SEDIMENTARY ARCHITECTURE OF SHALLOW AND DEEP SUBSURFACE QUATERNARY SEDIMENTS, SOUTHERN ONTARIO

SEDIMENTARY ARCHITECTURE OF SHALLOW AND DEEP SUBSURFACE QUATERNARY SEDIMENTS, SOUTHERN ONTARIO

By

JESSICA MARIE SLOMKA. B.Sc. (Hons)

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfillment of the Requirements

for the Degree

Master of Science

McMaster University

Master of Science (2011) McMaster University

(Geography and Earth Sciences) Hamilton, Ontario, Canada

TITLE: **SEDIMENTARY ARCHITECTURE OF SHALLOW AND DEEP QUATERNARY SUBSURFACE SEDIMENTS, SOUTHERN ONTARIO**

AUTHOR: Jessica Marie Slomka B.Sc. (Hons)

(McMaster University, Hamilton, 2009)

SUPERVISOR: Professor Carolyn H. Eyles

NUMBER OF PAGES: xii,126

ABSTRACT

Architectural element analysis (AEA) is a tool developed by Allen (1983) and Miall (1985) to describe and understand the internal and external geometry of fluvial sedimentary deposits observed in outcrop, and has been applied to a variety of depositional environments. AEA is a valuable methodology for the detailed reconstruction of sedimentary heterogeneity within stratigraphic units and aquifers/ aquitards, which is particularly important in areas strongly reliant on groundwater as a potable source of water such as the Georgetown area in southern Ontario.

This thesis involves a detailed facies and architectural analysis of subsurface Quaternary glacial sediments in the Limehouse and Georgetown area of southern Ontario. A local aggregate pit in Limehouse, Ontario provides several well-exposed outcrop faces primarily composed of coarse-grained sand and gravel deposits (Chapter 2). Architectural elements delineated from the outcrop faces in Limehouse serve as an analogue to deeper subsurface sediments recorded from fully-cored boreholes drilled in the Sixteen Mile Creek area of Georgeotwn, Ontario, which is an area devoid of outcrop exposures (Chapter 3). The Quaternary stratigraphy of the Limehouse and Georgetown area is significantly heterogeneous with a complex architecture recorded in both shallow and deep subsurface sediments (Chapters 2, 3). Aquitard and aquifer/recharge zone layers may be discontinuous and incised/truncated in some places, which may form a hydrologic connection between units and through till sheets (considered to be regional

aquitards) to underlying aquifer units (Chapters 2, 3). The geometry and architecture of stratigraphic units can improve the understanding of groundwater flow behaviour, contaminant migration pathways and may enhance the accuracy of local and regional three-dimensional geologic and hydrogeologic models in southern Ontario and for similar glaciated terrains elsewhere.

ACKNOWLEDGEMENTS

This thesis was funded by an OGSST QE II Graduate Scholarship and the Regional Municipality of Halton. Many thanks are indebted to Tim Lotimer for his extreme enthusiasm and support, for taking the time to look through core, sift through pages of data, and have lengthy discussions about various aspects of hydrogeology. Thank you to Steve Davies for providing various data and Colin Evans (and the many personnel) at Limehouse Pit for providing access to the pit property.

I am very grateful to all members of the Glacial Sedimentology Lab, including Stacey Puckering, Riley Mulligan, Paul Durkin, Kelsey MacCormack (who stored the core in her family garage for 2 years) and Prateek Gupta, for hours and days of fieldwork assistance and very useful discussion relating to this thesis. Thanks to Andy Brennan and Joe Boyce for discussion about downhole geophysical data from Georgetown and Nicole Fallon for discussion about GPR results from Limehouse. Also thanks to Andrew and Joey Slomka and Kevin Elmer for fieldwork assistance, transportation and listening to me talk about 'rocks and dirt'. I must also thank Rodrigo Narro and Nora Labbancz for help with editing and formatting this thesis.

Most importantly, this thesis would not have been possible without the full support of my supervisor Dr. Carolyn H. Eyles. Her enthusiasm for student learning and success, excitement for any opportunity to do field work and obvious passion for the earth sciences is reflected in my own found passion for glacial sedimentology. Thank you, Carolyn, for providing me with invaluable knowledge, skills, and opportunities

throughout my undergraduate and graduate career at McMaster, for which I am truly grateful and will never forget.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

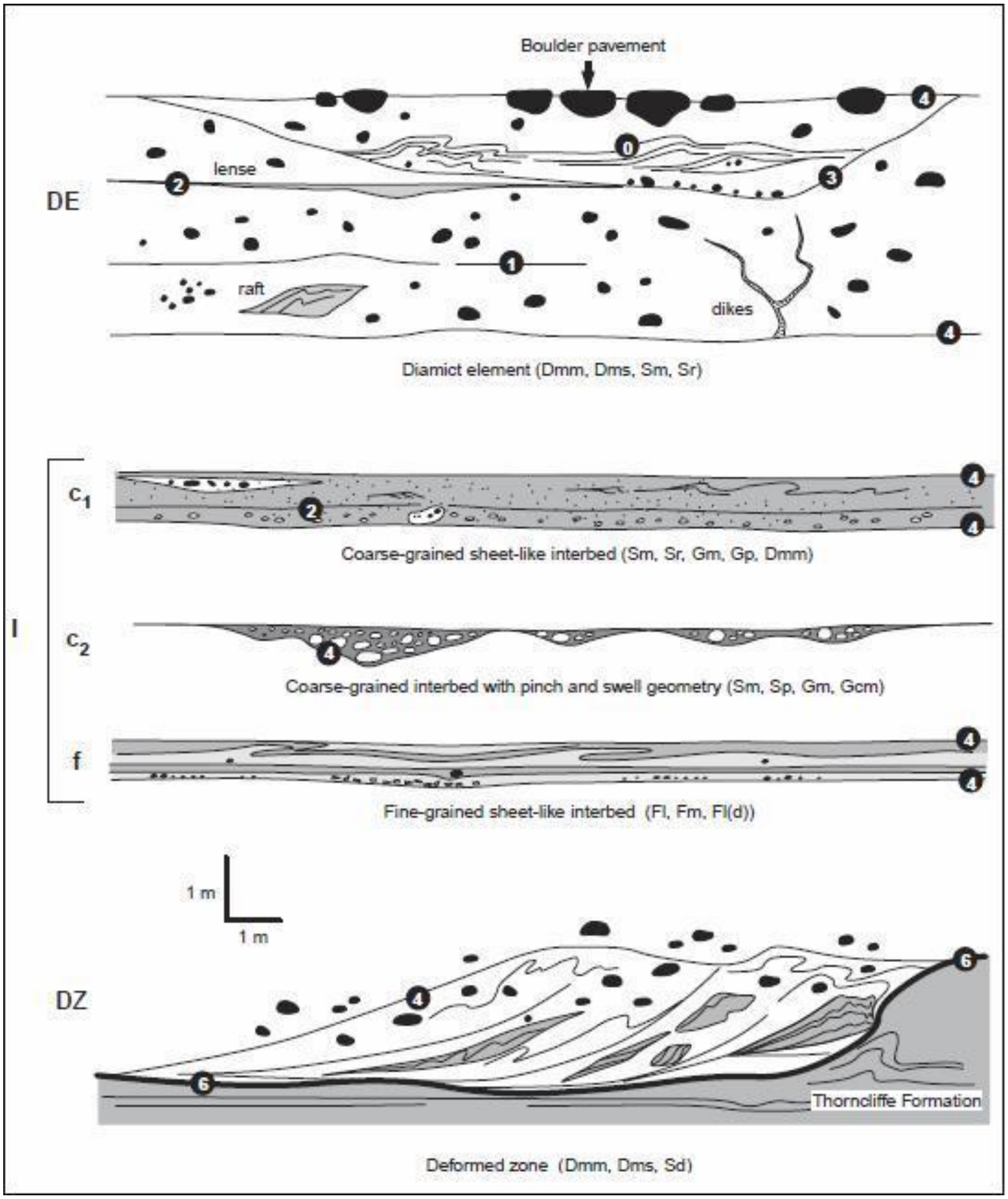
INTRODUCTION

Sedimentary deposits are formed in a variety of environments, including alluvial, glacial, eolian, marine and lacustrine depositional settings. Sediments deposited under similar environmental conditions and which can be traced over a large area as mappable units are grouped together as ‘stratigraphic formations’ (Blatt et al. 1972) or ‘stratigraphic units’ (Walker 1992). The mapping and understanding of the characteristics and geometry of stratigraphic units has significance for the fields of civil structural engineering, mineral exploration, aggregate production, groundwater resources, contaminant remediation studies, and the oil and gas industry. Some stratigraphic units are well known worldwide, such as the Devonian strata within the Western Canada Sedimentary Basin, Canada, which host significant amounts of oil and gas (Fowler et al. 2001).

Traditionally, ancient sedimentary deposits are recorded by identifying facies types in 1-dimensional vertical profiles taken from outcrop exposures and interpreted using geomorphological observations of modern system analogues (e.g. Cant & Walker 1976; Eyles et al. 1983; Walker, 1992). These sedimentary records were classified into ‘end member’ types of each environment for ease of comparison (e.g. fluvial environments; Miall 1977; and deltaic environments; Galloway 1975) and formed the basis of predictive ‘facies models’ (Walker 1992; Dalrymple and James, 2010). However, most sedimentary deposits do not entirely conform to one end member type and require a more comprehensive method of description and interpretation. Additionally, 1-dimensional vertical profiles do not provide any information regarding the internal and external geometry of sedimentary deposits or their component parts, which is important for any subsurface investigations, including those focused on petroleum and groundwater resource exploration (Miall 1985).

Architectural element analysis (AEA) is a methodology developed by Allen (1983) and Miall (1985) to describe, visualize and understand the morphologic changes and geometry (2- and 3-dimensional) of fluvial sedimentary deposits observed in outcrop (Dalrymple 2010). This methodology involves detailed facies description, identification of facies associations, delineation of bounding surfaces between facies, and demarcation of bounding surfaces in a hierarchy consistent with the degree of environmental change represented by each surface (Figure 1.1; Miall 1985, Boyce and Eyles 2000). Architectural element analysis has been widely applied to various environments, including eolian (Mountney et al. 1999), subglacial (Boyce & Eyles 2000), deltaic (Eriksson et al. 1995), and submarine channel (Miall 1989) environments, through the use of outcrop, core and geophysical data. AEA is a valuable tool for the detailed reconstruction of sedimentary heterogeneity within stratigraphic units, and has been successfully applied in the fields of hydrocarbon exploration (e.g. Clark & Pickering 1996) and groundwater resources (e.g. Asprion & Aigner 1997).

Figure 1.1: Facies types, architectural elements and bounding surface hierarchies recorded from a till sheet by Boyce & Eyles (2000).


Boulder pavement
lense
raft
dikes
DE
0
1
2
3
4
Diamict element (Dmm, Dms, Sm, Sr)
I
c_1
Coarse-grained sheet-like interbed (Sm, Sr, Gm, Gp, Dmm)
c_2
Coarse-grained interbed with pinch and swell geometry (Sm, Sp, Gm, Gcm)
f
Fine-grained sheet-like interbed (Fl, Fm, Fl(d))
1 m
1 m
DZ
6
Thorncliffe Formation
Deformed zone (Dmm, Dms, Sd)

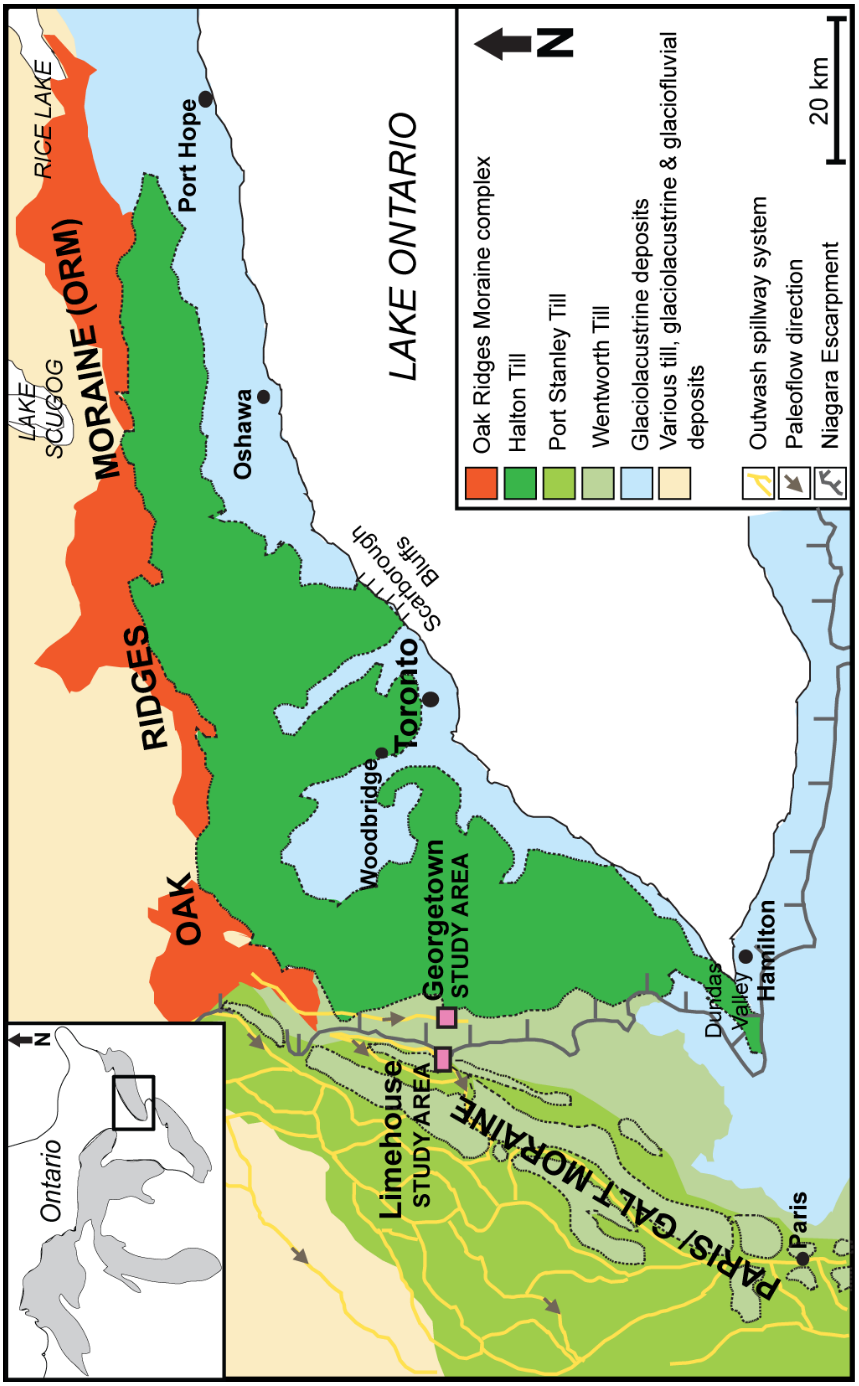
Objectives of this research

The primary objective of this research is to enhance the understanding of the origin and sedimentary architecture of glacial deposits in the Georgetown area of southern Ontario (Figure 1.2) by identifying facies types, characterizing the nature and hierarchical order of bounding surfaces, and applying architectural element analysis to shallow and deep subsurface Quaternary sediments. This work will provide in-depth understanding of the detailed internal and external geometry of regionally extensive stratigraphic units that have been previously mapped in the Georgetown area and elsewhere in southern Ontario.

Southern Ontario has experienced several episodes of glaciation over the past 2 million years, which resulted in the formation of thick successions of glacial and inter-glacial sediments (Eyles 2002). The oldest preserved record of glaciation in southern Ontario is the York Till, a clast- rich, sandy diamict overlying striated shale bedrock (Eyles & Clark 1988; Karrow 1989) attributed to deposition during the Illinoian glaciation (c. 135 000 ybp) and identified from the outcrop exposures in the Don Valley Brickyard in the Toronto area (Eyles 2002). The York Till is overlain by deltaic sands and fine-grained sediments deposited during the Sangamon Interglacial (c. 120 000 ybp) which comprise the Don Formation (Eyles & Eyles 1983; Eyles & Clark 1988).

The most complete record of glaciation preserved in southern Ontario is from the late Wisconsinan glaciation (c. 80 000 to 12000 ybp), which occurred during the Late Quaternary when the Laurentide Ice Sheet (LIS) migrated over southern Ontario,

Figure 1.2: A map of southern Ontario showing the location of the two study areas (Limehouse and Georgetown) used in this thesis, including surficial sedimentary cover and major geomorphological features (data from OGS 2003; Chapman & Putnam 1984).


OAK
RIDGES
MORAINE (ORM)
RICE LAKE
LAKE SCUGOG
LAKE ONTARIO
Port Hope
Oshawa
Scarborough Bluffs
Toronto
Woodbridge
Georgetown STUDY AREA
Limehouse STUDY AREA
PARIS/GALT MORAINE
Dundas Valley
Hamilton
Paris
Ontario
N
Oak Ridges Moraine complex
Halton Till
Port Stanley Till
Wentworth Till
Glaciolacustrine deposits
Various till, glaciolacustrine & glaciofluvial deposits
Outwash spillway system
Paleoflow direction
Niagara Escarpment
20 km

reaching its maximum extent around 20 000 ybp (Eyles 2002). The Wisconsinan record consists of a thick succession of lacustrine, glaciolacustrine and deltaic sediments which comprise the Scarborough and Thorncliffe Formations (c. 60 000 and c. 45 000 ybp, respectively), a thick sandy till sheet (the Northern/ Newmarket Till; c. 20 000 ybp), interstadial outwash sediments (the Mackinaw Interstadial; c. 13 300 ybp), and a relatively thin veneer of clayey till (the Halton Till; c. 13 000 ybp; Eyles 2002). This stratigraphy has been mapped as regional units across southern Ontario, using outcrop exposures, fully cored boreholes, geophysical data, palaeontological information, and water well records. Although detailed sedimentological studies have been conducted in some parts of southern Ontario (e.g. Dreimanis 1958; Eyles & Eyles 1983; Eyles & Clark 1988; Brennand 1994; Karrow et al. 2001; Russell et al 2003; Meyer & Eyles 2007), the internal heterogeneity, geometry and interconnectedness of the major Quaternary stratigraphic units and aquifers they host are still very poorly understood.

This thesis involves thorough sedimentological study and architectural element analysis of shallow subsurface sediments exposed in the Limehouse Pit (Chapter 2), and of deeper, cored sediments from five boreholes drilled in the Sixteen Mile Creek area of Georgetown, Ontario (Chapter 3; Figure 1.2). Several outcrop faces in the Limehouse aggregate pit expose sand and gravel deposits that are thought to have formed in a large outwash system which drained the retreating LIS, flowing southward adjacent to the Niagara Escarpment (c. 13 000 ybp; Costello & Walker 1972; Chapman & Putnam 1984). Sedimentologic and architectural analysis of exposures within the Limehouse Pit has identified a series of facies types, bounding surfaces, and architectural elements that may be used as an analogue to help refine interpretation of the origin and sedimentary architecture of similar coarse-grained sedimentary units identified from the deeper, more complex stratigraphy within the Sixteen Mile Creek cores (Chapter 3).

Thesis Structure

The major research findings are presented in two main chapters (Chapter 2 & Chapter 3), which are formatted for submission for publication as separate papers in two different scientific journals. Chapter 1 gives an introduction to the thesis topic and Chapter 4 provides a summary and conclusions and presents ideas for future work. The content of Chapters 2 and 3 are outlined below.

Chapter 2 – Sedimentary architecture of a Late Quaternary glaciofluvial deposit, Limehouse, Ontario, Canada

Thick successions of glacial outwash sediment formed during the Late Quaternary (c.a. 25 000-13 000 ybp) host significant regional aquifers throughout southern Ontario. It is important to understand the sedimentary characteristics and architecture of such coarse-grained outwash deposits for the purposes of groundwater modelling and prediction of contaminant fate and transport pathways. Although nearly three million Ontarians currently rely on groundwater as a potable source of water, the sedimentology, geometry, and interconnectedness of aquifers in southern Ontario are very poorly understood.

This study presents an investigation of the sedimentary geometry of Late Quaternary outwash sediments exposed in a local aggregate pit in the Limehouse area, southern Ontario, Canada. In total, 31 sedimentary logs are recorded from various outcrop exposures and allow the identification of nine different facies types: gravel facies (Gm, Gp, Gt), sand facies (Sr, Sp, St, Ss) and fine-grained facies (Fl and Fd). Facies contacts were delineated as bounding surfaces of varying significance in a hierarchical fashion (1^{st}- to 5^{th}-order), corresponding to the degree of environmental change they record. The arrangement of facies types and bounding surfaces allowed the delineation of five architectural elements which include: sand complex (SC), gravel sheet (GS), fine-grained sheet (FS), large-scale foreset body element (GFB), and concave fill (CF) element. The grouping of architectural elements relative to the location of bounding surfaces recorded in three laterally extensive outcrop faces allows the identification of six sedimentary units ('element associations'; EAs). The six EAs identified in this study record different fluvial depositional settings, which are the sandy braided-river environment (EA1), delta front environment (EA2 and EA4), delta top gravel braided-river environment (EA3), gravel-dominated braided-river environment (EA5), and sand-dominated fluvial environment (EA6).

The in-depth facies analysis and application of architectural element analysis in this study helps to reconstruct the Late Quaternary post-glacial history and sedimentary geometry of the Limehouse area. This study provides an enhanced understanding of the detailed sedimentary heterogeneity of the Limehouse area, which may have significant implications for modelling of contaminant fate and transport pathways, groundwater flow and deep subsurface geologic models in southern Ontario and elsewhere.

Chapter 3 – Sedimentolgy and stratigraphic architecture of subsurface Quaternary glacial sediments in the Sixteen Mile Creek area of Georgetown, Ontario

Groundwater exploration programs focusing on unconsolidated sediments in southern Ontario require a comprehensive understanding of the subsurface Quaternary stratigraphy directly overlying bedrock. The town of Georgetown, Ontario relies on groundwater as a potable source of water and is at the centre of a multi-year groundwater exploration program conducted by the Regional Municipality of Halton.

The ongoing groundwater investigation in Georgetown, Ontario provided an opportunity to study the deep subsurface stratigraphy from 5 fully cored boreholes which penetrate a thick succession of Quaternary glacial sediment overlying Paleozoic bedrock. Detailed sedimentological analysis of the core samples allows the identification of twelve facies types: gravel facies (massive/ deformed and crudely bedded); sand facies (rippled; cross bedded; horizontally bedded and massive/deformed sand); fine-grained facies (laminated; massive/crudely bedded with dropstones; and massive/deformed); and diamict facies (clast-rich; clay-rich; and sand-rich). The organization of facies assemblages, combined with the delineation of major bounding surfaces in a hierarchical order (4^{th}- to 7^{th}-order), helps to distinguish nine different architectural elements: gravel lens (GL), gravel complex (GC), sand lens (SL), sand complex (SC), fine-grained lens (FL), fine-grained complex (FC), diamict lens (DL), diamict complex (DC) and diamict deformed zone (DZ). The arrangement of architectural elements and bounding surfaces facilitates the reconstruction of past depositional environments and delineates seven major stratigraphic units (U1-U7): weathered bedrock/ colluvium (U1), sand-dominated glaciofluvial (U2), lower till complex (U3), gravel-dominated glaciofluvial (U4), glaciolacustrine/deltaic (U5), upper till complex (U6) and glaciofluvial sand and gravel (U7). The detailed internal and external stratigraphic architecture documented in this study provide insight into the potential heterogeneity, geometry and interconnectedness of aquifers and aquitards in the Georgetown area.

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CHAPTER 2

SEDIMENTARY ARCHITECTURE OF A LATE QUATERNARY GLACIOFLUVIAL DEPOSIT, LIMEHOUSE, ONTARIO, CANADA

Abstract

This study presents an architectural analysis of predominately sand and gravel deposits exposed in an aggregate quarry in the Limehouse area of southern Ontario, Canada. Nine different facies types are identified from 31 sedimentary logs recorded from outcrop exposures: gravel facies (Gm, Gp, Gt), sand facies (Sr, Sp, St, Ss) and fine-grained facies (Fl and Fd). Five orders (1^{st}- to 5^{th}-order) of bounding surfaces and five architectural elements are also delineated including sand complex (SC), gravel sheet (GS), fine-grained sheet (FS), large-scale foreset body element (GFB), and concave fill (CF) element. The arrangement of bounding surfaces and architectural elements in three laterally extensive outcrop faces in the pit allows the identification of six sedimentary units ('element associations'; EAs): sandy braided-river (EA1), delta front (EA2 and EA4), delta top gravel braided-river (EA3), gravel-dominated braided-river (EA5), and sand-dominated fluvial (EA6). The utilization of architectural element analysis in this study helps in the reconstruction of the Late Quaternary post-glacial history of the Limehouse area, and provides insight into the sedimentological characteristics and geometries of more deeply buried coarse-grained sediments that form potential aquifers in the Georgetown region.

