The origin of the large valleys in which the lowlands plains landsystem lies has been debated, and attributed to either erosion by glacial ice (Straw, 1968) or subglacial meltwater erosion in tunnel valleys (Barnett, 1990; Sharpe et al., 2004). The presence of diamict interpreted as the Newmarket Till at the base of the large valleys suggests that direct glacial erosion may have been an important factor in the development of the valleys. Coarse-grained gravels at the base of the valley infill successions (Appendix A) indicate that these areas were also occupied by powerful glaciofluvial systems during the glacial or (de)glacial period. The LIS may have exploited (and enhanced) pre-existing topographic lows during initial phases of ice advance from the northeast sometime after

29.5ka BP, during the Michigan Subepisode (Figures 2.2, 2.3b). Drumlins observed within lowland areas, and along the flanks of uplands (especially along the western shore of Cook's Bay; Figure 2.4; Appendix B) align with valley orientation and provide further support that active glacier ice occupied the valleys (Figure 2.2).

2.4.4 Early deglaciation – formation of the Oak Ridges Moraine

Toward the end of the Nissouri glacial phase (Figure 2.2), retreat and thinning of the ice sheet resulted in the formation of distinct lobes in response to local topography (Figure 2.3c). During the subsequent Mackinaw interstadial phase (Figure 2.2), the Simcoe and Ontario ice lobes began to separate along an east-west axis currently occupied by the Oak Ridges Moraine (Section 2.3.3; Figures 2.3c, 2.15). The position of the moraine corresponds to a regional high on the topography of the underlying Newmarket Till sheet (which is a southern extension of streamlined uplands landsystem) and is likely controlled by the properties of underlying sediment groups and prominent bedrock features (Kassenar & Wexler, 2006; Eyles et al., 1993). The topographic high that lies beneath the modern Oak Ridges Moraine likely promoted separation of the Ontario and Simcoe ice lobes, opening extensive interlobate area(s) into which thick successions of (sub)glaciofluvial, glaciolacustrine, and ice-marginal sediments of the hummocky terrain landsystem were deposited over a short time span (Figures 2.15, 2.16; Barnett et al., 1998). Depositional environments were likely controlled by several factors, including water level fluctuations, ice-marginal positions, and meltwater input points. Rapid rates of sediment deposition are suggested by the abundance of soft sediment deformation features within hummocky terrain landsystem sediments (Figure 2.16). Burial and subsequent melting of ice blocks resulted in the formation of the hummocky topography characteristic of the Oak Ridges Moraine region within the study area (Figure 2.4a).

2.4.5 Deglacial events – kame terraces

To the west of the map area, early phases of ice retreat confined meltwaters to a narrow zone between the Niagara Escarpment and the retreating ice margin (Figures 2.3c, 2.6, 2.8; Sibul & Choo-Ying, 1971). This is recorded by the gravel bench landsystem (Section 2.3.1.2) that slopes toward the south (Figures 2.6, 2.7). Channels cutting down through the upper surface of the gravels record decreasing meltwater discharge or lowering base levels. This early deglacial meltwater system formed a broad kame terrace system in the study area, draining meltwater southward through Orangeville and Caledon, joining with well-developed glaciofluvial channels that emptied into the modern Lake Erie basin (Figure 2.6). The connection of the gravel bench (kame terrace) landsystem with the glaciofluvial channels to the southwest indicates that they formed while ice continued to occupy both the Lake Simcoe and Lake Ontario basins. This suggests ice-marginal positions along the eastern edge of the gravel terrace system (Simcoe lobe) and above the crest of the Niagara Escarpment in the south (Ontario lobe), in order to prevent eastward drainage of the fluvial systems through re-entrant valleys along the Niagara Escarpment. Development of the gravel terrace landsystem may correspond to the construction of the Banks moraine to the north of the study area (Burwasser, 1974; Gwyn, 1975) and with the construction of the Paris-Galt moraine by the Ontario ice lobe to the south (Straw, 1988). Kame terraces and meltwater channels in the study area developed following ice retreat away from the Singhampton Moraine and Niagara Escarpment (Figures 2.4, 2.6) in the west of the study area, suggesting that the construction of the Singhampton Moraine pre-dates the Paris-Galt Moraine system of the Ontario Ice lobe (Gwyn & Cowan, 1976).

2.4.6 Ice marginal conditions during deglaciation

Minor, localized fluctuations of the Simcoe ice lobe during the early deglacial period are recorded by sediments of the low-relief uplands landsystem (Section 2.3.2.2) in the south and western parts of the map area. Fine-grained diamicts interpreted as deformation tills (Kettlby Till) overlie deformed glaciolacustrine sediments that partially infill lows on the surface of the streamlined uplands (Figure 2.11a; Dreimanis, 1954; White, 1975). Widespread areas of interbedded silt, clay, diamict, and sand or gravel that characterize the low relief uplands landsystem record deposition by resedimentation processes in unstable subaqueous environments along the retreating Simcoe ice margin and steep slopes on the underlying Newmarket Till surface.

2.4.7 Fluvial Incision and postglacial lake evolution

South-trending glaciofluvial channels within the gravel bench landsystem that developed during the Mackinaw interstadial are cross-cut by a younger set of deep V-shaped channels and fills trending towards the northeast (Figure 2.8). The V-shaped valley and fills landsystem records fluvial incision and deposition associated with recession of the Simcoe ice lobe. Ice retreat allowed meltwaters to be routed through escarpment re-entrant valleys into newly-exposed basins in southern Simcoe County (Figure 2.3d). Continuous sets of lateral terraces along re-entrant valleys grade to deltas that record sediment delivery into a stable water body that developed in the early deglacial period (Figure 2.8b,c). The upper surface of the deltas at the mouths of the V-shaped valleys is at a similar elevation to beaches and wave-cut features found throughout southern Simcoe County, and suggests that these features formed in a stable, continuous water body that was extensive across the map area (Mulligan, 2011). The characteristics of this water body suggest it is correlative with glacial Lake Schomberg with water surface elevations of around 300m asl (Figures 2.8, 2.9, 2.12; Chapman & Putnam, 1984; Bajc et al., 2012). The high elevation of the water plane requires support from both the Simcoe ice lobe to the north, in the Barrie area, as well as the Ontario ice lobe to the south (Figure 2.3d). No conclusive geomorphologic or sedimentologic evidence for the position of drainage outlets for glacial Lake Schomberg were identified in this investigation; previous workers have suggested that early drainage was south, through topographic lows within the hummocky terrain landsystem of the Oak Ridges Moraine, or to the east in between the Moraine and the retreating Simcoe ice margin (Deane, 1950; Chapman & Putnam, 1984; Figure 2.3d).

Discontinuous sets of beaches and wave-cut scarps throughout the map area at elevations between 300m and 250m asl are interpreted to record continued retreat of the Simcoe ice lobe and step-wise drop in water levels in glacial Lake Schomberg, until a connection between water in the Simcoe and modern lake Huron basins was established around 12.5ka BP, forming early Lake Algonquin at approximately 250m asl (Figures 2.12, 2.18a; Eschman & Karrow, 1985).

Drainage of glacial Lake Schomberg caused a drop in regional base levels, resulting in perched water tables beneath the streamlined uplands and hummocky terrain landsystems. The new hydraulic gradients that developed are interpreted to have shifted and accelerated groundwater flow, causing increased groundwater discharge in the hummocky terrain landsystem and out the flanks of streamlined uplands through discrete sand beds (Section 2.3.2.4). Erosion of the sands undercut the overlying Newmarket Till on uplands and caused headward erosion, forming large groundwater piping scars or amphitheatres (Figure 2.14; Haggerty, 1991a; Barnett, 1997; Fox et al., 2006). In the hummocky terrain landsystem, base level drop and increased groundwater discharge is interpreted to be responsible for the formation of the large valleys that dissect the northern margins of the ORM (Figure 2.15).

Drainage of glacial Lake Schomberg exposed the streamlined uplands, but the lowland plains landsystem continued to be occupied by glacial lakes. Wave erosion in these lakes carved steep bluffs along the rim of lowland plains at elevations of between 220 and 235m asl (Figures 2.17, 2.18). The prominence of the bluffs surrounding the lowland plains suggests a relatively persistent, stable water body (Larson and Shaetzl, 2002). Broad ridges extending into the lowlands record beach and spit progradation into the lake (Krist and Shaetzl, 2001). Erosion and re-working of sediments from waves and fluvial systems surrounding the basin (Figures 2.17, 2.18) resulted in deposition of a thick sediment succession, which now forms the flat-lying floor of the lowland plains landsystem (Chapter 3). The regional elevation and tilt of the bluffs is consistent with reports of glacial Lake Algonquin shorelines within the study area (Deane, 1950; Chapman & Putnam, 1984; Finamore, 1985). Glacial Lake Algonquin (Figures 2.3e, 2.17d) fully inundated the lowland plains landsystem within the study area and existed in three distinct stages: i) early Lake Algonquin, 12.5-12ka BP; ii) Kirkfield Low phase, 12-11.5ka BP; iii) Main Lake Algonquin 11.5-10.4ka BP (Karrow et al., 1975; Lewis et al., 2008; Chapter 3).

2.4.8 Holocene lake drainage

Drainage of glacial Lake Algonquin from the map area occurred when retreat of the LIS exposed isostatically-depressed outlets in the French River and North Bay areas, diverting water east through the Ottawa River valley and resulting in a drop of regional water levels by nearly 100m (Eschman & Karrow, 1985). During early phases of drainage, localized depressions in the surface of lowland plains in the Cookstown and Holland Marsh valleys may have been isolated from the main parts of the Huron basin, allowing small (enclosed?) lakes to develop, and allowing the deposition of fine-grained lacustrine sediment until around 8190 ka BP (Figures 2.17b, 2.18f; Appendix B). During this time, the Lake Simcoe basin was occupied by a low-lying, hydrologically-closed lake (Todd et al., 2008). Drainage of glacial Lake Algonquin resulted in exposure of the sandy lake floor sediments and allowed sands to be re-worked into large dunes that form part in the lowland plains landsystem in the northern part of the study area (Figure 2.17c).

Uplift of the North Bay outlet allowed the Georgian Bay basin to refill and water inundated the lowlands as far south as Angus, in the northern part of the map area by 5.75 ka years BP, partially back-filling parts of the Nottawasaga River valley (Figure 2.3f; Bajc & Rainsford, 2010; Chapter 3). Regional water levels have been falling to present levels since 5 ka (Karrow & Mackie, 2012).

2.5 DISCUSSION

Identification and analysis of Quaternary sediment-landform systems in the southern Simcoe County region has not only facilitated mapping of the complex associations of surface and near-surface sediments but has also enhanced interpretations of the origins of regional sediment-landform assemblages and their paleoenvironmental significance. There has been much debate regarding the extent of glacial ice cover across southern Ontario during the late Quaternary and the role of subglacial meltwaters in the generation of surface and subsurface landforms and sediments. One controversial, but popular model describing the Quaternary landscape evolution of south-central Ontario invokes catastrophic release(s) of large quantities of stored subglacial meltwater, during which: i) sheetflows separate ice sheet from the bed and erode the till sheet to carve drumlins; ii) waning flow results in channelization and incision to form tunnel valleys; iii) final stages of flow and lowering of ice base forms eskers and allows deposition of Oak Ridges Moraine sediments (simplified from Shaw, 1983; Shaw & Sharpe, 1987; Shaw & Gilbert, 1991; Brennand & Shaw, 1994; Sharpe et al., 2004). This model suggests that many of the sediments and landforms in the study area were formed almost synchronously as the result of a single 'megaflood' event. (Brennand & Shaw, 1994; Sharpe et al., 2004) However, the characteristics and spatial relationships of the landsystems described here suggest that they may have formed over prolonged time periods, under both subglacial and proglacial conditions. In particular, the morphology, orientation, and sedimentary in-fills of the lowland plains that separate streamlined uplands, and the changing morphology of the streamlined uplands landsystem (the Newmarket Till surface) across the study area are difficult to reconcile with a subglacial megaflood origin.

2.5.1 Valleys underlying the lowland plains landsystem

The broad valleys that host the lowland plains landsystem have previously been interpreted as tunnel valleys, recording catastrophic release(s) of stored subglacial meltwater around 14 ka BP (Barnett, 1990; Sharpe et al., 2002; Sharpe et al., 2013). Coarse-grained deposits at the base of the valley in-fill successions in the Cookstown, Barrie, and Holland Marsh Valleys (Figure 2.1; Appendix A) record the presence of high-energy glaciofluvial systems that may have significantly deepened the valleys (Bajc et al., 2012; Bajc & Mulligan, 2013). However, the occurrence of diamict interpreted as Newmarket Till and drumlins beneath and along the flanks of the lowland plains suggests that the formation of the valleys underlying the lowlands predates drumlin formation, and that the valleys have been modified by glacial ice (Sections 2.3.2.1, 2.3.4.1). The differing depths and perpendicular orientation of the Barrie and adjacent Cookstown valleys (Figure 2.17d) may suggest diachronous development of some of the valleys in the study area (Section 2.3.4.1). The size of the valleys (up to 9-18km wide, measured from shoulder to shoulder) is much larger than reports of other Pleistocene tunnel channel systems described in Europe and North America (O'Cofaigh, 1997; Kehew et al., 2012).

2.5.2 Drumlins

The drumlins within the study area form the western extension of the Peterborough drumlin field (Chapman and Putnam, 1984). The origin of drumlins has long been a contentious issue, however they are largely ascribed to subglacial sediment deformation (Boulton & Hindmarsh, 1987; Evans et al., 2006; Benn & Evans, 2010; Maclachlan & Eyles, 2013), or by erosion during catastrophic release(s) of subglacial meltwater (megaflood hypothesis; Shaw & Sharpe, 1987; Sharpe et al., 2004; Shaw, 2010). Systematically changing orientations of drumlin long axes (Figures 2.1, 2.10, 2.12, 2.17; Appendix B) suggests diverging flow directions across the region. The changes in the morphologic expression of the surface of Newmarket Till, from highly streamlined (drumlinized) in the south to gently undulating in the north (Figures 2.1, 2.4), may hold important implications for current theories on subglacial dynamics (regardless of whether the upper surface of the till sheet reflects subglacial topography or an erosional surface following a sheetflow event). Drumlinized terrain appears to palimpsest onto, rather than be truncated by, valleys underlying the lowlands plains. This relationship suggests that streamlined terrain developed subsequently to formation of the valleys. Furthermore, the orientation of the upper reach of the Cookstown valley is perpendicular to former ice flow directions in the north and approximately parallel to ice flow in the south (Figures 2.1, 2.17d). This may have led to differential ice flow velocities between the two areas and could have been a contributing factor to the differences in the observed morphology of drumlins in this area.

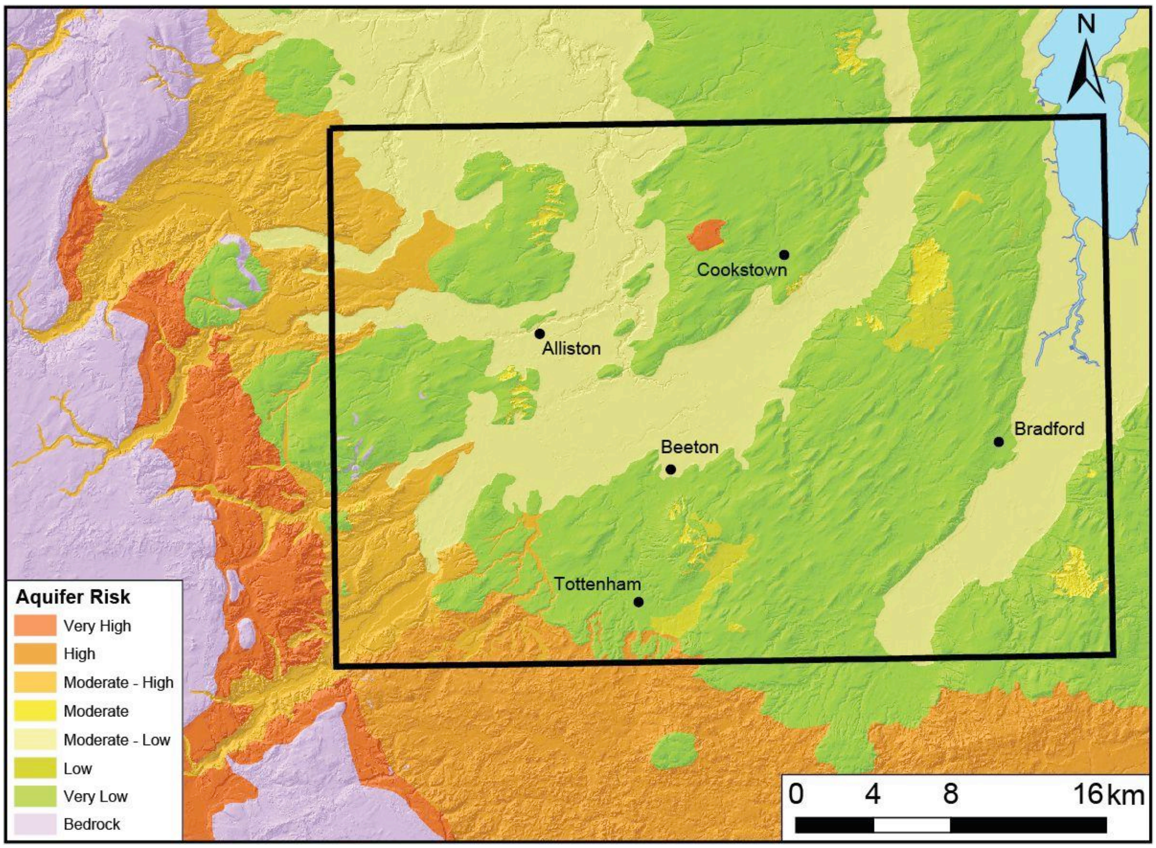
2.5.3 Deglacial Lakes

Establishing the timing of the evolution and drainage of glacial Lake Schomberg has long been a contentious issue, due to a lack of datable material and identifiable outlets (Deane, 1950; Chapman & Putnam, 1984; Mulligan, 2011). Unfortunately, the northern limits of glacial Lake Schomberg deposits could not be determined in this study. Sediments attributed to deposition in glacial Lake Schomberg are likely correlative with ice-contact and glaciolacustrine facies mapped at high elevations on uplands in the Barrie and Elmvale areas (Barnett, 1990). To support the elevated glacial Lake Schomberg water plane, retreating ice margins must have abutted the Niagara Escarpment to prevent drainage to the north. Ice marginal positions around the Oro, Banks and/or Edenvale moraines may have provided the northernmost shorelines for glacial Lake Schomberg (Burt & Dodge, 2011). Further investigation into landform relationships to the north of the study area is required to test this suggestion. Improved terrain data has assisted in the identification of wave-eroded scarps in between the Schomberg (300m asl) and Algonquin (235m asl) lake stages (Figure 2.14). Successively lower scarps within the streamlined uplands suggest that the final drainage of glacial Lake Schomberg was gradual, punctuated by periods of stable water planes, rather than a rapid basin-wide drop in water levels.

