ANALYSIS OF SUBGLACIAL DEPOSITS AND LANDFORMS IN SOUTHERN ONTARIO USING SEDIMENTOLOGY AND GEOMATICS

ANALYSIS OF SUBGLACIAL DEPOSITS AND LANDFORMS IN SOUTHERN ONTARIO USING SEDIMENTOLOGY AND GEOMATICS

By

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ABSTRACT

This research utilizes sedimentology and geomatics to investigate relationships between sediment types, landforms and former glacial movement in southern Ontario, Canada. The research integrates qualitative field observations of sedimentary successions with quantitative assessment of landforms, specifically drumlins, using Geographic Information Systems (GIS). A detailed sedimentological analysis of late Quaternary sediments exposed in Vineland Quarry, Ontario identifies glaciolacustrine deposits which were subsequently overridden and deformed by glacial ice. The gradual transition from undisturbed, laminated sediment to increasingly deformed sediment and structureless diamict exposed at Vineland is consistent with theoretical models of subglacial deformation and suggests that the succession records a single episode of ice advance across the Vineland region.

The second component of this research is presented within two research papers that explore a computational methodology within GIS which allows identification of drumlins and their morphological characteristics from existing topographic digital data. The two studies examine the form and spatial distribution of drumlins within the Arran, Galt and Guelph drumlin fields and from a portion of the Peterborough drumlin field. Drumlins and their morphological characteristics, such as elongation ratio and long axis orientation, are identified and documented using a computer-based process that allows direct comparison of forms within and between individual drumlin fields. The computer-based spatial analysis shows that drumlins are not randomly distributed across the regions, but show distinct patterns of clustering. Drumlins with particular morphological characteristics also show a clustered distribution that may be related to spatial changes in sediment thickness, duration of ice cover, and the direction of ice movement. The ability to consistently identify and characterize drumlin morphology and distribution allows objective and systematic comparison of these landforms both within and between drumlin fields and will enhance understanding of the spatial controls on the development of these enigmatic landforms.

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CHAPTER 1
INTRODUCTION

The history of ice advance and retreat during the Quaternary period has exerted widespread influence over the sedimentary deposits and geomorphology found across the province of Ontario (Chapman and Putman 1984, Barnett 1992). The Laurentide Ice Sheet (LIS) covered much of Canada and extended across Ontario into the northern regions of the United States 20,000 years ago (Karrow 1984, Fulton et al. 1986, Barnett 1992, Karrow et al. 2007). As the ice sheet retreated, large lakes and fluvial systems developed in marginal positions and allowed the deposition of intercalated glacial, lacustrine and fluvial sediments across southern Ontario (Barnett 1992, Hicock and Dreimanis 1992). Interpreting the environmental and depositional history preserved within these late Quaternary sediments and landforms is complex and is often hindered by limited amounts of data and inappropriate analytical tools. As a consequence, there is still an incomplete understanding of the late Quaternary glacial history of southern Ontario with contrasting interpretations resulting from examination of landform (e.g. Trenhaile 1975, Piotrowski 1987, Shaw and Sharpe 1987, Boyce and Eyles 1991) and sedimentological data (e.g. Eyles and Eyles 1983, Kelly and Martini 1986, Howard et al. 1995, Boyce and Eyles 2000, Russell et al. 2003).

The late Quaternary history of ice advance and retreat, lake formation and drainage in southern Ontario, has allowed a relatively thick succession of interbedded glacial, fluvial and lacustrine sediments to accumulate on the eroded Paleozoic bedrock surface and in topographic lows created by buried bedrock valleys (Meyer and Eyles 2007, Cummings et al. 2011, Gao 2011, Martini et al. 2011). These Quaternary sediments include a variety of stadial deposits, including diamicts equivalent to the predominantly sand-rich Northern (Newmarket) Till, and clay-rich Halton Till, fluvial sands and gravels deposited during the Mackinaw interstadial, and lacustrine/deltaic silts and sands formed as lakes were ponded in front of advancing and/or retreating ice margins (Dreimanis 1961, Eyles and Eyles 1983, Kelly and Martini 1986, Hicock and Dreimanis 1989, Barnett 1992, Boyce and Eyles 1991, 2000). The history of ice advance and retreat and associated environmental change has created a complex geomorphologic and sedimentological signature. This complex signature requires a range of tools and approaches to decipher, many of which still need to be developed, tested and refined (e.g. Napieralski et al., 2007).

Understanding the nature of subglacial processes is an important first step in the interpretation of the sedimentological and geomorphological record they produce. Early field research on subglacial processes and sediments was conducted in areas where modern glaciers were retreating over bedrock substrates. Lodgement processes dominated in these ‘stiff bed’ environments in which sediment carried in the basal debris zone of a glacier is smeared onto underlying bedrock to produce a structureless and dense lodgement till (e.g. Boulton 1986, Evans et al. 2006). As understanding of subglacial processes evolved it became apparent that glacial beds are not always formed by passive, rigid substrates (Boulton and Jones 1979, Boulton 1986) but can form part of a complex system where unlithified subglacial sediment is mobilized as a 'deforming bed' by stresses imparted by the overriding ice (Figure 1.1; Boulton 1996). The mobilization of unlithified sediment beneath the glacier also contributes to glacier movement (Boulton 1986, Boulton 1996, Evans et al. 2006). Given that southern Ontario has been repeatedly overridden by extensive ice sheets, understanding these processes and their geomorphological and sedimentological products is an essential tool to be used in the reconstruction of late Quaternary depositional histories.

In order to enhance current understanding of the glacial history of southern Ontario, this thesis employs sedimentologic and geomatic techniques to explore the sedimentological and geomorphological record of subglacial processes and environments. The focus is on recognizing the processes responsible for deposition of subglacial sediments now exposed at surface as tills (Chapter 2), and the landforms (specifically drumlins) that ornament them (Chapters 3 and 4). The study areas within southern Ontario are depicted in Figure 1.2.

Figure 1.1: Various modes of movement at the glacier ice-bed interface (adapted from Boulton 1996).

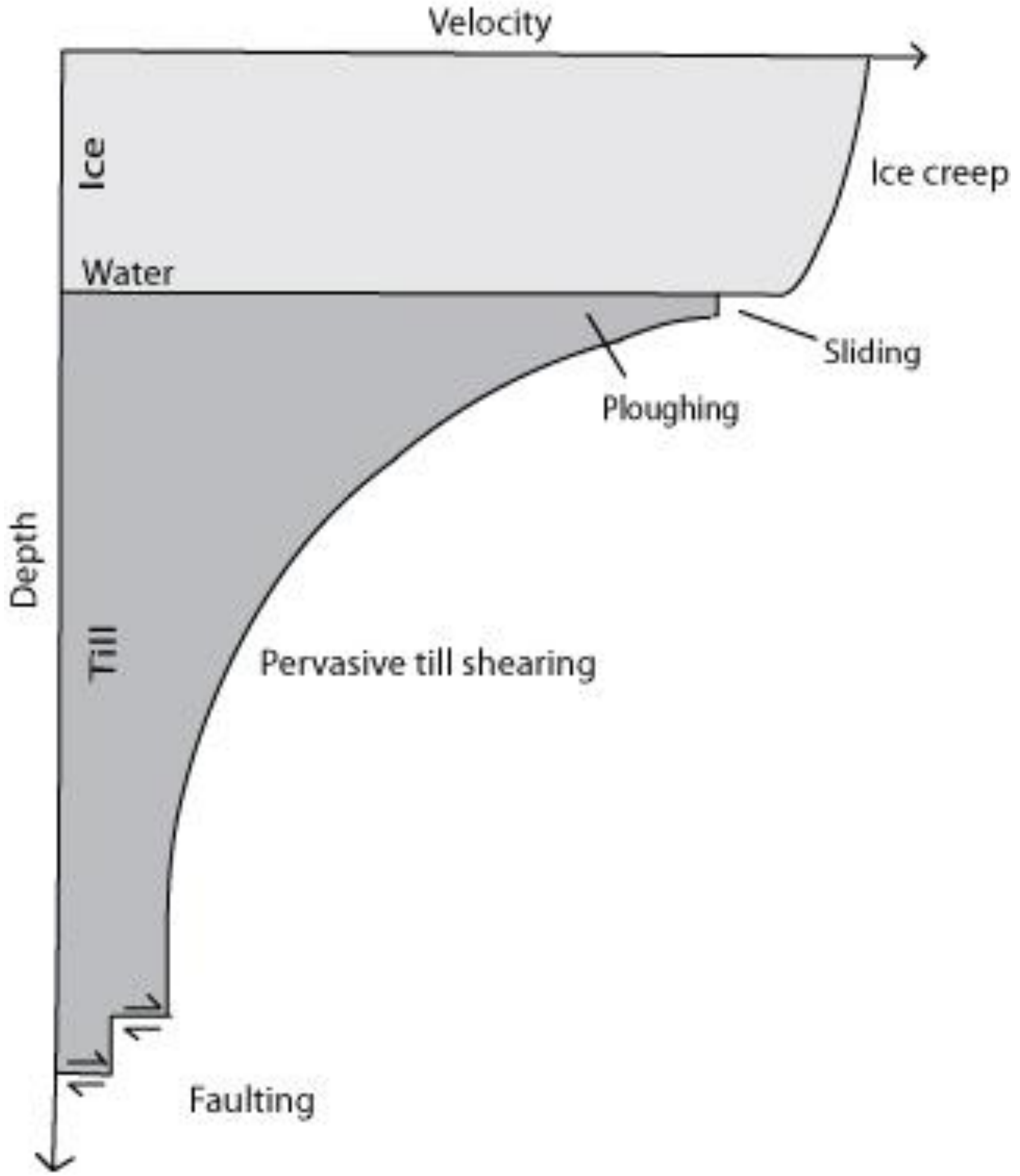
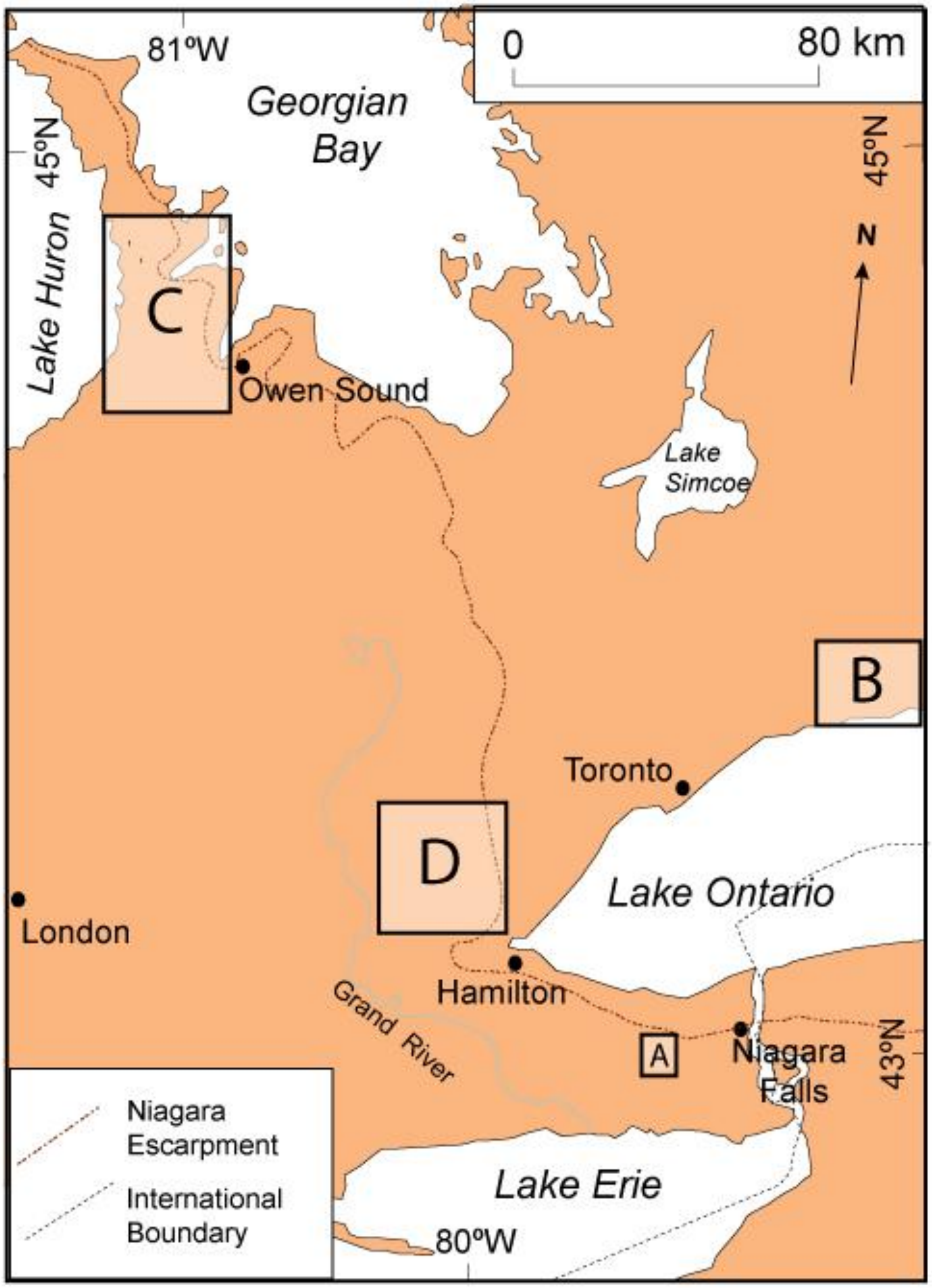