2.1 Introduction

Significant local and regional groundwater aquifers in southern Ontario are hosted within thick packages of glacial outwash sediment deposited during the late Quaternary period (ca. 25000-13000 ybp; Barnett 1992). Nearly 3 million people in Ontario rely on groundwater extracted from these aquifers as a source of potable water (Ontario Ministry of Natural Resources 2009). It is therefore important to understand the nature of the coarse-grained outwash sediments comprising the aquifers in order to more accurately predict groundwater behaviour and model contaminant fate and transport pathways. However, the sedimentary characteristics, subsurface geometry, and interconnectedness of aquifers in southern Ontario are very poorly understood and not well documented. The limited amount of sedimentological and stratigraphic data pertaining to subsurface outwash deposits is largely a function of the restricted availability of outcrop exposures and/or core data, and the primary focus of past investigations on regional and surficial geologic mapping (e.g. Chapman & Putnam 1984; Sharpe et al. 1997) and the development of depositional models (e.g. Costello & Walker 1972; Eynon & Walker 1976; Brennand 1994). Although some studies very thoroughly describe the nature of Quaternary sediments exposed at surface and in core samples (e.g. Russell et al. 2003; Brennand 1994; Eyles & Eyles 1983; Eynon & Walker 1974), information on the detailed two- and three-dimensional geometry and architecture of these deposits in the subsurface is lacking.

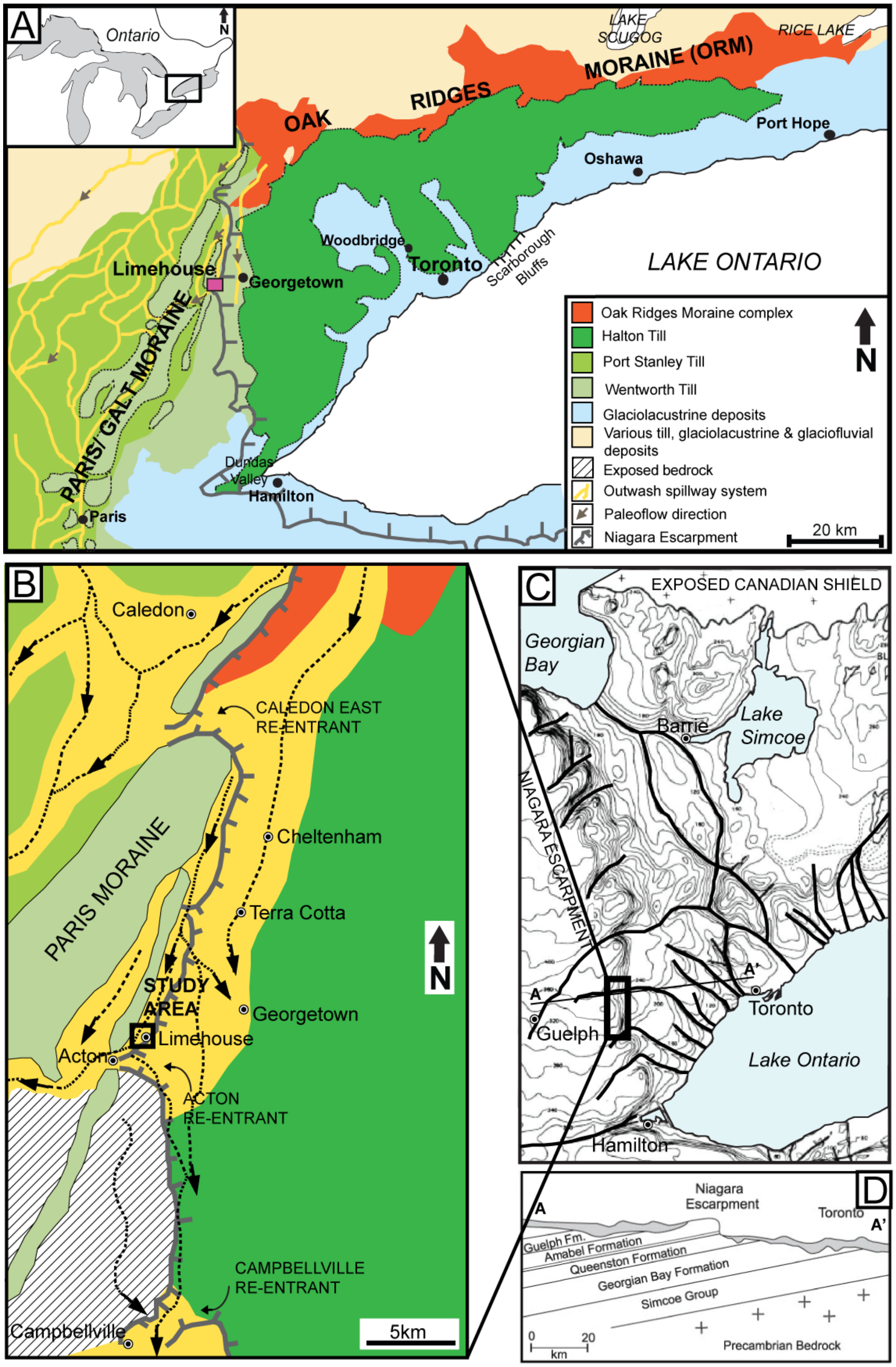
In order to document the characteristics and geometry of coarse-grained subsurface sediments, a descriptive and interpretive tool that was developed for the analysis of sedimentary successions and for applications in the resource industry is used here to analyse coarse-grained sediments exposed in the Limehouse Pit, Ontario (Figure 2.1). Architectural element analysis (AEA) was first introduced by Allen (1983) and Miall (1985) and has been used to describe and interpret the geometry of sedimentary sequences of fluvial origin (Allen 1983; Miall 1985) and, more recently, to sediments deposited in aeolian (Mountney et al. 1999), subglacial (Boyce & Eyles 2000), deltaic (Eriksson et al. 1995), and submarine channel (Miall 1989) environments. AEA involves the delineation of distinct units of individual (or groups of) facies types (facies associations), separated by contacts or bounding surfaces (Miall 1985, 2010). Bounding surfaces record changes in depositional conditions of various scales (Miall 2010) and can be organized as a hierarchy consistent with the degree of environmental change they represent. AEA allows site-specific description and visual representation of the variation in subsurface sediment geometry and environmental change over space and time. This is accomplished through the integration of data describing lateral and vertical variation in the geometry of sedimentary packages at various scales and their relationship to the hierarchy of bounding surfaces (Miall 1985). The characterization of architectural elements and bounding surfaces can be modified by the user to best represent any study area using a systematic classification scheme (e.g. Miall 2010), which can be readily translated for comparison to other areas.

The purpose of this study is to provide a detailed sedimentological and architectural element analysis of coarse-grained Quaternary age deposits observed in outcrop exposures in the Limehouse area of southern Ontario (Figure 2.1) to better understand sediment unit geometries and to reconstruct the depositional environments in which they formed. Sedimentological and architectural information gathered in this study can be used to enhance understanding of the architecture of more deeply buried subsurface sediments that function as productive aquifers in this study area and elsewhere.

2.2 Geological Setting

The bedrock of southern Ontario consists of Paleozoic sedimentary rocks (deposited ca. 400-600 Ma; Eyles 2002) underlain by Proterozoic basement rocks of the Canadian Shield. The Paleozoic bedrock is well exposed along the Niagara Escarpment, a bedrock scarp that stretches from the Niagara Peninsula to Georgian Bay (Figure 2.1; Eyles 2002). The Paleozoic bedrock surface is dissected by a network of valleys and escarpment re-entrants (Figure 2.1C), thought to be carved by an ancient drainage system of the Laurentian River (ca. 2.5 Ma) and subsequent glacial and fluvial erosion (Straw 1968; Gao 2011). The orientation of most bedrock valleys and postglacial drainage systems in southern Ontario correspond to regional jointing patterns and are described as ‘tectonically predesigned’ (Eyles et al. 1997).

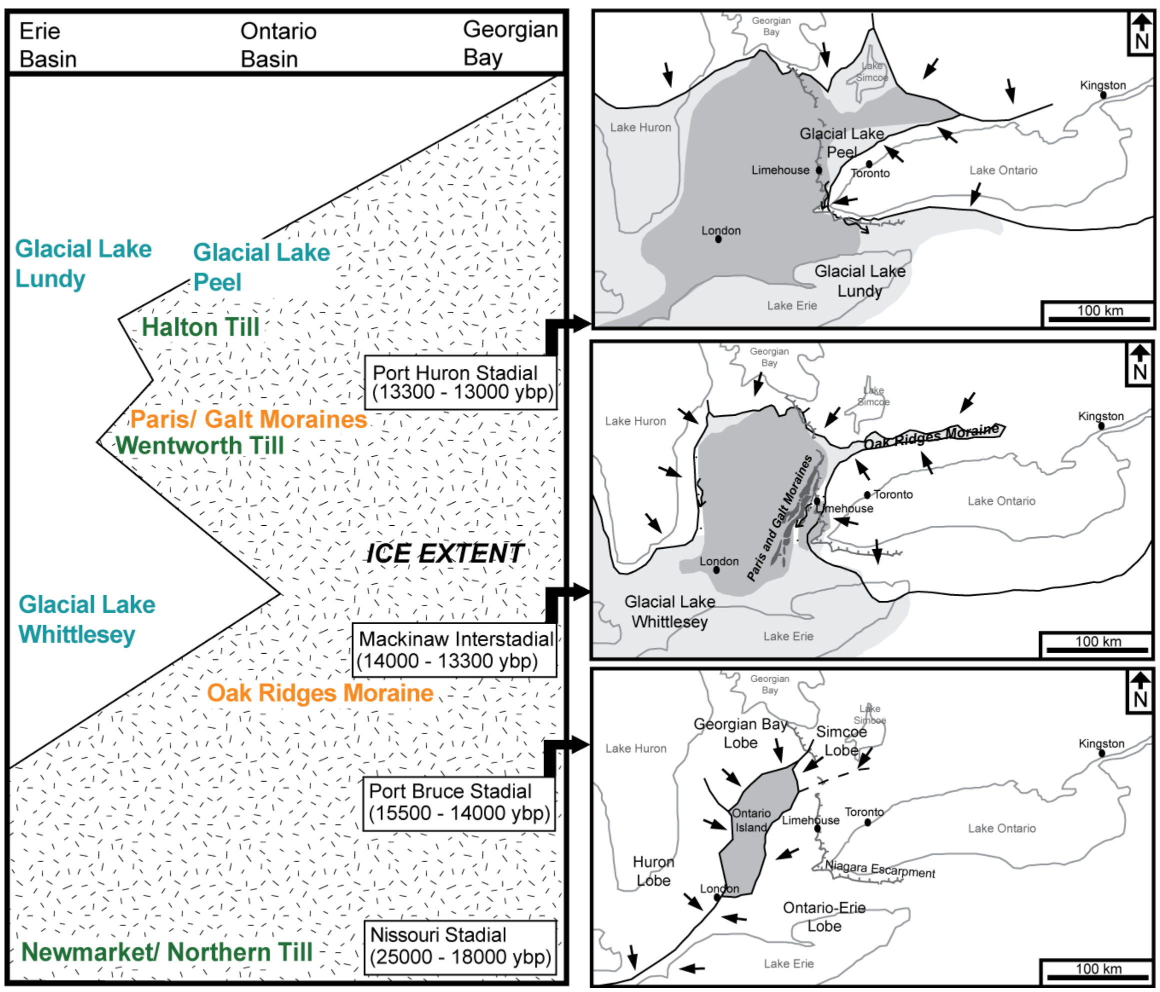
Figure 2.1: Study area at Limehouse, Ontario, Canada. A. Map of southern Ontario showing surficial sediment types and location of study area at Limehouse (data from OGS 2003; Chapman & Putnam 1984). B. Surficial geology of the Limehouse region showing position of the Niagara Escarpment and former fluvioglacial pathways (modified from Chapman 1985; Chapman & Putnam 1984; Costello & Walker 1972; Straw 1968 and OGS 2003). C. Regional bedrock topography showing the location of bedrock valleys (modified from Eyles et al. 1993). D. Paleozoic stratigraphy of southern Ontario (modified from Gao 2011; Meyer & Eyles 2007; and Eyles et al. 1993)


A
Ontario
N
LAKE SCUGOG
RICE LAKE
OAK RIDGES MORAINE (ORM)
Port Hope
Oshawa
Woodbridge
Toronto
Scarborough Bluffs
LAKE ONTARIO
Limehouse
Georgetown
PARIS/ GALT MORAINE
Dundas Valley
Hamilton
Paris
Oak Ridges Moraine complex
Halton Till
Port Stanley Till
Wentworth Till
Glaciolacustrine deposits
Various till, glaciolacustrine & glaciofluvial deposits
Exposed bedrock
Outwash spillway system
Paleoflow direction
Niagara Escarpment
20 km
B
Caledon
CALEDON EAST RE-ENTRANT
Cheltenham
Terra Cotta
PARIS MORAINE
STUDY AREA
Georgetown
Limehouse
Acton
ACTON RE-ENTRANT
CAMPBELLVILLE RE-ENTRANT
Campbellville
5km
C
EXPOSED CANADIAN SHIELD
Georgian Bay
Barrie
Lake Simcoe
NIAGARA ESCARPMENT
A
A'
Toronto
Guelph
Lake Ontario
Hamilton
D
Niagara Escarpment
Toronto
Guelph Fm.
Amabel Formation
Queenston Formation
Georgian Bay Formation
Simcoe Group
0
20
km
Precambrian Bedrock

Several episodes of glacial advance and retreat during the Quaternary have covered the Paleozoic bedrock with a succession of glacial and post-glacial sediment up to 198 m thick (Barnett 1992; Bajc et al. 2009). The regional stratigraphy of southern Ontario is exposed at the Don Valley Brickyard and Scarborough Bluffs in Toronto, and has been partially correlated to sections exposed along the north shore of Lake Ontario and Lake Erie, and in the Oak Ridges Moraine (Figure 2.1; Eyles & Eyles 1983; Barnett et al. 1998; Dreimanis & Gibbard 2005). Glacial and fluvial outwash systems have incised and eroded the Early and Middle Wisconsin stratigraphy, resulting in highly complex and poorly understood stratigraphic relationships within the southern Ontario region (Figure 2.1; Chapman & Putnam 1984; Sharpe et al. 2004; MacCormack et al. 2005; Meyer & Eyles 2007).

To the east of Limehouse, in the Georgetown area below the escarpment (Figure 2.1), a network of buried bedrock valleys are infilled by sediment that records pre-late Wisconsin glaciofluvial deposition followed by two episodes of glacial advance and retreat (Meyer & Eyles 2007). These glacial events are recorded by the deposition of the Northern-Newmarket till and associated Mackinaw Interstadial outwash sediments (e.g. Brampton Esker and Maple Formation), and the Halton Till Complex deposited during the Port Huron Stadial (Figure 2.2; Meyer & Eyles 2007; Barnett 1992). To the west of Limehouse, the Paris Moraine is dissected and eroded by a large glaciofluvial system that flowed from the north through Limehouse and emptied into glacial Lakes Whittlesey and Lundy forming a delta (Figures 2.1, 2.2; Chapman 1985). During this time, water was impounded between the Niagara Escarpment and the northern margin of the Ontario ice

Figure 2.2: Glacial history of the Limehouse area, southern Ontario. Includes a time-distance diagram showing Late Wisconsin (c. 12500-14000 ybp) ice and lake cover from the Erie basin to Georgian Bay, corresponding glacial and lacustrine deposits, and paleogeographic reconstructions (data from Chapman & Putnam 1984; Barnett 1992; and Meyer & Eyles 2007).



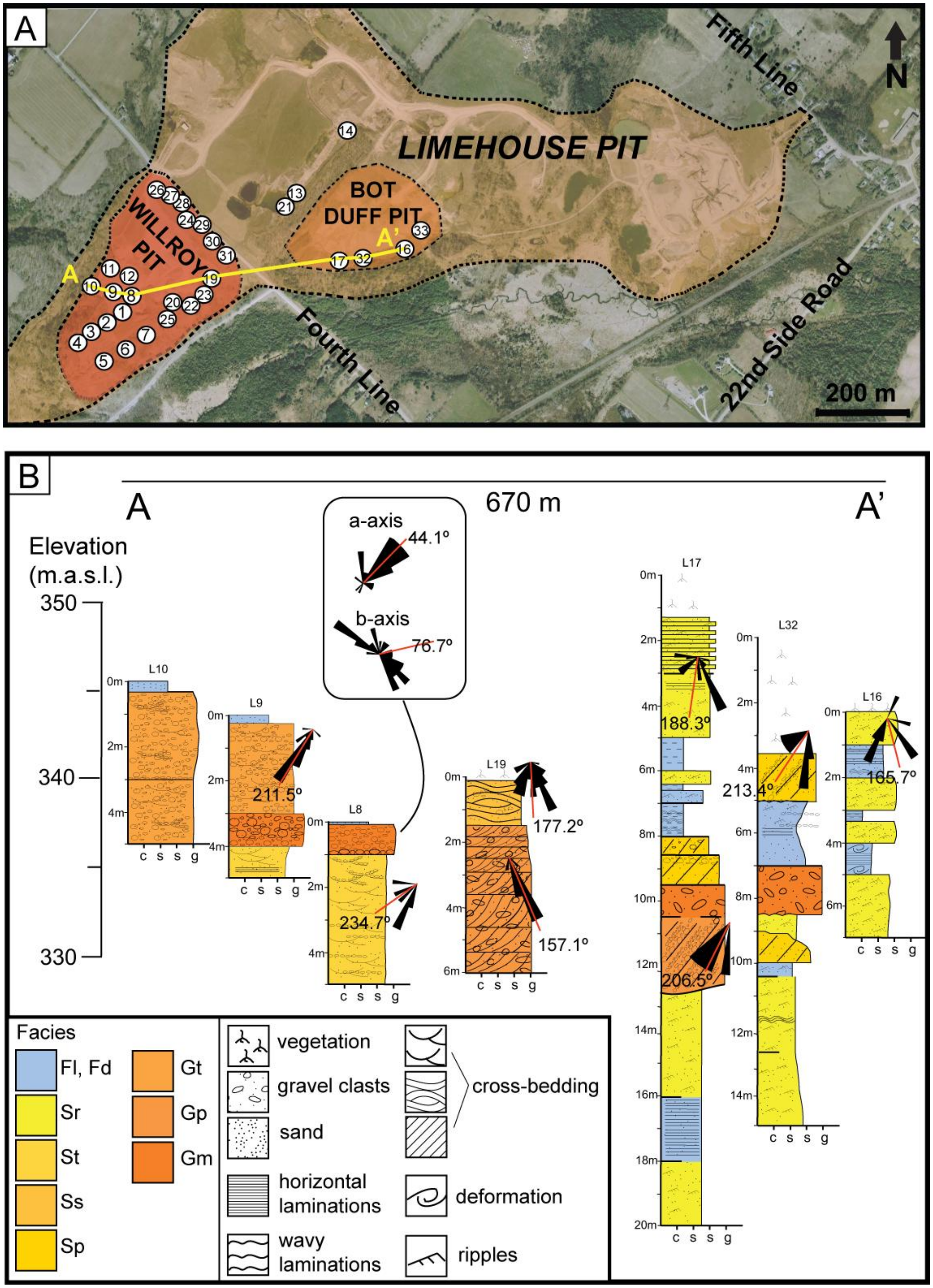
Erie Basin
Ontario Basin
Georgian Bay
Glacial Lake Lundy
Glacial Lake Peel
Halton Till
Port Huron Stadial (13300 - 13000 ybp)
Paris/ Galt Moraines
Wentworth Till
ICE EXTENT
Glacial Lake Whittlesey
Mackinaw Interstadial (14000 - 13300 ybp)
Oak Ridges Moraine
Port Bruce Stadial (15500 - 14000 ybp)
Newmarket/ Northern Till
Nissouri Stadial (25000 - 18000 ybp)
Lake Huron
Glacial Lake Peel
Limehouse
Toronto
Lake Ontario
Kingston
London
Glacial Lake Lundy
Lake Erie
100 km
N
Oak Ridges Moraine
Paris and Galt Moraines
Glacial Lake Whittlesey
Georgian Bay Lobe
Simcoe Lobe
Ontario Island
Niagara Escarpment
Huron Lobe
Ontario-Erie Lobe

lobe, which had not yet receded below the escarpment brow south of Acton (Figures 2.1, 2.2; Chapman 1985). This body of standing water is referred to as Glacial Lake Peel (Barnett 1992) and is thought to have extended from the Oak Ridge Moraine to the Georgetown area (Figures 2.1, 2.2; Costello & Walker 1972; Chapman 1985).

2.3 Study Area and Methodology

This study focuses on the description and interpretation of coarse-grained deposits that are well exposed in outcrop faces within an aggregate pit in Limehouse, Ontario. The pit has been in operation since 1965 and is operated by Canada Building Materials (CBM) of St. Marys Cement Inc. (Canada). Limehouse Pit is subdivided into two areas: the Wilroy Pit, consisting of mostly gravel, and the Bot Duff Pit, containing mostly sand (Figure 2.3). The Bot Duff Pit is up to 25m deep and occupies an area of approximately 0.1 km^2. The Wilroy Pit is located 300m southwest of the Bot Duff Pit and occupies an area of 0.24 km^2 (Figure 2.3). The Wilroy Pit exposes gravel and sand in an outcrop face about 300 m long and 20-30 m high (L24, 26-31; Figure 2.3). A 5m- thick deposit of fine-grained sand is exposed in the southwestern area of the Wilroy Pit (L1-7; Figure 2.3). Local borehole and water well information at Limehouse suggests that the limestone bedrock lies at least 26 m below the surface and that the sediment cover comprises two coarsening-upwards successions of sand and gravel separated by fine-grained deposits (till or glaciolacustrine muds).

Figure 2.3: Study area at Limehouse Pit, Limehouse, Ontario. A. Air photo of the Limehouse Pit area showing location of sedimentary logs. Cross-section A-A' shown in B. B. West-east cross section through selected logs positioned along transect A-A' (location of transect shown in A).



A
Fifth Line
N
LIMEHOUSE PIT
BOT
DUFF PIT
WILLROY
PIT
A
A'
Fourth Line
22nd Side Road
200 m
B
670 m
A
A'
Elevation
(m.a.s.l.)
350
340
330
a-axis
44.1°
b-axis
76.7°
L10
L9
L8
L19
L17
L32
L16
211.5°
234.7°
177.2°
157.1°
188.3°
213.4°
165.7°
206.5°
c s s g
Facies
Fl, Fd
Sr
St
Ss
Sp
Gt
Gp
Gm
vegetation
gravel clasts
sand
horizontal
laminations
wavy
laminations
cross-bedding
deformation
ripples

Where feasible, outcrop faces were cleaned of debris and a total of 31 sedimentary logs were recorded (L1-L33; note: L15 and 18 are omitted from this study due to poor data quality associated with limited accessibility to outcrop exposures at these locations; Figure 2.3) using standard sedimentary logging techniques (e.g. Eyles & Eyles 1983), and noting grain size, clast lithology and shape, sedimentary structures and the nature of bounding surfaces (e.g. erosional, planar, concave). Paleocurrent direction was measured by recording the steepest foreset dip angle of cross bedded facies and corresponding dip direction (perpendicular to strike) in degrees (Stow 2005). Clast fabric analysis was conducted by measuring the steepest dip angle and corresponding dip direction of the a- and b- axis of a sample of individual clasts within each facies type, where feasible (Stow 2005). Different facies types were assigned to depositional units with similar sedimentary characteristics (e.g. sedimentary structure, grain size and sorting; Miall 2010).

Although some authors have expressed concern that architectural element analysis (AEA) uses interpretive terms for descriptive purposes (Bridge 1993), this paper utilizes AEA as a descriptive tool, with elements identified on the basis of careful observation of facies assemblages, geometry and bounding surfaces. The classification of architectural elements is loosely based on the eight architectural elements for fluvial deposits proposed by Miall (1985). In this study, five architectural elements were distinguished by internal and external facies geometry, scale and the nature of upper and lower bounding surfaces (Figures 2.3- 2.6). Five different hierarchies (1^{st}- to 5^{th}- order) of bounding surfaces were also delineated on the basis of the type of facies contact, contact geometry, and the nature

Figure 2.4: Summary of facies types identified in this study (based on Miall 2010). See Figure 2.5 for photographs of each facies type.