2.6 HYDROGEOLOGICAL APPLICATIONS

The complex arrangements of heterogenous Quaternary sediments in the southern Simcoe County region have hindered the development of effective hydrostratigraphic models for the region. In particular, the high topographic variability of the Newmarket Till sheet has posed problems for determining both vertical and lateral variability in sediment permeability and aquifer distribution across the region. However, the landsystems approach used in this study has greatly enhanced the ability to map and model the topography of the till sheet. By combining the distribution and stratigraphic position of mapped sediments (Appendix B) with knowledge of sediment hydraulic properties, a preliminary risk assessment map of potential aquifer contamination can be constructed (Figure 2.19). Streamlined and low-relief uplands capped by the Newmarket sand draped by extensive fine-grained glaciolacustrine (glacial Lake Schomberg deposits) from excellent surficial aquitards and have a low risk of surface water infiltration (Figure 2.19). Gravel benches, hummocky terrain and V-shaped valley landsystems contain thick successions of coarse-grained glaciofluvial material which locally incise through the Newmarket Till, creating potential hydraulic windows and posing a high risk to subsurface aquifers. Most upland landsystems contain relatively thin drapes of coarse-grained sediment above the Newmarket Till and therefore can be considered as relatively

Figure 2.19: Preliminary aquifer vulnerability map. Assessed risk for surface contaminant migration to deeper aquifers based on landsystem sediment characteristics, thickness, stratigraphic position, and inferred hydraulic properties.


N
Cookstown
Alliston
Beeton
Bradford
Tottenham
Aquifer Risk
Very High
High
Moderate - High
Moderate
Moderate - Low
Low
Very Low
Bedrock
0
4
8
16km

low risk, except west of Cookstown where wave erosion has exposed pre-Newmarket facies at surface, creating a direct pathway and very high risk for surface water (and contaminants) to enter the subsurface (Figure 2.19). Pre-Newmarket Till facies are also exposed within groundwater piping scars (amphitheatres), but based on the groundwater gradients required to form these features, it seems that these areas are likely to continue to promote groundwater discharge, rather than recharge to aquifers, reducing the risk of contamination of deeper aquifers (Figure 2.19). Lowland plain landsystems contain abundant coarse-grained material at the ground surface, but are underlain by thick successions of fine-grained sediment, often floored by the Newmarket Till aquitard and are therefore considered here to be of low risk (Figure 2.19, Chapter 3). It is hoped that the preliminary risk assessment map of potential aquifer contamination presented here (Figure 2.19) can serve as a guide for future hydrostratigraphic and hydrogeologic investigations in the southern Simcoe County region.

2.7 CONCLUSIONS

Detailed analysis of sediment-landform assemblages in the southern Simcoe County region has provided valuable information that may be used to discern the nature of paleoenvironmental changes that affected the region during and following the last glacial episode. Prominent bedrock features in the region (the Niagara Escarpment) appear to have played a role in constraining ice flow directions, and controlling the limits of ice advance during the deglacial period. Thick successions of glaciolacustrine deposits underlying the streamlined uplands landsystem record the presence of an extensive lake body that inundated the study area prior to Wisconsin ice advance (Figures 2.3a, 2.16; Appendix A). These deposits may be correlative with the Thorncliffe formation in the

Greater Toronto Region (Karrow, 1967; Eyles & Eyles, 1983; Sharpe et al., 2011). The streamlined uplands landsystem is capped by a regional till sheet (the Newmarket Till; Gwyn, 1972; Russell & Dumas, 1997) that records ice advance from the northeast during the main glacial phase of the Wisconsin Episode (Nissouri phase; Figure 2.2). The Newmarket Till appears to have a highly undulating and drumlinized surface topography (Figures 2.10, 2.16) with much greater regional surface relief than previously thought.

In the southern part of the study area, hummocky terrain of the Oak Ridges Moraine is underlain by up to 75m of sand with interbedded silt and gravel which in turn overlies the Newmarket Till (Figure 2.16; Appendix A) and records glaciofluvial and glaciolacustrine sedimentation between the Ontario and Simcoe ice lobes. Low-relief uplands are capped by interbedded diamict units overlying the Newmarket Till or fine-grained glaciolacustrine deposits (Figure 2.11). Locally, the Kettleby Till has characteristics similar to a deformation till and probably records minor, isolated ice advances over previously deposited fine-grained glaciolacustrine sediments during the early deglacial period.

Widespread glaciolacustrine deposits overlie the Newmarket Till on streamlined uplands, and localized coarse-grained deposits observed along scarps or flat plains around 300m asl indicate the presence of former shorelines that are interpreted here to belong to glacial Lake Schomberg (Figure 2.14; Appendix B). Glacial Lake Schomberg formed a stable water plane across the study area around 12.5 ka BP, which is marked by deltas in the west and beaches and shore bluffs in the east. In order to support a lake at this elevation, the Ontario lobe ice would need to be near its maximum extent (Port Huron phase?; Figure 2.3d) to prevent southward drainage through topographic lows on the

ORM. Drainage of glacial Lake Schomberg was gradual, forming a series of successively lower water planes during the transition to early Lake Algonquin around 12-10.5 ka BP. Large groundwater piping scars (amphitheatres) and valleys along the margins of the ORM are interpreted to record falling base levels following ice retreat and drainage of glacial Lake Schomberg.

V-shaped valleys that incise the margins of gravel benches adjacent to the Niagara Escarpment in the west and the Oak Ridges Moraine in the south are infilled with thick coarse-grained glaciofluvial deposits and grade down toward the surface of the lowland plains. The lowland plains landsystem is contained within a series of broad and extensive surface valleys (the Alliston Embayment and Barrie, Cookstown and Holland Marsh Valleys), which are underlain by up to 75m of glaciolacustrine and fluvial deposits that overlie the Newmarket Till in many areas (Figures 2.9, Chapter 3; Appendix A). The formation of the large valleys underlying lowland areas may pre-date advance of the Laurentide Ice Sheet into the study area.

Detailed analysis of the Quaternary landsystems in the Alliston map area has provided an improved framework for the understanding of the spatial and temporal relationships of major sediment units and landforms in the shallow subsurface. Analysis of the spatial configuration and internal composition of landsystems in the study area has aided in the development of a preliminary risk assessment map of potential aquifer contamination in the region. Understanding the stratigraphy of regional sediment groups within a highly undulating terrain has important implications for our understanding of the region's geologic history and hydrostratigraphy.

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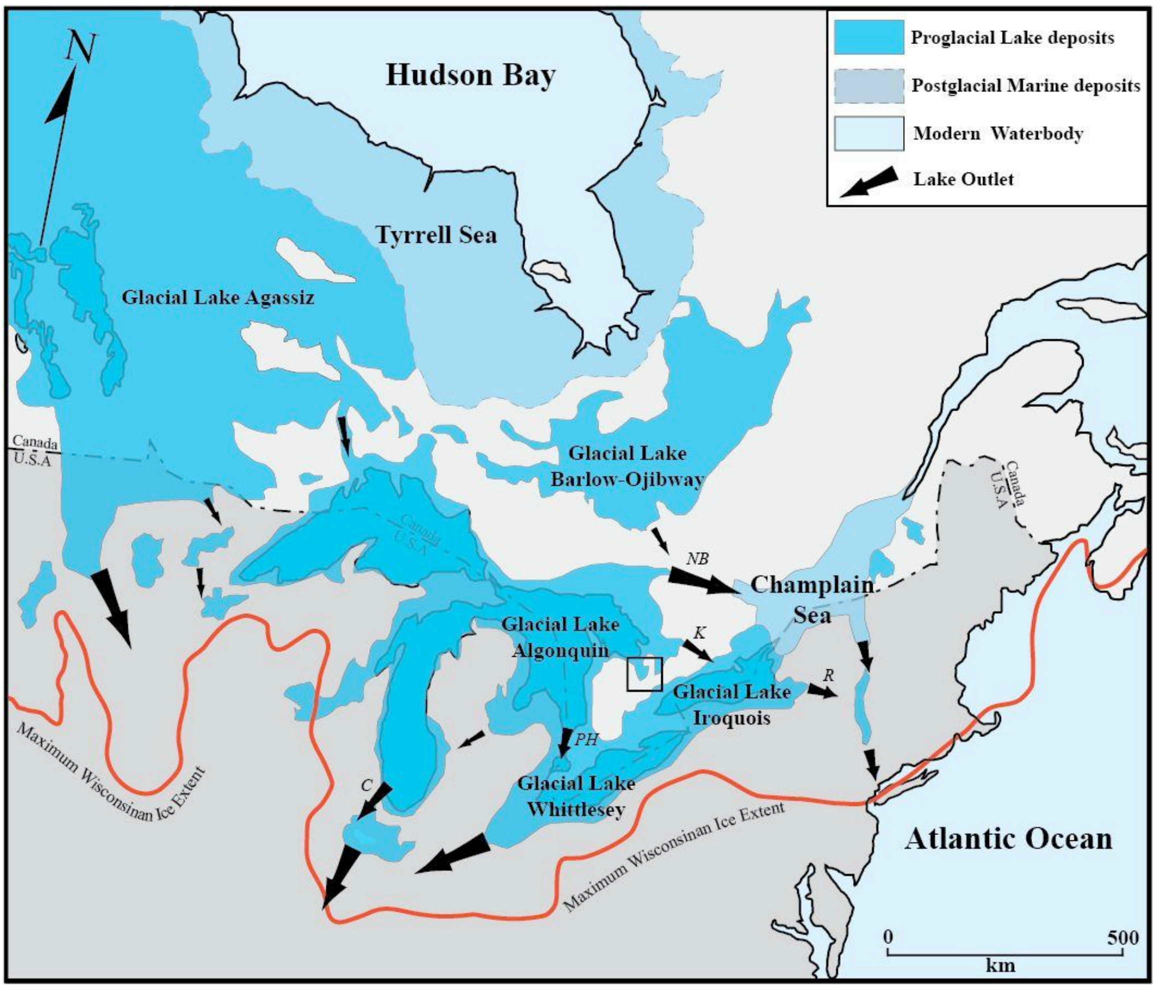
CHAPTER 3: PALEOENVIRONMENTAL ANALYSIS AND HYDROGEOLOGIC SIGNIFICANCE OF LATE WISCONSIN AND HOLOCENE GLACIOLACUSTRINE DEPOSITS, SOUTHERN SIMCOE COUNTY, ONTARIO, CANADA

3.1 INTRODUCTION

Large areas of Canada and the northern United States were covered by glacial lakes at the end of the Late Wisconsin glaciation, as meltwaters draining from retreating ice margins were ponded in isostatically-depressed basins bordering the ice front (Teller, 2001; Figure 3.1). In southern Simcoe County, Ontario (Figure 3.2), thick successions of glaciolacustrine sediment are found at surface, particularly within lowland areas, and record the evolution and drainage of a series of Late Wisconsin to Holocene deglacial lakes (Chapman & Putnam, 1984; Bajc et al., 2012). Glacial lakes Schomberg (13-12 ka), Algonquin (12-10.5 ka), and Nipissing (6-4 ka) inundated the study area and deposited sediments that contain a high-resolution record of post-glacial environmental change as ice margins withdrew from the region (Figure 3.3). The sediments deposited in these former glaciolacustrine basins now host significant regional and local aquifers (Sibul & Choo-Ying, 1971). Detailed sedimentological analysis of the deglacial lake deposits will enhance understanding of the three-dimensional (3D) distribution of sediment groups within the shallow subsurface, which is essential for future hydrogeological investigations in the region. Southern Simcoe County has been targeted for rapid urban and industrial development in the near future (Ministry of Public Infrastructure and Renewal, 2006) and this type of investigation is essential for the evaluation and protection of potable groundwater resources.

This paper presents a detailed sedimentological description and analysis of sediments attributed to deposition in deglacial lakes Schomberg, Algonquin and Nipissing that are well exposed along the Nottawasaga River in southern Simcoe County (Figures 3.2, 3.4). Previous investigations were undertaken as regional-scale studies that focused on shoreline correlation across the lake basins (e.g. Chapman and Putnam, 1984),

Figure 3.1: Extent of proglacial lake and postglacial marine deposits in central Canada and northern United States during the deglacial period. Lake outlets identified by black arrows; C=Chicago outlet, PH=Port Huron outlet, R=Rome outlet, K=Kirkfield outlet, NB=North Bay outlet. Red line identifies southernmost extent of Wisconsin glacial ice. Location of Figure 2b shown in black rectangle. Modified from Teller (1990).


Proglacial Lake deposits
Postglacial Marine deposits
Modern Waterbody
Lake Outlet
N
Hudson Bay
Tyrrell Sea
Glacial Lake Agassiz
Glacial Lake Barlow-Ojibway
Canada
U.S.A
Champlain Sea
Glacial Lake Algonquin
Glacial Lake Iroquois
Glacial Lake Whittlesey
NB
K
R
PH
C
Maximum Wisconsinan Ice Extent
Maximum Wisconsinan Ice Extent
Atlantic Ocean
0
500
km

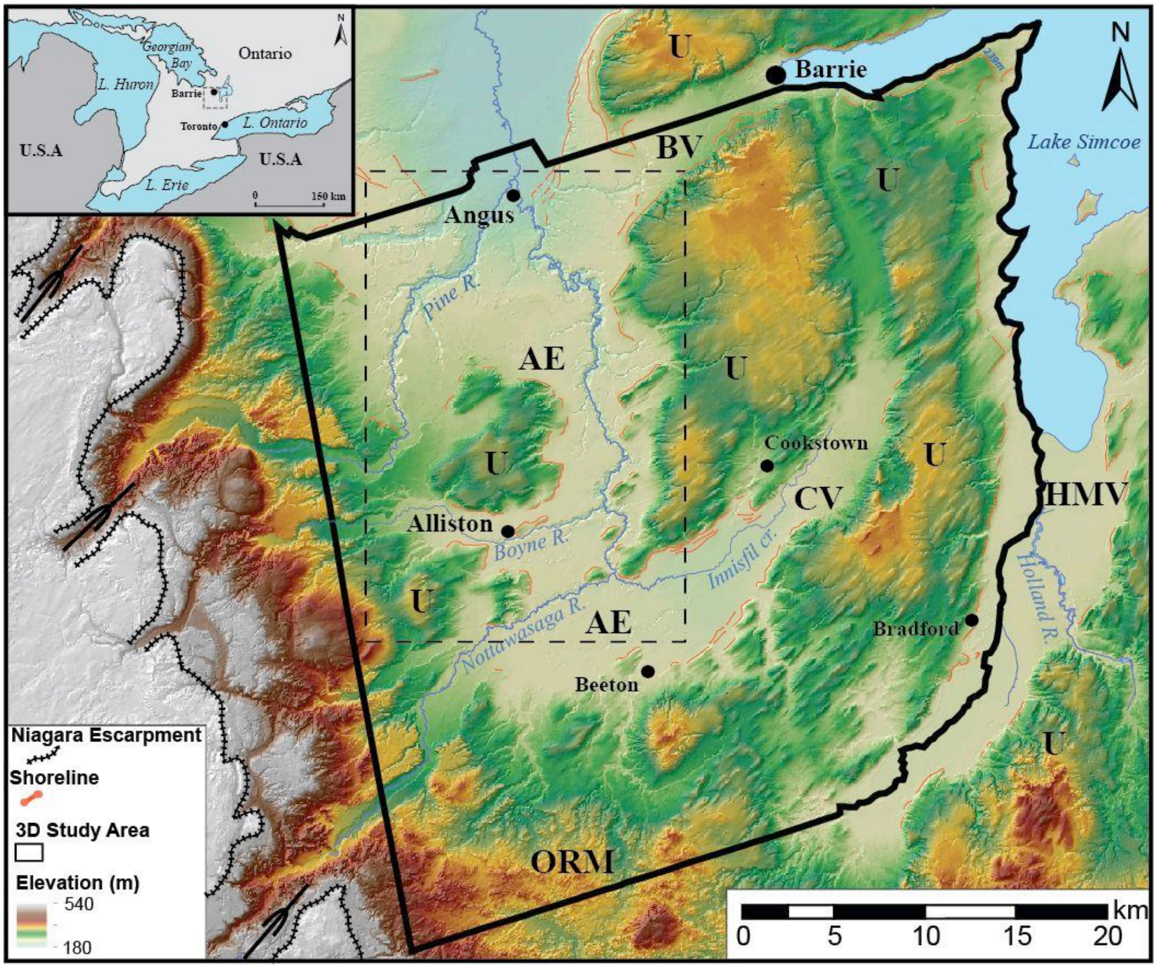
and sedimentological data are sparse (Deane, 1950; Gravenor & Coyle, 1985; Bajc et al., 2012). In this study, outcrop data are used to help develop an improved stratigraphic framework for lowland areas in the region and to better constrain data from fully-cored boreholes drilled as part of a regional-scale 3D mapping program conducted by the Ontario Geological Survey (OGS; Bajc & Rainsford, 2011; Bajc et al., 2012; Figure 3.4). Together, the outcrop and borehole data allow for the development of a stratigraphic framework that enhances paleoenvironmental interpretation of deglacial conditions within lowland areas in the southern Simcoe region and may be used to predict the hydraulic properties of shallow subsurface sediments as well as to identify controls on groundwater behavior.

3.2 GEOLOGIC BACKGROUND

The study area is underlain by a thick succession of Paleozoic strata lying above Precambrian basement rocks (Armstrong & Dodge, 2010). Differential erosion of thick successions of soft shales underlying more resistant dolostones created the Niagara Escarpment that stretches across central Ontario and forms the western border of the study area (Figure 3.2). This regional-scale feature is punctuated by a series of northeast-trending re-entrant valleys carved by fluvial and glacial erosion during and prior to the Quaternary (Figure 3.2; Straw, 1968). A system of buried bedrock valleys was also incised into the Paleozoic strata beneath the study area by pre-Quaternary fluvial erosion (Spencer, 1890; Eyles et al., 1985) and/or by subglacial meltwater erosion during the Wisconsin Episode (Gao, 2011).

The Paleozoic bedrock surface is overlain by Quaternary sediments that are attributed primarily to the Wisconsin Episode and form successions greater than 200m

Figure 3.2: Location of study area within Great Lakes region with location of study area shown in dashed rectangle (inset); Digital Elevation model (DEM) of study area showing the Niagara Escarpment, Oak Ridges Moraine (ORM), Upland areas (U), the Barrie (BV), Cookstown (CV) and Holland Marsh (HMV) valleys, Alliston embayment (AE), shoreline features of Lake Algonquin and its successors, and modern hydrological features. Location of Figure 4a shown in dashed rectangle. DEM from Ministry of Natural Resources (2002); shoreline data from OGS (2003) and Mulligan and Bajc, 2012 (Appendix B).