Velocity
Ice
Ice creep
Water
Sliding
Ploughing
Depth
Till
Pervasive till shearing
Faulting

Figure 1.2: Map of the study areas used in this research. (A) The location of the Vineland Quarry (Chapter 2) west of Niagara Falls, Ontario just above the crest of the Niagara Escarpment. (B) The location of the study area within the Peterborough drumlin field (Chapter 3). (C,D) The location and extent of the Arran (C), Guelph and Galt drumlin fields (D).


0
80 km
81ºW
45ºN
45ºN
N
Georgian Bay
Lake Huron
C
Owen Sound
Lake Simcoe
B
Toronto
D
Lake Ontario
London
Hamilton
Grand River
A
Niagara Falls
43ºN
Niagara Escarpment
International Boundary
Lake Erie
80ºW

1.1 Subglacial Transport and Deposition

Subglacial transport and deposition is determined by the interaction of many factors including the balance between the driving force of the glacier and the frictional forces of the glacier bed (Boulton 1982), the permeability of the sediment (Engelhardt and Kamb 1998), the amount of water available due to basal melt, and the configuration of the glacier bed (Evans et al. 2006, Benn and Evans 2010). New research into subglacial processes was initiated when understanding of subglacial process evolved beyond the idea that glacial beds were a rigid substrate (Boulton and Jones 1979, Boulton 1986) to one in which subglacial sediments can deform in response to stress imparted by overriding ice (Figure 1.1; Boulton, 1996; Evans et al. 2006). This paradigm shift in glaciology (Boulton 1986, Murray 1997) stimulated research into the variability of deforming bed conditions and the nature of resulting sediment packages (e.g. Evans et al. 2006). The connection between glacial motion and deformation of underlying sediments was identified, as well as the importance of glacial decoupling from the bed due to increased basal water pressure which limits the stresses transferred to the underlying till (Fischer and Clarke 1997). Sediment type appears to play a role in the decoupling of ice as clay-rich substrates significantly inhibit drainage allowing high pore water pressures to develop (Englehardt and Kamb 1998).

Recognition of the subglacial processes of deformation, sliding, melt-out, and lodgement initially resulted in the process-specific identification of subglacial sediment types (e.g. deformation till, lodgement till). However, subsequent research has shown that in many cases the process signature responsible for deposition of a particular sediment type cannot be accurately identified (Evans et al. 2006). This is due in large part to the fact that these various subglacial processes are spatially and temporally transitional and that any one subglacial deposit may be the product of several processes (Piotrowski and Kraus 1997). A new non-process specific classification of subglacial deposits has been proposed by Evans et al. (2006) and is used within this study. The term 'glacitectonite' is used to describe sediment that has undergone deformation by subglacial processes but retains a portion of the original structural characteristics of the parent material (Evans et al. 2006). The term 'subglacial traction till' describes sediment that has been largely homogenized by the overriding glacier (Evans et al 2006).

Despite the continuum of processes that may have been responsible for the accumulation of subglacial sediment at any particular site, the characteristics of the sediment should provide information about the specific conditions under which it formed. In attempt to identify the particular factors influencing subglacial sediment deposition in a part of southern Ontario, a recently exposed sediment package in Vineland Quarry, Ontario was analysed as part of this study (Chapter 2). The exposed sediment consists of a succession of glacially overridden lacustrine sediments on top of dolostone bedrock. Analysis of this particular sedimentary succession addresses questions of subglacial sediment mobilization and deformation as part of a ‘deforming bed’ (Evans et al. 2006), as well as issues related to the terminology and classification systems applied to subglacial sediments. The Vineland Quarry exposure is interpreted here to record a complete succession of subglacially deformed sediments passing from bedrock through glacitectonites to a subglacial traction till in a sequence similar to that proposed by Evans et al. (2006).

1.2 The Formation of Drumlins

Drumlins form an important component of the glacial landscape of southern Ontario (Chapman and Putnam 1984) and extensive drumlin fields can be found scattered across till surfaces throughout southern Ontario (Harry and Trenhaile 1987, Piotrowski 1987, Barnett 1992, Clark et al. 2009). Understanding the characteristics and formation of these glacial landforms is therefore critical to the interpretation of past ice sheet conditions and landscape development (Smith et al. 2007, Clark et al. 2009, Greenwood and Clark 2010, Spagnolo et al. 2011).

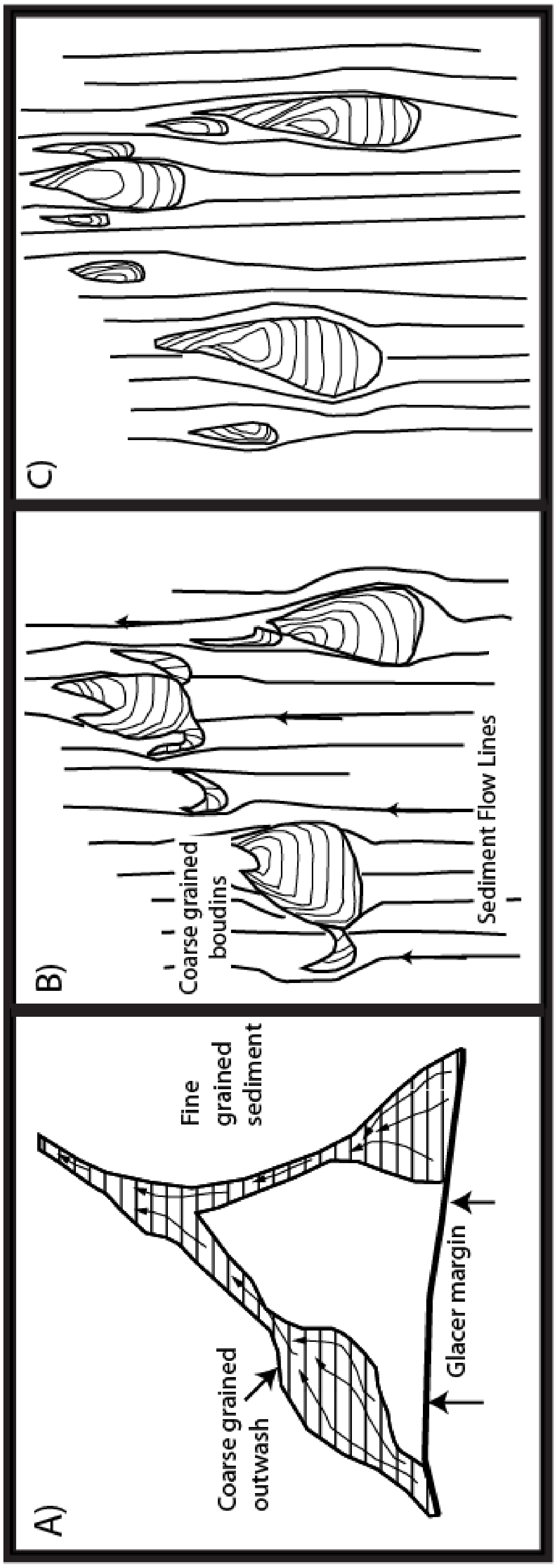
However, despite their importance, the formation of drumlins is still poorly understood (Knight, 2010) and has been linked to a number of processes including subglacial lodgement and deformation processes (Boulton and Hindmarsh 1987, Boyce and Eyles 1991, Benn and Evans 2006, Briner 2007), and catastrophic meltwater sheetfloods (Shaw 1983, Shaw and Sharpe 1987, Shaw 2010).

1.2.1 Drumlin formation by subglacial deformation

Drumlin formation has been related to deformation of water-saturated sediment beneath glacier ice (Boulton and Hindmarsh 1987, Boyce and Eyles 1991). In this model of drumlin formation, ice advancing over a relatively thick succession of heterogeneous sediment, will preferentially deform and remobilize water-saturated fine-grained sediments (silts and clays) to form a slurry at the ice base. Coarser-grained sediments overridden by the ice are better drained and less easily deformed and become streamlined, or 'boudinaged' into drumlinized forms (Figure 1.2; Boulton and Hindmarsh 1987). Drumlins formed in this way should therefore have a 'core' of relatively coarse-grained sediment, draped by a surface veneer of finer-grained deformation till (Boulton and Hindmarsh 1987, Boyce and Eyles 1991). Recently exposed drumlins in Iceland show these characteristics with an uppermost coarse-grained till layer recording ice advance over previously deposited sediments (Johnson et al. 2010).