Facies	Lithology	Sedimentary Structures	Bounding surfaces	Facies associations	Paleoflow direction	Interpretation
Gm	Gravel (2-50cm in diameter). Mostly shale, dolostone, limestone clasts. Rare sandstone, diorite, granite, gneiss clasts	Massive beds 0.5-6m thick. Imbricated clasts, cemented	Erosional lower surface. Conformable upper surface.	Commonly found with Gt, Gp, Sp, facies	Variable. Clast fabric analysis indicates weak imbrication to the southwest	Bedload in the form of migrating longitudinal bars or gravel sheets in a fluvial environment
Gt	Gravel (<1cm- 15cm in diameter). Mostly shale, dolostone, limestone clats. Rare granite, gneiss, quartzite clasts	Trough cross beds	Erosional, concave lower surface. Sharp unconformable upper surface.	Found with Gm, Gp facies	To the southwest	Formed by traction currents as migrating dunes or linguoid bars in a channel
Gp	Gravel (<1cm- >30cm in diameter). Mostly shale and dolostone clasts	Planar tabular cross bed sets (0.3-1m tall) and large-scale foresets (2-6m tall)	Erosional lower surface. Conformable, reworked or truncated upper surface.	Commonly found with Gm, Gt, St facies	To the southwest and southeast	Migration of linguoid bars and deltaic growths of older bar remnants in high energy fluvial system
St	Quartz-rich medium- to coarse-grained sand. Mostly shale and limestone but some rare granite, quartzite, and feldspar-rich clasts	Trough cross beds in cosets 1-4m thick.	Erosional lower surface and truncated surface	Associated with Sp, Gp facies	Variable (average direction is to the southwest).	Migration of sinuous crested dunes in a braided- river environment
Sp	Quartz-rich medium- to coarse-grained sand. Mostly shale and dolostone, some rare feldspar-rich clasts.	Planar tabular cross beds 0.3-1m tall in sets 0.5-1m thick.	Sharp erosional lower surface. Conformable to truncated lower surface	Associated with Gp, Gm, St, Sr facies	To the southwest	Formed by traction currents during migration of linguoid and transverse bars in a fluvial environment
Sr	Quartz-rich fine- to medium-grained sand.	Ripple cross lamination: sinusoidal, trough and climbing ripple types	Gradational conformable lower surface. Sharp truncated upper surface.	Associated with Sp, Fl, Fd facies	Variable. Predominately toward the southwest and southeast	Formed by traction currents in a fluvial/delta front environment
Ss	Quartz-rich medium- to coarse-grained sand. Rare well rounded dark shale clasts.	Sinusoidal cross lamination in cosets up to 3m thick	Erosional lower surface and truncated upper surface	None	To the south, south-west and southeast	Record the migration and subsequent erosion of dunes under fluctuating energy levels in a fluvial environment
Fl	Very fine- to fine-grained (quartz-rich) sand, silt and clay	Ripples, laminations, flaser bedding	Conformable, gradational and rarely concave lower surface. Conformable to truncated upper surface.	Commonly found with Sr, Fd facies	None	Record deposition by fallout from suspension and traction currents in a low energy ponded environment
Fd	Very fine- to fine-grained (quartz-rich) sand, silt and clay	Water escape structures, soft sediment deformation structures	Conformable, gradational to truncated lower and upper surface.	Commonly found with Sr, Fl facies	None	Record slumping and sediment loading in a low energy ponded environment

Figure 2.5: Photographs of facies types identified in this study: gravel facies Gm (a; L13), Gt (b; L11), Gp (c, d; L13, 28); sand facies Sp (e; L32), St (f; L8), Sr (g; L1), Ss (h, i; L22, 20); and fine-grained facies Fl (j, k; L3, 16) and Fd (l, m; L33, 3). See Figure 2.3 for log (L) locations.

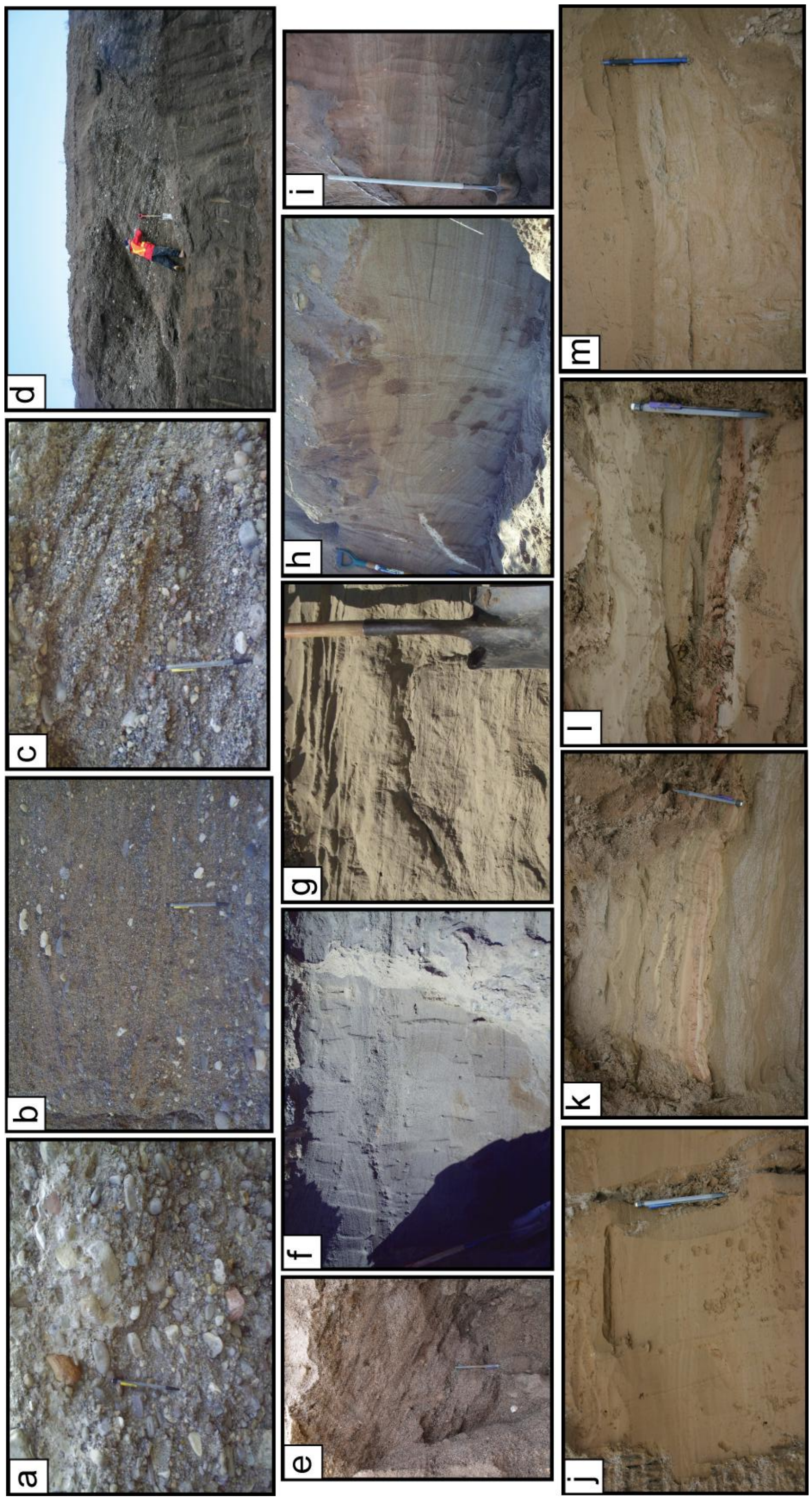
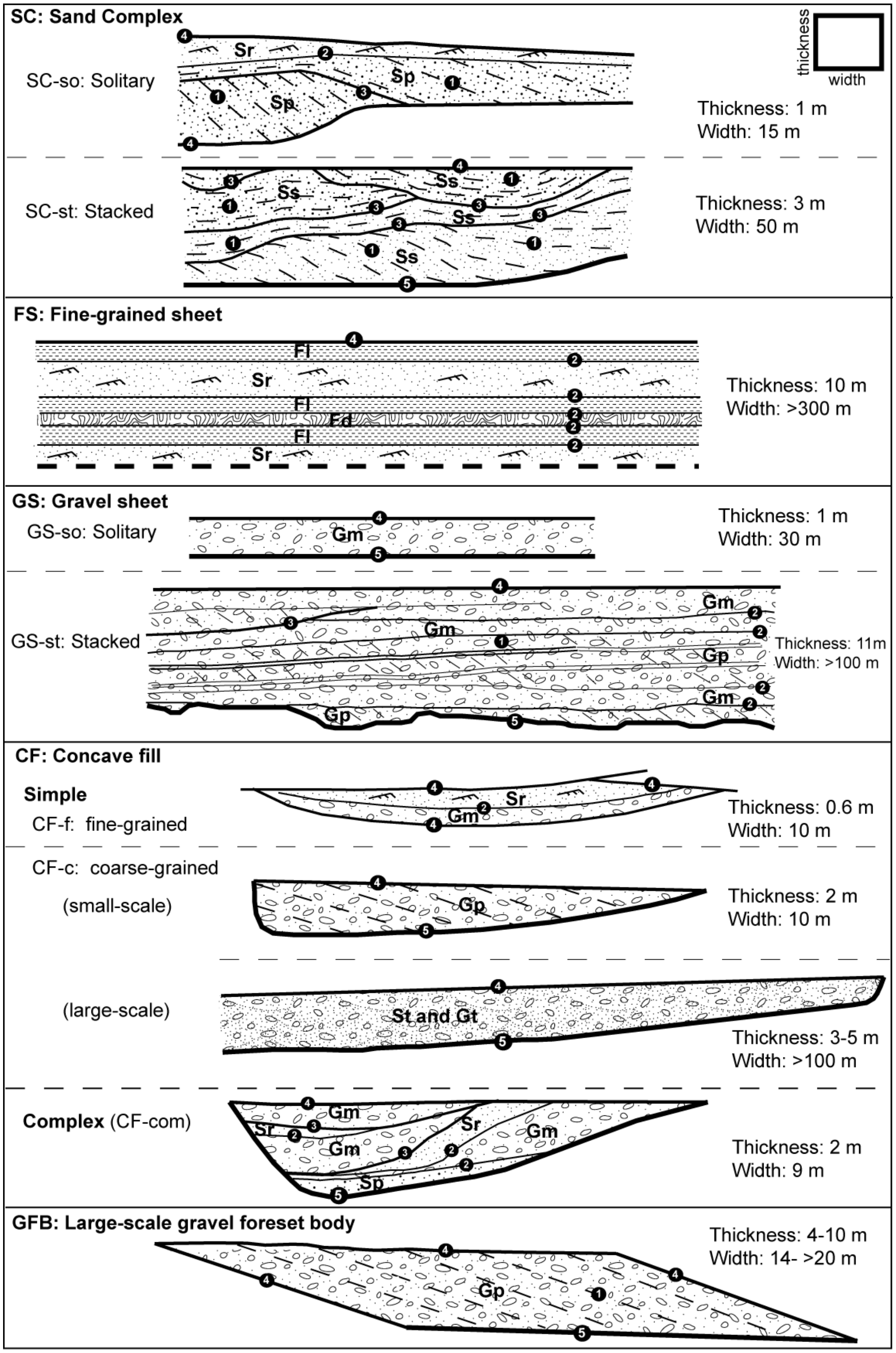

a
b
c
d
e
f
g
h
i
j
k
l
m

Figure 2.6: Architectural elements identified in this study (based on Bridge 1993; Eriksson et al. 1995; Hjellbakk 1997; Opluštil et al. 2005; Ghazi & Mountney 2009; Miall 2010)



SC: Sand Complex
thickness
width
SC-so: Solitary
Sr
Sp
Sp
Thickness: 1 m
Width: 15 m
SC-st: Stacked
Ss
Ss
Ss
Ss
Thickness: 3 m
Width: 50 m
FS: Fine-grained sheet
Fl
Sr
Fl
Fd
Fl
Sr
Thickness: 10 m
Width: >300 m
GS: Gravel sheet
GS-so: Solitary
Gm
Thickness: 1 m
Width: 30 m
GS-st: Stacked
Gm
Gm
Gp
Gm
Gp
Thickness: 11m
Width: >100 m
CF: Concave fill
Simple
CF-f: fine-grained
Sr
Gm
Thickness: 0.6 m
Width: 10 m
CF-c: coarse-grained
(small-scale)
Gp
Thickness: 2 m
Width: 10 m
(large-scale)
St and Gt
Thickness: 3-5 m
Width: >100 m
Complex (CF-com)
Gm
Sr
Sr
Gm
Gm
Sp
Thickness: 2 m
Width: 9 m
GFB: Large-scale gravel foreset body
Gp
Thickness: 4-10 m
Width: 14- >20 m

of facies changes on either side of the contact (Figure 2.6; Miall 1988, 2010). Higher-order bounding surfaces are difficult to identify from the pit walls because of the limited vertical and lateral exposures (Figures 2.3, 2.7). Facies types, bounding surface hierarchy and architectural elements were superimposed on a series of photomosaics of three well-exposed outcrop faces (Figure 2.7) and were used to assist in the interpretation of depositional processes and environments.

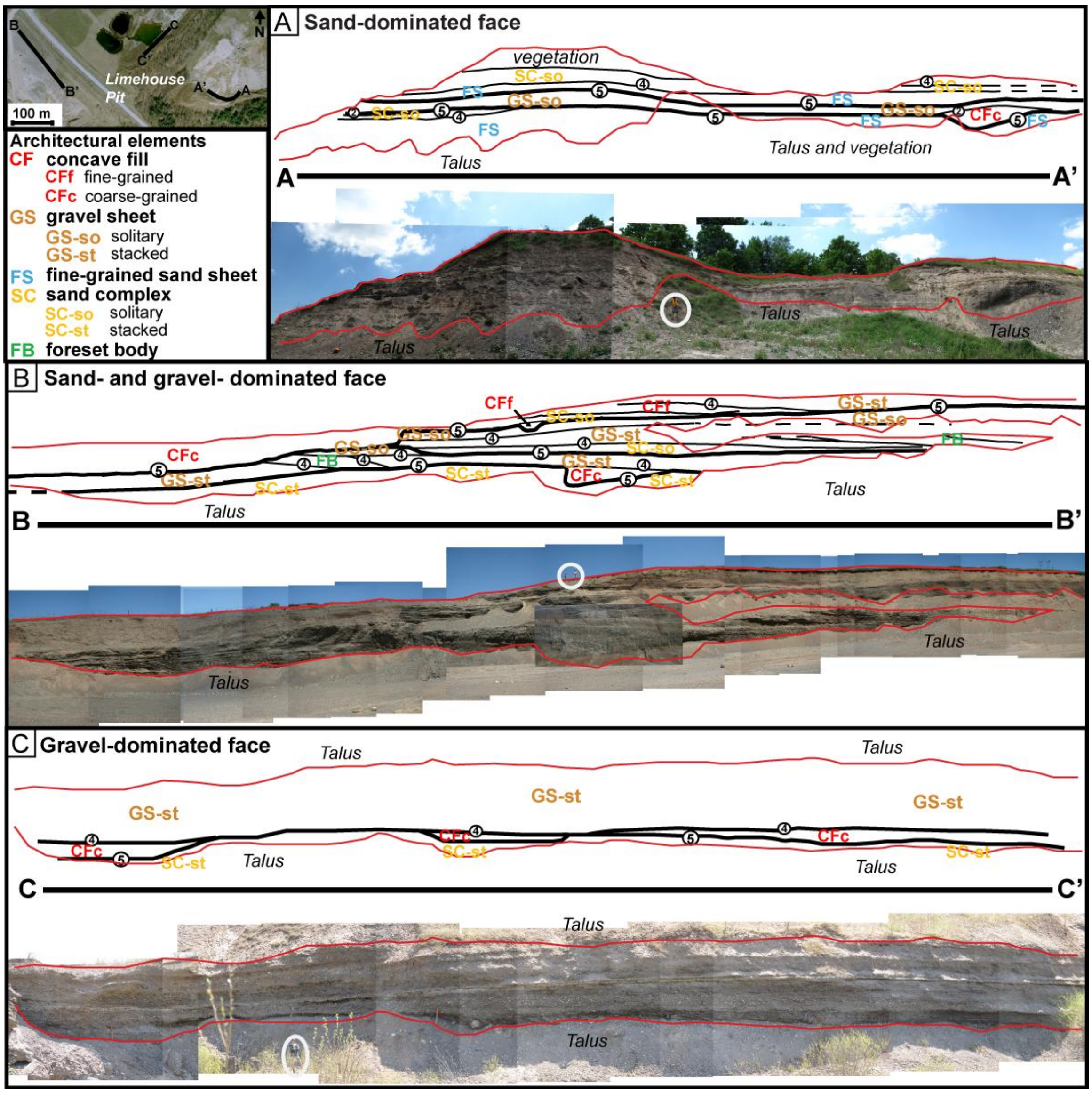
2.4 Facies description and interpretations

In total, 9 facies types were identified from the 31 sedimentary logs recorded within the Limehouse Pit (Figures 2.3- 2.5). The dominant facies types are sand and gravel, although fine-grained facies are also present. Facies types include massive and crudely bedded gravel (Gm); trough cross bedded gravel (Gt); planar cross bedded gravel (Gp); trough cross bedded sand (St); planar tabular cross bedded sand (Sp); rippled sand (Sr); sinusoidal cross-stratified sand (Ss); interbedded fine-grained sand, silt and clay (Fl); and deformed fine-grained sand, silt and clay (Fd; Figures 2.4, 2.5). A veneer (0.5-3m thick) of poorly sorted sediment was observed at the top of many outcrop faces in the pit which is most likely the product of anthropogenic quarrying activities and is not included in this study.

2.4.1 Gravel Facies

Description

Figure 2.7: Photomosaics and sketches showing architectural elements identified in three extensive outcrop exposures in the Limehouse Pit. For section locations see Figure 2.3.


Limehouse Pit
100 m
Architectural elements
CF concave fill
CFf fine-grained
CFc coarse-grained
GS gravel sheet
GS-so solitary
GS-st stacked
FS fine-grained sand sheet
SC sand complex
SC-so solitary
SC-st stacked
FB foreset body
A Sand-dominated face
B Sand- and gravel- dominated face
C Gravel-dominated face
Talus
Talus and vegetation
vegetation

Gravel facies consist of massive and crudely bedded gravel (Gm), trough cross bedded gravel (Gt), and planar tabular cross bedded gravel (Gp; Figures 2.4, 2.5). Gravel facies are 0.3 m- 6 m thick and consist of poorly sorted, clast-supported gravel that is either open-work (Gp) or contains a matrix of coarse-grained, sand and granule- sized sediment (Gt, Gm). Clasts are 0.5cm- 50cm in diameter and subangular to well-rounded in shape. Clasts are mostly of local derivation (e.g. dolostone and shale) although a few far-travelled rock types (e.g. granite, diorite, quartzite) are also present (Figures 2.4, 2.5).

Massive gravel facies are commonly cemented with carbonate cement and always have an erosional basal contact with underlying facies. Gravels occasionally form single clast layers that are recorded in logs L1, 2 and 8 in the southern part of the pit (Figure 2.3). Clast fabric analysis of the a- and b- axis orientation of gravel clasts of Gm facies indicates weak imbrication toward the southwest (Figures 2.3- 2.5). Trough cross bedded gravels (Gt) are found in the southwestern section of the pit overlying an erosive, channelized surface that cuts into underlying trough cross bedded sand (L8-12; Figure 2.3). Individual foresets within trough fills dip 15° (maximum dip of 28°) and have an erosive basal lag of gravel that fines upwards to small pebbles. Paleocurrent measurements recorded from foresets within trough fills of Gt facies indicate paleoflow direction towards the southwest (average of 211.5°; Figures 2.3- 2.5); clasts within the troughs also display crude imbrication of the b-axis in the direction of paleoflow (Figures 2.4, 2.5). Planar cross bedded gravel facies (Gp) consist of large-scale sets of planar tabular foresets between 2 and 6m in height and smaller-scale planar tabular cross bed sets 0.3- 1m thick (Figures 2.4, 2.5). The large-scale Gp foresets have an erosive basal contact and are overlain by a bed of massive gravel (Gm; L28, 17; Figures 2.3, 2.5d). Gp facies either form laterally extensive beds (greater than 30m long; logs L13, 21; Figure 2.3) or infill scours eroded into underlying rippled medium-grained sand (Sr; logs L13, 24; Figures 2.3, 2.7). The largest clasts within Gp facies (average of 50cm in diameter) are located at the base of these erosional scours (logs L13, 21; Figures 2.3, 2.7). The upper surface of individual sets of Gp facies may be truncated by low angle erosional surfaces that are commonly overlain by Gp and Gm facies (Figures 2.4, 2.5, 2.7). Measurements recorded from the steepest foreset dip and direction indicate paleoflow toward the southwest and southeast (Figures 2.3, 2.4).

Interpretation

Gravel facies are interpreted to have formed from deposition by traction currents, lee-side separation eddies, and clast avalanching in a braided river depositional environment (Miall 1977; Hein & Walker 1977). The crudely imbricated and clast-supported nature of the gravel facies suggest fluvial bedload deposition in the form of migrating low relief longitudinal bars or a diffuse gravel sheet (Gm), with migrating 3-dimensional dunes (Gt) and linguoid bars (Gt and Gp; Miall 1977; Smith 1990; Opluštil et al. 2005; Ghazi & Mountney 2009). The sand and granule matrix within the clast-supported gravels is interpreted to have filtered between clasts after initial deposition of the coarsest materials, and records a change in stage and/or the subsequent trapping of bedload and suspended load material (Miall 1977; Eynon & Walker 1974). The very large-scale planar tabular cross beds of facies Gp are interpreted as the product of delta growth into a standing body of water between 2 and 6m deep (Eynon & Walker 1974; Marren 2002). Cross-cutting erosional surfaces within gravel deposits are interpreted to be reactivation surfaces resulting from changes in flow conditions (Miall 1977).

2.4.2 Sand Facies

Description

Sand facies consist of 0.3m- 5m thick units of fine- to coarse-grained trough cross bedded sand (St), planar tabular cross bedded sand (Sp), rippled sand (Sr) and sinusoidal laminated sand (Ss; Figures 2.4, 2.5). Facies St, Sp and Ss contain clusters of subangular to well- rounded shale pebbles (up to 1cm in diameter) that lie parallel to bedding and display crude a- and b-axis imbrication in the direction of paleoflow (Figure 2.5).

Trough cross bedded sand facies (St) are found within a large channel (up to 5m deep; logs L26-28; Figure 2.3; see upper CF-c in Figure 2.7B) incised into a thick gravel deposit and are also exposed below channelized gravels at the base of the pit (logs L8, 9, 24, 28, 29; Figure 2.3). Troughs have erosional lower surfaces and cross cut one another. Palaeocurrent measurements derived from the steepest foreset dip angle within trough fills (average 22°) and direction (average 234.7°) indicate paleoflow towards the southwest. Planar tabular cross bedded sands (Sp) occur in sets up to 1m thick and paleocurrent measurements indicate flow toward 213.4° (southwest). Rippled sand facies (Sr) form laterally extensive units throughout the southern section of the study area (logs L1-7, 16, 17, 32, 33; Figure 2.3) and typically consist of Type A (climbing), Type B (trough-like) and sinusoidal ripples (Jopling & Walker, 1968; Figure 2.5g). In one exposure (logs L1, 2; Figure 2.3), sinusoidal ripples pass upwards into Type B ripples with preservation of both the lee and stoss side, and progressively change into Type A climbing ripples with only the lee side preserved (Figure 2.5g). Elsewhere, facies Sr consist of a cyclic transition of the pattern Type A- Type B- sinusoidal- Type B- Type A ripples. Measurements derived from the steepest ripple foreset and set boundary dip and direction indicate a variable paleoflow direction, but predominately toward the southwest and southeast (Figure 2.3). Sinusoidal laminated sands (Ss) consist of sigmoidal and concave-upwards laminated sand with erosional lower surfaces between successive bed sets (Figure 2.5h, i). Sinusoidal beds have wavelengths up to 2m and amplitudes between 0.3m and 1.5m. The paleoflow direction measured from dipping surfaces and set boundaries within facies Ss (Figure 2.5) shifts quite rapidly up-section from a southerly trend at the base to a more south-easterly direction toward the top (Figure 2.3). Reverse faulting is common in facies Ss and usually extends upward from underlying gravel facies.