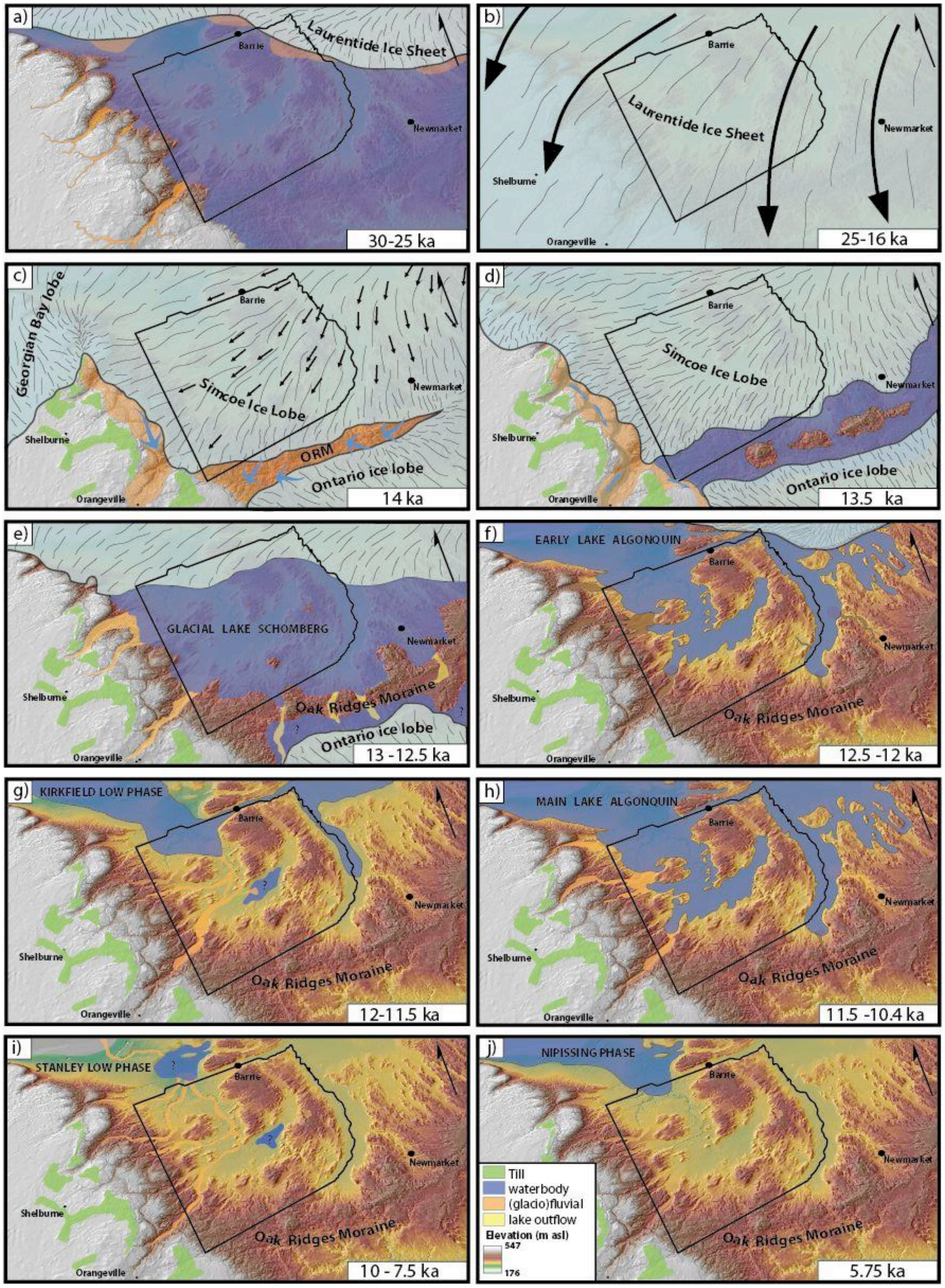

Georgian Bay
Ontario
L. Huron
Barrie
Toronto
L. Ontario
U.S.A
U.S.A
L. Erie
0
150 km
N
U
Barrie
N
BV
Lake Simcoe
U
Angus
Pine R.
AE
U
U
Cookstown
U
CV
HMV
Alliston
Boyne R.
Innisfil cr.
U
AE
Nottawasaga R.
Bradford
Holland R.
Beeton
U
Niagara Escarpment
Shoreline
3D Study Area
Elevation (m)
540
180
ORM
km
0
5
10
15
20

thick above bedrock valleys (Gao et al., 2006). Pre-Wisconsin Episode deposits exposed along the Scarborough bluffs and underlying the Toronto region to the south, host aquifers suitable for groundwater extraction (Howard et al, 1996). These pre-Wisconsin sediments may also exist within the study area, but have not been confirmed to date (Bajc et al., 2012).

During the later phases of the Wisconsin glacial episode (25-15 ka), the Laurentide Ice Sheet (LIS) advanced into the study area from the north and northeast and deposited the Newmarket Till as an extensive subglacial till sheet (Gwyn, 1972; Sharpe et al., 2004; Figures 3.3a,b). The Newmarket Till forms a drumlinized and highly undulating topographic surface across the study area (Sharpe et al., 2002) and can be observed capping broad upland areas (Figure 3.2) that are separated by a series of narrow valleys (labeled AE, BV, CV, HMV; Figure 2). During the early stages of ice recession (16-15 ka), the margin of the LIS thinned and became lobate (Barnett, 1992; Figure 3.3c). Thick accumulations of glaciofluvial and glaciolacustrine sediment were deposited in an interlobate setting, between the Simcoe ice lobe to the north and the Ontario ice lobe to the south, resulting in the formation of the Oak Ridges interlobate moraine complex (herein referred to as the Oak Ridges Moraine; Howard et al., 1996; Barnett et al., 1998; Sharpe et al., 2002; Figure 3.3c).

A succession of shoreline features and surficial lacustrine sediments record the development of a series of lakes across the area during later phases of deglaciation (after 13 ka) (Deane, 1950; Chapman & Putnam, 1984; Lewis et al., 2008; Figures 3.3e-j). In many places, glaciolacustrine sediments directly overlie the Newmarket Till (Mulligan, 2011). This series of post-glacial lakes, termed glacial lakes Schomberg, Algonquin and

Figure 3.3: Late Wisconsin – Holocene paleogeographic reconstructions of central Ontario overlain onto regional DEM (3D study area outlined in black): a) ice advance from the northeast into aerially extensive lake; b) regional ice cover during late Wisconsin glacial maximum showing ice flow directions (black arrows) as reconstructed from drumlin and striae orientation; c) separation of ice lobes and formation of Oak Ridges Moraine and kame terrace deposits. Direction of meltwater paleoflows shown with blue arrow; d) incision of kame terraces and development of early ice marginal lakes; e) extent of glacial Lake Schomberg; f-h) extent of glacial Lake Algonquin during several distinct phases; i) Stanley low water phase; j) Nipissing phase. Data from multiple sources; references within text.



a)
Barrie
Laurentide Ice Sheet
Newmarket
30-25 ka
b)
Barrie
Laurentide Ice Sheet
Newmarket
Shelburne
Orangeville
25-16 ka
c)
Georgian Bay lobe
Barrie
Simcoe Ice Lobe
Newmarket
Shelburne
ORM
Ontario ice lobe
Orangeville
14 ka
d)
Barrie
Simcoe Ice Lobe
Newmarket
Shelburne
Ontario ice lobe
Orangeville
13.5 ka
e)
GLACIAL LAKE SCHOMBERG
Newmarket
Shelburne
Oak Ridges Moraine
Ontario ice lobe
Orangeville
13 -12.5 ka
f)
EARLY LAKE ALGONQUIN
Barrie
Newmarket
Shelburne
Oak Ridges Moraine
Orangeville
12.5 -12 ka
g)
KIRKFIELD LOW PHASE
Barrie
Newmarket
Shelburne
Oak Ridges Moraine
Orangeville
12-11.5 ka
h)
MAIN LAKE ALGONQUIN
Barrie
Newmarket
Shelburne
Oak Ridges Moraine
Orangeville
11.5 -10.4 ka
i)
STANLEY LOW PHASE
Barrie
Newmarket
Shelburne
Oak Ridges Moraine
Orangeville
10 - 7.5 ka
j)
NIPISSING PHASE
Barrie
Newmarket
Till
waterbody
(glacio)fluvial
lake outflow
Elevation (m asl)
547
176
Oak Ridges Moraine
5.75 ka

Nipissing, occupied the study area during discrete phases of the deglacial period (e.g. Chapman & Putnam, 1984; Eschman & Karrow, 1985). Glacial Lake Schomberg was the first to develop (13-12.5 ka), forming a stable water plane at 300m asl, as meltwaters were dammed between the Niagara Escarpment to the west, the Oak Ridges Moraine (and Ontario ice lobe) to the south, and the retreating Simcoe ice lobe to the north (Figures 3.2, 3.3e). Subsequent ice retreat of the Simcoe lobe from the Niagara Escarpment in the north allowed waters of Lake Schomberg to coalesce with those occupying the Lake Huron basin forming glacial Lake Algonquin (12.5-10.5 ka; Figure 3.3f; Eschman & Karrow, 1985). Several discrete phases of this lake have been identified from shoreline studies across the region and record progressive retreat of ice from the basin and isostatic uplift of outlets (Figures 3.3f-h). Early Lake Algonquin (Karrow et al., 1975) developed after the final phase of drainage of glacial Lake Schomberg, as water levels fell to incrementally lower levels (from 300m to approximately 250m asl; Figure 3.3f). A low-water phase (Kirkfield low; 12-11.5ka) marks the opening of a new outlet to the east near Fenelon Falls (Kaszycki, 1985; Figure 3.3g). Isostatic rebound of this lake outlet allowed the basin to refill and form main Lake Algonquin (11.5-10.4ka) with a water surface elevation of 230m asl (Finamore, 1985; Figure 3.3h). Ice recession beyond isostatically-depressed outlets in the northern parts of Algonquin Park and near North Bay, Ontario around 10.6 ka resulted in drainage of glacial Lake Algonquin from the study area and the establishment of the Stanley Low Phase (Lewis et al., 2008; Figure 3.3i). Finally, uplift of the North Bay outlet following deglaciation allowed refilling of the basin and the establishment of the Nipissing Phase of the Upper Great Lakes (6-4 ka) with a water plane elevation of 190m asl (Figure 3.3j). Detailed discussion of regional lake level changes during the deglacial period are provided by Deane (1950), Gravenor (1957), Eschman & Karrow (1985), and Lewis et al. (2008).

3.3 FACIES ANALYSIS

Inundation of the study area by extensive lakes during the deglacial period resulted in deposition of a thick sediment succession characterized by a wide variety of sediment types as water levels fluctuated during discrete lake phases. Detailed analysis of these sediments allows interpretation of paleoenvironmental conditions and, ultimately, improved prediction of subsurface unit geometries, a critical component of 3D modeling efforts.

3.3.1 Data Sources

Glaciolacustrine sediments are extensively exposed along rivers within the Nottawasaga River drainage basin (Figure 3.4a; Karrow et al., 1975; Fitzgerald, 1985; Mulligan, 2011; Bajc et al., 2012); 56 exposures were identified and logged in this study (Figure 3.4a). Sections were cleaned and logged using standard sedimentological logging techniques, recording grain size, bedding, sedimentary structures, bed contacts, clast lithologies, unit geometry and continuity of contacts between sediment groups, and paleocurrent directional indicators (Figure 3.4b). Qualitative descriptions of groundwater seepage zones observed on the outcrops were also made.

The sedimentological data obtained from section logging are used to supplement core data obtained from four fully-cored boreholes drilled by the OGS within the Alliston Embayment of the former Lake Algonquin plain during the summers of 2011 and 2012 (Figures 3.2, 3.4a; Bajc & Rainsford, 2011; Bajc et al., 2012; Appendix A). Digital data used to create surface maps were obtained from the Ontario Ministry of Northern

Figure 3.4: a) DEM of Nottawasaga River valley showing location of measured sections (green dots) and OGS boreholes (white dots). Location of Figures 3.10 and 3.14 shown in dashed black rectangles. Outcrop sections used to construct Figure 3.13 shown by red dots; b) idealized stratigraphic log summarizing the overall stratigraphy of the Nottawasaga River valley. Facies are grouped into facies associations (FA1 through 6 – see text for detailed descriptions). Legend for sediment logs (Figures 3.12-3.14 and 3.16) shown at right.

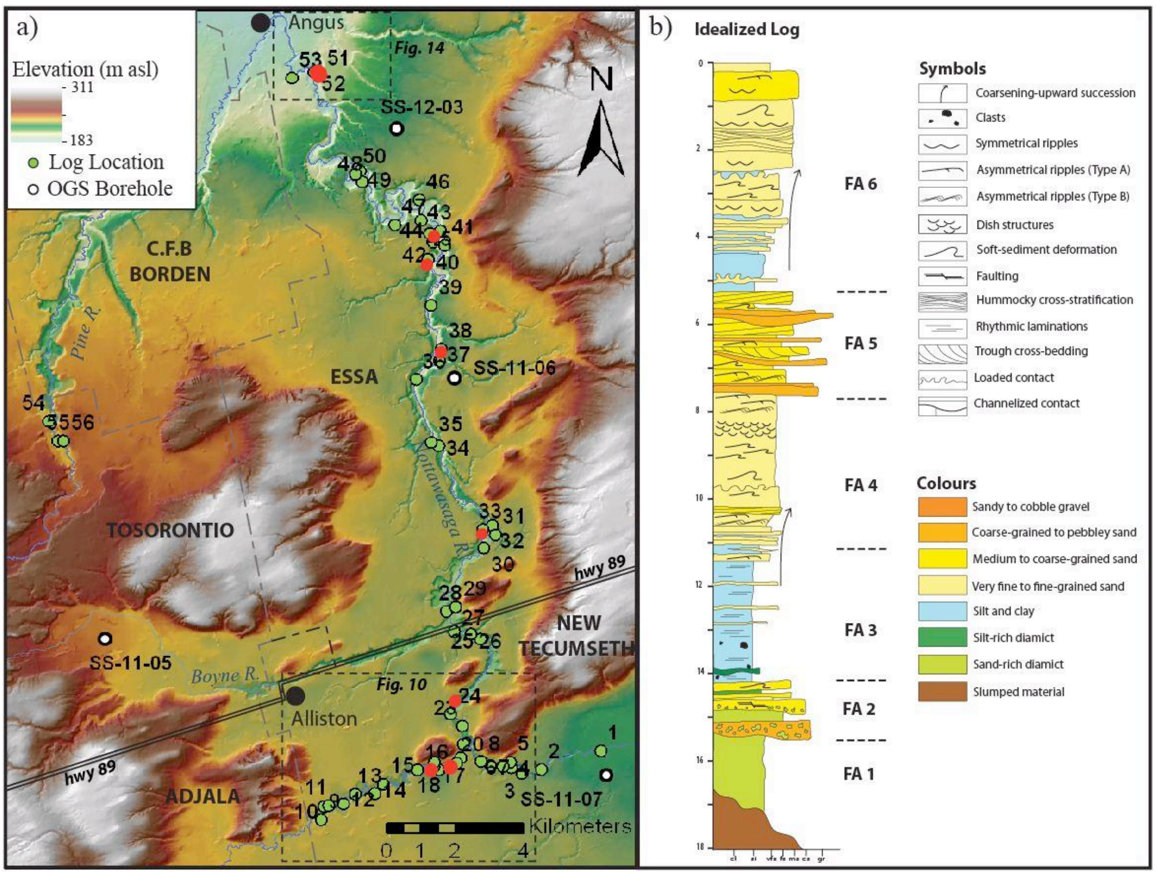

a)
Elevation (m asl)
311
183
Log Location
OGS Borehole
Angus
Fig. 14
SS-12-03
C.F.B
BORDEN
ESSA
SS-11-06
TOSORONTIO
NEW
TECUMSETH
hwy 89
SS-11-05
Boyne R.
Alliston
Fig. 10
ADJALA
SS-11-07
Kilometers
0 1 2 4
Pine R.
Nottawasaga R.
b)
Idealized Log
FA 6
FA 5
FA 4
FA 3
FA 2
FA 1
Symbols
Coarsening-upward succession
Clasts
Symmetrical ripples
Asymmetrical ripples (Type A)
Asymmetrical ripples (Type B)
Dish structures
Soft-sediment deformation
Faulting
Hummocky cross-stratification
Rhythmic laminations
Trough cross-bedding
Loaded contact
Channelized contact
Colours
Sandy to cobble gravel
Coarse-grained to pebbley sand
Medium to coarse-grained sand
Very fine to fine-grained sand
Silt and clay
Silt-rich diamict
Sand-rich diamict
Slumped material

Table 3.1: Description and interpretation of lithofacies associations (FA's) identified in outcrop exposures.

	Thickness	Description	Interpretation
FA 6	2 - 8m	coarsens-upward from laminated silt into fine- to medium-grained sand with symmetrical ripples, HCS, deformation structures, horizontal truncation horizons, starved asymmetrical ripples; fossiliferous	**Shallow glaciolacustrine**
FA 5	1 - 4m	gradational lateral facies change from sandy gravel in the south to planar-laminated fine- to medium-grained sand with large silt rip-ups in the north;northward paleocurrent indicators; planar unit geometry except in large channel-ized features into underlying FA's; mollusc-bearing; observed at two stratigraphic intervals	**Fluvial braid plain**
FA 4	2 - 8m	sand beds in FA 3 grade into 5m thick packages of rippled and deformed fine-grained sand with 10cm thick silt drapes; large-scale deformation features, dish struc-tures, type-A and B asymmetrical ripples present in sand; paleocurrents toward the north; variable thickness, occurs at two stratigraphic intervals; paleosols and buried organic horizons cap the upper unit at Angus	**Prograding delta**
FA 3	2 - 12m	rhythmically-laminated silt and clayey silt with sand beds increasing in thickness and frequency up section; strati-fied silt-rich diamict beds 10cm thick and clast horizons near base of unit, clasts deform underlying layers; inter-nal laminae observed in coarse and fine-grained rhyth-mite beds, often small-scalle deformation horizons; sands horizontally-bedded with planar laminae or starved ripples; unit observed in all sections	**ice-contact glaciolacustrine**
FA 2	up to 3m	interbedded sand-rich diamict with very fine to fine-grained sand or gravel; sands highly faulted and deformed; ripples, planar bedding and silt drapes preserved; diamict facies crudely stratified; clasts up to 30cm, individual diamict packages up to 1m thick; highly localised distribution, near steep slopes on FA 1	**Subaqueous ice-marginal debris flows**
FA 1	up to 15m	massive, occasionally crudely stratified or fissile matrix; 5-10% clasts; dominantly local carbonates occasional Precambrian clasts, up to 3m diameter; sub-rounded to angular, striated and faceted; striae and long axes oriented WSW-SW; occasional boulder horizons; highly variable surface topography	**Subglacial till**

Development and Mines and include a 5m digital elevation model (DEM), hillshade model, aerial photography, and surficial geology data.

3.3.2 Facies Associations

Individual facies types have been grouped into genetically-related facies associations, as these provide the most appropriate basis for paleoenvironmental interpretation (Miall, 1978; Plint, 2010). Six lithofacies associations (FA's) were identified in the exposures along the Nottawasaga River Valley and form a stratigraphic succession that can be traced consistently along the valley (Figure 3.4b). The stratigraphy is floored by a sand-rich diamict (FA 1; Figures 3.4b, 3.5) capped locally by interbedded sands and sand-rich diamict (FA 2; Figures 3.4b, 3.6). Silt rhythmites (FA 3; Figures 3.4b, 3.7) overlie these units and pass upwards into rippled fine-grained sand (FA 4; Figures 3.4b, 3.8). A coarser-grained unit of channelized fine-grained sand to gravel (FA 5; Figures 3.4b, 3.9) overlies and is incised into underlying units, and is overlain by a coarsening-upward succession of sand and silt rhythmites (FA 6; Figures 3.4b, 3.11). The overall Nottawasaga River valley stratigraphy consists of two coarsening-upward successions overlying the diamict of FA1 (Figure 3.4b).