The morphology of drumlins is also affected by their mode of formation and can be influenced by factors such as time under the ice, drift thickness, bedrock topography, and substrate type. Drumlins formed by subglacial deformation are expected to show a down-field change in shape and size as a result of changes in the duration of subglacial deformation (Boulton and Hindmarsh 1987, Boyce and Eyles 1991, Kerr and Eyles 2007). Drumlin morphology may also be affected by drift thickness and substrate type as a relatively thick cover of 'deformable' sediment over bedrock and relatively high pore water pressures are required for subglacial deformation processes to operate effectively. Drift thickness is strongly influenced by bedrock topography and the location of bedrock valleys (MacCormack et al. 2005, Meyer and Eyles 2007).

Figure 1.3: Conceptual model of drumlin formation based on subglacial deformation of material of different permeability and resistance. (A) Coarse grained outwash within fine grained deposits. (B, C) Progressive development of drumlins from coarse-grained sediment (adapted from Boulton and Hindmarsh 1987).

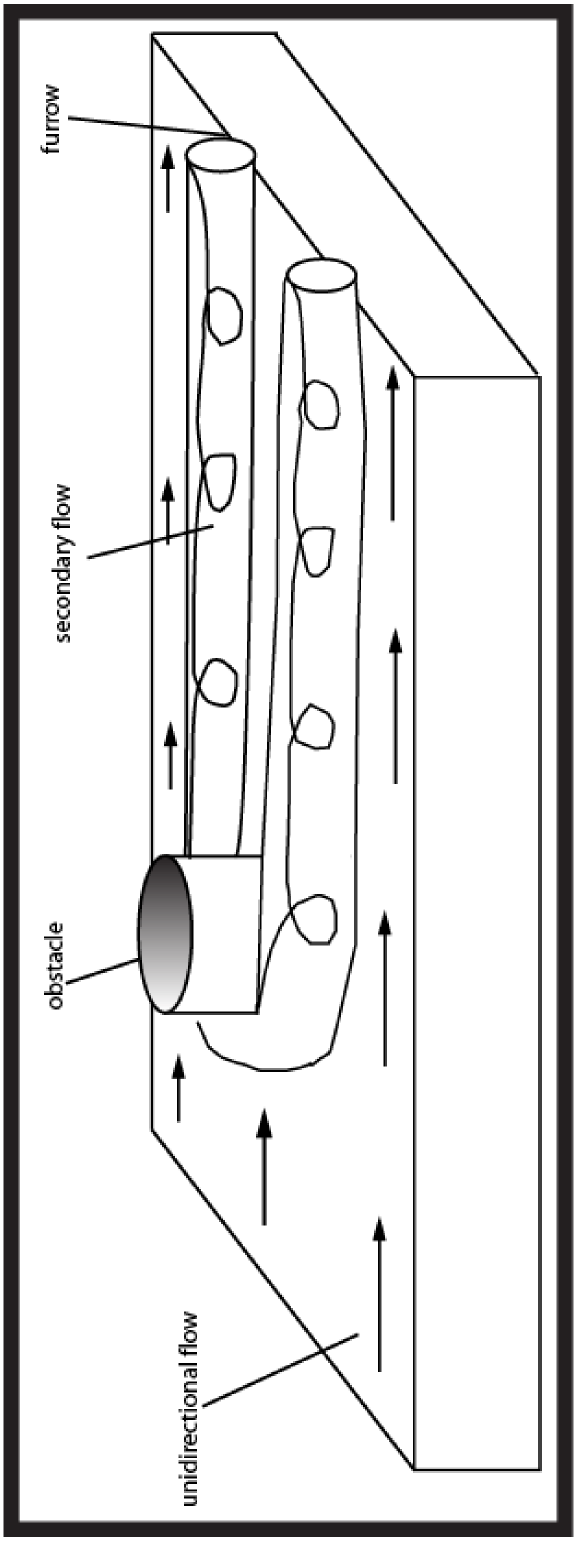

A)
Coarse grained outwash
Glacer margin
Fine grained sediment
B)
Coarse grained boudins
Sediment Flow Lines
C)

1.2.2 Drumlin formation by subglacial meltwater floods

An alternative model of drumlin genesis involves formation of widespread fields of erosional and depositional drumlins beneath laterally extensive sheetfloods of turbulent subglacial meltwater (Shaw 1983, Shaw and Sharpe 1987, Shaw 1989). As the main proponent of this model, Shaw (1983) first considered drumlins as depositional features, formed by the infilling of large subglacial cavities eroded into the base of the ice by catastrophic subglacial meltwater floods. A form analogy between drumlins and erosional marks associated with turbidites and karst solution features was used to develop this theory, despite several orders of magnitude difference in the scale of the features (Shaw 1983). Shaw and Sharpe (1987) later interpreted drumlins as erosional landforms created by subglacial meltwater floods, and again used a form analogy, this time with centimeter scale rattails observed on glacially eroded bedrock surfaces (Figure 1.3). In both of these models of drumlin formation, subglacial meltwater flows were required to be of great magnitude and velocity and were proposed to be catastrophic, instantaneously affecting many thousands of square kilometers of the ice base. (Shaw 1989).

Identifying the fundamental glacial processes responsible for drumlin formation in southern Ontario requires the analysis of drumlin form both within individual fields and between fields in the same geographic region. This thesis reports on the analysis of four drumlin fields in southern Ontario (the Arran, Galt, Guelph and Peterborough drumlin fields) using new Geographic Information Systems (GIS) based techniques that allow the

Figure 1.4: Conceptual model of erosional drumlin formation by subglacial meltwaters with unidirectional flow (adapted from Shaw and Sharpe 1987).


unidirectional flow
obstacle
secondary flow
furrow

statistical analysis of digital data (Chapters 3 and 4). Spatial analysis of the changing form and distribution of drumlins within drumlin fields will increase the amount of data available to determine and assess possible controls on drumlin development and will enhance understanding of the glacial history of southern Ontario.

1.3 Objectives of this Research

The overall objective of this research is to better understand subglacial processes and the depositional history of southern Ontario through analysis of subglacial sediments and landforms. Field documentation of subglacial sediment characteristics and analysis of glacial landforms using digital data within a Geographic Information System are integrated in this thesis to increase understanding of the relationships between glacial landforms (specifically drumlins), sediments, and former glacial processes. The methodology presented here to identify and analyse the morphological characteristics of drumlins represents an important development in the use of existing digital data in geomorphological studies. The creation and detailed documentation of an automated GIS based methodology allows for both verification of results by users and establishes a systematic template that may be used in other studies. This will ensure compatibility of results between drumlin fields and will improve understanding of the morphological spatial variability of these landforms across larger geographic areas. The results of this work will assist in the more accurate interpretation of glacial depositional histories in the region and in the reconstruction of former local and regional ice sheet dynamics.

Each of the individual chapters in this thesis contributes toward the overall research objectives. Chapter 2 presents a sedimentological analysis of laterally extensive sediment exposures overlying bedrock in Vineland Quarry, on the crest of the Niagara Escarpment, and identifies asuccession of late Quaternary subglacially deformed sediments. This well exposed sedimentary succession provides valuable field data on the characteristics of subglacial deposits that allow exploration and testing of various models of subglacial sediment deposition. A unique GIS based methodology for the identification and assessment of drumlins from digital elevation data is used to analyse the spatial distribution of drumlins within a portion of the Peterborough drumlin field (Chapter 3). The Peterborough drumlin field has been interpreted as the product of catastrophic meltwater floods (Shaw and Sharpe 1987) and of subglacial sediment deformation (Boyce and Eyles 1991). Geomatic techniques are also applied to analysis of the Arran, Galt and Guelph drumlin fields (Chapter 4) in order to determine potential controls on the spatial distribution and morphology of drumlins within each of these fields. Quantitative results stemming from this study allow comparison of drumlin morphological characteristics between different fields and will provide insight into how analysis of the spatial variability of drumlins within a drumlin field can be used to reconstruct former ice conditions. Analysis of the variability of drumlin forms and identification of potential controls on the spatial distribution of these forms will also enhance understanding of the glacial process responsible for drumlin creation (Knight 1997, 2010, Clark et al. 2009).

1.4 Thesis Structure

The objectives of this thesis are addressed within the second, third and fourth chapters. All chapters are formatted for publication in scientific journals and their contents are summarized below. The paper presented as Chapter 2 is published in Sedimentary Geology (Maclachlan and Eyles 2011). The work compiled as Chapter 3 was submitted to Geografiska Annaler: Series A, Physical Geography in February 2011. At the time of thesis submission Chapter 4 has not been submitted for publication. The content of each chapter is briefly summarized below.

Chapter 2 - Subglacial deforming bed conditions recorded by late Quaternary sediments exposed in Vineland Quarry, Ontario, Canada

This paper presents a detailed sedimentological description and analysis of a succession of late Quaternary deposits exposed within the Vineland Quarry, in Vineland, Ontario, Canada. The field site lies close to the crest of the Niagara Escarpment within the Lake Ontario Basin and is interpreted to record subglacial overriding and deformation of previously deposited lacustrine sediments. The predominately fine-grained sediments record deposition under glaciolacustrine conditions followed by deformation by overriding glacial ice. The pattern of sediment deposition and deformation observed at the field site is consistent with an origin as 'glacitectonite' and ‘subglacial traction till', deposits that form as a result of downward penetrating stresses imparted by an overriding ice sheet.

Chapter 3 - Quantitative geomorphological analysis of drumlins in the Peterborough Drumlin Field, Ontario, Canada

This paper presents a computational methodology, using Geographic Information Systems, to identify drumlins from readily available digital evaluation models in order to more thoroughly understand the dynamic relationships between their geomorphic spatial variability and the subglacial process responsible for their formation. The study area is a portion of the Peterborough drumlin field. Drumlins are analyzed using both spatial and non-spatial techniques in an effort to enhance understanding of the factors that influence the form and distribution of these subglacial landforms.

Chapter 4 - Spatial analysis of drumlins within the Arran, Guelph, and Galt drumlin fields of southern Ontario

The objective of this paper is to evaluate the shape and distribution of drumlins within the Arran, Galt, and Guelph drumlin fields using readily available Digital Elevation Model data within a Geographic Information System. The digital quantitative assessment of drumlins within the three study areas is used to explore the spatial relationships between drumlins and various factors that could affect their development. Field observations from a partially excavated drumlin within the Guelph drumlin field illustrate a stratigraphy similar to drumlins recently exposed in Iceland (Johnson et al. 2010). Comparison of data from each of the three fields provides valuable information pertaining to the spatial distribution of controls on drumlin formation.

Chapter 5 - Conclusions and Recommendations for Future Work

This chapter summarizes the discussion and conclusions reached within this thesis and discusses potential directions for future research.