Interpretation

Sand facies are interpreted to have formed in a braided- river/delta front depositional setting and record the migration of sinuous crested 3-dimensional dunes (St, Ss), linguoid and transverse bars (Sp), and ripple trains (Sr; Miall 1977, 1978; Hjellbakk 1997; Opluŝtil et al. 2005). The pebbly lag at the base of individual troughs and foresets is interpreted to record deposition of rolling bedload. The common transition from sinusoidal ripple lamination to Type B ripples to Type A ripples represents deposition of large amounts of suspended sediment by traction currents of increasing velocity (Jopling

& Walker 1968). Rippled sands that lie on the upper surface of Sp facies are interpreted to record deposition during waning flow or migration of a ripple train over the larger bedform (Miall 1977). Thick packages of Sr facies associated with fine-grained facies (Figure 2.3) are interpreted to record rapid deposition of suspended sediment in a delta front environment (Eyles & Clark 1988). The sinusoidal forms characteristic of Ss facies are formed by the erosion of dune crests during high energy conditions and the subsequent draping and infilling with laminated sand from suspension during periods of low energy (Allen & Underhill 1989). This pattern of sedimentation commonly results from alternating periods of bed load and suspended load deposition, such as during a storm event (Allen & Underhill, 1989).

2.4.3 Fine-grained facies

Description

Fine-grained facies consist of interbedded (Fl) and deformed (Fd) fine-grained sand, silt and clay (Figures 2.4, 2.5). These facies are 1- 3 m thick and form tabular, laterally extensive deposits, infilling broad channels in rare instances (logs L24, 29; Figure 2.3; see upper CF-f element in Figure 2.7B). Fine-grained facies primarily consist of laminated and rippled fine- and very fine-grained sand with flaser beds of clay and silt (each 0.5cm to 10cm thick) on the upper surface of Type B ripple sets (Jopling & Walker 1968). Flaser bedding is discontinuous along the upper surface of the ripple set and may not be present on some ripple surfaces (Figure 2.5j, k). Fine-grained facies also contain soft-sediment deformation structures and water escape (flame) structures, as well as deformed laminations, occasional small clasts (< 1cm in diameter) and interbeds of rippled coarse-grained sand (Figure 2.5 l, m). This facies type is found primarily in the southern reaches of the study area (logs L1-7, 16, 17, 32, 33; Figure 2.3).

Interpretation

Fine grained facies are interpreted to have formed in a low energy lacustrine environment subject to alternating periods of deposition by traction currents and fallout of fine-grained sediment from suspension (Eyles & Clark 1988; Martin 2000). Soft sediment deformation features are interpreted to record water escape and slumping, most likely as a result of rapid sediment deposition and slope failure (Eyles & Clark 1988).

2.5 Architectural elements

Architectural elements are identified on the basis of internal and external facies geometry, facies assemblages, scale, and the hierarchy of upper and lower bounding surfaces (Miall 1985, 2010). Bounding surfaces are characterized by the nature of the contact and change in facies type on either side of the bounding surface (Miall 2010). A hierarchy of 1^{st}- to 5^{th}- order bounding surfaces are identified using the classification scheme of Miall (2006; Figure 2.6).

The five main architectural elements identified in the Limehouse Pit are: sand complex (SC), gravel sheet (GS), fine-grained sheet (FS), large-scale gravel foreset body element (GFB), and concave fill (CF) element (Figure 2.6). Not all elements are observed in all outcrop faces and the ability to record the entire geometry and bounding surfaces of each element is limited by the degree of exposure. Those architectural elements and bounding surfaces that could be identified were overlain on photomosaics of three laterally extensive outcrop faces, each with distinctive textural characteristics: Section 1 (sand-dominated); Section 2 (sand-and-gravel- dominated); and Section 3 (gravel-dominated; Figure 2.7). Facies types, architectural elements and their vertical and spatial distribution provided the foundation on which to base paleoenvironmental reconstructions of the Quaternary succession exposed in the Limehouse pit.

2.5.1 Sand complex element (SC)

Description

The sand complex (SC) element is 1-3 m thick, up to 50 m in length (or width), and consists of either solitary sets (‘solitary SC element’; SC-so) or stacked cosets (‘stacked SC element’; SC-st) of Sp, St and Ss facies that typically comprise a coarsening-upwards succession (Figures 2.4- 2.7). In rare instances, thin beds of Sr facies conformably overlie sets of Sp facies, forming a local fining-upward succession in SC-so elements (Figure 2.6). Paleoflow directions measured from SC elements are predominately towards the southwest (Figure 2.3). The SC element has an erosional, planar to irregular lower bounding surface of 4^{th}- or 5^{th}- order and a flat or irregular upper surface of 4^{th}- or 5^{th}- order, usually truncated by overlying GS elements (Figures 2.6, 2.7). Internal bedding surfaces typically onlap and downlap onto the lower bounding surface (Figure 2.6). The SC element has either a wedge or sheet-like 2-dimensional geometry and commonly alternates with GS and FS elements (Figures 2.6, 2.7). The SC element identified in this study is similar to the sand bedform (SB) and lateral accretion (LA) elements identified by Miall (1985).

Interpretation

SC elements are interpreted to record fields and trains of sand dunes (composed of facies St and Ss) and bars (composed of facies Sp) formed in a sand-dominated braided-river/delta front environment (Figures 2.4- 2.6; Miall 1985). The coarsening-upward succession in the SC-st element that is truncated by a 5th-order upper bounding surface and is found at the base of the outcrop exposures (logs L8-12, L28, 29, 24; Figures 2.3; 2.7B, C) is interpreted to record the progressive development of high stage flow conditions within a sandy braided-river environment. The SC-so element positioned between GS elements (Figure 2.7B) is interpreted to record a short-term change to low stage flow conditions in a gravel dominated fluvial environment. Other SC-so elements located between fine or coarser-grained elements (Figure 2.7A) are similarly interpreted to record short-term changes to higher or lower stage flow conditions (Miall 1985).

2.5.2 Gravel sheet element (GS)

Description

The gravel sheet (GS) element is the most common architectural element recorded within the study area and is composed of Gp and Gm facies (Figures 2.4, 2.5). It has a sheet-like geometry and is between 9 m and over 100m in length and 10cm to 11m in thickness with an erosional, planar to irregular lower bounding surface (4th- or 5th-order), and a sharp and planar or irregular upper bounding surface (4th- or 5th-order; Figures 2.6, 2.7). The GS element typically consists of stacked, alternating planar-tabular beds of Gm and Gp facies (Figures 2.4, 2.5) that may form distinct sets or may laterally and vertically grade into each other and contain reactivation surfaces delineated by 3rd-order bounding surfaces (‘stacked GS element’, GS-st; Figures 2.6, 2.7). Bedding planes within the GS-st element lie subparallel to the lower bounding surface. GS-st elements are interbedded with SC and GFB elements and conformably overlie CF-c elements (Figure 2.7). The GS element also forms thin, solitary massive gravel beds (Gm facies; Figures 4, 5) between FS elements (Figures 2.6, 2.7) with bed thickness ranging from a single clast to 1m (‘solitary GS element’, GS-so; logs L1-3, 5, 8, 9; Figure 2.3). Paleocurrent measurements recorded from GS elements indicate paleoflow direction toward the southwest and southeast. The GS element described in this study is comparable to the gravel bar and bedform (GB) element, or possibly the sediment gravity flow (SG) element, described by Miall (1985).

Interpretation

The GS element is interpreted to record aggradation and downstream growth of gravel bars in a gravel-dominated braided-river/ delta top environment (Miall 1985). The multi-storey GS-st elements that directly and conformably overlie CF-c elements are interpreted to record aggradation and progradation of bars within a high energy braided-river system (Figures 2.6, 2.7; Miall 1985). The GS-so element positioned between FS elements records the migration of a diffuse gravel sheet deposited during a rare high discharge event, possibly within a delta front environment (Figure 2.6, 2.7; Hein & Walker 1977; Miall 1985).

2.5.3 Fine-grained sheet element (FS)

Description

Architectural element FS is the most fine-grained element exposed in the Limehouse Pit and dominates the southern part of the study area (Figures 2.3, 2.7). The fine-grained sheet (FS) element consists of Fl, Fd and Sr facies (Figures 2.4, 2.5) with internal bedding planes lying parallel and slightly sub-parallel to the lower bounding surface (Figure 2.6). This element has a sheet- and wedge-like geometry and is 5- 10m in height and 50- >300m in width (Figures 2.6, 2.7). The lower bounding surface is of 4th-order significance and conformably overlies the GS element. The upper bounding surface is 4th- or 5th- order and is truncated by GS, SC and CF elements (Figures 2.6, 2.7). Paleocurrent measurements recorded from Sr facies within the FS element are highly variable and deviate between a westerly and easterly direction (Figures 2.3, 2.4). There was no organic material identified in this study; however a thin, continuous horizon (2cm thick and at least 30m wide) of cemented Fl facies was located within the lowermost FS element (log L32, 17; Figures 2.3, 2.7A). The FS element identified in this study is similar to the overbank fines (OF) element identified by Miall (1985).

Interpretation

The FS element is interpreted to record vertical aggradation of fine-grained facies (e.g. Sr, Fl, Fd; Figure 2.4) within a low-energy depositional environment, such as in an abandoned channel or a standing body of water (e.g. a lacustrine or delta front environment; Eyles & Eyles 1983; Miall 1985). Truncation and incision of the FS element by coarser-grained elements (GS, SC and CF) is interpreted to record erosion during infrequent high stage flow conditions (Miall 1985).

2.5.4 Gravel foreset body element (GFB)

Description

Gravel forest body (GFB) elements are closely associated with GS elements and, in most cases, the two elements transition into each other (Figure 2.7). The designation of either a GS or GFB element depends on the degree of preservation of sedimentary structures, the scale and facies geometry, and the extent and orientation of the outcrop exposure. GFB elements may be incised by active channels or truncated and reworked by migrating gravel bedforms of GS elements, making it difficult to discern the external and internal geometry and large scale required to characterize the deposit as a GFB element (Figure 2.6).

GFB elements identified in the study area are solely composed of Gp facies (Figures 2.4, 2.5), which form simple foresets that are between 4m high and up to 14m long (meso-scale; Figure 2.6), and 10m high and greater than 20m long (macro-scale; Figure 2.6). A laterally and vertically extensive outcrop exposure is required to observe the complete macro-scale GFB element, making it difficult to properly record its geometry; however it appears to have a wedge- or parallelogram-like 2-dimensional geometry that tapers to the south-southeast (Figures 2.6, 2.7B). The GFB element has a 4^{th}- order upper bounding surface that is planar and conformable with overlying Gm facies of the GS-so element (Figures 2.6, 2.7). It was not possible to observe the lower bounding surface of the macro-scale GFB element because of thick talus cover at the base of the pit; however the meso-scale GFB element has an erosional planar lower bounding surface of 5th-order significance (Figures 2.6, 2.7B). Foreset dip direction in GFB elements is to the southeast.

Interpretation

The meso-scale GFB element is interpreted to record the downstream growth and avalanching of gravel clasts originating from GB elements within a gravel-dominated braided-river environment into a standing water body at least 4m deep (Miall 1985; 1988; Ghazi & Mountney 2009). The macro-scale GFB element is also interpreted to record southward progradation of a high-energy braided-river system into a deeper water body (at least 10m deep), possibly within a Gilbert-type deltaic setting (Nemec et al. 1999; Breda et al. 2007).

2.5.5 Concave fill element (CF)

Description

The CF element contains facies Gt, Gm, Gp, St, Sp and Sr (Figures 2.4, 2.5) and has an erosional and asymmetrical concave-up lower bounding surface of 4th- and 5th-order significance, and a planar and sharp or gradational upper bounding surface of 4th-order significance, which is exposed at ground surface in some places (Figures 2.6, 2.7). The CF element is between 9m and over 100m in width and 0.6 m to 5m in thickness (depth; Figure 2.6). The width/depth ratio of the CF element varies and can be used to identify fixed channel (width/depth ratio less than 15) to sheet-like channel elements (width/depth ratio greater than 100; Miall 1985). The CF element is comprised of various other architectural elements, such as GFB, SC and GB elements (Figures 2.6, 2.7).

The CF element can be subdivided into two major types: 1) CF elements containing a simple fill, subdivided into coarse-grained (CF-c) and fine-grained (CF-f) and 2) CF elements with more complex fills (CF-com; Figures 2.6, 2.7), of which the former is the most commonly observed CF element. The CF-f element has a broad 4th-order lower bounding surface that is overlain by a basal lag of Gm facies, which is separated from overlying Sr and Fl facies by a 2nd-order internal bounding surface (Figures 2.4- 2.6). The upper bounding surface of the CF-f element is a 4th-order surface produced by overlying CF-f elements, which form a stacked complex of successive CF-f elements (Figure 2.6). The CF-c element can be either small (10m wide) or large (> 10m wide) scale. The CF-c element has an asymmetrical, concave-up 5th-order lower bounding surface and is infilled with Gp, Gm and St facies (Figures 2.4- 2.6). The outer margins of the lower bounding surface observed in the CF-c element consists of one steep (high angle) and one broad (low angle) margin (Figure 2.6). The upper bounding surface of CF-c elements is of 4th-order significance. The CF-com element has an asymmetrical, concave-up 5th-order lower bounding surface with one steep and one broad margin and is infilled with various other elements such as GB, FS and SC. The upper bounding surface of CF-com elements is of 4th-order significance and is planar or exposed at ground surface (Figures 2.6, 2.7). The CF element identified in this study is similar to the channel (CH) element identified by Miall (1985).

Interpretation

The CF element is interpreted to record a variety of channel types within a fluvial environment (Miall 1985). CF-f elements record deposition within secondary ephemeral channels during high-stage flow conditions, channel abandonment during periods of low stage flow, and successive truncation by reactivated channels (Miall 1985). Small-scale CF-c elements are interpreted to record deposition within scours or ephemeral channels formed during infrequent high magnitude discharge events, and large-scale CF-c elements are interpreted to record deposition within large, broad channels during high stage flow conditions (Miall 1985). CF-com elements are interpreted to record deposition within fixed channels that experience frequent fluctuations in stage (Miall 1985).

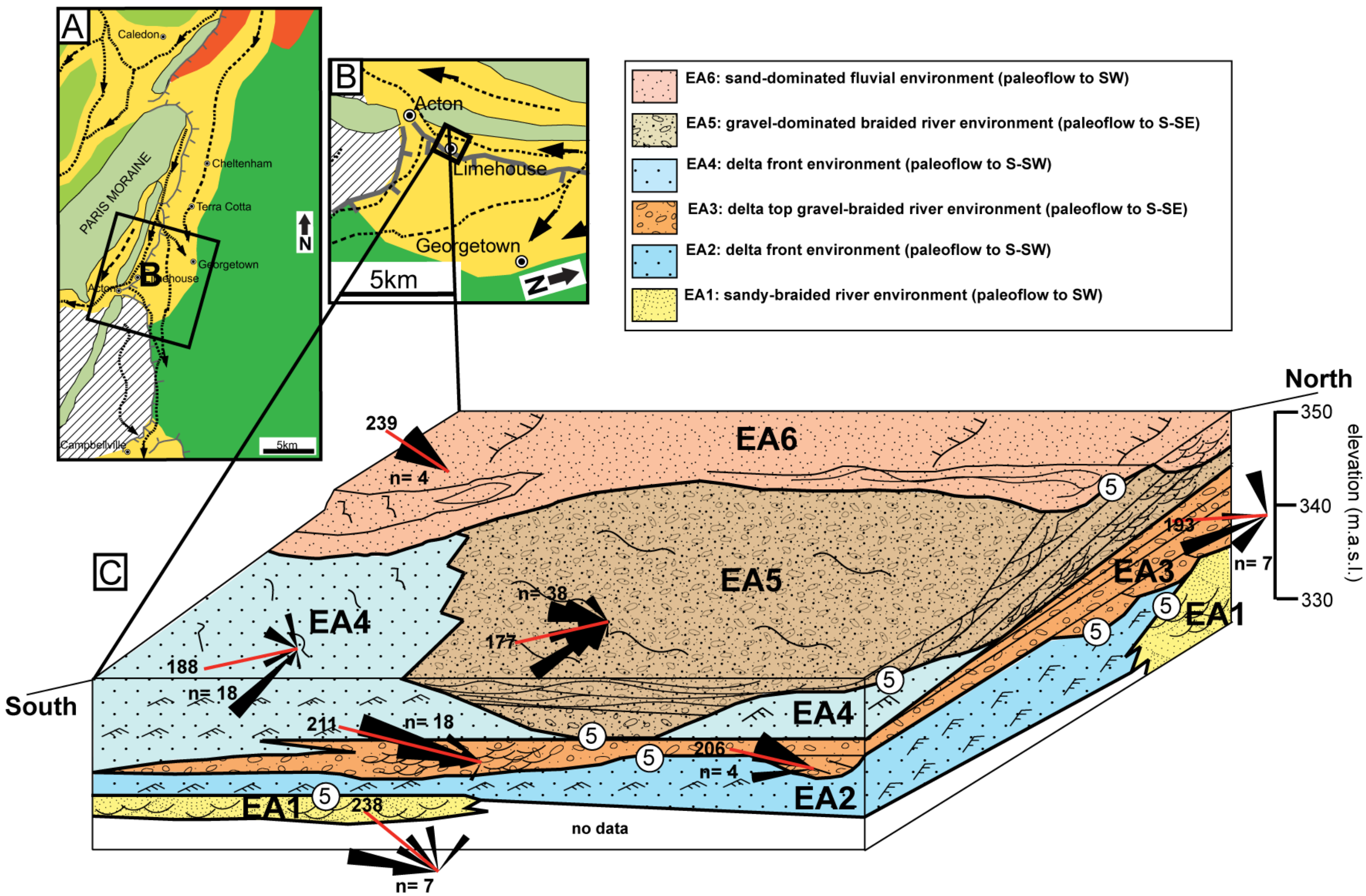
2.6 Element associations

The vertical and spatial arrangement of sedimentary facies and architectural elements in three laterally extensive outcrop faces in the Limehouse Pit (Figure 2.7) were used to reconstruct the environment of deposition and late Quaternary history of the Limehouse area (Figure 2.8). Packages of spatially- and genetically-related architectural elements identified in outcrop faces can be organized into six 'element associations' (EAs), defined by laterally continuous 5^{th}-order bounding surfaces. These EAs represent the sandy braided-river environment (EA1), delta front environment (EA2 and EA4), delta top gravel braided-river environment (EA3), gravel-dominated braided-river environment (EA5), and sand-dominated fluvial environment (EA6; Figure 2.8).

2.6.1 Element Association 1: sandy braided river environment

EA1 is the lowermost (oldest) element association exposed at the base of the Limehouse Pit and is spatially discontinuous across the study area, although this

Figure 2.8: Block diagram of Element Associations and major bounding surfaces reconstructed from detailed mapping of outcrop exposures in the Limehouse Pit. Inset maps (A and B) show orientation of block diagram relative to former outwash channels (dashed lines with arrows). See Figure 2.1 for surficial sediment types.



A
Caledon
PARIS MORAINE
Cheltenham
Terra Cotta
Georgetown
Limehouse
Acton
Campbellville
B
N
5km
Acton
Limehouse
Georgetown
5km
N
EA6: sand-dominated fluvial environment (paleoflow to SW)
EA5: gravel-dominated braided river environment (paleoflow to S-SE)
EA4: delta front environment (paleoflow to S-SW)
EA3: delta top gravel-braided river environment (paleoflow to S-SE)
EA2: delta front environment (paleoflow to S-SW)
EA1: sandy-braided river environment (paleoflow to SW)
C
North
South
elevation (m.a.s.l.)
350
340
330
EA6
EA5
EA4
EA4
EA3
EA2
EA1
EA1
239
n= 4
n= 38
177
188
n= 18
211
n= 18
206
n= 4
238
n= 7
193
n= 7
5
no data

observation may be influenced by the limited exposure of the pit base. EA1 is overlain by EA2 in the eastern part of the study area and by EA3 in the west and is separated from both by a 5th-order upper bounding surface (Figure 2.8). The lower bounding surface of EA1 is not observed in the pit. EA1 consists exclusively of SC-so and SC-st elements (Figures 2.6, 2.7) with an abundance of trough cross bedded sand (facies St; Figure 2.4). EA1 is interpreted to record deposition in a sandy-braided river environment (Miall 1977) with paleoflow toward the southwest (Figure 2.8).

2.6.2 Element Association 2: delta front environment

EA2 directly overlies EA1 and is spatially extensive throughout the study area, except in places of possible non-deposition or where it has been completely removed by erosion prior to deposition of overlying EAs (Figures 2.7, 2.8). EA2 consists primarily of FS elements (with an abundance of Sr facies; Figure 2.4) but also includes some SC-so elements (Figures 2.6, 2.7). It has a 5th-order upper bounding surface and is overlain by EA3 (Figure 2.8). EA2 is interpreted to record rapid deposition of fine-grained facies from suspension, slumping and slow moving traction currents. This style of deposition is typical of standing water bodies supplied with large amounts of fine-grained suspended sediment from a fluvial source and EA2 may thus record a delta front depositional environment (Figure 2.8). The SC-so elements are interpreted to record migrating mouth bars in a terminal distributary channel (Olariu & Bhattacharya 2006).

2.6.3 Element Association 3: gravel braided river to delta top environment

EA3 is the most coarse-grained EA and forms a laterally extensive wedge-like unit that tapers to the south and southeast (Figure 2.8). This association forms a flat-topped sheet of gravel facies and consists of GS, GFB and CF elements (Figures 2.7, 2.8). The lower bounding surface of EA3 is channelized in some places and both the upper and lower bounding surfaces are of 5th-order significance. Paleocurrent measurements from EA3 indicate paleoflow toward the south-southeast (Figure 2.8). EA3 is interpreted to record deposition within a gravel braided-river to delta top environment.

2.6.4 Element Association 4: delta front environment

EA4 directly overlies EA3 in the southern and eastern parts of the study area but is absent in areas where EA5 directly overlies EA3 in the north and southeast (Figure 2.8). EA4 is composed of FS (Sr and Fl facies are most common; Figure 2.4) and SC elements and is laterally discontinuous in areas where it has been truncated by overlying EAs (Figures 2.6- 2.8). Paleocurrent measurements recorded from ripple foresets and set bounding surfaces indicate paleoflow direction toward the south (Figure 2.8). EA4 formed under very similar conditions to EA2 and is interpreted to record a delta front depositional setting.

2.6.5 Element Association 5: gravel-dominated braided-river environment

EA5 consists of a wide variety of facies types (Gp, Gt, Ss, Sr; Figure 2.4) and architectural elements, including GS, SC and GFB elements (Figures 2.6, 2.7). It has a 5th-order lower bounding surface that is planar in most areas where it directly overlies

EA3, but is irregular in the southwest where EA4 is present (Figure 2.8). EA5 is spatially discontinuous across the study area, and is truncated by EA6 (Figure 2.8). The upper bounding surface of EA5 is of 5th-order significance in the north- and south where it is truncated by the overlying EA6 (Figure 2.8). In other areas, the upper bounding surface is exposed at the ground surface and has been disturbed by active pit operations. Paleocurrent measurements taken from within EA5 indicate paleoflow direction toward the south-southeast (Figure 2.8). EA5 is interpreted to record deposition within a gravel-dominated braided-river environment that is also supplied with finer-grained sand-rich sediment.

2.6.6 Element Association 6: sand-dominated fluvial environment

EA6 is delineated by a lower 5th-order bounding surface that records a large concave fill (CF) element in the upper section of the outcrop face (Figures 2.7, 2.8) and contains SC elements (facies Sp and St; Figure 2.4). On the margins of the CF element, the 5th-order lower bounding surface is scoured by CF-c and CF-f elements (Figure 2.6) which are interpreted to be 2nd-order (chute) channels and bar-top channels, respectively (Williams & Rust 1969; Vos & Tankard 1981). EA6 is interpreted to record a sand-dominated fluvial environment formed after a period of decreasing discharge and a reduction in coarse-grained sediment supply (Miall 1977; Orton & Reading 1993). Paleocurrent measurements within the large-scale CF-c element indicate paleoflow toward the southwest (Figure 2.8).

2.7 Discussion

The coarse-grained deposits exposed in the Limehouse Pit are interpreted here to record deposition in a braided-river system that transitions into a delta-front depositional setting toward the south and southwest. The general southerly paleocurrent directions recorded from the coarse-grained deposits indicates a water and sediment source to the north of the study area, possibly originating from the area now occupied by the Oak Ridges Moraine (Figures 2.1, 2.2). A retreating ice margin in the north would be able to supply the appropriate amount of meltwater required to transport and deposit the thick deposits of sand and gravel found in the study area (Eynon & Walker 1974). Meltwater was probably transported through a large braided spillway system that flowed along the eastern edge of the Niagara Escarpment towards the south and southeast, possibly exiting to glacial Lake Whittlesey or glacial Lake Peel in the south (Figures 2.1, 2.2; Costello & Walker 1972; Eynon & Walker 1974; Chapman & Putnam 1984; Chapman 1985). The absence of glacial till capping the coarse-grained sediments now exposed in the Limehouse Pit suggests that deposition of the coarse-grained deposits either occurred after the ice margin of the Laurentide Ice Sheet had completely retreated from the study area in the Late Wisconsin, or that local removal of till by stratigraphically younger EAs has occurred (Barnett 1992).