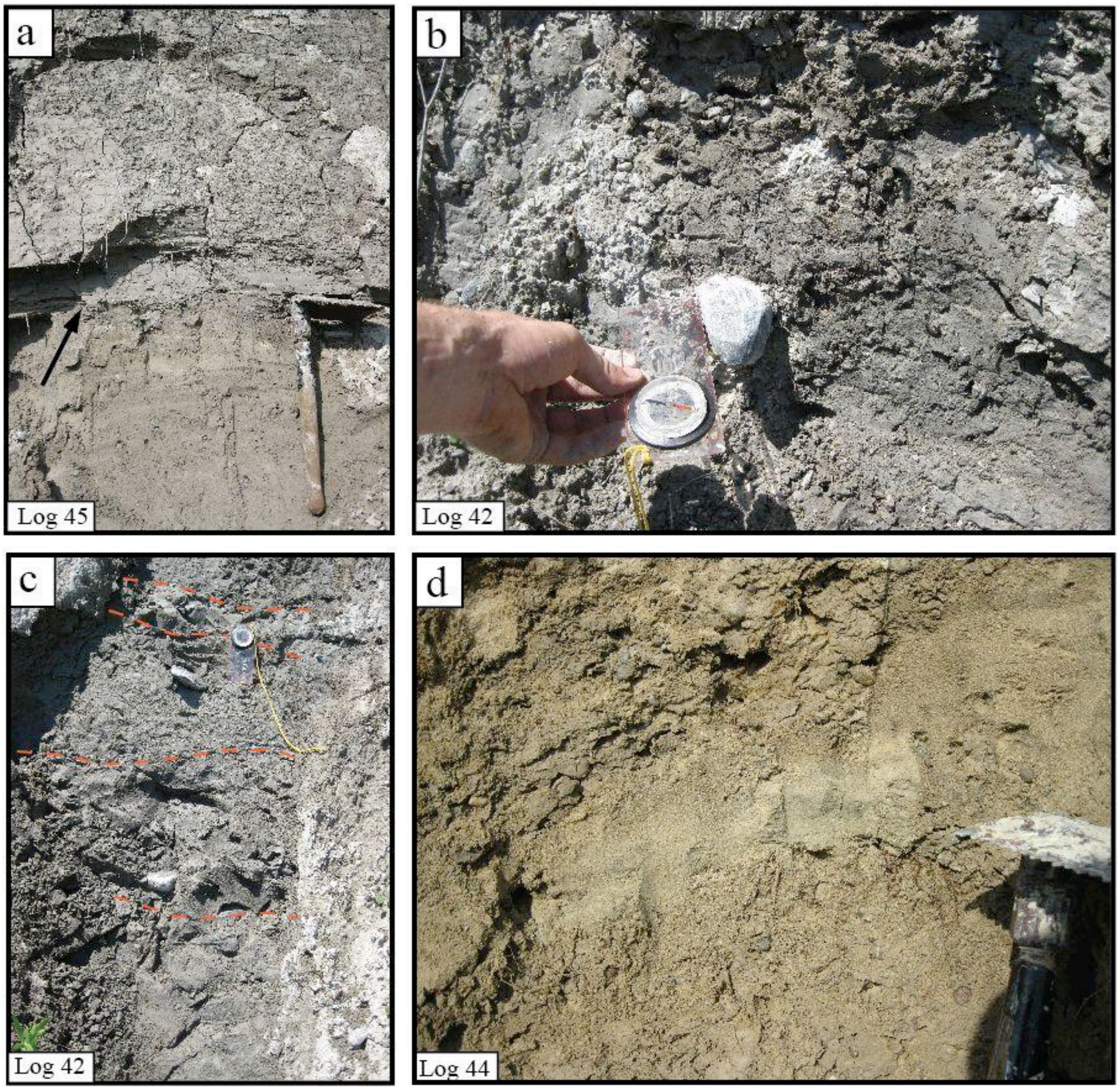
3.3.2.1 FA 1: Sand-rich diamict

A unit of silt to sand-rich diamict up to 15m thick is observed at several locations along the base of cut bank exposures along the Nottawasaga, Pine, and Boyne Rivers (Figure 3.4a). The diamict appears massive at most locations (Figure 3.5a,b), but crude stratification of more silt-rich facies can be observed at some outcrops (Figure 3.5c). The diamict matrix is poorly sorted and highly consolidated, often displaying well-developed fissility (Figure 3.5c). Clasts comprise less than 5-10% of the diamict and are dominantly sub-angular to sub-rounded, composed of locally-derived carbonate lithologies. Clast size ranges from granules to boulders over 3m in diameter. Most of the boulder-sized clasts (>1m diameter) are composed of more resistant lithologies of far-travelled Precambrian rocks. Carbonate clasts are often striated and faceted with flattened tops or bullet shapes (Figure 3.5b). Long axes of the clasts tend to be sub-horizontal and show a preferred northeast-southwest orientation (Figure 3.5b).

Occasional weakly-developed horizontal boulder horizons are observed within FA1, often in association with thin silt to gravel lenses and interbeds (Figure 3.5d). Groundwater is commonly observed discharging from the outcrop faces at the upper surface of the diamict unit or along the base of interbeds composed of sand or gravel. FA1 ranges in thickness from 1 to 15m (Figure 3.13) and its occurrence is discontinuous along the river due to an undulating upper surface. The lower bounding surface of this unit is not exposed anywhere along river cutbank exposures. The surface topography FA 1 is highly variable, with changes in elevation of up to 8m observed within a single outcrop, and by more than 20-40m between exposures (Figure 3.13).

The characteristics of FA 1 suggest a subglacial origin for this unit. The presence of striated clasts with a preferred parallel and sub-horizontal orientation, poor textural sorting, and high consolidation and fissility of the diamict matrix, are all consistent with subglacial deposition (e.g. Boulton & Deynoux, 1981; Evans et al., 2006; Benn & Evans, 2010). Coarse-grained interbeds within FA 1 probably record the activity of sub-glaciofluvial systems draining meltwater toward the former ice margin. The physical

Figure 3.5: FA1: a) massive diamict (lower half) directly overlain by silt rhythmites (upper half, FA 3). Contact shown with black arrow at left; shovel is 50cm long; b) massive, blocky matrix of diamict with striated clast in-situ. Clast long axis and striae are parallel (orientation 230 degrees N); compass is 12cm long; c) crude stratification in FA 1 showing massive, blocky texture at base, fissile beds and silt-rich beds near top; contacts between beds shown in red dashed lines, ice flow was into page; d) coarse-grained pebbley sand interbed within FA 1.

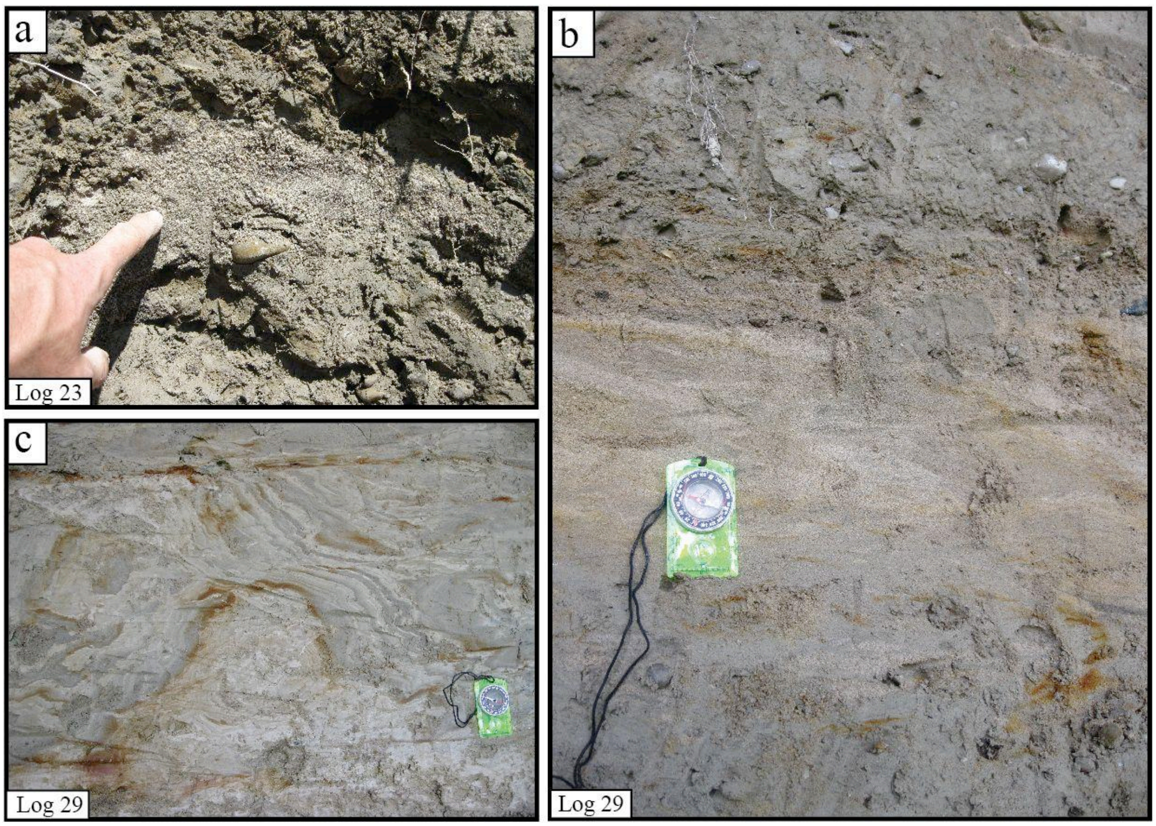

a
Log 45
b
Log 42
c
Log 42
d
Log 44

characteristics of FA 1 are similar to those reported for the Newmarket Till (Gwyn, 1972; Russell & Dumas, 1997), and its surface topography, and stratigraphic position (Todd et al., 2008; Bajc et al., 2012) are also consistent with an interpretation of FA1 as correlative to the Newmarket Till (Figure 3.3b). Outcrops of FA 1 are typically found close to areas where Newmarket Till has been mapped at the surface (Figure 3.4a; Appendix B). The highly variable surface elevation of FA1 along the Nottawasaga River may reflect drumlinization of the till surface beneath lowland areas, as reported in marine seismic investigations by Todd et al. (2008) in the Lake Simcoe basin.

3.3.2.2 FA 2: Interbedded sand and sand-rich diamict

Localized deposits of interbedded crudely stratified sand and sand-rich diamict lie directly above FA1 (FA2, Figure 6). Grain size in FA2 ranges from silt to very fine to coarse-grained sand or gravel in the coarse-grained, sorted layers (Figure 3.6a). These facies are often highly deformed by shearing, folding and faulting when overlain by diamict beds (Figure 3.6b,c); in places, primary bedding features are preserved and consist of asymmetrical ripples, planar beds and occasional silt drapes. Diamict facies contain clasts up to 30cm in diameter and range from stratified, stone-poor, silt-rich diamict to structureless, well-consolidated, clast- and sand-rich diamict. Sand and sand-rich diamict are interbedded in FA 2, with individual beds reaching up to 1m thick. Contacts between individual facies types are typically sharp, highly deformed, and irregular (Figure 3.6). FA 2 is generally less than 3m thick and is only locally observed above FA 1, most commonly in areas where the surface of FA1 is irregular and has high relief, as was observed near the flanks of isolated ridges of Newmarket Till mapped at

Figure 3.6: FA 2: a) interbedded coarse-grained sand and silt-rich diamict; b) deformed and faulted medium to coarse-grained sand and sand-rich diamict beds. Diamict beds have textural similarities to FA 1; c) highly deformed unit of silt and very fine-grained sand.


a
Log 23
b
Log 29
c
Log 29

surface (Figures 3.2, 3.13; Appendix B). The overall spatial distribution of this unit in the study area is poorly constrained.

The localized distribution of FA 2 capping FA 1, combined with its poor sorting, crude stratification, and pervasive deformation features suggest an ice-proximal depositional environment (Benn and Evans, 2010). Deformed asymmetrical ripple forms within sand facies and thin silt drapes suggest a subaqueous origin for the well-sorted beds. FA 2 is interpreted to record early deglacial sedimentation along steep slopes on the surface of FA 1 adjacent to a retreating ice margin. Well-sorted beds imply sedimentation into an ice-marginal lake by density underflows and settling of finer-grained layers (Smith & Ashley, 1985); diamict facies are interpreted to record slumping off the ice front and local topographic highs during the earliest phases of deglaciation (Figures 3.3e, 3.3f; Mills, 1983; Benn, 1989).

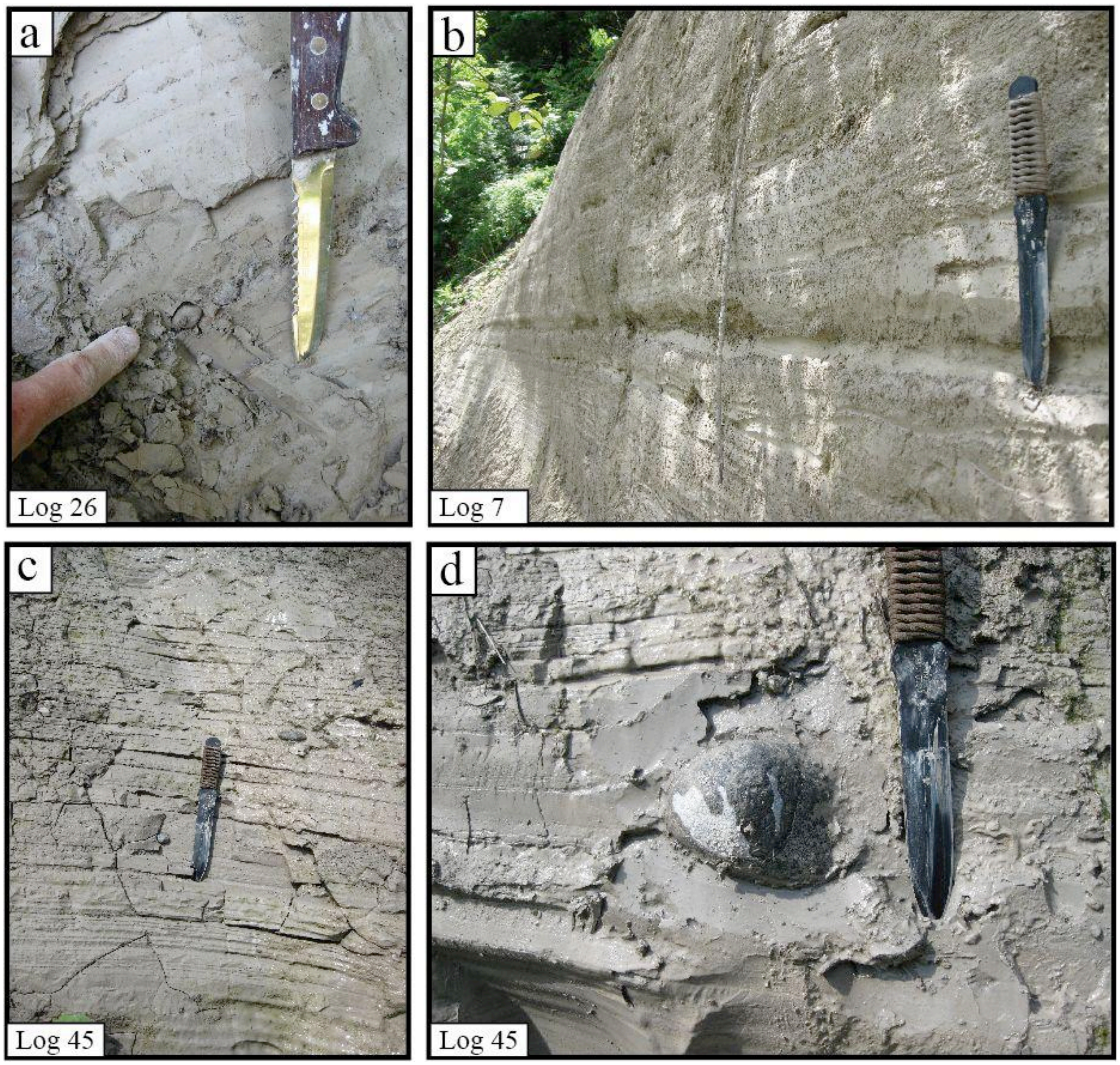
3.3.2.3 FA 3: Silt rhythmites with diamict horizons

Silt rhythmites and minor interbedded diamicts of FA3 drape the upper surfaces of both FA 1 and 2 (Figures 3.4b, 3.7), and were observed in all sections logged along the Nottawasaga River (Figure 3.13). FA3 is up to 12m thick and consists of a succession of rhythmites composed of silt and clayey silt couplets ranging from a few mm up to 4cm thick with interbedded diamict horizons. The silt fraction of the rhythmites is usually thicker and lighter coloured than the finer-grained clayey silt cap layers, although variations in layer thickness are observed within the unit and between sections. Horizontal laminae were observed within both the coarse and fine-grained portions of the rhythmites, but are more common in the coarser silt portions. These laminae often display small starved ripples and small-scale soft sediment deformation features less than 0.5 cm in amplitude. No organic material or macrofossils were observed within FA 3.

Thin, silt-rich diamict beds and clast horizons within FA3 are often crudely stratified to laminated, with individual clasts commonly deforming underlying rhythmites (Figure 3.7a,c,d). Individual diamict beds are typically less than 5-10cm thick and grade upward into clast-free rhythmite facies. Diamict beds and clast horizons within the silt rhythmites decrease in frequency up-section. In the upper part of the rhythmite succession of FA3, thin, planar beds of very fine to fine-grained sand are observed that increase both in thickness and frequency up-section (Figures 3.4b, 3.7b, 3.12). These sand beds range from 0.5cm to 3cm in thickness and are composed of massive to laminated or asymmetrically rippled sand. They form laterally continuous beds that can be traced along entire outcrop faces, and often discharge groundwater along seepage planes or small groundwater piping features (Figures 3.7b, 3.15). Sand bodies within FA 3 have a horizontal orientation, except at the base where FA 3 drapes the irregular upper surface of FA 1 or FA 2 and sand beds dip parallel to the contact with the underlying FA's. The upper surface of FA 3 is sub-horizontal and grades transitionally into FA 4 (Figure 3.4b).