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CHAPTER 2

SUBGLACIAL DEFORMING BED CONDITIONS RECORDED BY LATE QUATERNARY SEDIMENTS EXPOSED IN VINELAND QUARRY, ONTARIO, CANADA

Abstract

There has been considerable interest in recent years in the development of theoretical models of subglacial transport and deposition of sediment, but relatively few studies report field documentation of the resultant sediment stratigraphies. This paper presents detailed sedimentological description and analysis of a succession of late Quaternary deposits interpreted to record subglacial overriding and deformation of previously deposited lacustrine sediments exposed in the Vineland Quarry that sits close to the crest of the Niagara Escarpment within the Lake Ontario basin. The predominately fine-grained sediments record deposition under glaciolacustrine conditions followed by deformation and deposition by overriding glacial ice. Laminated silt and clay deposits overlie the striated bedrock surface and were deposited within a lake that formed as the Ontario Lobe of the Laurentide Ice Sheet advanced during the Port Huron stadial and ponded water against the Niagara Escarpment. The laminated silt and clay facies show increasing amounts of deformation up-section, passing from planar through ductile to brittle deformation. This succession of deformed facies is overlain by a macroscopically massive clay-rich diamict that caps the section. This pattern of sediment deposition and

deformation is consistent with that proposed by current models of subglacial sediment deformation with the disrupted laminated silts and clays representing ‘glacitectonites’ resulting from downward penetrating stresses imparted by an overriding ice sheet. The uppermost massive diamict unit represents full macroscopic homogenization of the overridden sediment and is classified as a subglacial ‘traction till’. The gradual transition from undisturbed laminated deposits through increasingly deformed sediment to structureless, diamict suggests that these deposits record a single episode of ice advance across the region. This ice advance was probably the short-lived advance of the Ontario Lobe of the Laurentide Ice Sheet that occurred at approximately 13,000 ybp.

2.1 Introduction

In recent years the process of subglacial sediment deformation has been recognized as an important mechanism of sediment transport and deposition in glaciated regions underlain by relatively thick sedimentary successions (Boulton 1996, Phillips et al. 2008, Lesemann et al. 2010). Subglacial sediment deformation processes involve the entrainment, transport and deposition of substrate materials by overriding glacier ice when shear stresses induced by the overriding ice exceed the shear strength of the substrate materials. Mobilized substrate sediments undergo attenuation by shear stresses and form a deforming subglacial bed that enhances lateral ice motion and increases net ice velocity (Boulton and Caban 1995, Benn and Evans 1996, Hindmarsh and Stokes 2008). The shear strength of the substrate is controlled to a large extent by grain size and water content of the sediment (Schoof and Clarke 2008, Boulton 2010) and deformation commonly takes place when sediments are fine-grained with high pore water content (Hart and Roberts 1994, Benn 1995). Incorporation of pre-existing sediment into the deforming subglacial bed, together with the addition of sediment melted out from the ice base, replenishes the deforming bed and ultimately allows accumulation and deposition of thick packages of poorly sorted subglacial till (Waller et al. 2008, McKay et al. 2009).

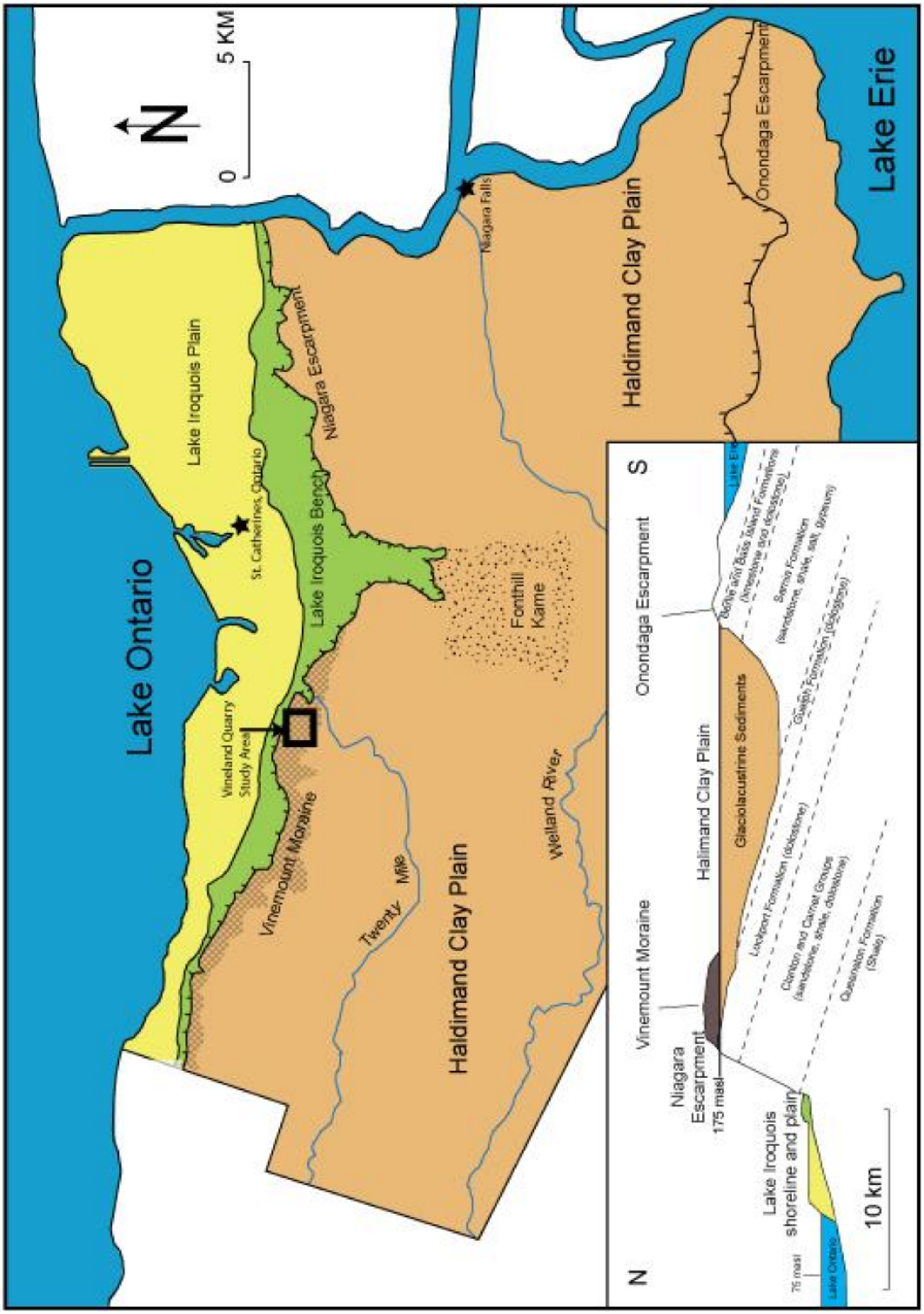
Given the practical difficulties of documenting these processes and their depositional products in modern subglacial environments, much research has focussed on establishing the theoretical relationship between subglacial deformation processes and resulting sediments (‘the deforming bed model’; Boulton and Jones1979, Boulton 1986, Boulton and Hindmarsh 1987, Alley 1989, Boulton and Dobbie 1993, Boulton 1996, van der Meer et al. 2003, Evans et al. 2006, Boulton 2010). This model of ice movement and sediment deposition differs substantially from that proposed for glaciers moving across rigid substrates where frictional retardation of sediment contained within the ice base allows deposition of relatively thin sheets of subglacial sediment by lodgement processes (Iverson 1999, Stokes and Clark 2003, Larsen et al. 2006). The deforming bed model has particular significance for the interpretation of glacial stratigraphies in continental areas where glacial ice advanced over relatively thick successions of pre-existing sediment, such as regions fringing the margins of the southern Great Lakes basins in North America.

This paper presents the detailed sedimentological description and analysis of a series of late Quaternary deposits in southern Ontario that are interpreted to record subglacial overriding and deformation of previously deposited lacustrine sediments within the Lake Ontario basin. These sedimentological data will add to the limited information available from field observations of modern subglacial deformation processes and recent sediments such as those reported from Iceland and Antarctica (Alley et al. 1986, Benn 1995, Hart and Rose 2001, Roberts and Hart 2005) and may be used to validate theoretical models of subglacial deformation discussed within the literature (Alley 1989, Menzies 1989, Boulton 1996, Evans et al. 2006).

2.2 Geological background and study area

A series of exposures through late Quaternary sediments have been created by bedrock quarrying operations at the Vineland Quarry, located approximately 10 km south of Lake Ontario on the Niagara Peninsula of southern Ontario (Figure 2.1). Quarrying operations are active and extract Paleozoic Lockport Dolostone, the caprock of the Niagara Escarpment. The quarry itself sits on the brow of the Niagara Escarpment overlooking Lake Ontario to the north (Figure 2.1).

Figure 2.1: Physiographic regions and schematic north-south cross section of the study area. Modified from Haynes, 2000; Shaw, 2005.


Lake Ontario
Lake Erie
N
0
5 KM
Lake Iroquois Plain
Lake Iroquois Bench
St. Catharines, Ontario
Vineland Quarry Study Area
Niagara Escarpment
Vinemount Moraine
Niagara Falls
Fonthill Kame
Twenty Mile
Welland River
Haldimand Clay Plain
Haldimand Clay Plain
Onondaga Escarpment
N
S
Lake Iroquois shoreline and plain
75 masl
Lake Ontario
Niagara Escarpment
175 masl
Vinemount Moraine
Halimand Clay Plain
Glaciolacustrine Sediments
Onondaga Escarpment
Lake Erie
Bertie and Bass Island Formations (limestone and dolostone)
Salina Formation (sandstone, shale, salt, gypsum)
Guelph Formation (dolostone)
Lockport Formation (dolostone)
Clinton and Cataract Groups (sandstone, shale, dolostone)
Queenston Formation (Shale)
10 km