Although deposits of laminated silts and clays, typical of lacustrine depositional environments, were not observed in the Limehouse Pit, elevation data collected at the contact between the flat-topped gravel braided-river deposits (EA3) and delta front deposits (EA4) in the pit provide an estimated minimum elevation for a standing water body at between 339- 348 m.a.s.l.. This minimum water surface elevation is consistent with water levels of between 312 and 377 m.a.s.l. suggested by other workers to account for fine-grained sediment and deltaic deposits found on the crest of the Oak Ridges Moraine (Chapman 1985; Barnett et al. 1998). Small ephemeral glacial lakes were likely ponded between the ice margin and the Niagara Escarpment in the Limehouse area during deglaciation, possibly extending as far north as the Oak Ridges Moraine. Given the large amount of meltwater produced by the Laurentide Ice Sheet as it retreated northward (Brennand 2000) there is a very high probability that ephemeral glacial lakes existed in the Georgetown region during the Late Wisconsin (Barnett 1992).

In many hydrogeological studies, sand and gravel deposits are treated as homogenous coarse-grained units with uniform permeability characteristics. However, this study demonstrates that there is a considerable amount of spatial variability in sedimentary and textural characteristics and geometries within coarse-grained successions even at a local-scale. Architectural element analysis provides an effective tool to describe the variation in observed sediment heterogeneity and facilitates the visualization of the geometry of heterogeneous coarse-grained sedimentary packages (‘elements’; Figures 2.6-2.8). The architectural information provided in this study can be applied to interpretation of the infill of other re-entrant valleys along the Niagara Escarpment to better understand the spatial extent, connectivity and stratigraphic relationships of these coarse-grained units that may be found either at surface or deeply buried. The ability to describe and illustrate the heterogeneity and spatial relationship of coarse-grained units has strong implications for groundwater recharge and groundwater flow models. Thus, the architectural information presented here from surface exposures can be used as an analogue with which to interpret and predict the geometry of more deeply buried coarse-grained sediment bodies that may host productive aquifers in other regions of southern Ontario and elsewhere.

2.8 Conclusions

This study identifies nine different facies types from 31 sedimentary logs recorded from outcrop exposures of sand and gravel dominated deposits in the Limehouse area of southern Ontario. The facies types observed in this study include gravel facies (Gm, Gp, Gt), sand facies (Sr, Sp, St, Ss) and fine-grained facies (Fl and Fd). Bounding surfaces between distinctive sediment packages were identified and characterized by the nature of the contact between different sediment types, the degree of facies change on either side of the contact, and its lateral extent. In total, 5 orders (1^{st}- to 5^{th}-order) of bounding surfaces were delineated in this study, which were ordered in a hierarchical fashion corresponding to the degree of environmental change represented by each surface.

Architectural element analysis is used here to delineate the 2-dimensional geometry of gravel, sand and fine-grained deposits recorded from various outcrop exposures in the Limehouse Pit. The grouping of facies types and arrangement of bounding surfaces allowed the delineation of six architectural elements consisting of:

sand complex (SC), gravel sheet (GS), fine-grained sheet (FS), large-scale gravel foreset body (GFB), and concave fill (CF) elements. The identification and grouping of these architectural elements in three laterally extensive outcrop faces allowed the delineation of five major sedimentary units ('element associations') which represent different fluvial depositional settings characterized by varying water depths and paleoflow directions. From oldest to youngest, the EAs delineated in this study represent the sandy braided-river environment with paleoflow toward the southwest (EA1), the delta front environment with paleoflow toward the south-southwest (EA2 and EA4), the delta top gravel braided-river environment with paleoflow toward the south-southeast (EA3), the gravel-dominated braided-river environment with paleoflow toward the south-southeast (EA5), and sand-dominated fluvial environment with paleoflow toward the southwest (EA6; Figure 2.8). The vertical and spatial heterogeneity and geometry of these coarse- and fine-grained sedimentary units identified through the application of architectural element analysis has implications for the identification of contaminant fate and transport pathways and groundwater flow models in the study area and can be applied to similar studies in other parts of southern Ontario and elsewhere.

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CHAPTER 3

SEDIMENTOLOGY AND STRATIGRAPHIC ARCHITECTURE OF SUBSURFACE QUATERNARY GLACIAL SEDIMENTS IN THE SIXTEEN MILE CREEK AREA OF GEORGETOWN, ONTARIO

Abstract

Groundwater exploration programs in southern Ontario have prompted the need for detailed mapping of the subsurface Quaternary sediments. An ongoing groundwater initiative in Georgetown, southern Ontario offered the opportunity to study the sedimentology and subsurface stratigraphic architecture of 5 fully cored boreholes that penetrate various unconsolidated Quaternary glacial sediments and Paleozoic bedrock. Twelve facies types were identified from the core samples: gravel facies (massive/ deformed and crudely bedded); sand facies (rippled; cross bedded; horizontally bedded and massive/deformed sand); fine-grained facies (laminated; massive/crudely bedded with dropstones; and massive/deformed); and diamict facies (clast-rich; clay-rich; and sand-rich). The identification of facies assemblages, combined with the hierarchical ordering and position of major bounding surfaces (4^{th}- to 7^{th}-order) that separate facies types , allowed the demarcation of nine different architectural elements: gravel lens (GL), gravel complex (GC), sand lens (SL), sand complex (SC), fine-grained lens (FL), fine-grained complex (FC), diamict lens (DL), diamict complex (DC) and diamict deformed zone (DZ). The arrangement of these architectural elements and their bounding surfaces

was then used to delineate seven major stratigraphic units (U1-U7) and to reconstruct past depositional environments. These seven units include: weathered bedrock/ colluvium (U1), sand-dominated glaciofluvial (U2), lower till complex (U3), gravel-dominated glaciofluvial (U4), glaciolacustrine/deltaic (U5), upper till complex (U6) and glaciofluvial sand and gravel (U7). The detailed architecture of the seven stratigraphic units provides insight into the heterogeneity, geometry and interconnectedness of aquifers and aquitards in the Georgetown area.

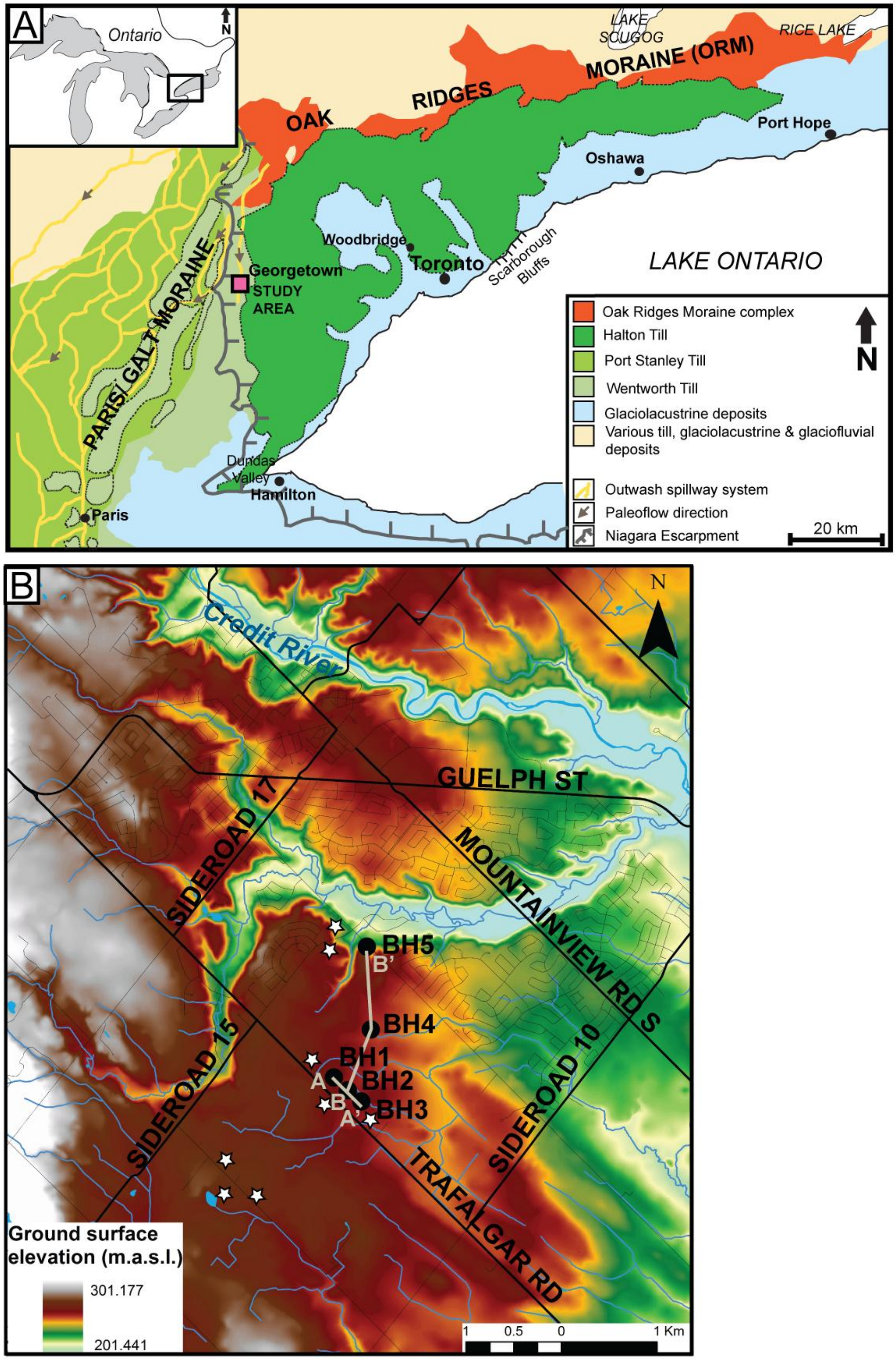
3.1 Introduction

The surficial cover of Quaternary glacial sediments across southern Ontario has been extensively mapped and described on a regional scale for regional surficial mapping projects (e.g. 'OGS Earth', OGS 2011; Chapman & Putnam 1984). More recently, groundwater exploration programs in southern Ontario have initiated the need for widespread mapping of the deeper subsurface sediments and bedrock using borehole and geophysical data (e.g. Sharpe et al. 2003, 2004; Meyer & Eyles 2007; Ministry of Northern Development, Mines and Forestry 2011). Thick deposits of coarse-grained glaciofluvial, alluvial and deltaic sediments found within bedrock- and sediment- hosted valleys and interlobate moraines across southern Ontario host significant regional aquifers, which serve as potable water sources for many communities (e.g. the Oak Ridges Moraine; Sharpe et al. 2003, 2004). Most groundwater exploration programs focus on local-scale subsurface investigations, but there is now considerable need to understand the broader regional context and interconnectivity of aquifers in order to determine their long term sustainability and to design effective protection strategies. In particular, thorough documentation and interpretation of regional Quaternary stratigraphies and the location and geometry of coarse-grained sedimentary units, that could potentially host productive aquifers, is required. This is especially important for growing urban centres dependent on groundwater as a potable water source, such as Georgetown, Ontario which is currently experiencing a water shortage and cannot supply sufficient amounts of water for future housing development initiatives (AECOM 2009).

Detailed subsurface stratigraphic mapping and correlation is difficult in many areas of southern Ontario that lack outcrop exposure and/or closely spaced and high quality borehole data required for the identification of small-scale (within 10s to 100s of metres) heterogeneities in subsurface deposits. Most subsurface mapping studies in southern Ontario rely on the Ontario Waterwell Database (OWD) for spatially extensive subsurface data coverage; however subsurface sedimentological descriptions provided in the OWD are often vague and insufficient for detailed stratigraphic investigations. The OWD is also known to contain various georeferencing and geological errors (MacCormack & Eyles 2010; Gao, 2011). To better understand the nature and form of coarse- and fine-grained units within sedimentary deposits, architectural element analysis (AEA; Allen 1983; Miall 1985) has been widely applied to the analysis of laterally extensive outcrop exposures through fluvial, deltaic, eolian, and glacial sediments (Davis et al. 1993; Eriksson et al. 1995; Hjellbakk et al. 1997; Mountney et al. 1999; Boyce & Eyles 2000; Ghazi & Mountney 2009). Only recently has this technique, which involves the identification of a hierarchy of sedimentary units and their bounding surfaces, been applied to subsurface core data (e.g. Plint & Wadsworth 2003; Boyce & Eyles 2000). However, AEA is a valuable tool that may be used to facilitate the identification, description and analysis of coarse- and fine-grained sedimentary units that determine the geometry and continuity of sediment-hosted aquifers.

This study explores the application of architectural element analysis to the description and interpretation of core data obtained from Quaternary sediments in the Georgetown region of southern Ontario (Figure 3.1). Sedimentological information from 5 closely spaced (188-1754m apart), fully-cored boreholes is used to identify facies types, delineate major bounding surfaces, and define architectural elements within the deep subsurface stratigraphy. The boreholes are drilled in an area devoid of outcrop exposures and penetrate up to 53m into late Quaternary sediments deposited during the last major ice advance and subsequent deglaciation of the region. Coarse-grained facies within the complex subsurface stratigraphy host productive aquifers that supply residents of the town of Georgetown but the geometry and subsurface extent of these units is very poorly understood. The detailed stratigraphic architecture from the 5 boreholes, in combination with information from previous stratigraphic studies in the area (e.g. Meyer & Eyles 2007; Karrow 2005; Costello & Walker 1972), is used here to enhance understanding of the subsurface sediment heterogeneity, stratigraphic framework and hydrostratigraphy of the Georgetown area.

Figure 3.1: A. Surficial sediment types, regional till sheets and physiographic features,including the location of the study area at Georgetown, Ontario (data from OGS 2003; Chapman & Putnam 1984). B. Ground surface digital elevation model (DEM) in metres above sea level (m.a.s.l.) within the Sixteen Mile Creek area of Georgetown, showing the location of boreholes BH1-BH5 used in this study. White lines indicate transects along two cross sections (A-A' and B-B') and white stars represent the approximate location of boreholes from Meyer & Eyles (2007; G1, 2, T1-3, and SL1-3; DEM data from Ontario Ministry of Natural Resources 2005-2006)

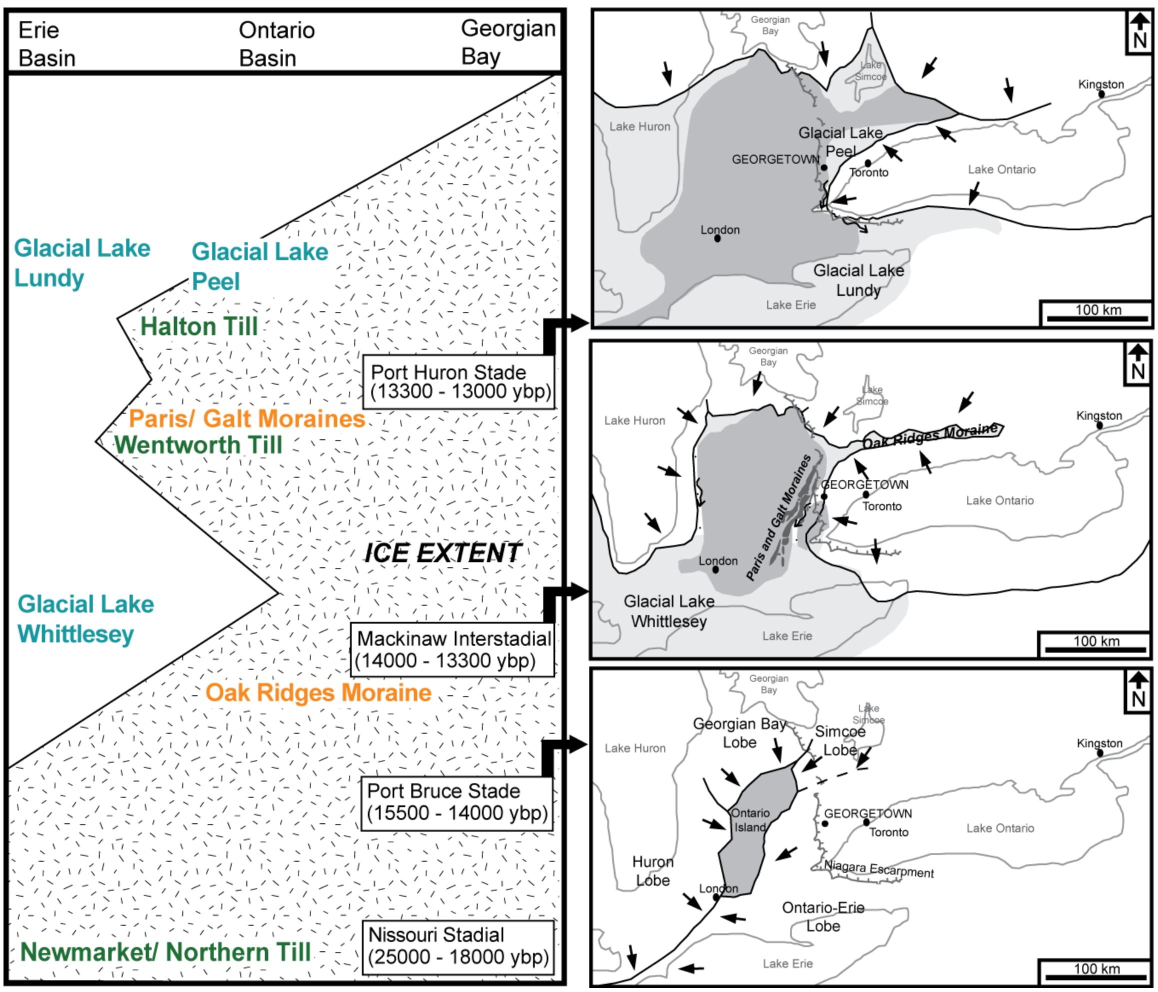

A
Ontario
N
LAKE SCUGOG
RICE LAKE
OAK RIDGES MORAINE (ORM)
Port Hope
Oshawa
Woodbridge
Toronto
Scarborough Bluffs
LAKE ONTARIO
PARIS/ GALT MORAINE
Georgetown
STUDY AREA
Dundas Valley
Hamilton
Paris
Oak Ridges Moraine complex
Halton Till
Port Stanley Till
Wentworth Till
Glaciolacustrine deposits
Various till, glaciolacustrine & glaciofluvial deposits
Outwash spillway system
Paleoflow direction
Niagara Escarpment
20 km
B
Credit River
GUELPH ST
SIDEROAD 17
MOUNTAINVIEW RD S
SIDEROAD 15
SIDEROAD 10
TRAFALGAR RD
BH5
B'
BH4
BH1
BH2
BH3
A
B
A'
Ground surface elevation (m.a.s.l.)
301.177
201.441
1 0.5 0 1 Km

3.2 Geologic background

Southern Ontario is underlain by a basement of mid-Proterozoic rocks that are exposed on the peneplained Canadian Shield (Eyles et al 1997). The overlying cover of Paleozoic (Ordovician and Silurian) sedimentary rocks consists of interbedded limestone, dolostone, sandstone and shale which dip to the southwest. The bedrock has been subject to extensive fracturing by tectonic reactivation and uplift of the underlying basement rocks and differential erosion by fluvial and glacial processes (Eyles et al 1997; Straw 1968). Paleozoic bedrock underlying the Georgetown area belongs to the Ordovician Queenston Formation and consists of red and grey shale unconformably overlain by Silurian carbonates and sandstones which are well exposed in the Niagara Escarpment (Brogly et al. 1998). Georgetown lies at the base of the escarpment, where several buried bedrock valleys carved into the Queenston shale have been identified; however their interconnectedness and continuity are not well understood (Karrow 2005). Buried valleys in the Georgetown area are 30- 60 metres deep and appear to follow a northwest-southeast trend, parallel to the orientation of modern stream systems (Figure 3.1; Eyles et al. 1993; Karrow 2005; Meyer & Eyles 2007).

For the past 2 million years southern Ontario has been subjected to repeated episodes of glaciation and deglaciation (Figure 3.2; Barnett 1992). The youngest and most complete record of glaciation recorded in sediments across southern Ontario is the Wisconsinan glaciation (115000-10000 ybp.; Barnett 1992). The regional Wisconsinan stratigraphy, consisting of interbedded subglacial, glaciolacustrine and glaciodeltaic

Figure 3.2: Time-distance diagram showing ice extent, glacial lake cover and regional till sheets/moraines from the Erie basin to Georgian Bay through the Late Wisconsinan (c. 12500-14000 ybp), accompanied by corresponding paleogeographic reconstructions (data from Chapman & Putnam 1984; Barnett 1992; and Meyer & Eyles 2007).


Erie Basin
Ontario Basin
Georgian Bay
Glacial Lake Lundy
Glacial Lake Peel
Halton Till
Port Huron Stade (13300 - 13000 ybp)
Paris/ Galt Moraines
Wentworth Till
ICE EXTENT
Glacial Lake Whittlesey
Mackinaw Interstadial (14000 - 13300 ybp)
Oak Ridges Moraine
Port Bruce Stade (15500 - 14000 ybp)
Newmarket/ Northern Till
Nissouri Stadial (25000 - 18000 ybp)
Georgian Bay
Lake Simcoe
Lake Huron
Glacial Lake Peel
GEORGETOWN
Toronto
Kingston
Lake Ontario
London
Glacial Lake Lundy
Lake Erie
100 km
N
Oak Ridges Moraine
Paris and Galt Moraines
Glacial Lake Whittlesey
Georgian Bay Lobe
Simcoe Lobe
Ontario Island
Huron Lobe
Niagara Escarpment
Ontario-Erie Lobe

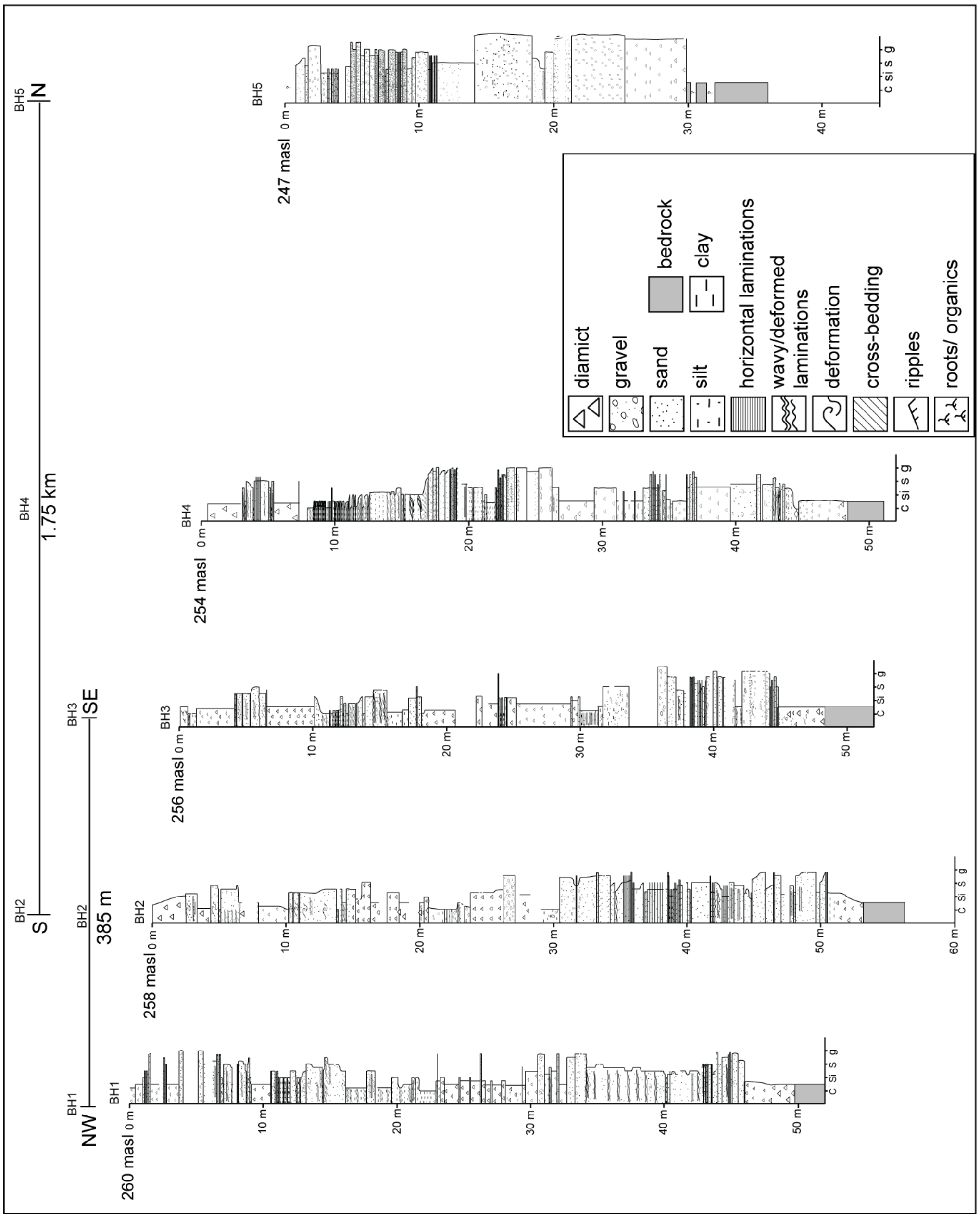
sediments, is well exposed at the Scarborough Bluffs and has been correlated with stratigraphies exposed along the north shore of Lake Ontario and below the Oak Ridges Moraine (ORM), located 40 kilometres north of Toronto (Figure 3.1; Brookfield et al. 1982; Eyles & Eyles 1983; Karrow et al. 2001; Russell et al. 2003).