The overall fine-grained texture of FA 3 suggests a low energy subaqueous (lacustrine) depositional environment. Fine-grained clayey silt beds were likely deposited from suspension settling whereas coarser-grained sediments were delivered via density underflows entering the lake from subglacial meltwater streams and fluvial systems surrounding the basin (Van Der Meer & Warren, 1997). Clasts within rhythmites of FA 3 are interpreted to record deposition of ice-rafted debris from icebergs calved off a

Figure 3.7: FA 3: a) dipping beds and a clast-rich horizon (pebble band) within silt rhythmites (knife is 20cm long); b) silt rhythmites and sand interbeds within FA 3. Note continuity of sand bed (light coloured bed at knife tip) along entire outcrop face; knife is 25cm long; c) scattered clasts within FA 3; beds dipping gently to the right in response to underlying topography of FA 1; d) clast within laminated silts and clays of FA 3. Clast deforms underlying beds and overlying beds drape clast surface.


a
Log 26
b
Log 7
c
Log 45
d
Log 45

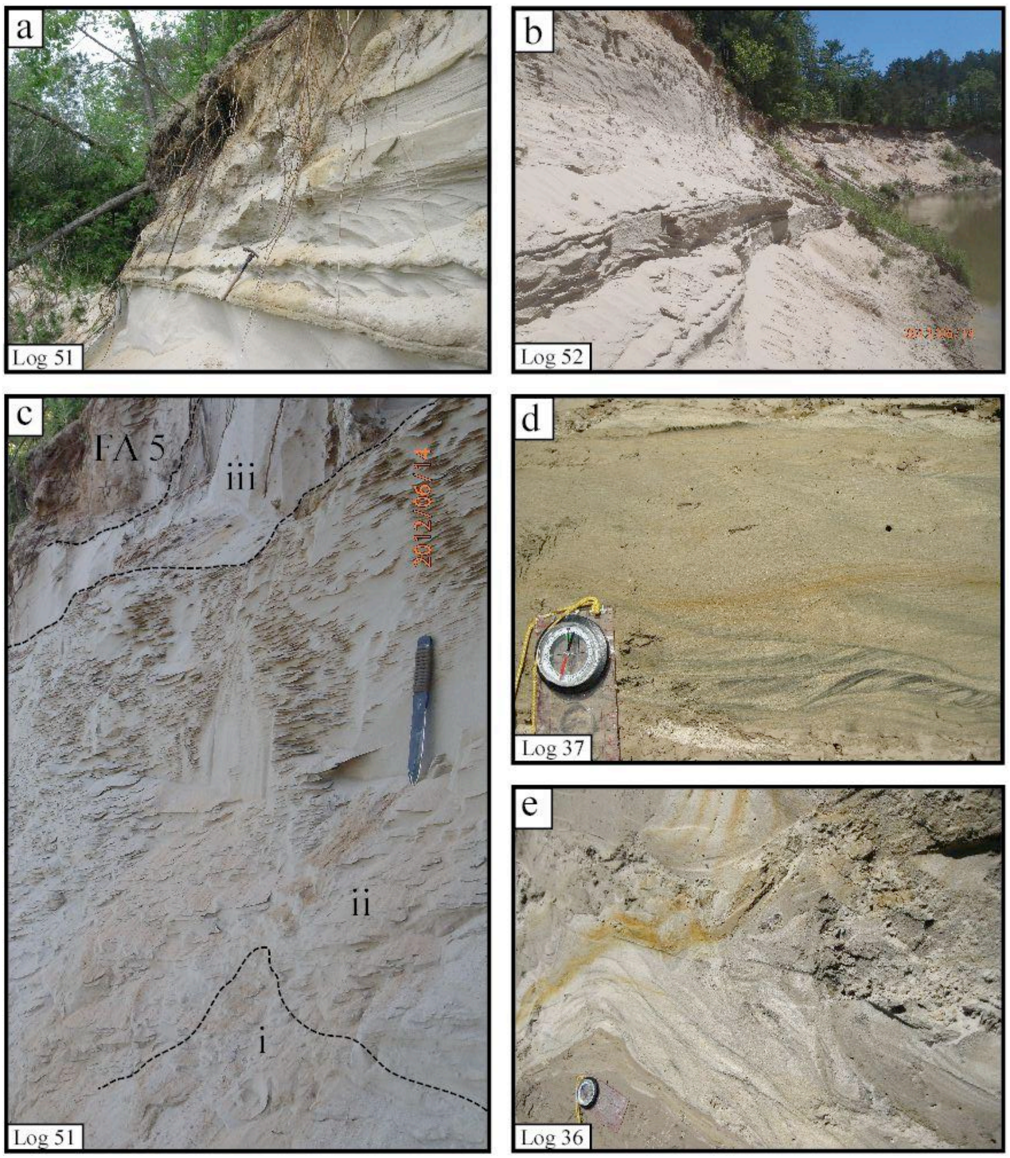
retreating ice front (Dowdeswell & Dowdeswell, 1989; Condon et al., 2002), or from break-up of river or lacustrine seasonal ice (Martini et al., 1993). Interbedded diamict horizons may record deposition of coarse-grained debris from retreating ice (by subaquatic flows or rainout), or from sediment re-working by debris flows generated along the steep slopes on the underlying surfaces of FA's 1 and 2, or from the margins of prograding fluviodeltaic systems (e.g. Bennett et al., 2002).

Seasonal ice cover and precipitation patterns probably exhibited important cyclical controls on sedimentation. Rhythmites may record a combination of annual (Breckenridge et al., 2004) or diurnal (Schneider & Bronge, 1996) sedimentation patterns, individual storm events, or rapid snow melt (Lamoureux, 2000), turbidites in a prodelta setting (Harrison, 1975), or distal subaquatic fan sedimentation (Gravenor & Coyle, 1985).

3.3.2.4 FA 4: Rippled fine-grained sand

Sand interbeds within FA 3 increase in frequency and thickness up-section and grade upward into a thick unit of asymmetrically rippled fine to very fine-grained sand with silt interbeds (FA 4: Figure 3.4b, 3.8). Ripple packages reach thicknesses of up to 5m and are often separated by silt drapes up to 10 cm thick (Figure 3.8a, b). Ripples display both A and B-type climbing patterns (Figure 3.8c; Jopling and Walker, 1968) and are commonly associated with horizons of large-scale soft sediment deformation characterized by ball and pillow structures and/or dish structures (Figure 3.8c, e). Paleocurrent measurements from ripple crest orientations show consistent paleoflow directions from north-northwest to north-northeast. Silt-rich interbeds are massive to crudely laminated. Soft sediment deformation is apparent in all facies of FA 4 and forms

Figure 3.8: FA 4: A) rhythmically-bedded rippled fine-grained sand with silt drapes overlying deformed fine-grained sand; B) 4m thick package of type-A climbing rippled fine-grained sand; c) facies transition from fine-grained sand with large-scale soft sediment deformation structures at base (i) into fine-grained sand with dish structures (ii), type-B ripples and type-A ripples at top (iii); d) type-A climbing ripples passing upward into type-B ripples with steep, decreasing climb angle; e) large-scale soft sediment deformation structures involving thick silt beds that both underlie and drape the sand body


a
Log 51
b
Log 52
c
FA 5
iii
2012/06/14
ii
i
Log 51
d
Log 37
e
Log 36

horizons up to 2m thick (Figure 3.8c,e). The thickness of FA 4 varies along the Nottawasaga River valley, but generally thins toward the north, except near Angus, where a second occurrence of FA 4 is observed at a higher stratigraphic position (Figure 3.13). Near Angus, FA4 is composed of very well sorted, mollusc-bearing fine-grained sand with relatively few silt interbeds (Figure 3.13); at this location the top of FA 4 is incised and draped by thin matts of humified peat and an underlying paleosol (Figure 3.14). Coarse-grained sediments of FA 5 cap the sediment sequence at this location. Groundwater is typically discharging along the contact between the base of rippled sand packages and the tops of thicker silt drapes (Figure 3.15b,f).

The gradual up-section increase in sand content from FA 3 to FA 4 suggests northward progradation of the coarse-grained sediment supply. Asymmetrically rippled sand is deposited by unidirectional traction currents and the presence of thick packages of Type-A and B climbing ripples suggests rapid deposition from flows carrying large quantities of suspended sediment (Jopling & Walker, 1968). The association of climbing ripples with silt-rich horizons characterized by large-scale soft sediment structures indicates rapid, but fluctuating rates of sediment deposition (e.g. Winsemann et al., 2007; Benn & Evans, 2010). The gradual coarsening-upward succession of fine-grained rhythmites (FA 3; Figure 3.4b) passing into rippled sands (FA 4; Figure 3.4b) is consistent with a prograding deltaic system (Harrison, 1975; Kelly & Martini, 1986; Bhattacharya, 2010). Thick silt drapes and variations in unit thickness along the Nottawasaga River exposures (Figure 3.13) may record depositional lobe and distributary channel migration during delta progradation.

FA 4 is observed in two stratigraphic positions along the Nottawasaga River outcrops (Figure 3.13). A lower unit of FA 4 (Figure 3.13) is characterized by frequent, thick silt drapes and is not observed north of log 39 (Figure 3.4a), marking a potential northern limit for the lower deltaic system. The upper unit of FA 4, only observed near Angus (Figure 3.13), is interpreted to be younger. The peat and paleosols associated with this upper deltaic unit likely record lake drainage and a significant lowstand of water levels in the Huron basin (Eschman & Karrow, 1985).

3.3.2.5 FA 5: Channelized fine-grained sand to gravel

FA 5 is characterized by fine-grained planar laminated to rippled sand (Figures 3.9d,e, 3.13) and trough, cross-bedded sandy gravel and gravelly sand (Figures 3.9a,b,c, 3.13). FA 5 typically forms a thin planar tabular sheet nearly 2m thick, but can be thicker where it infills incisions cut into underlying FA's (Figures 3.12, 3.13). Incised channels range in size from 2 to 10m wide and 1 to 4m deep (Figures 3.9d, 3.12b, 3.13) and contain stacked smaller-scale channelized elements. Paleocurrent measurements indicate east-northeasterly to northerly flow in the gravel facies and north-northwesterly to north-northeasterly flow in the sand facies. FA5 often contains abundant fossil molluscs including articulated bivalve shells concentrated along bed foresets.

Gravel cross-beds form in shallow, high-energy fluvial systems (e.g. Eynon & Walker, 1974) and FA 5 is interpreted here to record deposition on an extensive fluvial braid plain that covered much of the study area during periods of lake drainage. The incision of underlying units by FA 5 suggests periodic rapid change in the energy of the system. Consistent northward paleocurrent directions record fluvial flow toward new, lower elevation lake shorelines to the north.

Figure 3.9: FA 5: a) trough cross-bedded gravel and sand; b) cross bedded pebble gravel directly overlying silt rhythmites (FA 3); c) large-scale cross-beds in gravelly sand south of Angus; d) small (1m deep x 4m wide) channel feature infilled with planar-laminated fine-grained sand with large silt rip-up clasts; e) base of larger channel feature (2.5m deep x 8m wide) showing truncation of underlying strata and rip-up clasts (up to 12cm diameter; arrowed).

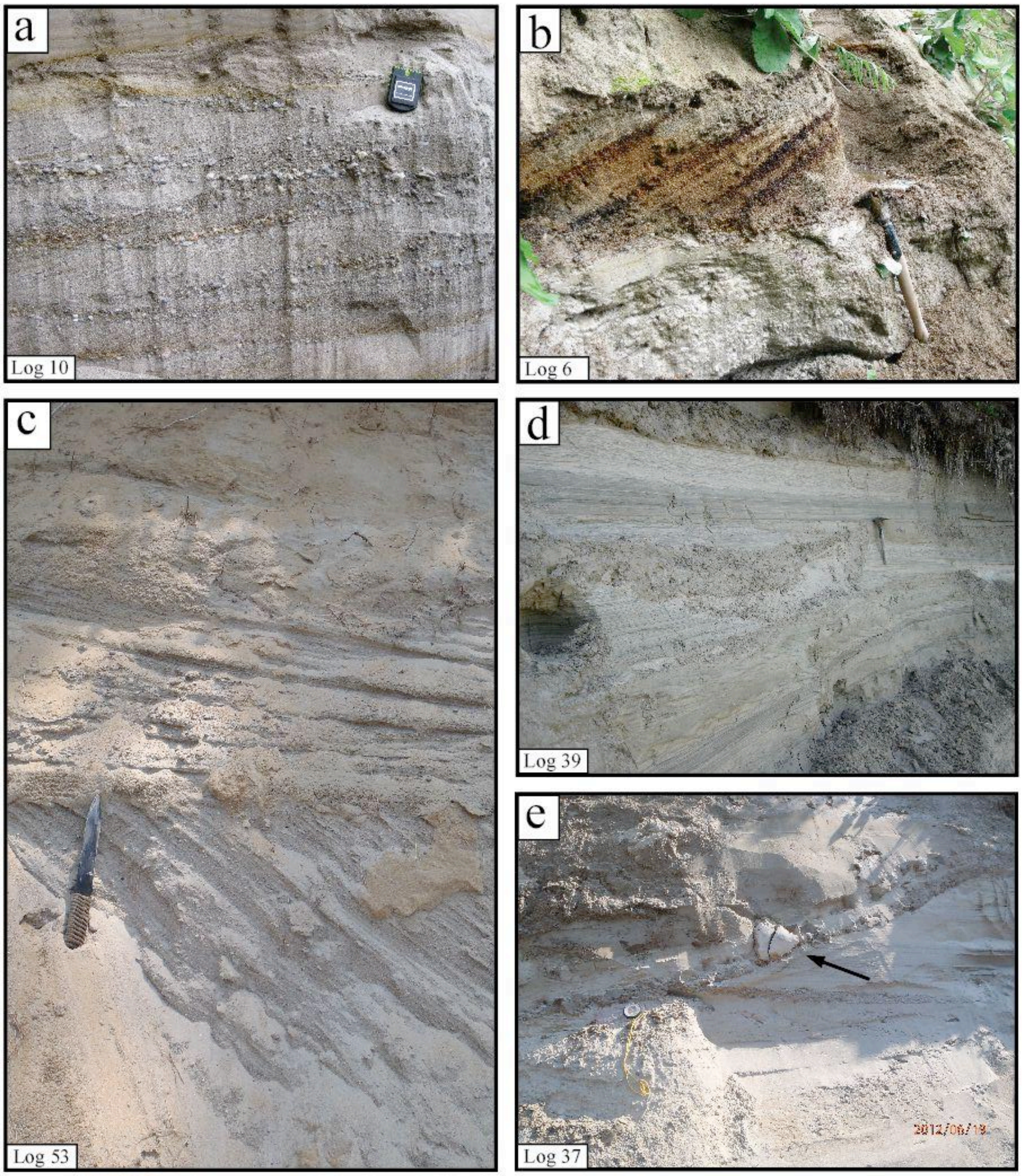

a
Log 10
b
Log 6
c
Log 53
d
Log 39
e
Log 37

Figure 3.10: GeoEye image of the former Lake Algonquin plain southeast of Alliston (northwest corner) taken April, 2011. Sinuous, NE-trending dark toned areas (marked with black arrows) represent position of former braided fluvial channels that deposited FA 5. Paleoflow is toward northeast. Green areas show upland areas situated above Lake Algonquin water plane. Image Courtesy of Google Earth.


N
0
2.5 km
Image © 2013 DigitalGlobe
Google earth

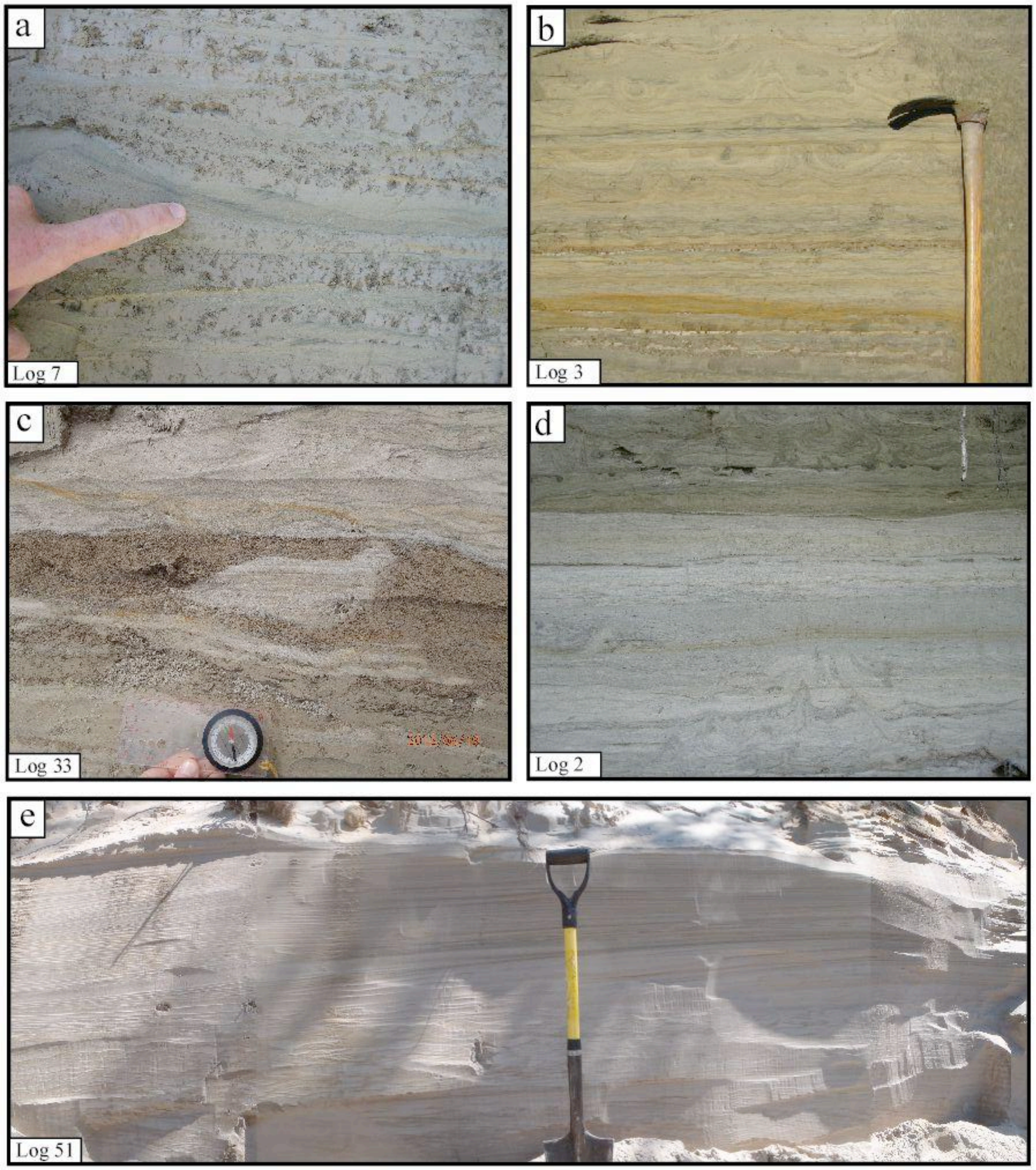
FA 5 occurs at two stratigraphic intervals along the Nottawasaga River (Figure 3.13). In the south, the lowermost unit of FA 5 is composed of trough cross-bedded sandy gravel and gravelly sand (Figures 3.9a,b,c, 3.13), and shows gradational lateral facies change toward the northern parts of the river basin where it is composed of fine to medium-grained planar laminated to rippled sand with silt rip-up clasts (Figures 3.9d,e, 3.13). Northward fining of the grain size in this lower unit is proportional to transport distance away from sediment sources to the south and west of the basin. The upper unit of FA 5 is found at surface at several locations in the study area, and is composed of broadly channelized units of interbedded pebbly gravel and silt (Figure 3.13). In areas where lower FA 5 deposits are found at shallow depths beneath the ground surface, the morphology of the braided channel systems are palimpsest and can be identified on aerial photography (Figure 3.10). Near Angus, in the northern part of the study area, the upper unit of FA 5 contains an abundance of detrital wood and molluscs, including large unionid clams (logs 51, 52, 53; Figures 3.13, 3.14). In this area, FA 5 is found at low elevations (190m asl), overlying accumulations of peat and thin paleosols that cap FA 4 (Figure 3.14). Deposits of FA5 along the Nottawasaga River are interpreted to record the Kirkfield low water phase and (12-11.5 ka BP) and transgression of water levels to the Nipissing phase of the upper great lakes (6-4ka BP).