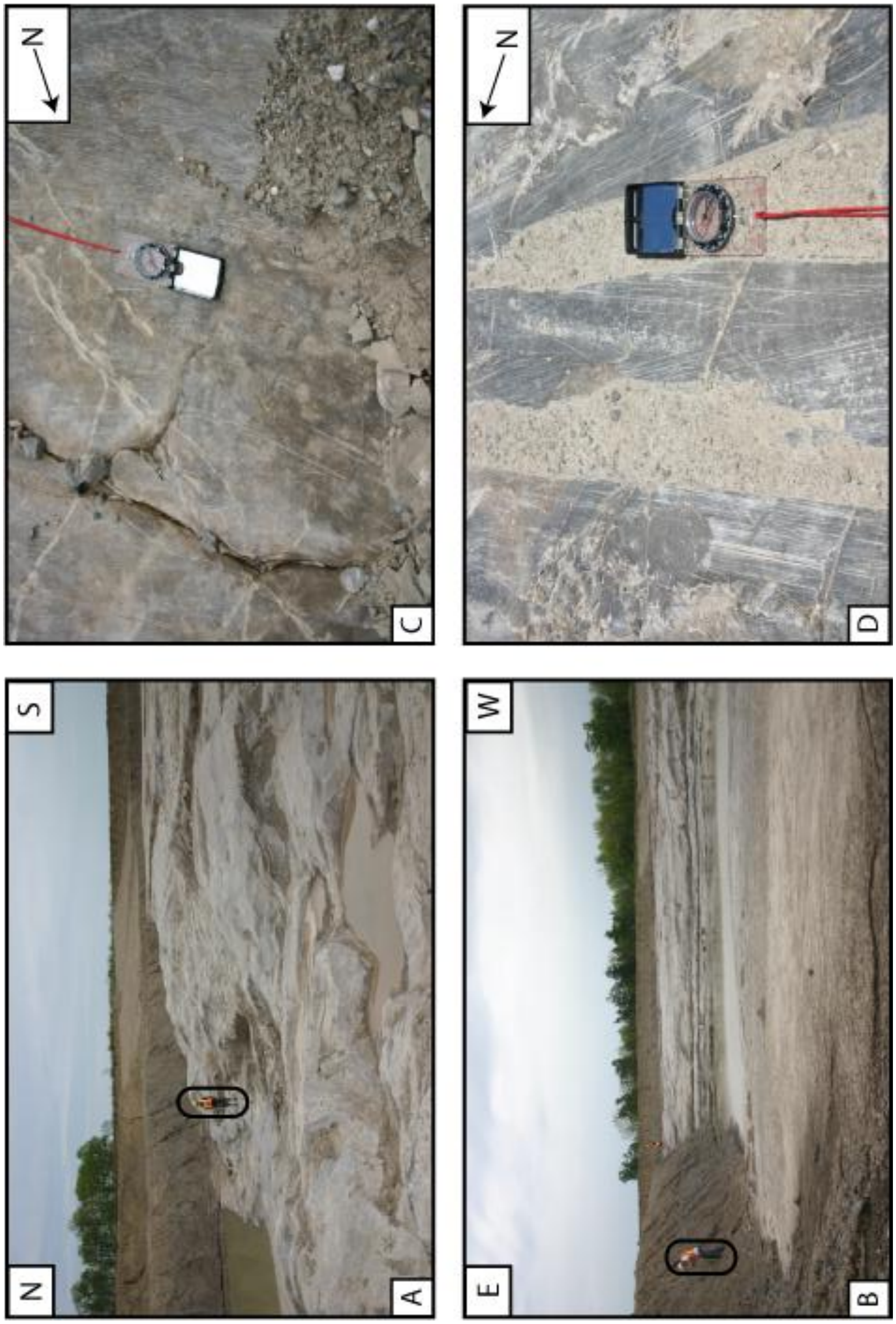
The late Quaternary depositional history of this area of southern Ontario records the complex interaction between glacial and lacustrine processes operating along the southern margin of the Lake Ontario basin as well as the influence of the topographic barrier created by the Niagara Escarpment (Figure 2.1). The southern margin of the Ontario basin was completely overridden by the Laurentide Ice Sheet (LIS) during the Nissouri Stadial (between 22 and 16 Ka; Dreimanis and Karrow 1972). Ice withdrew from the region during the Mackinaw Interstadial (Karrow 1984, Meyer and Eyles 2007) and the final re-advance of the Ontario Lobe of the LIS during the Port Huron Stadial (around 13 Ka) allowed the ice to breach the crest of the Niagara Escarpment (Tinkler and Stenson 1992). Advance of ice toward the northward-facing portion of the Niagara Escarpment from the north and east allowed the development of extensive proglacial lakes between the ice margin and the escarpment and encouraged rapid movement of the ice over freshly deposited fine-grained, water saturated glaciolacustrine sediments (Menzies 2001). The southernmost extent of the Port Huron ice advance at 13 Ka is recorded by the extensive low relief moraine ridge of the Vinemount Moraine that stretches from the Dundas Valley in the west towards Niagara Falls in the east (Figure 2.1; Barnett 1992). The Fonthill Kame, a large (approximately 6 km across and 77 m high) body of sand and gravel that stands above the surrounding Haldimand clay till plain, lies to the south of the moraine (Figure 2.1) and is interpreted to have formed as an ice-contact delta during this time (Feenstra 1981).

Quarrying operations in the Vineland Quarry involve the excavation and removal of Quaternary sediment from the Paleozoic bedrock surface. The quarry has been in operation since 1974 (Walker Industries 2010) and new exposures through the Quaternary sediments are generated on an ongoing basis. This paper describes sediment exposures created along the eastern and southern faces of the active quarry during the summers of 2007 and 2010 (Figure 2.1). The thickness of Quaternary sediment overlying bedrock is not uniform across the area of active quarrying and ranges between 3 and 8 m on top of the gently undulating and striated dolostone surface. The bedrock surface dips slightly from west to east with one distinct bedrock low in the westernmost part of the study area. Elongate sinuous ridges trending in an approximately northeast to southwest direction ornament the exposed bedrock surface close to the southern quarry face. These bedrock ridges have a relief of between 2 and 5 cm with crests spaced up to 20 cm apart (Figure 2.2). Striations on the bedrock surface are oriented approximately northeast-southwest and indicate ice flow to the southwest.

In the eastern section of the study area the bedrock surface is highly sculpted with topographic relief of up to 5 m (Figure 2.3A; Figure 2.3B). Many types of erosional bedform are displayed on this surface including s-forms and scallops, particularly on north-facing (up-ice) surfaces. South-facing (down-ice) bedrock forms are sharply truncated along joint surfaces and show similar characteristics to the ‘plucked’ ends of roches moutonnées (Sugdenet al. 1992). Comparable erosional features have been reported on Paleozoic bedrock exposures elsewhere (Kor et al. 1991, Tinkler 1993, Reaet al. 2000). Striations on the bedrock surface trend consistently northeast-southwest, although those identified on north-facing, highly sculpted areas, show much higher directional variability (Figure 2.3C; Figure 2.3D).

Figure 2.2: Bedrock surface exposed in the southern study area within Vineland Quarry. The camera lens cap is approximately 6 cm in diameter with the north facing sediment exposure in the upper section of the photograph.

Figure 2.3: North-south (A) and east-west (B) views of sculpted bedrock surfaces in the eastern study area within the Vineland Quarry. Striations within the sculpted forms showing directional variability (C, D). The overlying Quaternary sediment has been removed from this area to facilitate quarrying operations.


N
S
A
E
W
B
N
C
N
D

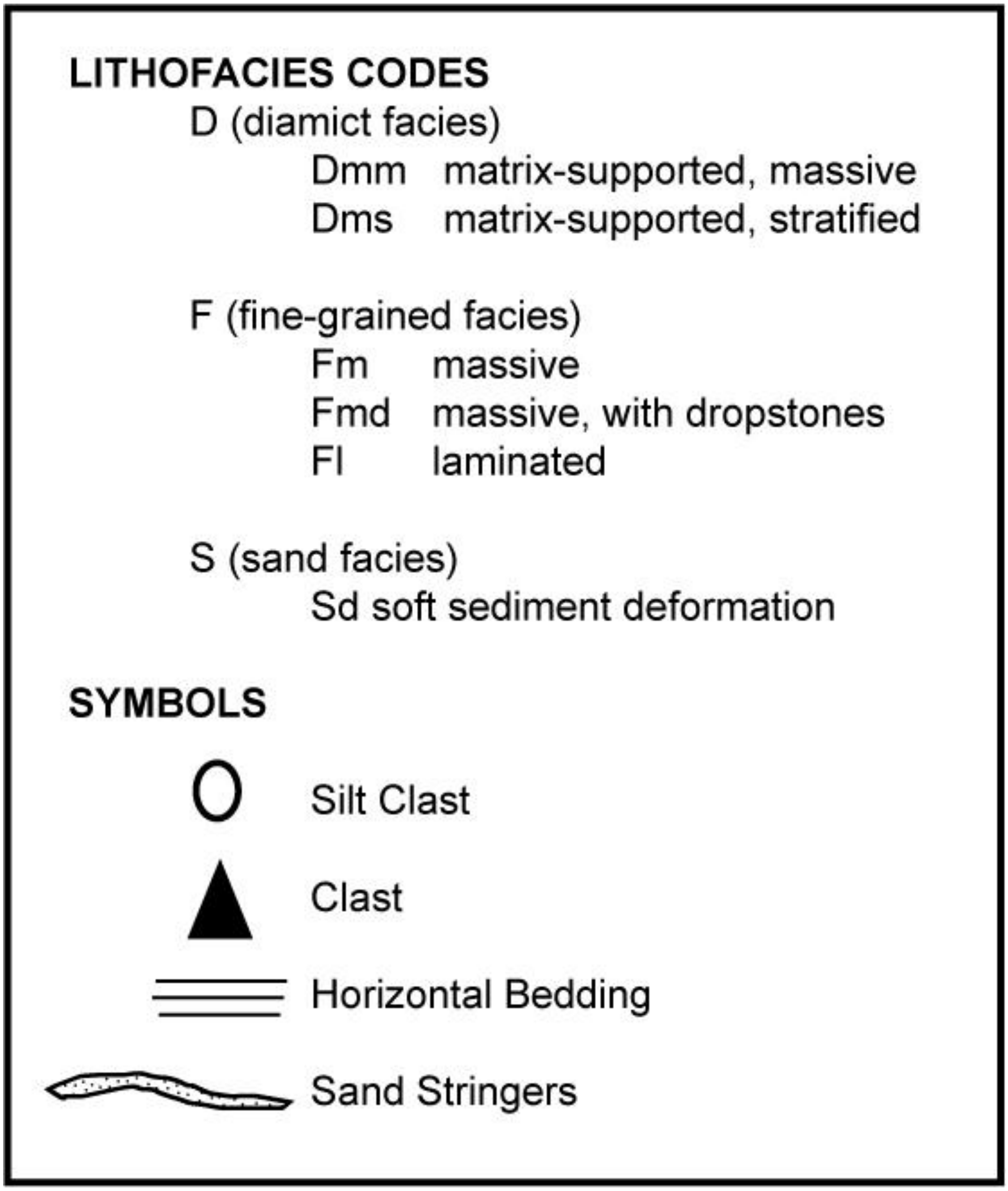
2.3 Sediment Description

A total of six vertical sections were logged through Quaternary sediments exposed along the eastern and southern faces of the Vineland Quarry (Figure 2.1). Details of sediment texture, sedimentary structures (including laminae thickness and deformation features), unit contacts and lateral and vertical changes in sediment type were recorded using standard sedimentological logging techniques and a standard lithofacies code (Figure 2.4; Eyles et al. 1983). Six distinct facies types were identified (crudely bedded clays, finely laminated clays, finely laminated clays with clasts, deformed laminated clays, structureless silty-clay diamict, and structureless silty-clay diamict with sand stringers: Figure 2.4, 2.5, 2.6) that were subsequently grouped into four stratigraphic units on the basis of stratigraphic position, similarity of sediment type and inferred depositional environment. The four stratigraphic units identified are numbered 1 through 4 (oldest to youngest: Figure 2.4, 2.5, 2.6). Sediment samples were also collected in the field for laboratory-based textural analysis using standard sieving techniques and a Beckman LS Coulter Counter.