The early to mid Wisconsinan stratigraphy of southern Ontario comprises fluvial, glaciolacustrine and glaciodeltaic sediments equivalent to the Sunnybrook and Thorncliffe formations exposed along the Scarborough Bluffs (Eyles and Eyles, 1983; Karrow et al. 2001). These sediments are overlain by a series of subglacial and ice marginal sedimentary units deposited during the advance and punctuated retreat of the Laurentide Ice Sheet (LIS) during the late Wisconsinan glaciation (Barnett, 1992). The Northern/ Newmarket till sheet is broadly spread across southern Ontario and was deposited by the LIS (ca. 20000 ybp.; Figure 3.2) which, at its maximum, extended as far south as Missouri, U.S.A. (Barnett 1992). Subsequent retreat of the LIS during the Mackinaw Interstadial (ca. 13300 ybp; Figure 3.2), allowed deposition of coarse-grained fluvial gravels and sands across many areas of southern Ontario (Eyles 2002). Readvance of the southern margin of the LIS as lobate ice masses that flowed preferentially along the Ontario and Simcoe basins (Figure 3.2) created more localized till sheets such as the Halton Till. The Halton Till has been regionally mapped by several workers and extends from the Lake Ontario shoreline in the south to the southern flank of the Oak Ridges Moraine (ORM) in the north and from the base of the Niagara Escarpment in the west to the Rice Lake area in the east (Figures 3.1, 3.2; Karrow 2005). The ORM formed between the Ontario and Simcoe lobes of the LIS as an interlobate moraine consisting of relatively coarse-grained fluvial, lacustrine and deltaic sediments and now serves as a major aquifer recharge area. The subsurface stratigraphy preserved in the Georgetown region should contain a depositional record of many of these Wisconsinan events (Meyer & Eyles, 2007).

3.3 Study area and methodology

A series of 5 boreholes were drilled in the Middle Sixteen Mile Creek area of Georgetown, Ontario (Figures 3.1, 3.3) in 2009 as part of an ongoing groundwater exploration program conducted by the Regional Municipality of Halton. The boreholes were continuously cored in 1.5m run intervals using the PQ coring technique (9cm diameter core samples) and drilled between 36 and 56m in depth to bedrock. Core samples were wrapped in plastic sleeves and encased in pre-cut PVC tubing. The core was logged using standard sedimentary logging techniques (e.g. Eyles et al. 1983), recording grain size, sedimentary structure, clast characteristics (e.g. rounding, maximum diameter and lithology), the nature of bounding surfaces (e.g. erosional, irregular, conformable), facies types, and other pertinent information (e.g. sections of no core recovery, contents of drill cuttings, and run depths). These logs were used as a basis for the identification of distinctive changes in the vertical succession of sediment types (bounding surfaces) and to delineate stratigraphic units. Analysis of the hierarchy of bounding surfaces and the stratigraphic units they define is the foundation of architectural element analysis (AEA).

Figure 3.3: Sedimentary logs of boreholes BH 1- 5 logged in the Sixteen Mile Creek area of Georgetown represented in two cross-sections: northwest to southeast (A- A') and south to north (B-B'). Logs are hung relative to the ground surface elevation in metres above sea level (m.a.s.l.) at the borehole location and horizontal distance is indicated along each cross-section transect line. See Figure 1 for borehole and cross-section locations.


NW
BH1
SE
BH3
385 m
BH2
S
BH2
N
BH5
BH4
1.75 km
260 masl
258 masl
256 masl
254 masl
247 masl
c si s g
diamict
gravel
sand
silt
horizontal laminations
wavy/deformed laminations
deformation
cross-bedding
ripples
roots/ organics
bedrock
clay

3.4 Facies descriptions and interpretations

A detailed study of cores obtained from the five fully cored boreholes identified twelve facies types: gravel facies (massive/ deformed and crudely bedded); sand facies (rippled; cross bedded; horizontally bedded and massive/deformed sand); fine-grained facies (laminated; massive/crudely bedded with dropstones; and massive/deformed); and diamict facies (clast-rich; clay-rich; and sand-rich). The characteristics of the twelve facies types and their interpreted depositional origin are summarized below (Figures 3.4, 3.5).

3.4.1 Diamict facies

Diamict facies include clast-rich (Dc), sand-rich (Ds) and clay-rich (Df) diamict types.

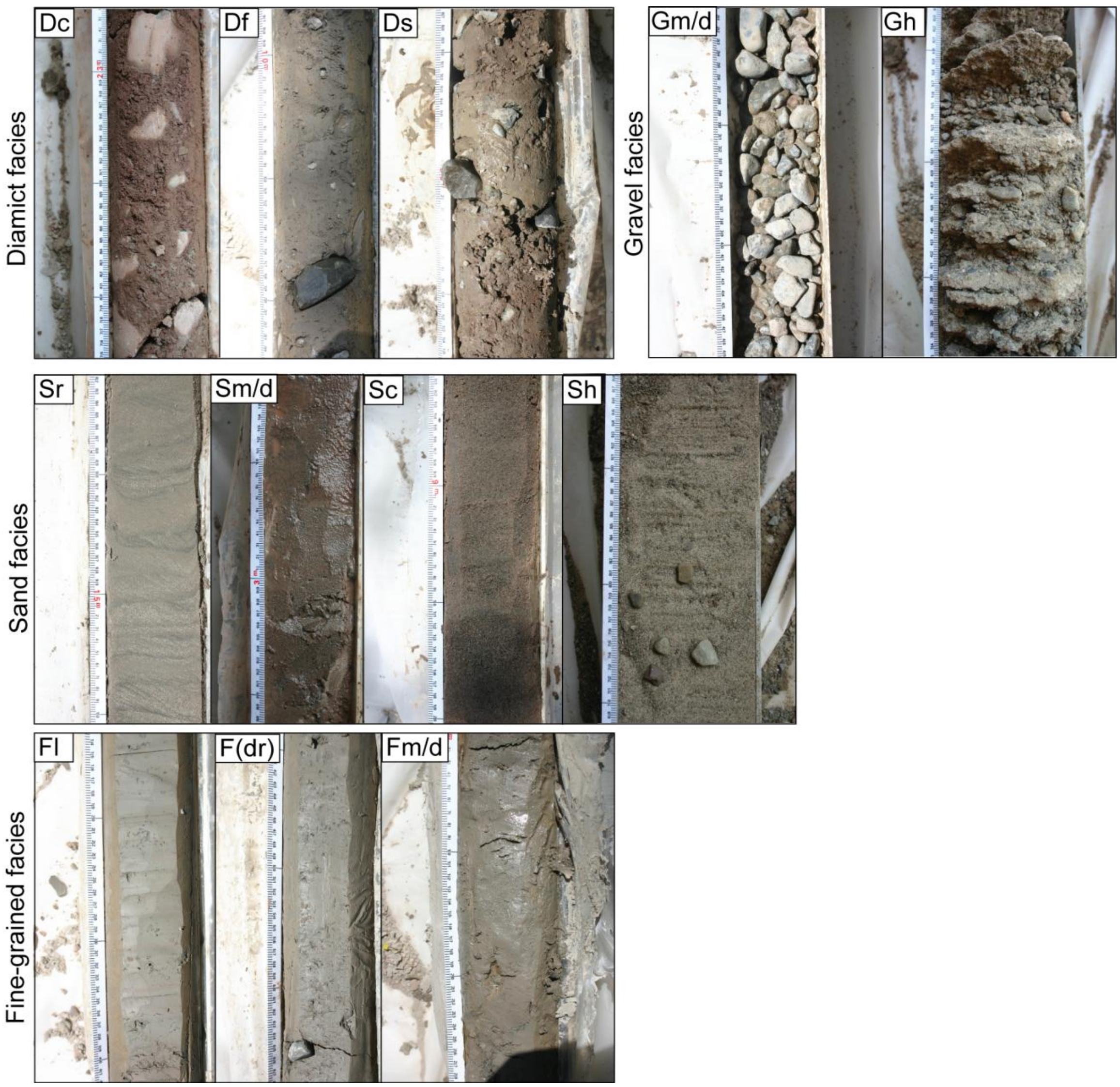
3.4.1.1 Clast-rich diamict (Dc)

Clast-rich diamict (Dc) facies are 3.5m to 5m thick and are composed of abundant clasts within a reddish-brown fine-grained matrix (Figure 3.5). Clasts contained in Dc facies are exclusively composed of shale derived from the Queenston Formation. Individual clasts are very angular to subangular in shape and 1mm- >9cm in diameter. Dc facies is massive, very poorly sorted, and always directly overlies bedrock of Queenston Formation shale (Figures 3.4, 3.5, and 3.6).

Figure 3.4: Description and interpretation of facies types identified in this study (based on Eyles et al. 1983; Miall 2010)

Facies	Thickness	Grain size and lithology	Sedimentary structure	Interpretation
Dc	3.5- 5m	Very poorly sorted and clast-rich. Very angular- subangular shale clasts within a silt and clay matrix. Individual clasts are 1mm- >9cm in diameter.	Massive	Formed through near-surface weathering of the shale bedrock and fluvial/ mass wasting processes
Ds	0.1- 7.2m	Very poorly sorted and sand-rich. Composed of clasts (0.5cm- >9cm in diameter) within a reddish- to greyish- brown sandy matrix. Clasts are very angular- subrounded and of local (e.g. dolostone, shale) and far-travelled (e.g. feldspar, gneiss, granite) lithologies.	Massive	Deposited as subglacial till by lodgement and deformation processes
Df	0.1- 5m	Very pooly sorted and clay-rich. Composed of subangular- subrounded clasts within a fine-grained matrix. Clasts are 0.5cm- >9cm in diameter and of local lithologies (shale and dolostone).	Massive	Deposited as subglacial till by lodgement and deformation processes
Gm/d	0.02- 2.3m	Poorly to well sorted. Openwork and sandy gravel. Consists of clasts 0.5cm- >30 cm in diameter, (subangular to well rounded) and of local (e.g. dolostone and shale) and far-travelled (e.g. granite, gneiss and quartzite) lithologies.	Massive/ deformed and cemented in units up to 30cm thick	Formed by bedload transport of clasts as gravel sheets and longitudinal bars in a (glacio-) fluvial environment
Gh	0.6-1m	Poorly to well sorted. Openwork and sandy gravel. Consists of clasts 0.5- 10 cm in diameter, (subangular to well rounded) and of local (e.g. dolostone and shale) and far-travelled (e.g. granite, gneiss and quartzite) lithologies.	Crudely bedded	Formed by bedload transport as migrating bars and bedforms in a (glacio-)fluvial environment
Sr	0.3-0.7m	Well sorted. Fine- to medium-grained sand.	Ripples	Formed by traction currents in a fluvial/ deltaic environment
Sc	0.1- 0.9m	Well sorted. Fine- to coarse-grained sand.	Cross bedding	Formed by the migration of dunes and bars in a fluvial environment
Sh	0.02- 1m	Moderately well sorted. Fine- or coarse-grained sand. Contains rare clasts 0.5- 2 cm in diameter, which are subangular to subrounded and mostly of local (e.g. dolostone and shale) lithologies.	Horizontal lamination	Finer-grained Sh facies formed under low energy conditions and coarser-grained Sh facies formed under high energy conditions in a fluvial/deltaic environment
Sm/d	0.05- 3m	Moderately well to poorly sorted. Fine- to coarse-grained sand. Contains rare clasts 4- 8 cm in diameter, which are subangular to subrounded and of local (e.g. dolostone and shale) and far-travelled (e.g. granite and gneiss) lithologies.	Massive/ deformed	Formed either by slumping and water-escape deformation in a ponded or fluvial/ deltaic environment or by subglacial deformation at the base of an ice sheet
Fm/d	0.02- 0.45m	Very fine-grained sand, silt and clay	Massive/ deformed	Formed by slumping and soft sediment deformation in a (glacio-) lacustrine environment and by subglacial deformation at the base of an ice sheet
F(dr)	0.15- 1.6m	Massive and crudely laminated clay and silt with rare angular-rounded clasts (1->9cm in diameter) composed of shale and feldspar-rich lithologies.	Massive/ crudely laminated	Fine-grained sediment is deposited in a (glacio-)lacustrine environment. The clasts record the rainout of debris released from floating ice in a glaciolacustrine environment
Fl	0.01- 4m	Very fine-grained sand, silt and clay	Laminated	Formed by fallout from suspension in a (glacio-)lacustrine environment

Figure 3.5: Photographs of facies types identified in this study: diamict facies Dc (BH2), Df (BH1), Ds (BH1); gravel facies Gm/d (BH3) and Gh (BH5); sand facies Sr (BH3), Sm/d (BH2), Sc (BH3), Sh (BH5); and fine-grained facies Fl (BH1), F(dr)(BH3), Fm/d (BH1). See Figure 3.3 for facies descriptions.


Diamict facies
Dc
Df
Ds
Gravel facies
Gm/d
Gh
Sand facies
Sr
Sm/d
Sc
Sh
Fine-grained facies
Fl
F(dr)
Fm/d

The sedimentological characteristics and stratigraphic position of facies Dc indicates an origin as ‘head’ formed through near-surface weathering of the shale bedrock and minor remobilization by fluvial and slope processes (Meyer & Eyles 2007).

3.4.1.2 Sand-rich diamict (Ds)

Sand-rich diamict (Ds) facies are massive, dense and highly consolidated, consisting of scattered clasts within a reddish-brown to greyish sandy matrix (Figure 3.5). Clasts are 0.5cm- >9cm in diameter, angular to rounded, and of both local (e.g. dolostone, shale) and far-travelled (e.g. feldspar, gneiss, granite) lithologies. In core, Ds facies are 10cm to 7.2m thick and are commonly interbedded with gravel, sand and fine-grained facies at elevations of between 214 and 243 m.a.s.l. (Figures 3.4, 3.5).

The absence of sedimentary structures and the poorly sorted nature of Ds facies signifies a lack of sorting by water and the dense, highly consolidated nature of the diamict is indicative of a subglacial depositional origin. The large range in clast size, shape and lithology suggests both local and long distant transport of materials (e.g. the Canadian Shield) and the sandy matrix is indicative of overriding and incorporation of previously deposited sand-rich sediment. The thick succession of stacked beds of Ds facies identified in core suggests long-term aggradation of sediment formed under similar depositional conditions (Meriano & Eyles 2009). Interbeds of gravel, sand and fine-grained facies indicate intermittent transport and deposition of fluvial sediment (Boyce & Eyles 2000; Meriano & Eyles 2009). In combination, these sedimentary characteristics suggest that Ds facies formed by lodgement and deformation processes, with intermittent fluvial deposition, in a subglacial environment (Boulton 1996; Evans et al. 2006).

3.4.1.3 Clay-rich diamict (Df)

Clay- rich diamict (Df) facies are very poorly sorted and form units between 10cm and 5m thick. Df facies have a brownish grey, fine-grained matrix and abundant clasts which are 0.5cm- >9cm in diameter, subangular to subrounded, and mostly consist of local lithologies (shale and dolostone), with a few far-travelled lithologies (e.g. granite; Figures 3.4 & 3.5.). Df facies are interbedded with Sm/d, Gm/d and Sc facies (Figures 3.4, 3.5).

Df facies have very similar characteristics to Ds facies and a similar depositional origin, as subglacially deposited till, is proposed here (Boulton 1996; Evans et al. 2006). Clasts indicate transport of material from local and more distant sources, and the clay-rich diamict matrix suggests subglacial reworking and incorporation of previously deposited fine-grained sediment. Interbedded sand and gravel facies indicate episodic deposition of sorted, water-laid sediment in subglacial fluvial environments (Meriano & Eyles 2009).

3.4.2 Gravel facies

Gravel-dominated facies include massive/deformed (Gm/d) and crudely bedded (Gh) gravel. Gm/d facies form beds between 2cm and 2.3m thick and consist of openwork and sandy gravel containing clasts that range in diameter from 0.5cm to more than 30cm. Gh facies are 60cm to 1m thick and consist of crudely bedded gravel with clasts ranging from 0.5cm to 10cm in diameter. Clasts contained within Gm/d and Gh facies are subangular to well rounded and are composed of local and far-travelled lithologies (Figures 3.4 & 3.5).

The subangular to well- rounded clast shape and relatively narrow range in grain size of Gm/d and Gh facies indicates transport and sorting by the action of water. The coarse-grained nature of Gm/d and Gh facies indicates transport under high-energy conditions and subsequent deposition during falling stage relatively close to the sediment source area (Miall 1977). The lack of sedimentary structure in Gm/d facies suggests rapid deposition during high-discharge events without subsequent reworking of clasts (Nemec & Steel 1984). However, poor core recovery during the drilling process may have destroyed sedimentary structures in Gm/d facies (Meyer & Eyles 2007). The crude horizontal bedding of Gh facies indicates alternating migration of gravel clasts during relatively high-stage flow conditions and deposition of gravel beds formed during waning flood stage or decreasing discharge (Nemec & Steel 1984). Gm/d and Gh facies are interpreted to have formed as a result of bedload transport and deposition in the form of migrating bars and bedforms in a (glacio-) fluvial environment (Miall 1977).

3.4.3 Sand facies

Sand-dominated facies include horizontally bedded (Sh), rippled (Sr), cross-bedded (Sc) and massive/deformed (Sm/d) sands.

3.4.3.1 Rippled sand (Sr)

Rippled sand facies (Sr) form beds between 30cm and 70cm thick and consist of climbing ripples (‘Type A’ of Jopling and Walker 1968) which in some cores show evidence of soft sediment deformation. Sr facies are composed of fine- to medium-grained sand and are associated with Fl and Sd facies (Figures 3.4, 3.5). These facies are interpreted to have formed from the rapid deposition of suspended sand and migration of grains by low energy traction currents in a fluvial/ deltaic environment supplied with large amounts of suspended sediment (Miall 1977; Eyles & Clark 1988).

3.4.3.2 Cross-bedded sand (Sc)

Cross-bedded sand (Sc) facies are the least common facies recorded in the core samples and form beds between 10 and 90cm thick, consisting of cross-bedded (planar and trough?), fine- to coarse-grained sand (Figures 3.4, 3.5). Sc facies are interpreted to have formed under medium- to high-energy flow conditions during falling water stage and record the migration of dunes and bars in a distal braided-river (glacio-) fluvial environment supplied with a high volume of sand-rich sediment (Miall 1977: Eyles & Clark 1988).

3.4.3.3. Horizontally laminated sand (Sh)

Horizontally laminated sand (Sh) facies occur in units 2cm to 1m thick and consist of horizontal laminae of either fine- or coarse-grained sand, each between 1 and 1.5 cm thick. Coarse-grained Sh facies occur primarily in BH 5 and are associated with cross-bedded sands and massive and deformed gravels (Figures 3.4, 3.5). These facies record deposition under high energy planar bed flow conditions probably in a fluvial environment (Miall 1977). In contrast, fine-grained Sh facies are most commonly associated with Fl and Sr facies and show evidence of soft sediment deformation in some cored sections (Figures 3.4, 3.5). These facies record deposition under relatively low-energy flow conditions from fallout of sand grains from suspension and movement as bedload on a planar surface in a more distal (glacio-) fluvial to deltaic environment (Miall 1977). Deformation features in fine-grained Sh facies are interpreted to record water-escape processes after initial deposition of the sand (Miall 1977).

3.4.3.4 Massive/deformed sand (Sm/d)

Massive/deformed sand (Sm/d) facies consist of moderately well to poorly sorted fine- to coarse-grained sand and occur in units 5cm to 3m thick. Sm/d facies contain occasional subangular to subrounded clasts (4- 8 cm in diameter) composed of local (e.g. dolostone and shale) and far-travelled (e.g. granite and gneiss) lithologies (Figures 3.4, 3.5). This facies is most commonly associated with Ds, Df and Sr facies. Sm/d facies are interpreted to have formed as a result of deformation by overriding by glacial ice or from soft-sediment deformation and slumping of previously deposited sand in a (glacio-) fluvial/deltaic environment (Eyles & Eyles 1983). Clasts contained within these facies may either record deposition of ice-rafted material or incorporation of coarser-grained sediment from the overriding ice base or during slumping.

3.4.4 Fine-grained facies

Fine-grained facies consist of laminated (Fl), massive/deformed (Fm/d) and massive with dropstones (F(dr)) types.

3.4.4.1 Laminated fine-grained (Fl) facies

Laminated fine-grained (Fl) facies form units between 1cm and 4m thick and consist of brown-grey laminated very fine-grained sand, silt and clay. Individual laminations are <1- 5mm thick and may be slightly deformed and micro-faulted. A few angular clasts (1.5-2cm in diameter) are often present, and may occur either as solitary clasts or as a thin clast horizon (Figures 3.4, 3.5). Fl facies are commonly associated with Sr, Sd and Ds facies. Fl facies are interpreted to have formed in a low energy lacustrine or glaciolacustrine depositional environment supplied with a high volume of suspended fine-grained sediment (Miall 1977; Eyles & Eyles 1983). Rare solitary clasts and clast horizons may record infrequent rainout of debris from floating ice (Eyles et al. 1983) or resedimentation of material from the basin margin. Minor amounts of deformation and faulting are interpreted to have occurred after the deposition of Fl facies on unstable slopes or may have resulted from the core drilling and handling process.

3.4.4.2 Massive/deformed fine-grained (Fm/d) facies

Massive/deformed fine-grained facies (Fm/d) consist of beds of very fine-grained sand, silt and clay between 2cm and 45cm thick (Figures 3.4, 3.5). These facies are either structureless or contain abundant deformation and water-escape features and are interpreted to have formed by slumping and soft-sediment deformation in a (glacio-)

lacustrine environment. In some cores, Fm/d facies directly underlie diamict facies and may have formed by subglacial deformation at the base of an overriding ice sheet (Eyles & Eyles 1983)

3.4.4.3 Massive/crudely bedded fine-grained facies with dropstones (F(dr))

Massive/crudely bedded fine-grained facies with dropstones (F(dr)) form units 15cm to 1.6m thick that consist of massive to crudely laminated clays and silts with common red clay/silt clasts, and rare clasts of local and far-travelled lithologies (1->9cm in diameter; Figures 3.4, 3.5). The massive/ crudely bedded component of F(dr) facies is interpreted to have formed by rapid deposition of fine-grained sediment from suspension in a (glacio-) lacustrine/distal delta slope environment (Miall 1977). Red silt and clay clasts are probably intraclasts generated by slumping and disaggregation of previously deposited silt and clay beds that were remobilized on the delta slope. The rare lithic clasts are interpreted as dropstones originating as debris released from floating ice in a glaciolacustrine setting (Eyles & Eyles 1983).

3.5 Architectural elements

Architectural element analysis (AEA) is a technique used to describe the geometry of sedimentary deposits and involves the identification of distinctive sedimentary units separated by bounding surfaces. The technique was developed for the analysis of fluvial deposits exposed in outcrop (Allen 1983; Miall 1985) but has more recently been applied to sedimentary sequences of aeolian (Mountney et al. 1999) and subglacial (Boyce & Eyles 2000) origin, as well as to the integration of fully-cored borehole and downhole geophysical data.

Identification of the nature of the bounding surfaces separating sedimentary units is critical for paleo-environmental reconstructions because these surfaces record changes in depositional conditions of various scales (Miall 2010). A hierarchical scheme was developed by Allen (1983), and later refined by Miall (1985), to represent the degree of environmental change recorded by each bounding surface. Erosional, unconformable bounding surfaces often record substantial environmental changes, such as a major change in depositional setting (e.g. from a lacustrine to a subglacial environment). In contrast, erosional, conformable bounding surfaces within sand and gravel successions may represent localized environmental changes such as channel abandonment or fluctuations in paleoflow direction within a single fluvial environment (Miall 2010). Although core data lack information on lateral facies variability compared to extensive outcrop exposures, it is possible to reconstruct stratigraphic architecture from core data based on detailed observation of facies characteristics and the nature of bounding surfaces within and between boreholes (Plint & Wadsworth 2003; Boyce & Eyles 2000).