3.3.2.6 FA 6: Interbedded sand and silt

In many outcrops along the Nottawasaga River, especially at higher elevations, the coarse-grained facies of FA 5 are overlain by a coarsening upward succession of interbedded sand and laminated silt comprising FA 6 (Figures 3.11, 3.12, 3.13). Thick silt beds near the base of FA 6 are typically composed of thin, parallel laminae with occasional minor soft sediment deformation features. Individual sand beds near the base of FA 6 are typically less than 5cm thick (Figure 3.11a), but thicken up-section as silt content decreases. Sand beds throughout FA 6 are characterized by planar laminae, low-angle intersecting stratification (LAIS) or hummocky cross-stratification (HCS), starved asymmetrical ripples, soft sediment deformation structures, symmetrical ripples, and horizontal truncation horizons (Figure 3.11b,d,e). The occurrence of symmetrical ripples and horizons characterized by large-scale soft sediment deformation structures increases up-section as sand packages thicken. Bed contacts are sub-horizontal and continuous, but slightly deformed (Figure 3.11). FA6 also contains abundant fossil material in the form of gastropods and bivalves. Common groundwater piping features observed along the contact between sand and silt layers in FA6 have resulted in significant erosion of outcrop faces along the Nottawasaga River (Figure 3.15).

The coarsening-upward succession of FA 6 is interpreted to record flooding of the area by lake waters and deposition of interbedded silt and sand by alternating episodes of settling of suspended fines and traction current and/or wave activity (Rosenthal & Walker, 1986). Thicker sand bodies in the upper part of FA 6, characterized by wave ripples, LAIS, soft sediment deformation structures, and planar erosional unconformities, are interpreted to record sediment deposition in a shallow lacustrine environment between fair-weather and storm wave base, with water depths likely between 5 and 10 meters (Dumas et al., 2005). LAIS is most commonly preserved below fair-weather wave base where the record of oscillatory motion of storm wave energy can escape reworking on the lake floor (Hamblin & Walker, 1979). Soft sediment deformation features and horizontal erosional horizons likely reflect erosion by large waves during the onset of

Figure 3.11: FA 6: A) thinly bedded silt with fine-grained sand interbeds near the base of FA 6. Sand bed in centre of photo contains starved asymmetrical ripples; b) Interbedded sand and silt. Sand beds contain wave ripples (lower part of photo) and soft sediment deformation structures that are truncated along sub-horizontal erosion horizons (upper part of photo); grub hoe is approx. 1m long; c) sharp contact between silt-rich facies (base below compass) and sand-rich facies (top) d) deformed and rippled fine-grained sand within upper part of FA 6; note large dewatering structure in lower part of photo; head of shovel shown in bottom right corner; e) low-angle intersecting strata (possibly low-amplitude HCS) and rippled fine-grained sand, shovel is 1m long.


a
Log 7
b
Log 3
c
Log 33
d
Log 2
e
Log 51

storm events (Eyles & Clark, 1988) and dewatering caused by rapid sediment deposition and/or storm wave shock (Molina et al., 1998). The presence of sedimentary structures attributed to storm wave activity in the upper part of FA 6 indicates that the lacustrine environment in which deposition occurred was extensive with a large fetch allowing significant storm waves to develop.

3.4 PALEOENVIRONMENTAL RECONSTRUCTION

The sedimentary successions examined along the Nottawasaga River in southern Simcoe County contain a detailed record of deposition in glacial, fluvial, and lacustrine environments formed both during and after deglaciation of the region at the end of the Wisconsin Episode. The six facies associations identified in this study (FA 1-6) form 8 stratigraphic units (*SU 1-8*) that characterize the subsurface sedimentary succession found in lowland areas of southern Simcoe County. These stratigraphic units form two thick, coarsening-upward successions that record: the advance of ice into the region and deposition of Newmarket Till (FA1 – *SU 1;* Figure 3.3b); ice-proximal sedimentation during the early phases of deglaciation (FA 2 – *SU 2*; Figure 3.3e, f); glaciolacustrine sedimentation into glacial lakes Schomberg and early Lake Algonquin (FA3 – *SU 3*; Figure 3.3e,f); progradation of fluvial systems in early Lake Algonquin (FA 4 – *SU 4*; Figure 3.3f, g); a rapid drop in water levels during the Kirkfield low phase (FA 5 – *SU 5*; Figure 3.3g); rising water levels to form main Lake Algonquin during uplift of the Kirkfield outlet (FA 6 – *SU 6*; Figure 3.3h); northward delta progradation during post-Algonquin regression (FA 4 – *SU 7*; Figure 3.3h,i); and a low water phase (Stanley Low) followed by a transgression of water levels during the Nipissing Phase (FA 5 – *SU 8*; Figure 3.3i,j).

Figure 3.12: annotated photomosaics of a) 180 degree cutbank exposure of logged section 37 (Figures 4, 13). FA's 3-6 are well exposed and have planar tabular unit geometry; section is 14m high; b) 180 degree cutbank exposure of section 19 (Figures 4, 13). FA's 4 and 5 show finer grain sizes in a) (distal) than in b) (proximal) areas (see Figure 4a for section locations), and have a consistent planar tabular geometry except where FA 5 incises into FA 4 at left; channel feature infilled with FA 5 is 4m deep and 10-12m wide, section is 11m high.

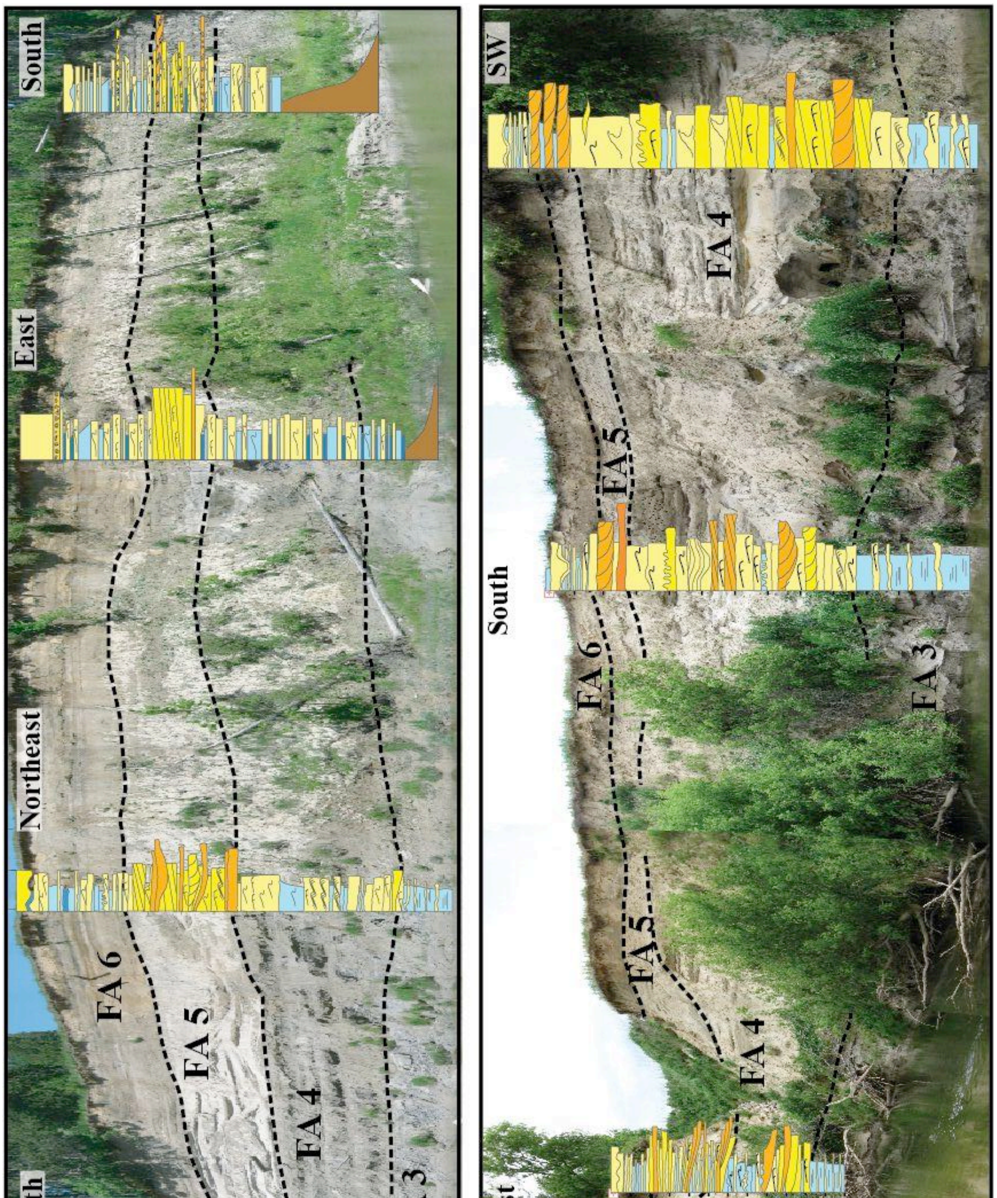
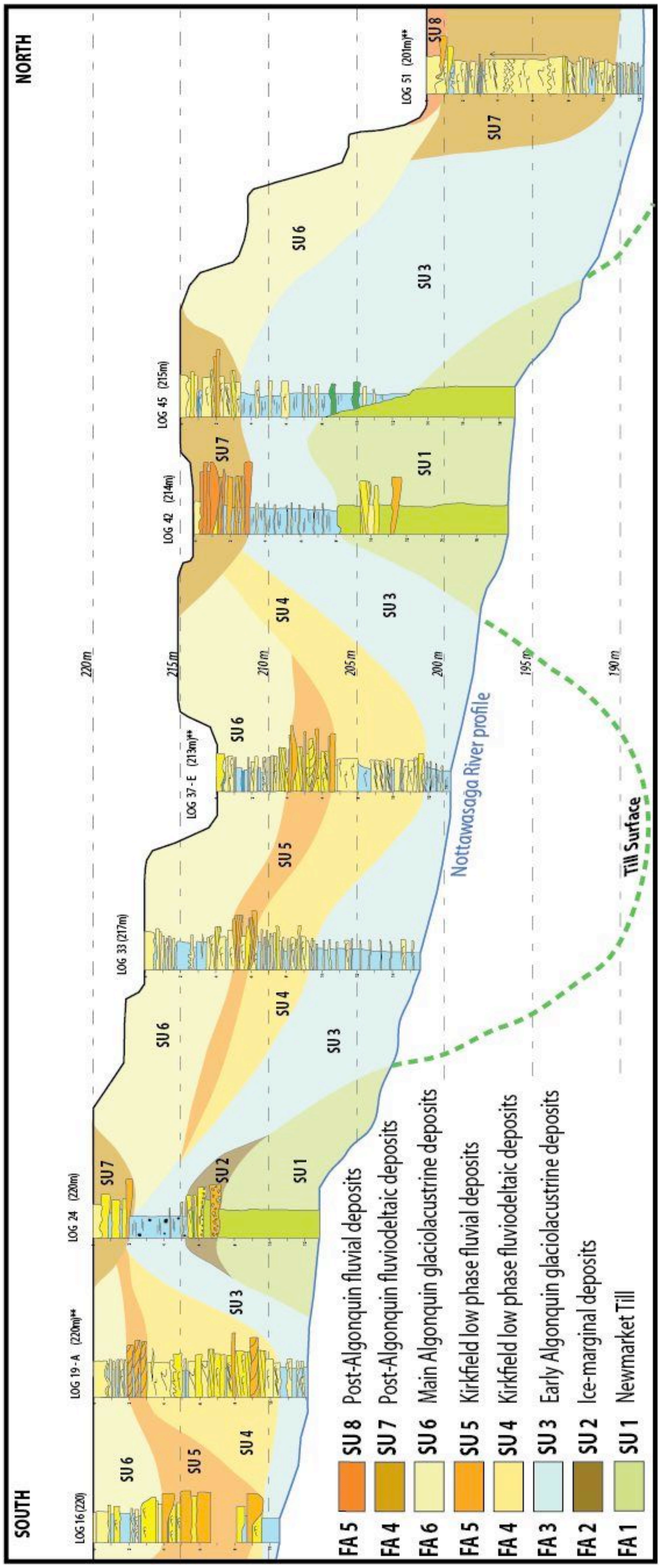

North
Northeast
East
South
FA 6
FA 5
FA 4
FA 3
East
South
SW
FA 6
FA 5
FA 4
FA 3

Figure 3.13: S-N cross-sectional profile showing distribution of facies associations (FAs) and correlative stratigraphic units (SUs) exposed along the Nottawasaga River. Refer to Figure 3.4a for log locations. Note the truncation of upper FA's where FA 1 is well-exposed and thickening of units when FA 1 is at lower elevations. Elevations not corrected for isostatic tilt.


SOUTH
NORTH
LOG 16 (220)
LOG 19 - A (220m)**
LOG 24 (220m)
LOG 33 (217m)
LOG 37 - E (213m)**
LOG 42 (214m)
LOG 45 (215m)
LOG 51 (201m)**
220m
215m
210m
205m
200m
195m
190m
SU 1
SU 2
SU 3
SU 4
SU 5
SU 6
SU 7
SU 8
Nottawasaga River profile
Till Surface
FA 5 SU 8 Post-Algonquin fluvial deposits
FA 4 SU 7 Post-Algonquin fluviodeltaic deposits
FA 6 SU 6 Main Algonquin glaciolacustrine deposits
FA 5 SU 5 Kirkfield low phase fluvial deposits
FA 4 SU 4 Kirkfield low phase fluviodeltaic deposits
FA 3 SU 3 Early Algonquin glaciolacustrine deposits
FA 2 SU 2 Ice-marginal deposits
FA 1 SU 1 Newmarket Till

SU 1 is identified in the lowermost parts of the Nottawasaga River exposures and is interpreted to record the advance of ice into the basin from the northeast and deposition of the Newmarket Till (FA 1, Figures 3.3b, 3.5, 3.13). The till appears to have a drape- ;ike geometry (Sharpe et al., 2011), and is characterized by an undulating and drumlinized upper surface, with several drumlins rising up above the level of the series of lakes that subsequently formed in the basin (Todd et al., 2008; Mulligan & Bajc, 2012). The elevation of the upper surface of the till sheet beneath the flat surface of the lowlands varies by more than 40m over distances of less than 5km (208m asl in Log 42 vs. 176m asl in borehole SS-11-06; Figure 3.4a; Bajc & Rainsford, 2011) and can be as much as 75m below the surface within lowlands (borehole SS-11-07; Figure 3.4a; Appendix A; Bajc & Rainsford, 2011).

The glacial event responsible for deposition of *SU 1* (Figure 3.3b) was followed by initial ice retreat and localized slumping of sediment in an ice-proximal lacustrine environment (*SU 2*, Figures 3.3e, 3.6, 3.13). The poor sorting, pervasive deformation, highly localized spatial distribution, and close association of *SU 2* with *SU 1* suggest that *SU 2* deposits formed in subaqueous ice-marginal environments and record the earliest phases of deglaciation in the basin (Figure 3e).

SU 3 records the continued northward retreat of ice from the basin and sediment deposition into glacial Lake Schomberg and early Lake Algonquin (Figures 3.3e,f). Rhythmically laminated sediments within *SU 3* have previously been interpreted as annually generated varves (e.g. Chapman & Putnam, 1984). However, Gravenor & Coyle (1985) report that the magnetic fabrics of the fine and coarse-grained layers are identical and interpret the sediments in both layers to have been deposited under the influence of current activity in a distal subaquatic fan setting. Rhythmites of *SU 3* are interpreted here to record deposition in quiet water environments of ice-marginal glacial Lake Schomberg and early Lake Algonquin through a variety of depositional processes that may be influenced by a range of seasonal and/or non-seasonal controls. It was not possible to differentiate between the deposits of Lake Schomberg and early Lake Algonquin within the study area due to the absence of datable material. *SU 3* contains no visible organic material for radiocarbon dating, nor does it provide evidence of unconformities that could be attributed to rapid changes in water levels. It is suggested here that *SU 3* records gradual decreases in water plane elevation from 300m asl (glacial Lake Schomberg) to approximately 250m asl (early Lake Algonquin) as ice withdrew from the basin (Figures 3.3e,f).

Initial drainage of glacial Lake Schomberg is thought to have been either southward through topographic lows in the Oak Ridges Moraine, or eastward through outlets in the Peterborough area (Deane, 1950; Gravenor, 1957). A gradual decline in water levels, from Lake Schomberg to early Lake Algonquin, is recorded by the up-section increase in sand content within *SU 3* (Figures 3.3e,f). The sedimentological data reported here support the assessment of glacial Lake Schomberg as an age equivalent of early Lake Algonquin (Chapman & Putnam, 1984; Eschman & Karrow, 1985), until ice retreat allowed confluence of water between southern Simcoe County and the rest of the Lake Huron basin. Water levels in early Lake Algonquin were controlled by the southern outlet for the basin, at Port Huron (Figure 3.1), due to blockage of northern outlets by glacial ice (Deane, 1950; Larson & Shaetzl, 2001).

The rippled and deformed fine-grained sands with interbedded silt drapes characteristic of *SU 4* (Figure 3.8) are interpreted to record a decrease in accommodation space in early Lake Algonquin. This was likely due to a combination of sediment aggradation and lowering of water levels as new parts of the basin were uncovered by the continued retreat of ice. Consistent northward paleoflow indicators and increasing sand content up-section record the progradation of fluvial systems from the south (Figure 3.3g). The thick packages of rippled and deformed sands of *SU 4* suggest rapid rates of sediment deposition in a delta front environment. During this time, sediment-laden meltwater streams re-working coarse-grained deposits along high ground to the south and west supplied the sediments into the Alliston embayment as water levels in the early Lake Algonquin basin were falling (Figure 3.3e-g).

The delta front deposits of *SU 4* are overlain and incised into by coarse-grained sediments of *SU 5*. This incision event likely records a rapid drop in water levels during the Kirkfield low water phase, following the ice retreat beyond an isostatically-depressed outlet near Kirkfield or Fenelon Falls (Figure 3.3g; Finamore, 1985; Lewis et al., 2005). Water levels are reported to have dropped by as much as 10-30m during this time (Kaszycki, 1985; Lewis et al., 2005) and the incision of channels infilled with cross-bedded gravels (*SU 5*) into fine-grained silt rhythmites (*SU 3*) within the study area provides sedimentologic support for this drop in water level. Organic-rich sediments found in several outcrops within the former lake basin have been used to date the Kirkfield lowstand to between 12 and 11.5 ka (Karrow et al., 1975). Accelerator mass spectrometer radiocarbon dating of *Dryas integrifolia* leaves found in sand near the top of a coarsening-upward succession interpreted to be correlative with FA 5 in borehole SS-

11-06 (Figure 3.4a; Appendix A; Bajc and Rainsford, 2011), yielded radiocarbon ages of 12.41 and 12.46 ka, providing an upper estimate for the timing of this low-water event in Simcoe County. OSL dating and follow-up studies will help to test this interpretation. Routing of Lake Algonquin waters through the Kirkfield outlet (Figure 3.1) into Early Lake Ontario to the southeast resulted in the construction of deltas in Rice Lake (Eschman & Karrow, 1985) and incision of previously-deposited glacial Lake Iroquois sediments in the Ontario basin (Sly & Prior, 1984). This indicates that the outlet was exposed while glacial Lake Iroquois occupied the Lake Ontario basin, and must have been in use even after drainage of glacial Lake Iroquois around 12 ka (Karrow et al., 1975).