2.3.1 Unit 1

Unit 1 is the lowermost sedimentary unit identified in the Vineland Quarry and infills lows on the undulating bedrock surface. It consists of fine-grained crudely bedded clays and silty clays that contain scattered lithic clasts and/or silt clasts. This unit directly

Figure 2.4: The lithofacies code used for all logs and sediment descriptions (modified from Eyles et al. 1983).



LITHOFACIES CODES

D (diamict facies)

Dmm	matrix-supported, massive
Dms	matrix-supported, stratified

F (fine-grained facies)

Fm	massive
Fmd	massive, with dropstones
Fl	laminated

S (sand facies)

Sd soft sediment deformation

SYMBOLS

○	Silt Clast
▲	Clast
≡	Horizontal Bedding
▨	Sand Stringers

Figure 2.5: Sediment logs through exposures along the southern face of the study area. All logs are positioned accurately with respect to their relative elevation. (A) Clay-rich crudely stratified clays of Unit 1 containing a subangular dolostone clast. (B) Contact between Units 3 and 4 marked by a thin clast horizon. (C) Oblique aerial photograph of the southern study area with location of sedimentary logs illustrated.

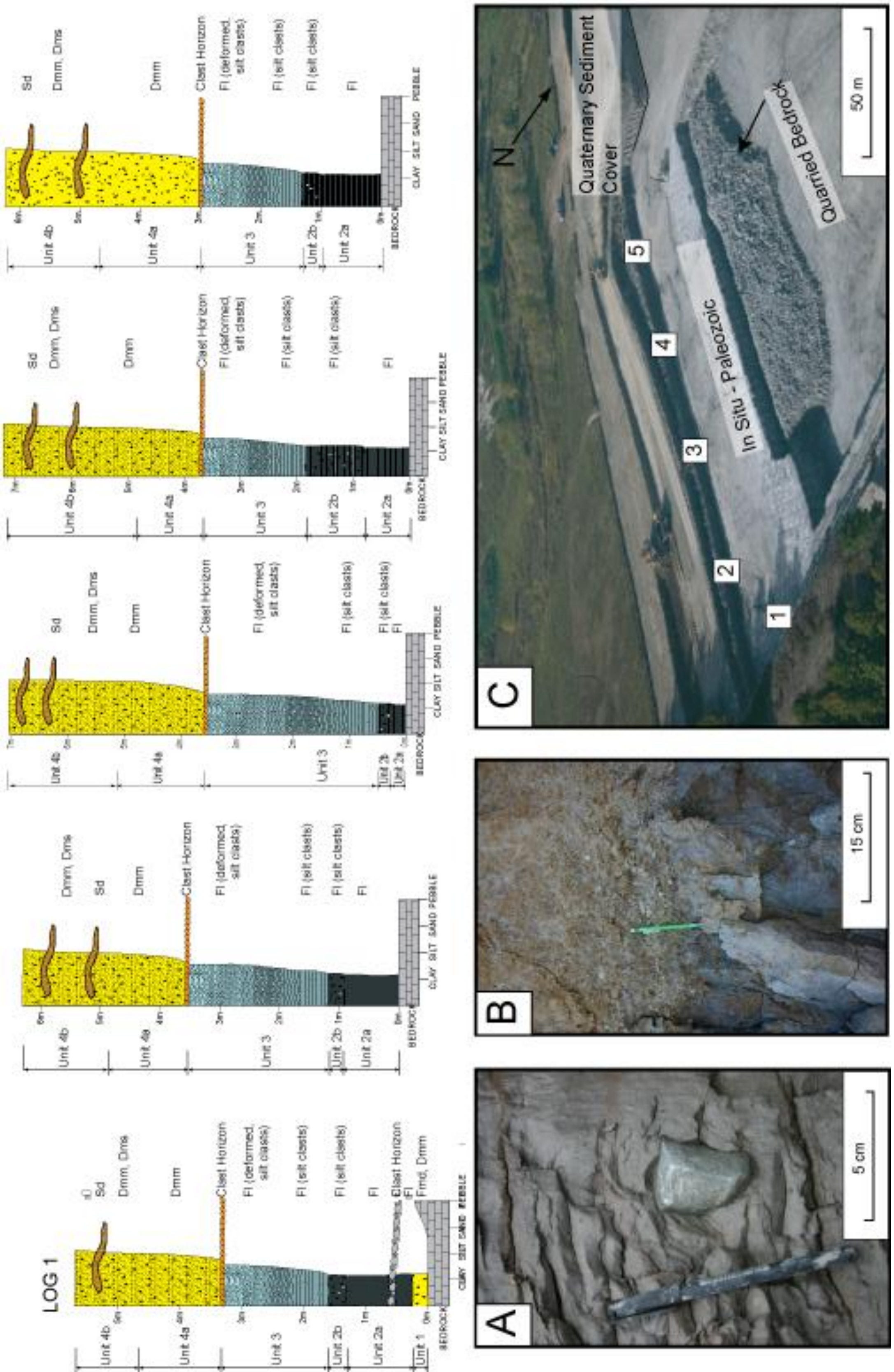
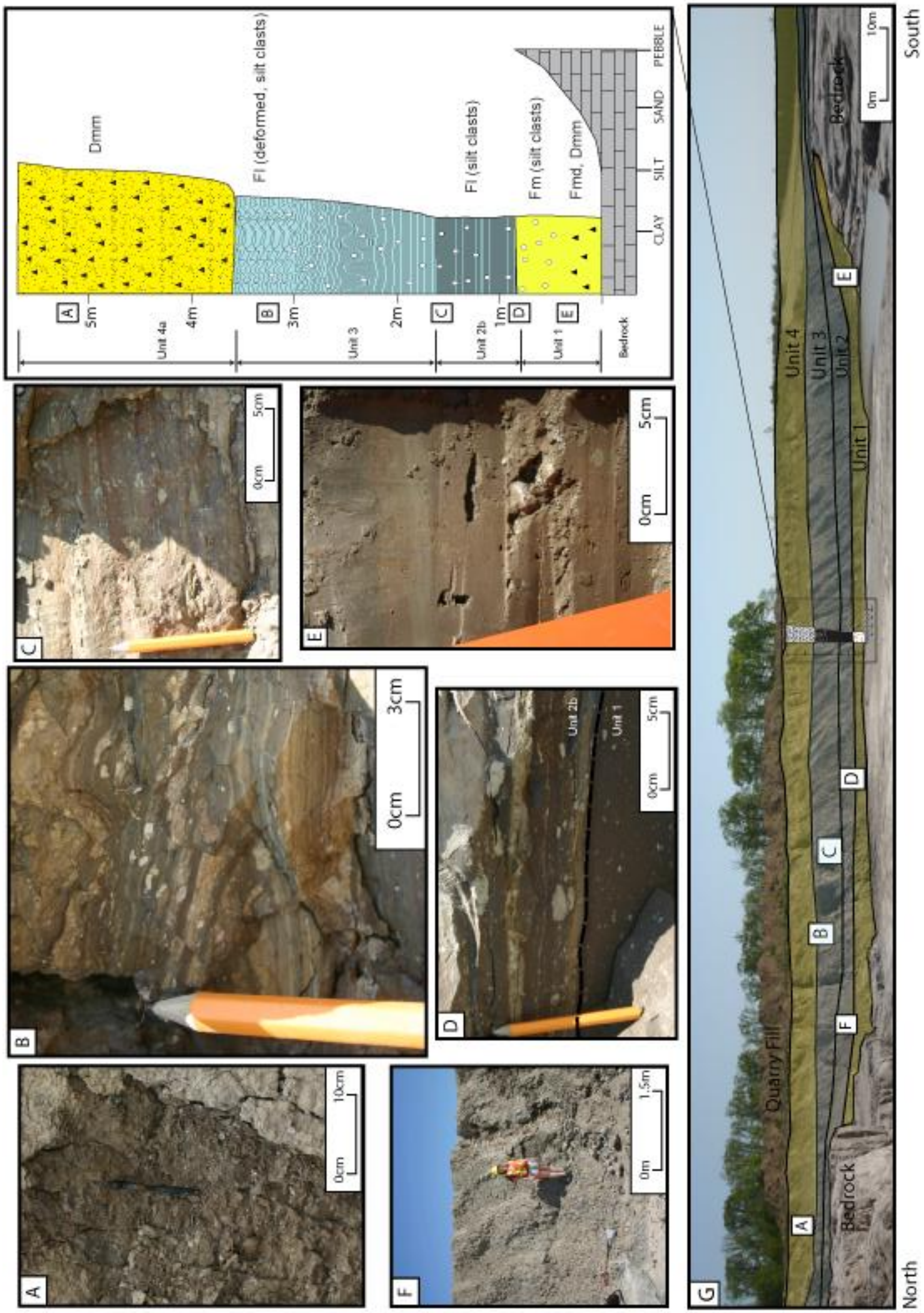

LOG 1
LOG 2
LOG 3
LOG 4
LOG 5
Unit 4b
Unit 4a
Unit 3
Unit 2b
Unit 2a
Unit 1
BEDROCK
CLAY SILT SAND PEBBLE
Sd
Dmm, Dms
Dmm
Clast Horizon
Fl (deformed, silt clasts)
Fl (silt clasts)
Fl
Fl
Fmd, Dmm
A
5 cm
B
15 cm
C
N
Quaternary Sediment Cover
Quarried Bedrock
In Situ - Paleozoic
1
2
3
4
5
50 m

Figure 2.6: Sedimentological log and photograph of the eastern study area within Vineland Quarry. The location of each photo (A through F) is illustrated on both the log and the outcrop photo. (A) Structureless diamict of Unit 4a. (B) Small scale faulting common within the laminated silts and clays in upper portions of Unit 3.(C) Minor deformation of silt and clay lamina at the contact between Units 2B and Unit 3. (D) Contact between Unit 1 (crudely stratified clay) and Unit 2b (laminated silts and clay). (E) Crudely stratified clay-rich Unit 1. (F) View of section face. (G) Photograph of eastern study area annotated with Unit boundaries and location photos A through F.


A
0cm
10cm
B
0cm
3cm
C
0cm
5cm
D
Unit 2b
Unit 1
0cm
5cm
E
0cm
5cm
F
0m
1.5m
Dmm
Fl (deformed, silt clasts)
Fl (silt clasts)
Fm (silt clasts)
Fmd, Dmm
CLAY
SILT
SAND
PEBBLE
A
5m
4m
B
3m
2m
C
1m
D
E
Unit 4a
Unit 3
Unit 2b
Unit 1
Bedrock
G
North
South
Quarry Fill
Unit 4
Unit 3
Unit 2
Unit 1
Bedrock
Bedrock
A
B
C
D
E
F
0m
10m

overlies the heavily striated bedrock and forms a laterally discontinuous unit between 20 and 60 cm in thickness (Figure 2.5A and 2.6E). The fine-grained sediment is compact to very compact within the bedrock lows and contains scattered subangular to subrounded clasts ranging in size from 0.5 to 5 cm composed predominately of limestone and dolostone. Lithic clasts have no preferred long axis orientation and constitute approximately 5% of the sediment volume. Small white silt clasts (1 to 10 mm diameter) are commonly observed in exposures along the southern section of the study area. Common small (1 to 10 mm diameter) subrounded to subangular silt clasts are found at the top of Unit 1 in the eastern section (Figure 2.6D).