Bounding surfaces identified from core data in this study were organized in a hierarchical scheme in a similar fashion to that outlined by Miall (1985, 2010) and Boyce & Eyles (2000). Bounding surfaces were delineated by recording the nature of the bounding surface itself (e.g. erosional or conformable, irregular or planar), the significance of changes in facies types/associations on either side of a bounding surface, and the extent to which the surface could be correlated with a high degree of confidence between the five boreholes. Surfaces of 0^{th}- to 3^{rd}- order represent small- scale environmental changes (e.g. bedform migration in a fluvial system; Miall, 2000) and have a low preservation potential. These surfaces are difficult to identify from core data and to correlate laterally between boreholes and are therefore not recognized in this study. Higher level bounding surfaces (4^{th}- to 7^{th}-order) record increasingly significant environmental changes and are more easily correlated between boreholes (Miall 2010).

The identification and arrangement of bounding surfaces and facies associations in the five cores examined in this study allowed for the classification of nine distinct architectural elements and a hierarchy of 4^{th}- to 7^{th}- order bounding surfaces (Figures 3.6, 3.7). The nine architectural elements identified from the Georgetown cores are: gravel lens (GL), gravel complex (GC), sand lens (SL), sand complex (SC), fine-grained lens (FL), fine-grained complex (FC), diamict lens (DL), diamict complex (DC) and diamict deformed zone (DZ; Figures 3.6, 3.7).

3.5.1 Gravel lens (GL)

The gravel lens (GL) element consists of Gm facies, is lens-shaped, and laterally discontinuous between boreholes (Figure 3.4). The GL element has a thickness of between 1 and 3m, and is enclosed by 4^{th}-order upper and lower bounding surfaces (Figures 3.6, 3.7). The textural and geometrical characteristics of the GL element suggest that it records deposition on gravel bars and bedforms formed within small channels in a (glacio-)fluvial environment, or meltwater deposits formed within a subglacial environment (Miall 1985; Boyce & Eyles 2000).

Figure 3.6: Architectural elements identified from fully-cored boreholes in this study (based on Bridge 1993; Eriksson et al. 1995; Hjellbakk 1997; Boyce & Eyles 2000; Opluštil et al. 2005; Ghazi & Mountney 2009; Miall 2010)

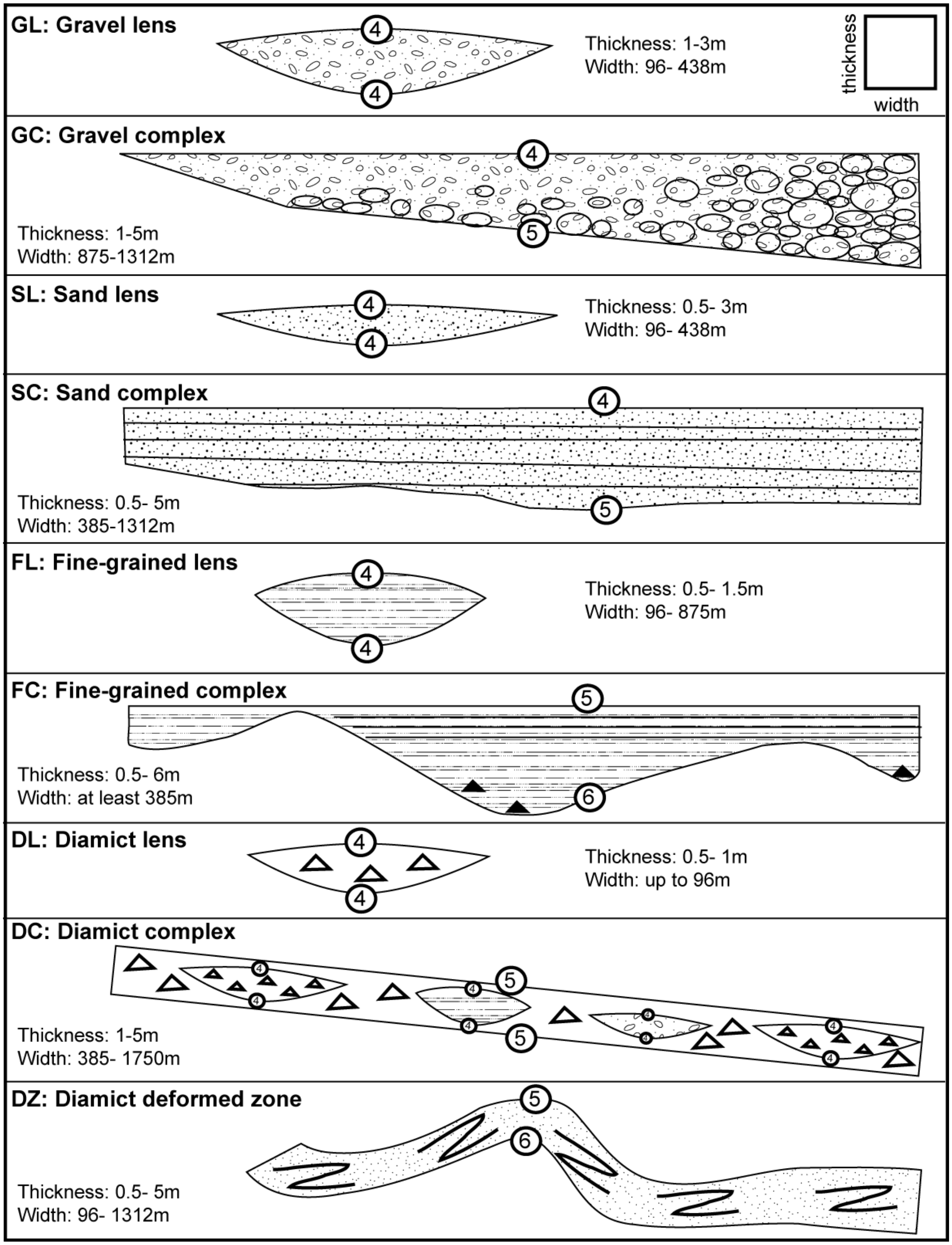
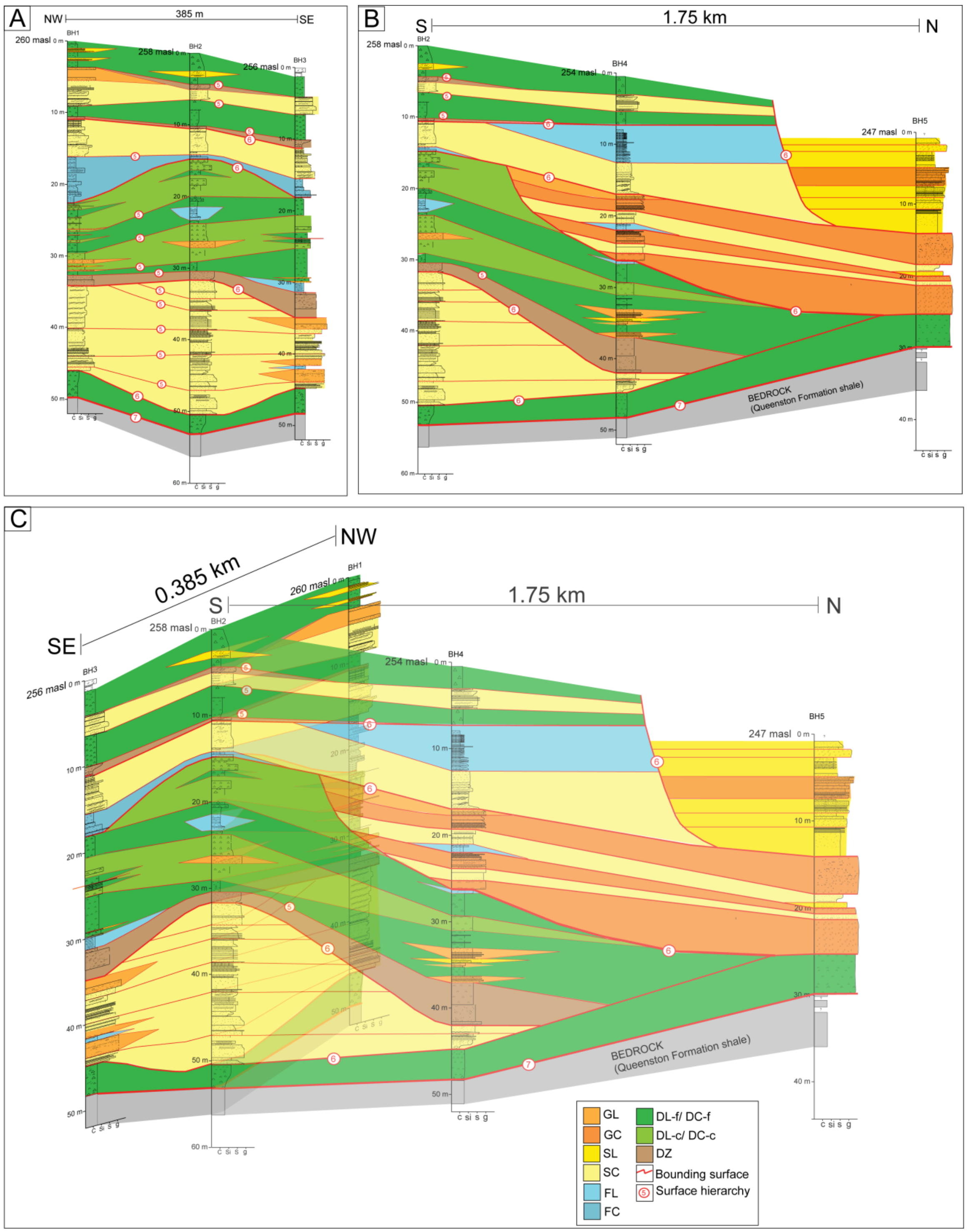

GL: Gravel lens
Thickness: 1-3m
Width: 96- 438m
thickness
width
GC: Gravel complex
Thickness: 1-5m
Width: 875-1312m
SL: Sand lens
Thickness: 0.5- 3m
Width: 96- 438m
SC: Sand complex
Thickness: 0.5- 5m
Width: 385-1312m
FL: Fine-grained lens
Thickness: 0.5- 1.5m
Width: 96- 875m
FC: Fine-grained complex
Thickness: 0.5- 6m
Width: at least 385m
DL: Diamict lens
Thickness: 0.5- 1m
Width: up to 96m
DC: Diamict complex
Thickness: 1-5m
Width: 385- 1750m
DZ: Diamict deformed zone
Thickness: 0.5- 5m
Width: 96- 1312m

Figure 3.7: A. Northwest-southeast cross-section of BH1-3 showing architectural elements and bounding surfaces identified in this study; B. South-north cross-section of BH2, BH4 and BH5 showing architectural elements and bounding surfaces identified in this study; and C. Fence diagram combining cross-sections from A. and B. showing the 2-dimensional and 2.5-dimensional geometry of architectural elements and bounding surfaces identified in BH1-5. See Figure 3.6 for summary of architectural elements.


A
NW
385 m
SE
BH1
260 masl
BH2
258 masl
BH3
256 masl
B
S
1.75 km
N
258 masl
BH2
BH4
254 masl
BH5
247 masl
BEDROCK
(Queenston Formation shale)
C
0.385 km
NW
SE
S
1.75 km
N
GL
GC
SL
SC
FL
FC
DL-f/ DC-f
DL-c/ DC-c
DZ
Bounding surface
Surface hierarchy

3.5.2 Gravel complex (GC)

The gravel complex element (GC) has a sheet-like geometry and can be correlated between two or more boreholes. GC elements consist of stacked Gm facies and are 1- 5 m thick and up to 1.3 km in length (Figures 3.6, 3.7). The 5^{th}-order upper and lower bounding surfaces of the GC element are erosional and relatively planar. However, the lower bounding surface of the oldest GC element in the cored stratigraphy is of 6^{th}-order and appears to have a concave-up form. In all five boreholes, the GC element is interbedded with sand complex (SC) elements and truncates diamict complex elements (DC; Figures 3.6, 3.7). The GC element is interpreted to represent sheet-like gravel bars and bedload deposits that formed within a glaciofluvial depositional environment (Miall 1985).

3.5.3 Sand lens (SL)

Sand lens (SL) elements are 0.5- 3m thick, lens-shaped, laterally discontinuous sand units composed of Sm/d facies and bounded by 4^{th}-order bounding surfaces (Figures 3.4, 3.5). SL elements are found within diamict complex (DC) elements and are interbedded with GC elements (Figures 3.6, 3.7). SL elements are interpreted to record deposition by meltwaters in a sand-rich subglacial or glaciofluvial depositional environment (Boyce & Eyles 2000).

3.5.4 Sand complex (SC)

The sand complex (SC) element is 0.5-5m thick and bounded by a 5^{th}- order lower surface and 4^{th}- to 6^{th}- order upper surfaces. SC elements are sheet-like with a semiplanar or concave-upward lower bounding surface (Figures 3.6, 3.7). These elements consist of genetically-related sand facies that comprise one or more fining-upward sequences and can be solitary or stacked. SC elements are most often associated with GL elements, but in some places they are associated with FL, FC and DZ elements (Figure 3.7). SC elements are interpreted to record sand bars and channel fill sand complexes formed within a (glacio-) fluvial depositional environment (Miall 1985).

3.5.5 Fine-grained lens (FL)

The fine-grained lens element (FL) is 0.5-1.5m thick, lens-shaped and cannot be correlated between boreholes. FL elements consist of packages of fine-grained facies (Fl, Fd, F(dr); Figures 3.4, 3.5) and are associated with diamict complex (DC), SC and GC elements (Figures 3.6, 3.7). FL elements are bounded by 4th and 5th- order lower surfaces and 4th- to 6th- order upper surfaces (Figures 3.6, 3.7). The FL element is interpreted to have formed under localized (glacio-) lacustrine conditions within a subglacial or glaciofluvial setting (Eyles & Eyles 1983; Boyce & Eyles 2000).

3.5.6 Fine-grained complex (FC)

Fine-grained complex (FC) elements consist of packages of fine-grained facies (Fl, Fd, F(dr); Figure 3.4, 3.5) and sand facies (Sr, Sd; Figures 3.4, 3.5). FC elements have a sheet-like geometry with an irregular 6th- order lower surface and a planar 5th- order upper surface (Figures 3.6, 3.7). The FC element is 0.5-6m thick and is associated with SC elements (Figures 3.6, 3.7). This element is interpreted to have formed under low-energy (glacio-) lacustrine conditions (Eyles & Eyles 1983; Miall 1985).

3.5.7 Diamict lens (DL)

Diamict lens elements (DLs) consist of one type of diamict facies such as Ds (sand-rich diamict) or Df (clay-rich diamict; Figures 3.4, 3.5) and are either fine-grained (DL-f) or coarse-grained (DL-c; Figure 3.6). The DL element is 0.5-1 m thick and is enclosed by 4th- order bounding surfaces (Figures 3.6, 3.7). DL elements are associated with DC, GL and SL elements and are interpreted to record subglacial deposition by lodgement, deformation and/or melt-out processes (Boulton 1996; Boyce & Eyles 2000; Evans et al. 2006).

3.5.8 Diamict complex (DC)

Diamict complex elements (DCs) are sheet-like, between 1 and 5m thick, are laterally extensive between boreholes, and are enclosed by 5th- to 7th-order upper and lower bounding surfaces (Figures 3.6, 3.7). Individual DC elements consist of one type of diamict facies (e.g. Ds, Dc or Df; Figures 3.4, 3.5) and are either coarse-grained (DC-c) or fine-grained (DC-f), depending on the composition of the matrix (e.g. DC elements primarily composed of Df facies are classified as DC-f elements; Figure 3.7). DC elements consisting of Ds (DC-c) and Df (DC-f) facies are most commonly stacked and also contain other architectural elements such as FL, SL, GL and DL (Figure 3.6, 3.7). A solitary, sheet-like DC element consisting of Dc facies, which does not contained interbeds of other elements, directly overlies bedrock and has a 7th-order lower bounding surface (Figure 3.7). The DC elements that contain other architectural elements are interpreted to record subglacial deposition by lodgement, deformation and/or melt-out processes (Boulton 1996; Evans et al. 2006). The solitary DC element overlying bedrock with a 7th-order lower bounding surface is interpreted to have formed by localized mass wasting and fluvial reworking of weathered material released from the bedrock surface (Meyer & Eyles 2007).

3.5.9 Diamict deformed zone (DZ)

The diamict deformed zone element (DZ) is sheet-like, between 0.5 and 5m thick, and consists of deformed and poorly sorted gravel, sand and fine-grained facies (Gm/d, Sm/d and Fm/d; Figures 3.4, 3.5). The DZ element has an irregular upper (5th-order) and lower (6th-order) bounding surface (Figures 3.6, 3.7). This element always overlies sand facies and is associated with the DC-f element (Figures 3.6, 3.7). The DZ element is interpreted to have formed by subglacial deformation and shearing processes and the incorporation and reworking of underlying pre-existing sediment into the basal debris zone of an overriding glacier (Boulton 1996; Boyce & Eyles 2000; Evans et al. 2006; Meriano & Eyles 2009).

3.6. Stratigraphic Units

The grouping of architectural elements and arrangement of the hierarchy of bounding surfaces identified above allows reconstruction of depositional environments and delineation of major stratigraphic units in the Sixteen Mile Creek area of Georgetown. Stratigraphic units represent groupings of genetically related facies types that can be used to reconstruct changes in depositional environments through time (Middleton 1973; Walker 1990; Meyer & Eyles, 2007). Seven stratigraphic units (U1-

U7) were identified in the five cores examined in this study (Figure 3.8). These units consist of weathered bedrock/ colluvium (U1), sand-dominated glaciofluvial sediment (U2), a lower till complex (U3), gravel-dominated glaciofluvial sediment (U4), glaciolacustrine/deltaic sediment (U5), an upper till complex (U6) and glaciofluvial sand and gravel (U7; Figure 3.8). The seven units are delineated by 6th-order bounding surfaces; however U1 is enclosed by a 7th-order lower bounding surface which records a major regional unconformity (Figure 3.8). Each of the seven units is described below in order of their stratigraphic position (from base to top). Figure 3.9 provides a summary of these characteristics and their equivalency to the stratigraphic units identified by Meyer & Eyles (2007) from boreholes drilled previously in the Georgetown region.

3.6.1 Stratigraphic Unit 1 (U1): weathered bedrock/ colluvium

U1 is present in all five boreholes and is the most laterally extensive and architecturally homogeneous of all stratigraphic units identified. U1 consists of clast-rich diamict facies (Df; Figures 3.4, 3.5) which comprise a single 3.5 to 5m thick architectural element (diamict complex element; Figures 3.6, 3.7). U1 is bounded by a 7^{th}-order lower bounding surface, which represents a regional unconformity between the Paleozoic bedrock of the Queenston Formation shale and the overlying Quaternary sediments, and a 6^{th}-order upper bounding surface (Figure 3.8). U1 is interpreted to record widespread *in situ* weathering of the bedrock surface, possibly enhanced by fracturing related to loading

Figure 3.8: A. Northwest-southeast cross-section through BHs1-3 showing major stratigraphic units (U1-3, U5 & 6) and bounding surfaces identified in this study; B. South-north cross-section of BH2, BH4 and BH5 showing major stratigraphic units (U1-7) and bounding surfaces; and C. Fence diagram of cross-sections from A. and B. showing the 2-dimensional and 2.5-dimensional geometry of major stratigraphic units and bounding surfaces identified in BHs1-5.

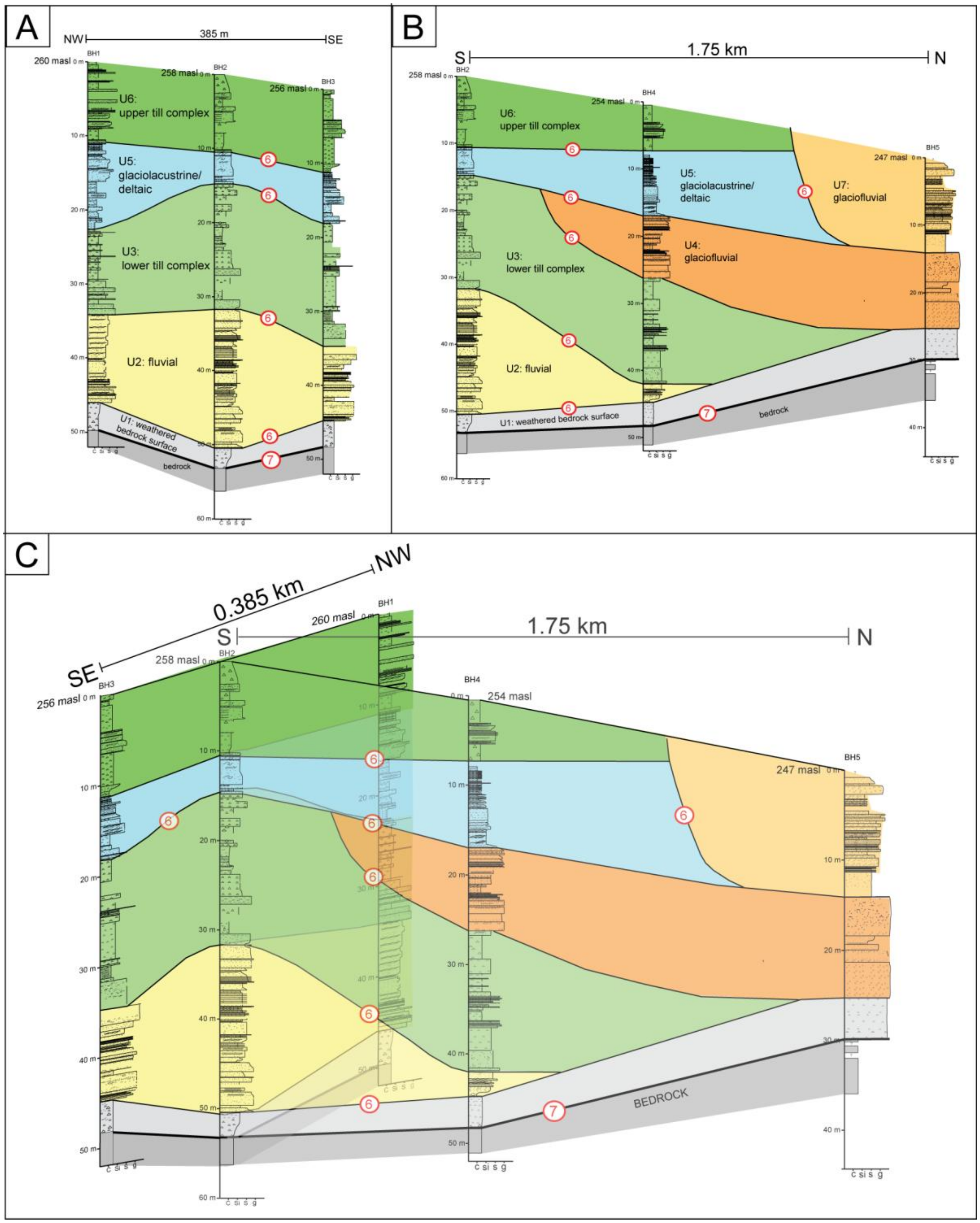
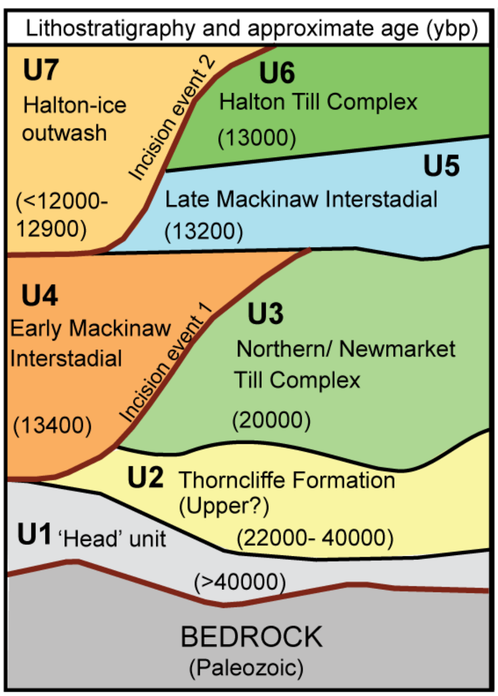

A
NW
385 m
SE
260 masl
258 masl
256 masl
BH1
BH2
BH3
U6: upper till complex
U5: glaciolacustrine/ deltaic
U3: lower till complex
U2: fluvial
U1: weathered bedrock surface
bedrock
B
S
1.75 km
N
258 masl
254 masl
247 masl
BH4
BH5
U7: glaciofluvial
U4: glaciofluvial
U1: weathered bedrock surface
C
0.385 km
SE
NW
BEDROCK

Figure 3.9: A. Description and interpretation of stratigraphic units (U1-7) identified in this study; B. Approximate age and stratigraphic relationships of U1-7 identified in this study. Episodes of significant erosion and incision are represented by 6^{th} and 7^{th} order surfaces (shown in dark red); C. Comparison of the stratigraphic units identified in this study (left column) to equivalent units recorded by Meyer & Eyles (2007).