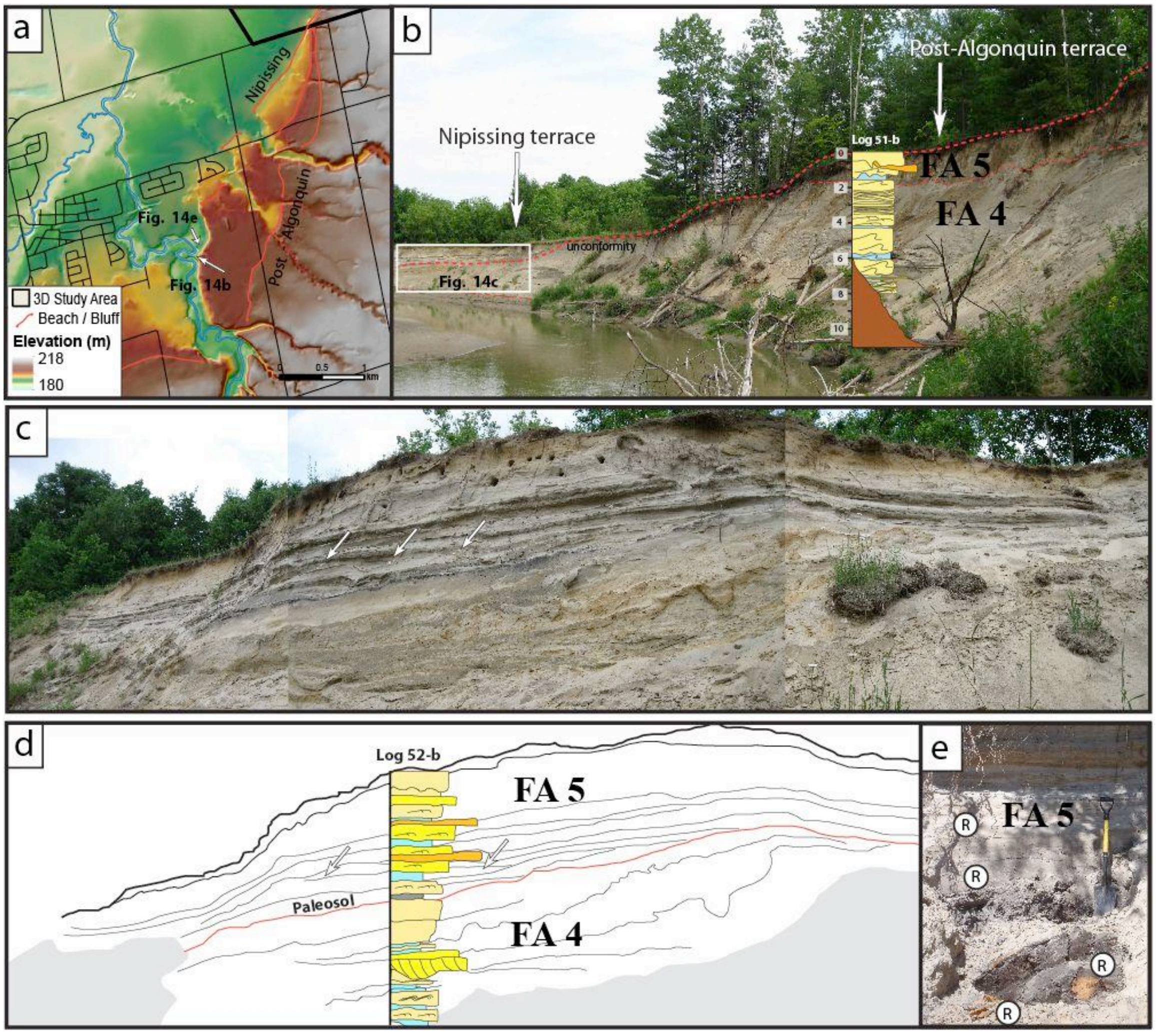
The coarse-grained facies of *SU 5* (Figure 3.9) are overlain by very fine-grained sand and laminated silt of *SU 6* (Figures 3.11, 3.12, 3.13). *SU 6* records the transgressive rise of water levels to main Lake Algonquin in response to isostatic uplift of the depressed Kirkfield outlet (Figure 3.3g,h; Finamore, 1985). Water levels rose by approximately 10-20m following the Kirkfield low-stand, burying the fluvial sediments of *SU 5*. The sediments that record the main Lake Algonquin phase (*SU 6*) contain a record of frequent storm activity (LAIS, soft sediment deformation, horizontal truncation horizons; Figure 3.11), and there is evidence of large spit growth at this time in Simcoe County and along the western margins of the basin (Krist & Shaetzl, 2001). Whether or not the Kirkfield outlet remained in use throughout the main Lake Algonquin phase, or if drainage was diverted south through Port Huron due to uplift at Kirkfield, remains controversial (Figure 3.3h; Finamore, 1985; Kaszycki, 1985; Lewis et al., 2005). Final drainage of main Lake Algonquin was initiated in response to the uncovering of northern outlets in the French River lowland and North Bay areas between 10.8 and 10.4 ka (Figure 3.3i; Karrow et al., 1975; Larson & Shaetzl, 2001).

In the northern part of the study area, near Angus, a younger package of deltaic (*SU 7*) and fluvial (*SU 8*) sediment caps the succession (Figures 3.13, 3.14). Several distinct shoreline and terrace features are observed in this vicinity (Figure 3.14a). These shorelines lie below the main Lake Algonquin water plane (Figure 3.2) and are interpreted here to record the presence of a series of post-Algonquin lakes that formed in response to the opening of lower outlets to the north (Figure 3.3i,j; Deane, 1950; Fitzgerald, 1985; Bajc et al., 2012). These younger deltaic sediments (*SU 7*) are characterized by very well-sorted rippled and highly deformed fine sand (Figure 3.14b,c,d). Radiocarbon dating of organic material from these outcrops has yielded dates around 9.95ka BP (Fitzgerald, 1985).

A channelized unconformity surface marked with paleosols and overlain by organic horizons truncates the thick (10m) deltaic sediment package of *SU 7* near Angus (Figure 3.13, 3.14), recording drastically lowered water levels in the region. Radiocarbon dating of organic material across this unconformity has produced dates of between 7.51 and 5.88 ka BP (Bajc & Rainsford, 2010), suggesting the unconformity surface could mark the Stanley low phase of the Huron basin within the study area (Figure 3i). *SU 8* is interpreted to record the transgression up to the Nipissing shoreline in the study area (Figure 3.3j, 3.14).

The succession of environments based on sedimentological data reported here are consistent with interpretations of multiple phases of Lake Algonquin made by previous workers (e.g. Deane, 1950; Karrow et al., 1975; Eschman & Karrow, 1985; Lewis et al.,

Figure 3.14: a) DEM showing surface morphology and location of logged sections 51 and 52 near Angus (see also Figure 4a), and location of wood sample used for radiocarbon dating shown in e); b) photo of cutbank exposure showing location of log 52, multiple post-Algonquin terrace levels (white arrows), unconformity surface (Stanley low; dashed red line) and location of photomosaic (white box) shown in c); c) photomosaic of lower terrace sediments. White arrows point to large (5-10cm) unionid clam fossils. d) sketch of exposure in c with corresponding sediment log. Buried unconformity surface shown in red; e) buried organic-rich horizon beneath fluviodeltaic sands of FA 5; R shows location of wood sample collected for radiocarbon dating, ages range from 7510 to 5850 ka BP.


a
Nipissing
Post - Algonquin
Fig. 14e
Fig. 14b
3D Study Area
Beach / Bluff
Elevation (m)
218
180
b
Post-Algonquin terrace
Nipissing terrace
Log 51-b
FA 5
FA 4
unconformity
Fig. 14c
c
d
Log 52-b
FA 5
Paleosol
FA 4
e
FA 5

2008). Fine-grained glaciolacustrine sediments (*SU 3*; Figures 3.3e,f, 3.13) drape a highly undulating Newmarket Till surface (*SU 1*; Figure 3.13), and record proximity to the retreating ice front (south and west of the eastern shoreline of modern Lake Simcoe: Figure 3.3f). Further ice recession resulted in the exposure of an isostatically-depressed outlet at Kirkfield, and water levels in the basin dropped nearly 20m (Figure 3.3g; Finamore, 1985). In southern Simcoe County, the Kirkfield low-water phase is recorded by the coarse-grained fluvial facies of *SU 5* (Figures 3.3g, 3.13), as rivers re-worked previously-deposited sediments and transported them toward the new, lower elevation shorelines. Isostatic rebound of the outlet at Kirkfield resulted in a transgression to the main Lake Algonquin water level in the Simcoe County area and marks the transition from *SU 5* to *SU 6* (Figure 3.3h, 3.13). Final drainage of glacial Lake Algonquin is recorded by incision of the stratigraphy by younger fluvial and deltaic sediments (*SU 7* and *SU 8*) near Angus (Figures 3.13, 3.14). Incision of the Lake Algonquin deposits and the presence of buried soil and peat horizons at Angus record the Stanley low-water phase (Figures 3.3i, 3.14). Fossiliferous, fluviodeltaic deposits lying above the buried soils and peats record the Nipissing transgression across the region (*SU 8*; Figures 3.3j, 3.13, 3.14).

3.5 APPLICATION TO THE SHALLOW GROUNDWATER REGIME

Sedimentological data gathered from exposures along the Nottawasaga River valley provide new insights into the hydrostratigraphic framework and potential for groundwater flow and contaminant transport within the southern Simcoe County region. The true three-dimensional (3D) distribution of individual facies and facies associations (FA's) cannot be determined from this study alone, but several observations from this investigation may yield valuable information about the control these sediment groups have on groundwater flow through the subsurface and their relation to aquifers in the basin (Table 3.2).

Groundwater sapping horizons observed in outcrops along the Nottawasaga River indicate that the majority of water escaping from the outcrop faces is travelling through FA's 4, 5, and 6 (Figure 3.15). Based on their sedimentological characteristics, stratigraphic position, and spatial distribution, these units are interpreted to be correlative with the 'Lake Algonquin Sand Aquifer' of Sibul & Choo-Ying (1971; Table 3.2). Variability in the thickness of the unconfined aquifer (Figure 3.13, 3.16) results from the high relief (up to 75m) on the surface of underlying FA 1 deposits that control the geometry of overlying units (Figures 3.13, 3.16). Aquifer thickness is also affected by the depth of FA 5 channel incision into underlying FA's by fluviodeltaic systems following drainage of glacial Lake Algonquin (Figures 3.3i, 3.13).

Past hydrogeological investigations in the study area report groundwater flow from the valley margins toward the Nottawasaga River and downstream toward the north (Sibul & Choo-Ying, 1971; Hill, 1982). Hill (1982) suggested that agricultural fertilization practices within the Lake Algonquin plain were a major source of nitrate contamination in wells hosted in the Lake Algonquin sand aquifer (FA's 4, 5, and 6). Marked decreases in nitrate concentration with increasing depth in the Lake Algonquin sand aquifer (Hill, 1982), may reflect widespread distribution of the thicker fine-grained interbeds observed within FA's 4 and 6 that could impede downward migration of the surface contaminants.

Table 3.2: sediment characteristics, inferred hydraulic properties, and regional correlation of facies associations identified within this study. Knife is 25cm long and compasses are 12 cm long in photos.

	Thickness	Characteristics		Photo	Correlation
FA 6	2 - 8m	coarsens upward, heterogeneous, horizontal contacts, interbedded sand and silt,	Aquifer		Lake Algonquin Sand Aquifer (Sibul and Choo-Ying, 1971; Hill, 1982); Borden aquifer (Sudicky and Illman, 2011)
FA 5	1 - 4m	channellized geometry, north-ward fining in grain size, northward gradient	Aquifer		
FA 4	2 - 8m	variable unit thickness, thick silt beds present, sub-horizontal contacts	Aquifer		
FA 3	2 - 12m	draped geometry, increasing sand content up-section, horizontal internal contacts	'leaky' aquitard		Lake Algonquin varves (Deane, 1950; Chapman and Putnam, 1984; Gravenor and Coyle, 1985
FA 2	up to 3m	local distribution, variable thickness, deformed and interbedded internal geometry	Aquifer/ Aquitard		Regional distribution unknown
FA 1	up to 15m	massive, fissile, over-consolidated, coarse-grained interbeds, irregular topography, variable thickness	'leaky' aquitard		Newmarket Till (Gwyn, 1972; Russell and Dumas, 1997; Mulligan and Bajc, 2012)

Although no outcrops were analyzed within the Canadian Forces Base Borden property (Figure 3.2), it is likely that the unconfined aquifer complex represented by FA's 4, 5, and 6 extends into the Base Borden property and shares similar hydrogeologic properties with unconfined aquifer units identified on the base. These aquifers have been

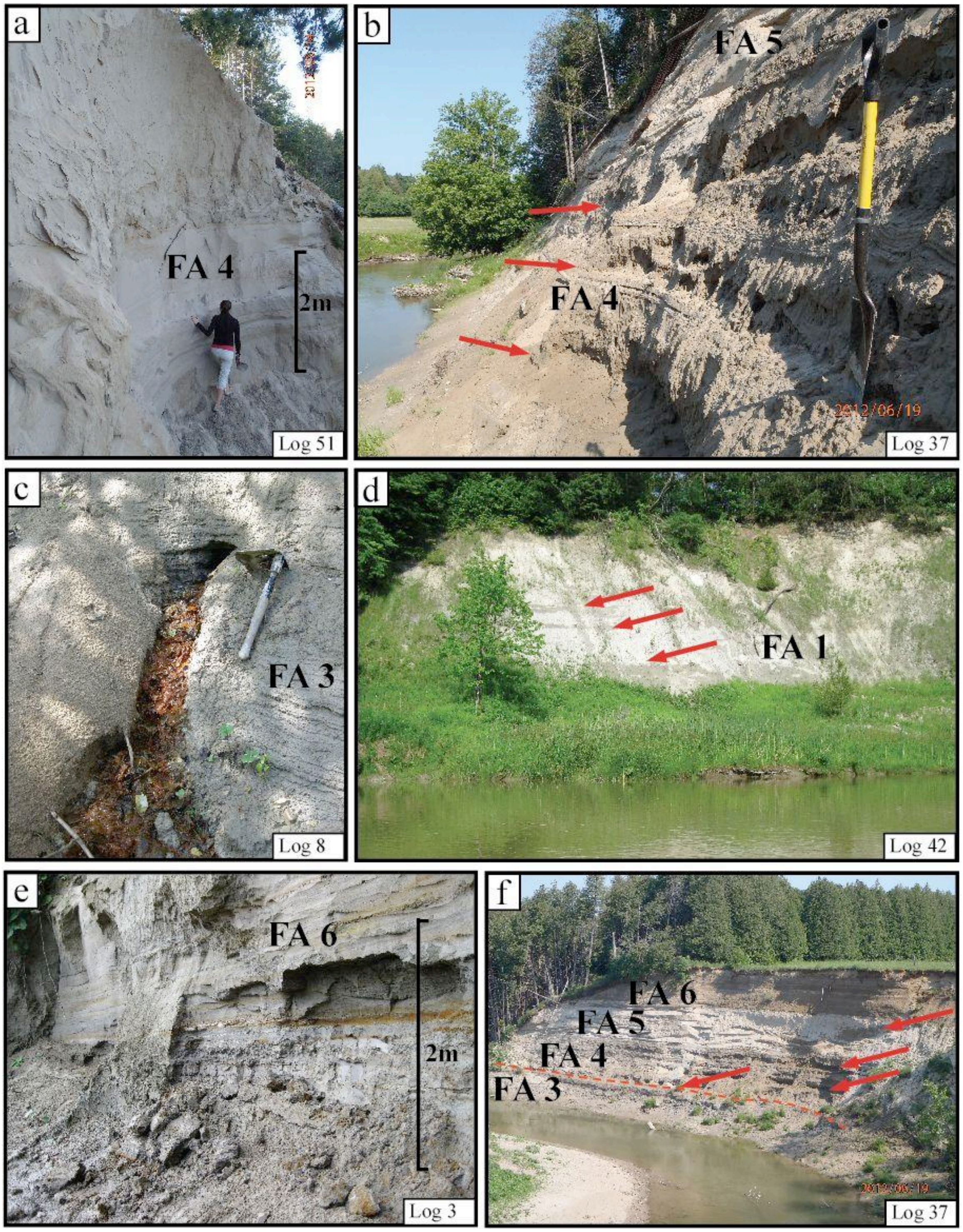
subjected to intense local hydrogeological and geochemical study (McFarlane et al., 1983; Sudicky & Illman, 2011). The 'Borden aquifer' is described as a heterogeneous unconfined aquifer hosted in a deglacial glaciolacustrine or fluviodeltaic unit between 6 and 9m thick that rests on a thick unit of sandy silt and clay (Sudicky and Illman, 2011). It is suggested here that the unconfined Borden aquifer is correlative with the sediments represented by FA's 4, 5, and 6, and the underlying silt and clay deposits at Borden represent early Lake Algonquin sediments (FA 3; Figures 3.4b, 3.13).

Groundwater flow directions and aquifer thickness within the Nottawasaga River valley appear to be controlled by the topography of the underlying fine-grained units of FA's 1 and 3. These units can be considered as aquitards that create a regional hydraulic barrier through which surface water has difficulties penetrating (Figures 3.15, 3.16).

However, textural heterogeneities within FA's 1 and 3 (Figures 3.5, 3.7) have lead to significant groundwater discharge though discrete coarse-grained interbeds within these aquitard units elsewhere in the region (Figure 3.13, 3.15, 3.16; Gerber and Howard, 1996; Gerber et al., 2001; Sharpe et al., 2002). These interbeds form localized conduits for groundwater flow, which may create hydraulic windows connecting surficial and deeply buried aquifer units (Boyce et al., 1995; Gerber & Howard, 1996).

The six FA's identified here comprise a hydrostratigraphic system characterized by an unconfined aquifer (FAs 4, 5 and 6; Figures 3.13, 3.16) resting on thick,

Figure 3.15: a) large amphitheatre-shaped piping scar within deltaic sediments of FA 4 southeast of Angus; b) groundwater seepage horizons (arrowed) within FA 4 sediments, section 37 (see Figure 3.4a for location); c) small piping feature within silt rhythmites of FA 3; d) surface seepage zones identify preferential flow paths of groundwater through coarser-grained interbeds within FA 1 (dark tones shown with red arrows); e) active erosion of outcrop from groundwater sapping processes. Note large blocks of sediment that have fallen from undercutting of more permeable sediments beneath; f) photo of northern portion of section 37, showing planar tabular geometry of facies associations (FA 3 – FA 6) and continuity of seepage horizons (dark coloured areas) along entire outcrop face; section is 14 m high.