2.3.2 Unit 2

Unit 2 consists of laminated clays and silty clays and can be divided into two subunits, each with slightly different characteristics (Figure 2.6C and 2.6D). ***Unit 2a*** is a 1 m thick unit of dark brown, finely laminated silty clay. This unit either overlies crudely bedded sediments of Unit 1 or rests directly on bedrock. Laminations are relatively planar with minor undulations and range in thickness between 1 mm and 2 cm. Contacts between silt and clay laminae are relatively sharp and no well graded beds were observed. There are no clasts present within this unit, with the exception of a single horizon of subrounded to subangular limestone clasts between 10 and 30 cm diameter (Figure 2.5, log 1). This clast horizon is only observed in a bedrock low found in the southern section of the study area where it extends horizontally for approximately 25 m and appears to be sourced from adjacent bedrock highs.

Unit 2b has a transitional lower contact with Unit 2a and forms a laterally extensive, slightly coarser grained unit of laminated silty clays that contain scattered lithic clasts and silt clasts. In the eastern portion of the study area Unit 2b sharply overlies Unit 1 (Figure 2.6D). Laminations are flat-lying to slightly undulating and range in thickness from several mm to 1 cm, becoming thicker up-section (Figure 2.6C). Rounded to subrounded silt clasts and dolostone clasts, ranging in size from mm to 1.5 cm, are incorporated within the laminations.

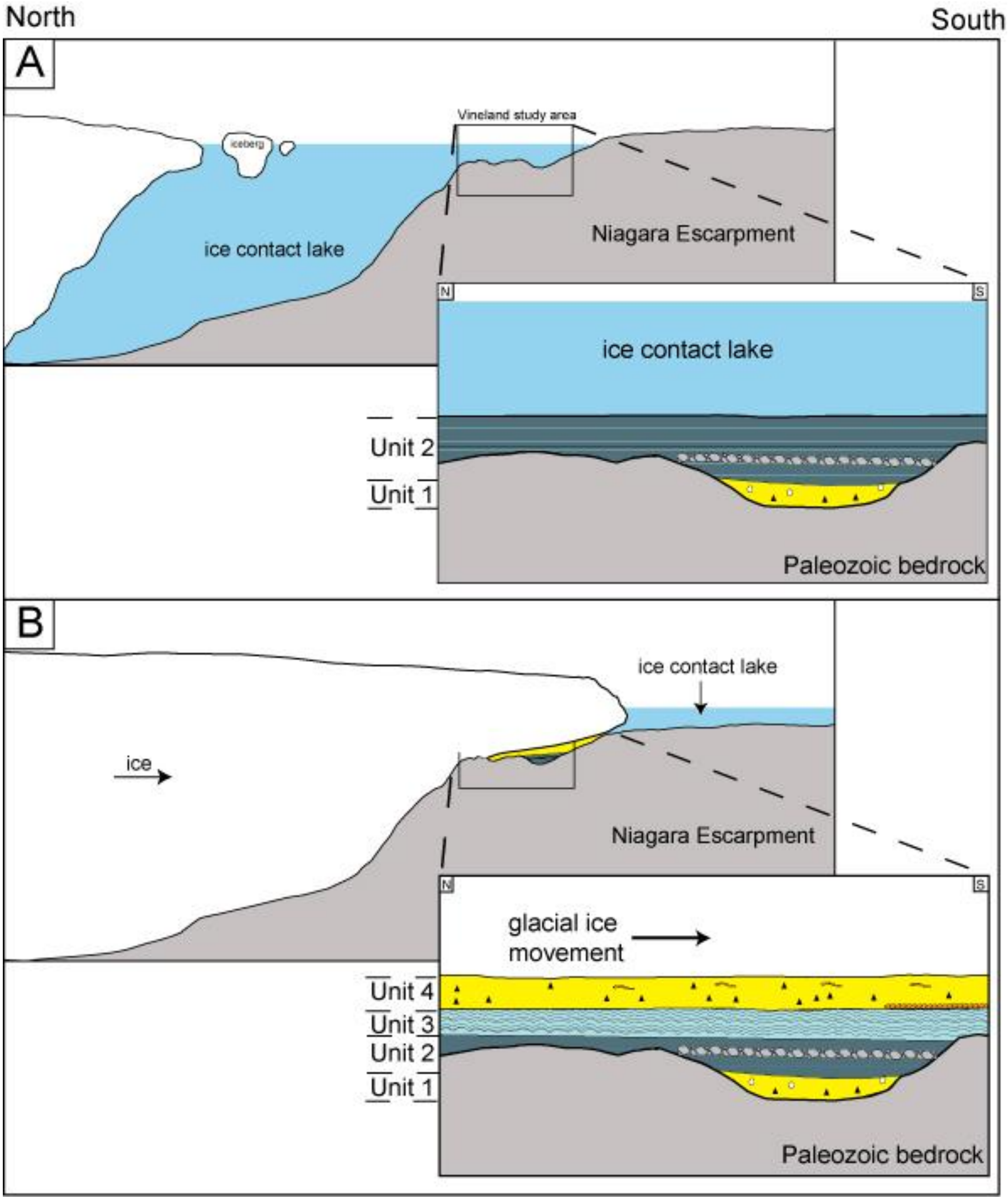
2.3.3 Unit 3

Unit 3 can be identified in all sections exposed in the quarry and consists of a 2 m thick unit of laminated clays and silts that show a progressive increase in deformation up-section. This unit has a transitional basal contact with Unit 2 and is slightly coarser grained, becoming increasingly silt-rich up-section (Table 2.1). Individual laminae are between 5 mm and 3 cm in thickness and pass from being essentially flat-lying and undeformed at the base to highly folded and faulted toward the top of the unit (Figure 2.6). The scale of deformation also increases up-section changing from mm scale undulations near the base of Unit 3 to larger folds and faults up to 5 cm in thickness close to the top (Figure 2.5,2.6,2.7). Evidence for both ductile (fold structures) and brittle (micro and macro faults) deformation is present within the uppermost deformed zone (Figure 2.6B). Rounded to subrounded silt clasts (mm to 3 cm size) are scattered throughout this unit but no lithic

Table 2.1: Results of grain size analysis using a Beckham LS coulter counter.

	Number of samples	Mean (µm)	Median (µm)	Variance (µm²)	Skewness (Right Skewed +)	Kurtosis
Unit 4	9	51	28	1700	1.7	2.8
Unit 3	12	6.1	4.1	34.1	1.3	0.8
Unit 2	8	4.1	3.1	12.4	1.8	1.1
Unit 1	5	3.7	2.4	11.7	1.4	1.2

Figure 2.7: A conceptual model describing the glacial history of the sediments exposed in the Vineland Quarry. (A) Sedimentation of Units 1 and 2 within an ice contact lake formed in front of an advancing ice sheet. (B) Advance of the partially buoyant ice sheet over pre-existing fine-grained lacustrine sediments resulting in subglacial deformation of Units 3 and 4A and deposition of Unit 4B.


North
South
A
Vineland study area
iceberg
ice contact lake
Niagara Escarpment
N
S
ice contact lake
Unit 2
Unit 1
Paleozoic bedrock
B
ice contact lake
ice
Niagara Escarpment
N
S
glacial ice movement
Unit 4
Unit 3
Unit 2
Unit 1
Paleozoic bedrock

2.3.4 Unit 4

Unit 4 is coarser grained and much more poorly sorted than underlying facies of Units 1, 2 and 3, forming an uppermost diamict unit that can be traced throughout the quarry. This diamict can be subdivided into two subunits. ***Unit 4a*** is a macroscopically structureless, matrix supported, silty clay diamict that rests sharply on underlying deformed silt and clay laminae of Unit 3 (Figure 2.6A). The diamict contains scattered dolostone clasts (up to 5 cm in diameter) of local derivation that show no preferred long axis orientation. A distinct horizon of clast-rich diamict, between 1 and 4 cm in thickness, lies at the contact with Unit 3 sediments below (Figure 2.5B). ***Unit 4b*** is differentiated from the underlying diamict of Unit 4a by the presence of clast lithologies characteristic of Canadian Shield sources, and discontinuous fine to medium-grained sand stringers and lenses up to 25 cm in width and 3 m long. The diamict matrix is extremely poorly sorted (Table 2.1) and clasts range in size from 5 mm to 30 cm.

2.3.5 Interpretation of stratigraphic units

The predominantly fine-grained sediments exposed at Vineland Quarry are interpreted to record proglacial lacustrine deposition distal to an ice margin (Units 1 and 2), followed by proglacial and subglacial deformation of those deposits (Unit 3), and subsequent subglacial deposition below over-riding ice (Unit 4). The extremely fine-grained sediments of Unit 1 are characteristic of quiet water lacustrine deposits and probably record flooding of the eroded bedrock surface during ice withdrawal at the end of the Nissouri Stadial, or the early stages of ice advance and lake level rise in the Ontario basin during the Port Huron Stadial (Figure 2.7A). Suspended sediment delivered to the basin as overflows and interflows generated from incoming meltstreams would settle to the lake floor to produce a fine-grained deposit (Ashley 1975). The predominantly structureless nature of Unit 1 sediments suggests that deposition may have been rapid, with high rates of delivery of fine-grained sediment to the basin (Fouch et al.1994, Mutti et al. 2003). Crude bedding, identified by slight textural changes in the deposit, may record variability in the caliber of sediment delivered to the site, but may also indicate transport of material by density underflows or sediment gravity flows into lows on the irregular bedrock surface (e.g. Eyles and Kocsis 1988). The presence of clasts within the lowermost sediments of Unit 1 suggests rafting of debris by glacial or seasonal ice, but could also record incorporation of lag material resting on the eroded bedrock surface into sediment gravity flows (Eyles 1987). Silt clasts in the upper part of Unit 1 indicate the reworking of previously deposited silt beds by slumping and/or lake floor currents (Roberts 1972, Fisher and Taylor 2002, Eyles et al. 2005).

Unit 1 deposits may thus record an early phase of glaciolacustrine deposition following withdrawal of Nissouri Stadial ice (around 16 Ka) and the readvance of ice into the Ontario basin during early Port Huron time (13 Ka). This ice advance blocked lake outlets to the east and significantly increased water depths in the Ontario Basin (Karrow et al. 2007).