A

Stratigraphic unit	Facies	Architectural elements	Bounding surfaces	Interpretation
U7	Gm/d, Gh, Sm/d, Sc, Sh Sr	Mostly SL, one GL	Upper: ground surface Lower: concave-up, 6th-order	Incision and deposition by fluvial processes
U6	Df, Sm/d, Gm/d, Sc	DC, SC, SL, DZ and one GL	Upper: ground surface Lower: planar, 6th-order	A till complex formed through various subglacial processes
U5	Sr, Sm/d, Sc, Fl, Fm/d, F(dr)	One of each SC, FC and FL	Upper: planar, 6th-order Lower: irregular, 6th-order	Deposition in a glaciolacustrine/ deltaic environment
U4	Gm/d, Gh, Sh, Sm/d, Sc, Sr, Fm/d	Mostly GC and SC and one of each SL, GL and FL	Upper: planar, 6th-order Lower: concave-up, 6th-order	A glaciofluvial depositional environment
U3	Ds, Df, Gm/d, Sm/d, Sc, Fl, F(dr), Fm/d	DC, DL, DZ, FL, SL, GL	Upper and lower: irregular, 6th-order	A till complex formed through various subglacial processes
U2	Sc, Sr, Sm/d, Gm/d, Fm/d	Mostly SC, few GL and one FL	Upper and lower: irregular, 6th-order	Deposition within a sandy braided-river environment
U1	Dc	DC	Upper (6th-order) and lower (7th-order): irregular	Weathering of the bedrock surface, fluvial and colluvial processes

B



C

Stratigraphic unit	Units of Meyer & Eyles (2007)
U7	not recorded
U6	SU VI: Halton Till Complex (c.132000- 12000 ybp)
U5	
U4	SU V: Mackinaw Interstadial gravels (c.14000- 13500 ybp)
U3	SU IV: Northern/ Newmarket tills (Nissouri Stadial; c.25000- 18000 ybp)
U2	SU III: fluvial sands (Nissouri Stadial) (c.25000- 18000 ybp)
	SU II: (glacio-)lacustrine
U1	SU I: fluvial, mass flow, colluvial deposits

and unloading by glacial ice and weathering of clay particles by groundwater seepage, as well as localized transport by fluvial and colluvial processes. This unit is equivalent to SUI of Meyer & Eyles (2007).

3.6.2 Stratigraphic Unit 2 (U2): sand-dominated glaciofluvial

Stratigraphic unit 2 (U2) is dominated by sand facies (Figures 3.4, 3.5) and consists of SC elements with few GL and FL elements (Figures 3.6, 3.7). U2 is delineated in four boreholes (BHs 1-4; Figure 3.8) but is not found in the most northern borehole (BH5; Figure 3.8). U2 directly overlies U1, is between 3 and 18m thick, and is enclosed by 6th-order upper and lower bounding surfaces (Figure 3.7, 3.8). U2 is interpreted to record deposition within a sandy braided-river environment and is probably equivalent to SUIII identified by Meyer and Eyles (2007; Figure 3.9). U2 may be stratigraphically equivalent to the Thorncliffe Formation (formed ca. 25000 ybp) which is well exposed at the Scarborough Bluffs and identified below the Oak Ridges Moraine (Figure 3.1; Miall 1985; Eyles & Clark 1988; Russell et al. 2003; Meyer & Eyles 2007).

3.6.3 Stratigraphic Unit 3 (U3): lower till complex

Stratigraphic unit 3 (U3) directly overlies U2 and can be identified in BHs 1-4 but is not present in BH5 (Figure 3.8). U3 is composed of six different architectural elements: DC, DL, DZ, GL, SL and FL, although it is dominated by DC elements (Figures 3.6, 3.7, 3.8). U3 is between 11-18m thick and is demarcated by 6th-order lower and upper bounding surfaces which have an irregular geometry (Figure 3.8). The base of U3 consists of a laterally extensive DZ element that is thickest in BH4 and thinnest in BH 1

& 2 (Figures 3.6, 3.7). The DZ element is overlain by four alternating DC-f and DC-c elements, each separated by 5th-order bounding surfaces (Figure 3.7).

U3 is interpreted as a till sheet complex that records deposition by a variety of processes including subglacial deformation and lodgement, settling of fine-grained sediment from suspension under subglacial lacustrine conditions and deposition of bedload in subglacial fluvial environments (Boulton 1996; Boyce & Eyles 2000; Evans et al. 2006; Meriano & Eyles 2009). U3 may be equivalent to the Northern/Newmarket till formed 25000- 18000 ybp (Gerber & Howard 1996; Boyce & Eyles 2000; Barnett 1992; Figure 3.9) and corresponds to SU IV identified by Meyer & Eyles (2007; Figure 3.9). The irregular upper surface of U3 may represent a buried drumlinized surface comparable to that identified on the surface of the buried surface of the Northern Till by Boyce & Eyles (2000).

3.6.4 Stratigraphic Unit 4 (U4): gravel-dominated glaciofluvial

Stratigraphic unit 4 (U4) is a gravel-dominated glaciofluvial unit composed primarily of gravel (GC) facies with sand (SC, SL) and a minor amount of fine-grained facies (FL; Figures 3.4, 3.5, 3.6, 3.7). U4 is 10-12m thick and is delineated by 6th-order upper and lower bounding surfaces in two boreholes in the north (BH4 & 5) but is not found in BH1-3 in the south (Figure 3.8). This element has a concave-up lower bounding surface that truncates U3 in BH4 & 5 and has a planar upper bounding surface (Figures 3.7, 3.8).

U4 is interpreted to record deposition in a gravel-dominated glaciofluvial depositional environment and is most likely equivalent to SU V of Meyer and Eyles (2007; Figure 3.9). This unit probably represents Mackinaw interstadial outwash sediments formed around 13000 ybp (Barnett 1992; Meyer & Eyles 2007).

3.6.5 Stratigraphic Unit 5 (U5): glaciolacustrine/deltaic

Unit 5 (U5) is present in four boreholes (BH1-4) and is composed of sand and fine-grained facies and FL, FC and SC elements separated by 5th-order bounding surfaces (Figures 3.4- 3.7). U5 is delineated by 6th-order upper and lower bounding surfaces and directly overlies both U3 and U4 (Figure 3.8). Lower bounding surfaces are irregular and upper bounding surfaces are relatively planar; this unit is completely absent in BH5 (Figures 3.7, 3.8). The SC element within U5 is laterally extensive and maintains a relatively consistent thickness in all four boreholes (BHs 1-4; Figure 3.8). In contrast, the FC and FL elements have highly variable thicknesses and are discontinuous within U5 (Figure 3.7).

U5 is interpreted to record deposition within a glaciolacustrine/deltaic environment and is probably equivalent to late Mackinaw interstadial sediments formed around 13000 ybp (lower sediments of SUVI of Meyer & Eyles 2007; Figure 3.9; Eyles & Clark 1988; Barnett 1992).

3.6.6 Stratigraphic Unit 6 (U6): upper till complex

U6 directly overlies U5 and is marked by a planar 6th-order lower bounding surface. The upper surface of this unit is the modern ground surface and is not designated with a hierarchical order. U6 consists of a variety of facies types, including diamict, gravel and sand facies and DC, DZ, SC, GL and SL architectural elements (Figures 3.4-3.8). U6 is identified in BHs 1-4 but is not present in BH5 (Figure 3.8). A thin, discontinuous DZ element is located at the base of U6 and is overlain by a 5th-order surface, which demarcates the base of an architecturally homogeneous DC-f element (Figure 3.8). The lower DC-f element has a planar 5th-order upper surface that is overlain by an SC element (and GL element in BH1) that maintains a constant thickness in BHs 1-4 (Figure 3.8). The SC element is overlain by a 5th-order bounding surface that delineates the base of a very thin, discontinuous DZ element and an upper DC-f element, which contains SL elements (Figure 3.8). U6 is interpreted to record a till complex formed through the processes of subglacial lodgement and deformation, and subglacial fluvial deposition (Boulton 1996; Evans et al. 2006). U6 is probably equivalent to the Halton Till Complex formed during the Port Huron Stadial (12000-13000 ybp; upper SU VI of Meyer and Eyles, 2007; Figure 3.9) which has been mapped throughout the western Ontario basin in southern Ontario (Barnett 1992; Meyer & Eyles 2007).

3.6.7 Stratigraphic Unit 7 (U7): glaciofluvial sand and gravel

Stratigraphic unit 7 (U7) is present in only one borehole (BH5) and consists of sand and gravel facies dominated by SL elements with one GL element (Figure 3.8). U7 is 14m thick (Figures 3.8, 3.9) and directly overlies U4 with a concave-upward 6th-order lower bounding surface that abruptly truncates U5 & 6 (Figure 7). U7 is interpreted to record incision and deposition by fluvial processes, possibly during the final stages of retreat of the Laurentide Ice Sheet from southern Ontario between 12900 and sometime after 12000 ybp (Barnett 1992).

3.7 Discussion

The detailed sedimentology and architecture of subsurface stratigraphic units are fundamental for paleoenvironmental reconstructions and for the accurate prediction and modeling of local and regional groundwater flow (Anderson 1989; Anderson et al. 1999; Klingbeil et al. 1999). Stratigraphic architecture enables the visualization of subsurface sediment unit geometries, and aquifer and aquitard heterogeneity. This is particularly important within till complexes which are commonly regarded as homogenous units that serve primarily as regional aquitards (Howard & Beck 1986; Gerber et al. 2001; Meriano & Eyles 2009).

Stratigraphic unit 2 (U2) identified in this study is regarded as the primary aquifer unit in the Sixteen Mile Creek area of Georgetown (Earthfx Incorporated 2010). U2 directly overlies the ‘head’ unit (U1) and consists of a thick succession of sand facies interbedded with gravel and fine-grained facies (Figures 3.7-3.9). Although U2 forms a prospective aquifer, it is truncated by the overlying till complex of U3 and is absent in some areas (Figures 3.8, 3.9). The discontinuous regional geometry of U2 (delineated in this study and also by Meyer & Eyles, 2007) may diminish its potential as a highly productive aquifer unit.

The coarse-grained sediments cored in BH5 (U4, U7; Figure 3.8) present a promising target for groundwater exploration in the study area. Both of these units are coarse-grained and may form productive aquifers. However, the upper sand-dominated unit (U7) is unconfined and incises into (and completely removes) the fine-grained aquitards U6 and U7 (Figure 3.8), which may compromise the integrity of the gravel-dominated unit below (U4; Figures 3.8, 3.9) and the quality of the water it contains.

The delineation and arrangement of architectural elements in this study also reveals the stratigraphic heterogeneity and geometry of diamict-rich units interpreted as the Northern/Newmarket and Halton till complexes (U3 & U6, respectively; Figure 3.7, 3.8). The lower till complex (U3) consists of alternating sheet-like, coarse- and fine-grained diamict complex elements (DC-c and DC-f; Figures 3.6, 3.7) which contain other architectural elements (DL, GL, SL and FL; Figures 3.6, 3.7). The DC-c elements are laterally extensive and may serve as conductive zones within the U3 till complex (Gerber & Howard 1996; Gerber et al. 2001; Meriano & Eyles 2009). Interbedded DL, GL, SL and FL elements are spatially discontinuous within the U3 till complex but interbedded coarse-grained elements (GL and SL) may be hydraulically connected and could serve as recharge zones to the sandy aquifer unit below (U2; Figures 3.7, 3.8; Meriano & Eyles 2009).

The upper till complex (U6) is composed of a DZ element at the base and a tripartite succession consisting of an SC element interbedded between two DC-f elements (Figure 3.8). The lower DC-f element is architecturally homogenous without any interbeds; however, the upper DC-f element contains several sand and gravel interbeds

(Figure 3.7). These sand elements may considerably increase the transmissivity of the U5 till complex and could serve as significant recharge zones to the underlying U5 glaciolacustrine/deltaic unit (Figure 3.8; Howard & Beck 1986; Gerber & Howard 1996; Gerber et al. 2001).

It is interesting to note that the dominant texture of the two till complexes (U3 & U6) appears to be related to the nature of the underlying sediment (Boulton 1996). The stacked SC elements within U2 are overlain by dominantly sand-rich diamict (Ds) facies which comprise DC-c elements of U3 above. Similarly, the fine-grained nature of U4 (fine-grained facies and SC, FL and FC elements) appears to influence the texture of the fine-grained diamict facies (Df) and DC-f elements of U6 above (Figure 3.8). The DZ element is located at the base of both till complexes but is best developed at the base of U3 and is thickest in places approaching topographically high points on the bedrock surface and in areas which overlie sandy sediments (Figures 3.7, 3.8). This suggests that areas of predominately sandy sediment directly below an overriding ice sheet are more susceptible to deformation. This may be caused by increased pore water pressures generated within sandy sediment beneath an ice sheet as the overriding ice approaches topographically high points on the bedrock surface, resulting in decreased shear strength and increased deformation (Evans et al. 2006). The DZ elements may represent Type A glacitectonite described by Benn & Evans (1996), which consists of glacially overridden and homogenized sediment displaying pervasive deformation and lacking recognizable pre-deformation sedimentary structures (Evans et al. 2006).

The two till complexes (U3 & U6) are separated from one another by a SC and FL element (comprising U5) in the southern part of the study area (BH1-3; Figures 3.7A, 3.8A). The fine-grained (FL) element in U5 is thickest in topographic lows on the upper surface of the lower till complex (U3) and may form an impermeable layer of variable thickness which bounds a laterally extensive, more permeable sandy element within U5 (SC; Figures 3.7, 3.8). In the north, U3 is truncated by gravel and sand elements of U4 (GC and SC; Figure 3.8). Similarly, U5 & U6 are incised by sand and gravel elements of U7 (SL and GL; Figures 3.7, 3.8). These two major incision events, marked by concave-upward 6^{th}-order surfaces, and subsequent deposition of relatively coarse-grained sediments may result in hydraulically connected beds that would have been isolated and confined prior to the incision events (e.g. DE-c and GL elements of U3 and GC elements of U4; Figures 3.8, 3.9). This would also promote local recharge through the till complexes and into the deeper subsurface aquifer units (Howard & Beck 1986; Gerber & Howard 1996; Gerber et al. 2001).

Overall, this study demonstrates that the identification of architectural elements within till sheets and coarse-grained units is an effective method for the description and delineation of subsurface heterogeneity and the internal geometry of major stratigraphic units. In particular, the architecture of two major till units identified in the Georgetown area, the Northern/Newmarket till complex (U3) and the Halton till complex (U6; Figures 3.7, 3.8), reveals complex 2-dimensional sedimentary variability and architectural heterogeneity.

3.8 Conclusions

Analysis of sediments recovered from five fully cored boreholes in the Sixteen Mile Creek area of southern Ontario (Figure 3.1) allowed the identification of twelve facies types separated by four orders of bounding surfaces (4^{th}- to 7^{th}- order). The vertical associations of facies types and the nature of intervening bounding surfaces are used here to delineate nine architectural elements (Figures 3.4-3.7). The assemblage of architectural elements and arrangement of bounding surfaces identified in the five boreholes also allowed the identification of seven stratigraphic units that can be correlated across the study area (Figure 3.8).

Detailed analysis of these architectural elements and stratigraphic units identifies the location and geometry of potential aquifers and has also revealed complex subsurface heterogeneities, particularly within till sheets that are commonly viewed as massive and homogenous stratigraphic units. These heterogeneities are likely to have significant impact on aquitard integrity and the distribution of groundwater recharge zones. The process of architectural element analysis used in this study can be applied more broadly to study the depositional history and subsurface sediment geometries in previously glaciated regions.

The identification of architectural elements may also allow better integration of sedimentological data with geophysical (surface or downhole), geochemical, and hydrogeological data. Geophysical data, derived from downhole geophysical probes measuring various parameters such as gamma, resistivity/conductivity and magnetic susceptibility, can be used to supplement subsurface information in areas without fully-cored boreholes (Boyce & Eyles 2000). The utilization of geophysical data can significantly enhance the cost-effectiveness of detailed subsurface stratigraphic and architectural investigations similar to this study (Slomka et al. 2011). Downhole geophysical data also provide additional information that cannot be readily obtained from the analysis of core samples. For example, continuously-logged downhole geophysical data may be useful in sections of boreholes with poor to no core recovery; this information is critical for sections where significant facies contacts and stratigraphic boundaries occur. Geophysical information may also be used to better define the position of 'fuzzy' contacts, such as that marked by the DZ element between U2 and U3 in this study, and for the identification of laterally significant interbeds (similar to the SC element in U6) that may not be immediately apparent in core samples (Slomka et al. 2011).

Architectural element analysis can also be used to better integrate sedimentological data with geochemical (e.g. titrium) and hydrogeological data. The ability to more effectively integrate these various data sources may enhance the accuracy of hydrostratigraphic and 3-dimensional subsurface models. Further work is needed to better understand the 3-dimensional geometry and subsurface heterogeneity of till complexes, which serve as regional aquitard units, and the hydrogeological significance of incised sediment-hosted valleys infilled with coarse-grained sediment. This study demonstrates that architectural element analysis can be very effectively applied to the detailed sedimentological analysis of core-based studies of Quaternary stratigraphies.

The approaches outlined here may be used to improve the accuracy of sedimentologic, hydrostratigraphic and 3-dimensional subsurface geologic models in other regions of southern Ontario and within other glaciated terrains across Canada and elsewhere.

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CHAPTER 4
CONCLUSIONS AND FUTURE WORK

Conclusions

This thesis reports the results of detailed sedimentological and architectural investigations of shallow subsurface sediments exposed in the Limehouse Pit, Ontario (Chapter 2) and of cores extracted from the deeper Quaternary stratigraphy underlying the Georgetown region of Ontario (Chapter 3). The approach used in this study utilizes sedimentological data to identify facies types, facies associations and the bounding surfaces that separate them in order to delineate architectural elements and their spatial form and distribution at each of the studied sites. This study is an analogue-based study, whereby the sedimentological (e.g. facies types and paleocurrent measurements) and architectural (bounding surface hierarchies and architectural elements) information collected from a shallow subsurface sedimentary succession in the Limehouse area is applied to sediments observed in core samples in the Georgetown area to better understand the architecture and sedimentary heterogeneity of deep subsurface sedimentary successions.

The study clearly demonstrates the value of applying AEA approaches to the investigation of both outcrop and core data in Quaternary sediment stratigraphies. The Quaternary stratigraphy of the Georgetown region is heterogeneous with a complex arrangement of coarse- and fine-grained units in both shallow and deep sediments

(Chapters 2, 3). AEA is a particularly useful tool in such areas as it allows the identification of the subsurface geometry and distribution of coarse-grained, permeable (aquifer/recharge zones) and fine-grained, impermeable (aquitard) units. It is essential to understand the complex spatial arrangements of these coarse- and fine-grained facies in complex stratigraphies in which permeable layers may be discontinuous and incised/truncated in places, possibly creating hydrologic connections between units and through till sheets to underlying aquifer units (Chapters 2, 3). Hence, AEA can be a very effective tool to determine the internal and external geometry of subsurface stratigraphic units when trying to understand groundwater flow behaviour, contaminant migration pathways and local and regional three-dimensional geologic models in glaciated terrains in southern Ontario and elsewhere.

In the Georgetown region, detailed analyses of shallow subsurface sediment architectures recorded from outcrop exposures (Chapter 2) can also be used as analogues to better understand the characteristics and geometry of the deeper subsurface stratigraphy observed in fully cored boreholes (Chapter 3). Similar facies types (e.g. Gm and Gm/d; Gt, Gp and Gh; St, Sp, Ss, Sr and Sc, Sh; Sr; Fl; and Fd and Fm/d, respectively), bounding surfaces (4^{th}- and 5^{th}- order) and architectural elements (GS and GC; SC; and FS and FC, respectively) identified from the Limehouse outcrop study were recognized in the deep subsurface stratigraphic analysis of the Georgetown cores (Figure 4.1). The sedimentological and architectural information collected from the shallow subsurface sediments exposed in outcrop in Limehouse and the deep subsurface sediments studied from core in the Georgetown area suggests that the sedimentary succession exposed in Limehouse is comparable to Stratigraphic Unit 7 (U7) delineated in the Georgetown area; however, exact stratigraphic equivalencies cannot be determined at this time. Although there are several similarities within the shallow and deep subsurface sedimentary successions, there were some significant and interesting differences between the facies types, bounding surfaces and architectural elements identified in the two studies (Figure 4.1).

First, there is a difference in the suite of sediment types recorded at each site (Figure 4.1). Fine-grained facies with dropstones (F(dr)) and three types of diamict facies (Dc, Ds, Df) identified in core samples from Georgetown are not observed in outcrop at Limehouse (Figure 4.1). Similarly, the diamict-dominated architectural elements (DE, DL and DZ) delineated from core in Georgetown are not identified in outcrop at the Limehouse Pit (Figure 4.1). These differences in facies types and architectural elements suggest that the sedimentary succession exposed in outcrop at Limehouse does not record the direct influence of sedimentation by glacial ice and was most likely deposited after deglaciation of the Limehouse area.

Figure 4.1: A summary of the facies types, bounding surface hierarchies and architectural elements identified in this thesis (from outcrop in Limehouse and fully-cored boreholes in Georgetown).

Facies	
Limehouse	Georgetown
gravel facies	
Gm	Gm/d
Gt	Gh
Gp	
sand facies	
St	Sc, Sh
Sp	
Ss	
Sr	Sr
fine-grained facies	
Fl	Fl
Fd	Fm/d
—	F(dr)
diamict facies	
—	Dc
—	Ds
—	Df

Bounding surface orders	
Limehouse	Georgetown
1	—
2	—
3	—
4	4
5	5
—	6
—	7

Architectural elements	
Limehouse	Georgetown
(gravel-dominated)	
GS	GC
GFB	GC, GL
CF	GC, GL, SL, FL
(sand-dominated)	
SC	SC
(fine-grained -dominated)	
FS	FC
(diamict -dominated)	
—	DE, DL, DZ

Secondly, bounding surfaces delineated from outcrop in the Limehouse Pit are of relatively small scale (1^{st} – to 5^{th}- order), whereas those surfaces identified from core in Georgetown are of 4^{th}- to 7^{th}- order (Figure 4.1) and represent more significant environmental changes. This difference in the types of bounding surface identified in each study may result from the fact that lower-order surfaces (1^{st}- to 3^{rd}- order) are difficult to delineate from core samples with confidence because of the lack of data on lateral facies variability and the poor preservation potential of these surfaces. Higher order surfaces can be identified with greater confidence from closely spaced core data that can be readily correlated between boreholes. Furthermore, the absence of higher order surfaces (6^{th}- to 7^{th}-order) delineated from outcrop in the Limehouse Pit suggests that the sedimentary succession exposed in outcrop comprises a single stratigraphic unit.

Future Work

The stratigraphic architectural analysis presented in this thesis can be refined and enhanced with additional data from fully-cored boreholes that penetrate to bedrock in the Limehouse and Georgetown area. This would allow better delineation of the regional stratigraphy. Integration of other data sources, such as downhole geophysics (a suite consisting of magnetic susceptibility, conductivity/resistivity, gamma and calliper probes) and ground penetrating radar (GPR), used to delineate heterogeneities in shallow coarse-grained deposits, may also provide more cost-effective substitutes for fully-cored boreholes in areas of little or no data. Integration of geophysical and sedimentological data would allow the construction of more detailed three-dimensional geological models in the Georgetown and Limehouse areas, and further integration with hydrological data (e.g. pump test data) may help improve the accuracy of hydrogeologic and groundwater flow models. It would be particularly beneficial to extend the use of architectural element analysis to the subsurface sediments in a larger region beyond the aggregate pit at Limehouse and the Sixteen Mile Creek area of Georgetown area to better understand the regional subsurface stratigraphy. The methodology used and results obtained in this thesis can be applied to similar study areas in southern Ontario and elsewhere to enhance the understanding of subsurface glacial deposits and heterogeneity of aquifers/aquitards, enhance the accuracy of regional three-dimensional geologic and hydrogeologic models and improve the prediction of contaminant fate and transport pathways and design of source water protection programs.