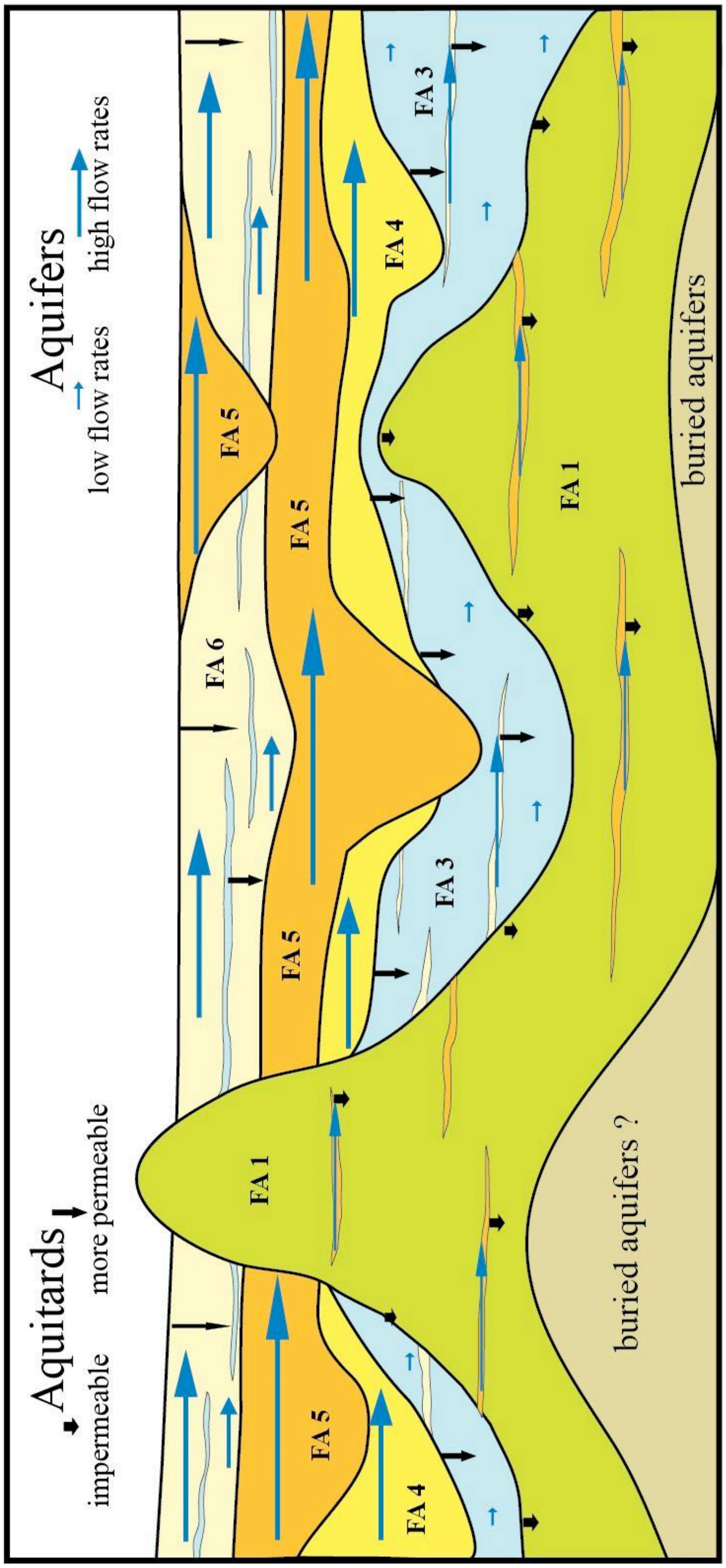

a
FA 4
2m
Log 51
b
FA 5
FA 4
2012/06/19
Log 37
c
FA 3
Log 8
d
FA 1
Log 42
e
FA 6
2m
Log 3
f
FA 6
FA 5
FA 4
FA 3
Log 37

impermeable units (FAs 1, 2 and 3; Figures 3.13, 3.16). Sedimentological analysis of these deposits has allowed the development of a conceptual model for shallow groundwater flow in the southern Simcoe region (Figure 3.16) and may be useful as an analogue for future hydrogeological investigations in areas where surficial aquifers overlie an undulating (drumlinized?) aquitard.

Assessing the risk of contamination of deep aquifers in the region as a result of surface activities remains problematic due to uncertainties with the distribution and potential connectivity of coarse-grained interbeds within the aquitards (FA's 1 and 3). Based on observations of groundwater flow discharging from shallow stratigraphic units within the Nottawasaga River basin, it seems that deep aquifers are reasonably well protected against contamination from surface contaminant sources in the former lake plain. However, the 3D distribution and potential connection of coarse-grained layers within the aquitard units is unclear and should be a focus of future research within the study area. Recent sediment drilling by the OGS has revealed that aquifers underlying the Newmarket Till (FA 1) beneath the former Lake Algonquin plain often display upward

gradients (Bajc et al., 2012). Geochemical investigations using tracers (i.e. nitrates and tritium) as a proxy for quantification of infiltration of surface water into the deep groundwater system may help to assess potential hydraulic connections between surficial and buried aquifer units. Improving our understanding of the stratigraphic framework and controls on groundwater flow in southern Simcoe County is essential, as this rural area is dominated by heavy agricultural use and is slated for major urban expansion in the near future (Ministry of Public Infrastructure and Renewal, 2006).

Figure 3.16: Conceptual model of groundwater flow through shallow subsurface sediments identified in this study. High flow rates are interpreted for FA's 4, 5, and 6 (large blue arrows). FA's 1 and 3 are interpreted to form hydraulic barriers (thick black arrows) that impede downward flow of groundwater. Note the coarse-grained interbeds within FA 1 and 3 are inferred to create thin, highly conductive flow paths (blue arrows) that may provide hydraulic connection between surface and buried aquifers. FA 2 not shown.



Aquitards
impermeable
more permeable
Aquifers
low flow rates
high flow rates
FA 1
FA 3
FA 4
FA 5
FA 6
buried aquifers ?
buried aquifers

3.6 CONCLUSIONS

Developing a better understanding of the depositional history of formerly glaciated basins is essential for the reconstruction of past environmental changes and the evaluation and preservation of modern groundwater resources. Detailed logging and sedimentological analysis of 56 exposures along the Nottawasaga River allowed identification of six lithofacies associations (FA 1-6; Figures 3.4, 3.13) that help establish the major controls on past sedimentation patterns. The exposed sediments provide a local record of regional-scale events that contributed to environmental changes during the deglacial and postglacial phases of the Late Wisconsin Episode and give valuable insights into potentially correlative subsurface successions elsewhere in the former glacial Lake Algonquin basin.

Qualitative observations of groundwater flow exiting outcrop faces suggests that groundwater is preferentially discharged into the Nottawasaga River, rather than percolating to deeply buried aquifers. However the potential connection between surficial and more deeply-buried aquifer units is unclear. Further research into the quantification and monitoring of groundwater flow and chemistry across the former lake plain is warranted. Integration of hydrogeological and hydrochemical data sets with the sedimentologic work presented here would aid in the development of an enhanced stratigraphic framework for the sediments underlying the former Lake Algonquin plain and may hold important implications for groundwater flow and contaminant transport pathways in other glaciolacustrine basins across North America.

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CHAPTER 4: CONCLUSIONS

This thesis presents a detailed analysis of Quaternary landforms and sediments in the Alliston region of southern Ontario utilizing both landsystems analysis and sedimentological approaches. The findings presented here significantly enhance understanding of the spatial distribution and depositional origin of landforms and near-surface sediments in the region. Analysis of Quaternary landsystems in the Alliston area (Chapter 2) provides an improved framework for the description and interpretation of regionally significant surficial deposits and landforms in south-central Ontario. This work has aided in refining knowledge of changing environmental conditions throughout the later phases of the Wisconsin Episode, by building and expanding on previous work that focused on analysis of the physiography of the terrain. The landsystems analysis approach facilitates determination of the depositional origin of features that span multiple physiographic regions and has helped to identify issues for further investigation that may help to clarify the spatio-temporal relationship of changes in major depositional systems during the late glacial period, including:

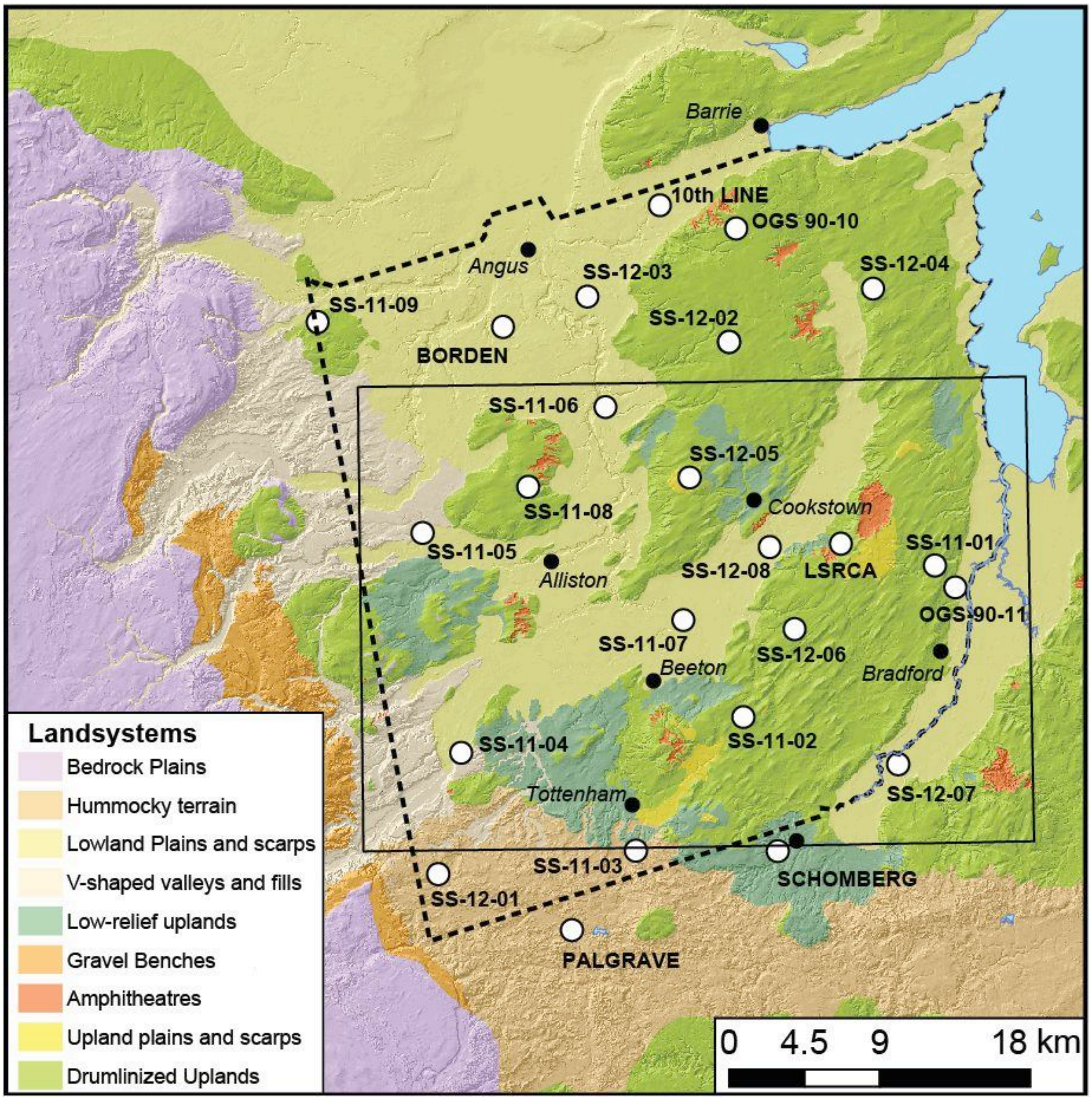
- the relationship between Thorncliffe equivalent deposits in the Alliston area and in the Greater Toronto Region
- the sedimentology, morphology, and hydraulic (aquitard?) properties of the Newmarket Till in the Alliston area
- the timing and mechanism(s) of valley formation, and in particular, the determination of subglacial (tunnel valley) or subaerial origins for these features
- determination of the age, northern extent and location of lake outlets of glacial Lake Schomberg

- determination of the full 3-D distribution of glacial Lake Algonquin deposits beneath the lowlands landsystem.

Detailed study of thick sediment successions within lowlands in southern Simcoe County (Chapter 3) augments the surficial landsystems investigation presented in Chapter 2 by providing sedimentologic support to test genetic interpretations and to characterize the nature of changes in deglacial glaciolacustrine environments within the region. Investigation into the sediment succession along Nottawasaga River Valley has helped determine the stratigraphic framework that characterizes the sediment in-fill of the lowlands plains landsystem and presents important data that have applications to interpretations of climate change during the deglacial period. These data can also be used to inform hydrogeological investigations within the broader Simcoe Lowlands region that was inundated by extensive glacial lakes during the deglacial period.

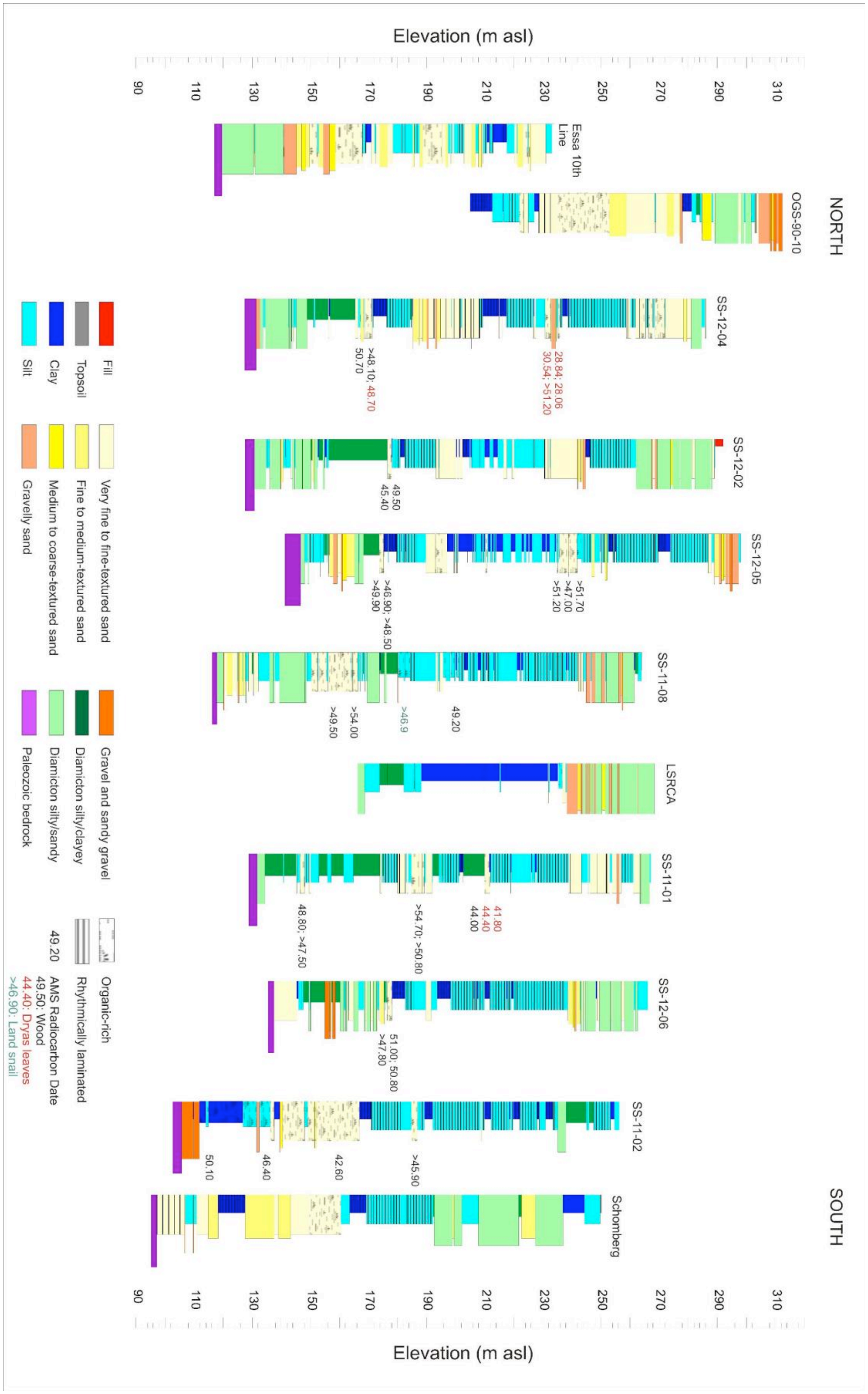
The two investigations presented in this study (Chapters 2 and 3) provide an improved framework for identification of environmentally sensitive areas in the southern Simcoe County region, particularly where coarse-grained deposits are exposed at surface, potentially in hydraulic connection with buried aquifers underlying the Newmarket Till. Delineation of these areas is essential in order to inform hydrogeological investigations and source water protection strategies as well as to ensure the preservation and protection of potable drinking water supplies for the region.

APPENDIX A: VERTICAL SEDIMENT DATA



Barrie
10th LINE
OGS 90-10
Angus
SS-12-03
SS-12-04
SS-11-09
SS-12-02
BORDEN
SS-11-06
SS-12-05
Cookstown
SS-11-08
SS-11-05
Alliston
SS-12-08
LSRCA
SS-11-01
OGS-90-11
SS-11-07
SS-12-06
Beeton
Bradford
SS-11-02
SS-11-04
SS-12-07
Tottenham
SS-11-03
SCHOMBERG
SS-12-01
PALGRAVE
Landsystems
Bedrock Plains
Hummocky terrain
Lowland Plains and scarps
V-shaped valleys and fills
Low-relief uplands
Gravel Benches
Amphitheatres
Upland plains and scarps
Drumlinized Uplands
0 4.5 9 18 km

Location of OGS boreholes (From Bajc and Rainsford, 2011; Bajc et al., 2012) overlain on landsystem map (this study).


NORTH
SOUTH
Elevation (m asl)
Essa 10th Line
OGS-90-10
SS-12-04
SS-12-02
SS-12-05
SS-11-08
LSRCA
SS-11-01
SS-12-06
SS-11-02
Schomberg
Fill
Topsoil
Clay
Silt
Very fine to fine-textured sand
Fine to medium-textured sand
Medium to coarse-textured sand
Gravelly sand
Gravel and sandy gravel
Diamicton silty/clayey
Diamicton silty/sandy
Paleozoic bedrock
Organic-rich
Rhythmically laminated
49.20 AMS Radiocarbon Date
49.50: Wood
44.40: Dryas leaves
>46.90: Land snail

NORTH
SOUTH
Elevation (m asl)
150
160
170
180
190
200
210
220
230
240
250
260
270
280
290
300
310
SS-11-09
43.90
38.90
SS-11-05
SS-11-04
39.80
45.20; 48.80; 43.90
SS-11-03
Palgrave
Fill
Topsoil
Clay
Silt
Very fine to fine-textured sand
Fine to medium-textured sand
Medium to coarse-textured sand
Gravelly sand
Gravel and sandy gravel
Diamicton silty/clayey
Diamicton silty/sandy
Paleozoic bedrock
Organic-rich
Rhythmically laminated
49.20
AMS Radiocarbon Date
49.50: Wood
44.40: Dryas leaves
>46.90: Land snail


Elevation (m asl)
NORTH
SOUTH
SS-12-03
SS-11-06
SS-11-07
SS-12-08
SS-12-07
12.41; >49.50; 12.46
54.8; >49.2
Fill
Topsoil
Clay
Silt
Very fine to fine-textured sand
Fine to medium-textured sand
Medium to coarse-textured sand
Gravelly sand
Gravel and sandy gravel
Diamicton silty/clayey
Diamicton silty/sandy
Paleozoic bedrock
Organic-rich
Rhythmically laminated
49.20 AMS Radiocarbon Date
49.50: Wood
44.40: Dryas leaves
110
120
130
140
150
160
170
180
190
200
210
220
230
240
250
Elevation (m asl)

APPENDIX B: SURFICIAL GEOLOGY OF THE ALLISTON AREA