The finely laminated clays and silts comprising Unit 2 are also interpreted as lacustrine deposits, resulting from sedimentation by fluctuating density underflows and/or intermittent turbidity currents. Slight coarsening and thickening of the laminae up-section suggest enhanced rates of sediment delivery to the site and increased proximity to the sediment source, likely caused by progressive ice advance into the region (Brazier et al. 1998, Last and Teller 2004). Clasts composed of local bedrock (dolostone) observed in Unit 2b may have been rafted into the lake by icebergs or shore ice (Ovenshine 1970). Sediment instability caused by rapid deposition, isostatic adjustments of the basin, wave activity or iceberg grounding would disrupt previously deposited silt beds and produce abundant silt clasts (Eyles et al. 1983). The lithic clast horizon observed within Unit 2a at the southern section of the study area could represent an erosional lag formed by the removal of fines by currents or liquefaction as lake levels fluctuated (Hart and Boulton, 1991). However, there are no clasts contained within underlying deposits and there is no clear evidence of erosional truncation of underlying clay and silt laminae. Given that the clast horizon lies at the same elevation as ‘highs’ on the bedrock surface, it is more likely that it formed due to erosion and transport of clasts from nearby bedrock outcrops by lake floor currents or sediment gravity flow processes (Eyles et al. 1987).

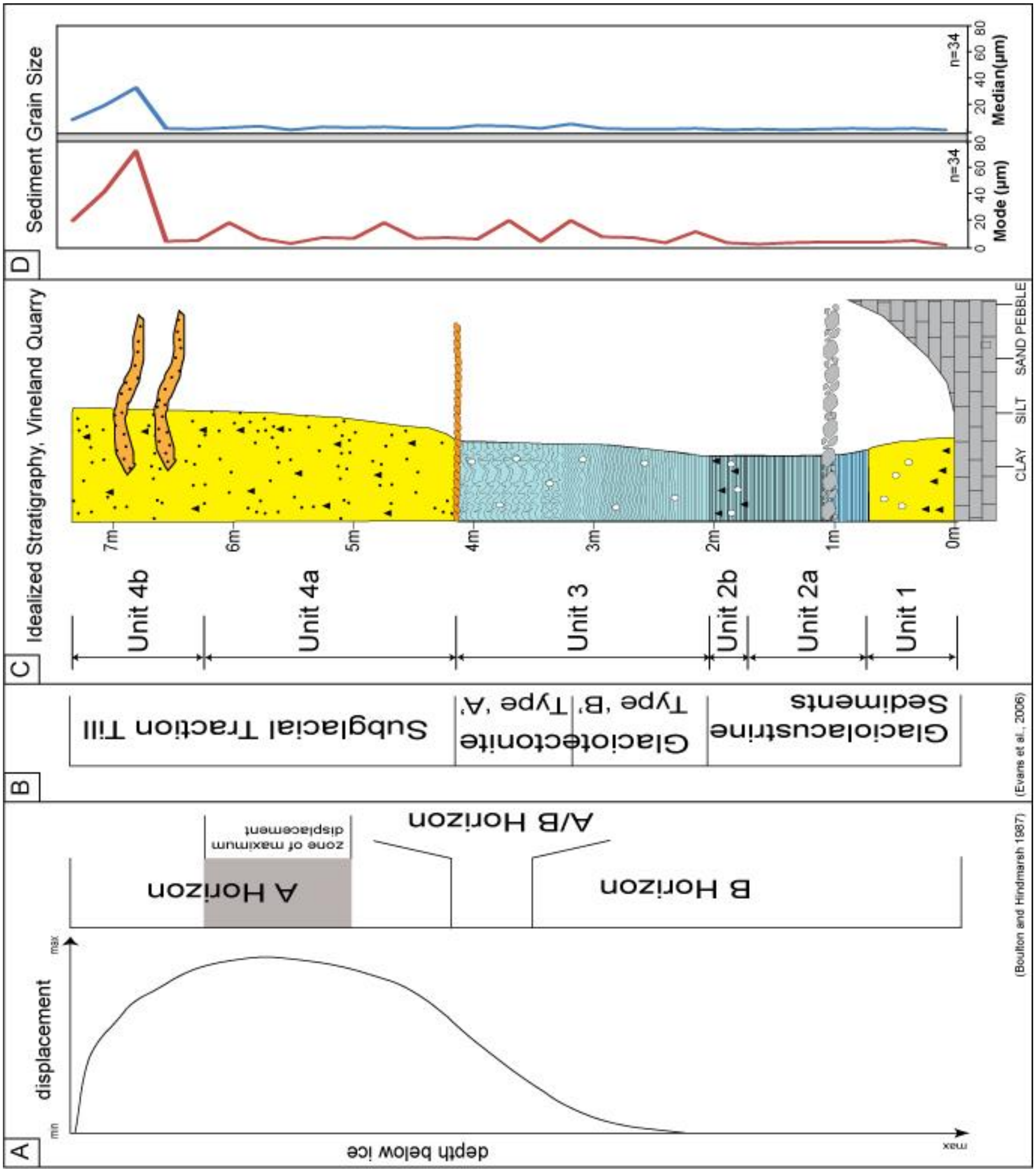
The silt and clay laminae characteristic of Unit 3 are also interpreted to have formed as a result of density underflow and/or turbidite deposition in a lacustrine environment (van Rensbergen et al. 1999). Discrete laminae composed of silt clasts probably record the disruption and downslope transport of previously deposited silt beds by sediment gravity flows. The most distinctive feature of Unit 3, however, is the progressive up-section increase in the amount and intensity of sediment deformation with uppermost laminae showing extensive disruption by folding and faulting (Figure 2.6B). The brittle and ductile deformation structures that characterize the upper part of Unit 3 could result from a number of processes including slumping, dewatering and/or overriding by glacier ice (Boulton 1986, Benn 1994).

Folding and disruption of silt and clay laminae are commonly reported from glaciolacustrine successions deposited on relatively high relief substrates in which sediment has been subject to downslope creep or slumping (Evans 1993, Chunga et al. 2007). In these situations, deformation occurs at either regular or irregular intervals in the succession as the shear stress of the sediment is exceeded and episodic downslope failure occurs. The progressive up-section increase in sediment deformation observed in Unit 3 is not consistent with disruption caused by episodic slope generated failure, and in the absence of any water escape structures associated with dewatering processes (Cheel and Rust 1986), a mechanism involving deformation by overriding ice is preferred.

Increasing intensity of deformation up-section within Unit 3 implies a downward penetrating deformation process with maximum stress being applied at the top of the bed and the intensity of deformation dissipating downward. This situation exists beneath ice overriding a 'soft' substrate and sediment packages showing similar up-section increases in deformation have been described from Late Wisconsin deposits in Northern Sweden (Linden et al. 2008), eastern Germany (Hoffmann and Piotrowski 2001, Piotrowski et al. 2004), modern ice margins at the Breiðamerkurjökull glacier in Iceland (Boulton and Hindmarsh 1987), and recent Icelandic tills (Evans 2000, Evans and Twigg 2002). The characteristics of Unit 3 conform closely to those proposed by Evans et al. (2006) to identify a 'glacitectonite' in which subglacial deformation of pre-existing sediment has been sufficient to disturb and disrupt sedimentary structures, but insufficient to cause complete mobilization or homogenization of the sediment (Benn and Evans 1996, Evans et al. 2006, Hiemstra et al. 2007, Waller et al. 2009). The upper section of Unit 3 shows evidence of downward penetrating deformation in which extreme folding of the sediment has created a deposit that is barely recognizable from its pre-deformational form and, using the terminology introduced by Evanset al. (2006), can be classified as a Type A glacitectonite. The lower portion of Unit 3 shows minor folding of pre-deformational sediment and can be classified as a Type B glacitectonite (Figure 2.8B; Evans et al. 2006). Unit 3 may also represent the 'B' Horizon of deformed pre-existing sediment identified in subglacial deformation tills by Boulton & Hindmarsh (1987; Figure 2.8A).

The changing nature of the deformation structures contained within Unit 3 may also result from up-section changes in sediment texture. Sediment in the lower portion of Unit 3 has extremely high clay content which can facilitate shearing and ductile deformation and allow the development of folds within the sediment (Alley 1989, Boulton 1996). Faulting is observed near the top of Unit 3 where sediment texture coarsens and becomes more silt-rich, reducing the plasticity of the material and allowing brittle failure to occur (Alley 1989, Hart and Rose 2001, Evans et al. 2006).

Figure 2.8: Summary stratigraphy of the Vineland Quarry (C) shown relative to grain size (D), and the classification of subglacial deformation zones proposed by Boulton and Hindmarsh (1987) (A), and the subglacial sediment classification scheme of Evans et al. (2006) (B). The uppermost sediments of Unit 4 conform to the 'A' horizon of Boulton and Hindmarsh (1987) with Unit 4a representing the zone of maximum displacement. The 'B' horizon of Boulton (1986) is equivalent to the relatively undeformed laminated silts and clays of units 1, 2 and the lower part of unit 3 and represents an area minimally influenced by the downward penetrative deformation imparted by the overriding ice sheet (A). The relatively thin 'A/B' horizon contains deformed material that retains some of its original structure and represents transition between the 'A' and 'B' horizons. (B) According to the sediment classification scheme of Evanset al. (2006) the homogeneous diamict of Unit 4 can be identified as subglacial traction till and Unit 3 as either a type A or type B glacitectonite depending upon the amount of deformation. (D) Sediment grain size analysis curves (mode, median) based on the analysis of 34 samples. Analysis conducted using a Beckman LS coulter counter.


A
displacement
min
max
depth below ice
max
A Horizon
zone of maximum displacement
A/B Horizon
B Horizon
(Boulton and Hindmarsh 1987)
B
Subglacial Traction Till
Glaciotectonite
Type 'A'
Type 'B'
Glaciolacustrine Sediments
(Evans et al., 2006)
C
Idealized Stratigraphy, Vineland Quarry
Unit 4b
Unit 4a
Unit 3
Unit 2b
Unit 2a
Unit 1
7m
6m
5m
4m
3m
2m
1m
0m
CLAY
SILT
SAND
PEBBLE
D
Sediment Grain Size
n=34
Mode (µm)
0 20 40 60 80
n=34
Median(µm)
0 20 40 60 80

Macroscopically structureless to crudely stratified diamict facies of Unit 4 are interpreted as subglacial sediments recording deposition from the Ontario Lobe of the LIS. As glacial ice overtopped the Niagara Escarpment, flowing from the Ontario basin toward the south, previously deposited silty-clays, similar to those of Unit 3, were extensively deformed and homogenized within a subglacial deforming bed and deposited as macroscopically structureless subglacial till. Microstructural studies of these structureless tills would likely reveal a variety of microscopic strain markers and grain fabrics that record the strain history of the deposits (e.g. Menzies 2001, Larsen et al. 2006), but these studies are beyond the scope of this paper. The tills appear to be structureless in field exposures and are therefore considered here to record macroscopic homogenization of overridden sediments.

The lower part of Unit 4 (subclassified as 4a; Figure 2.6A) consists almost entirely of reworked glaciolacustine deposits as evidenced by the fine grained matrix texture, identical to the texture of underlying deposits of Unit 3 (Figure 2.8D). Intense subglacial deformation of previously deposited glaciolacustrine silts and clays has produced a fully homogenized diamict in a similar manner to that proposed for the development of subglacial traction till by Evans et al. (2006). The homogenization of glacially overridden sediments is hypothesized to result from complete penetrative deformation of the substrate by stresses imparted by the overriding glacier (Piotrowski et al. 2004, Evans et al. 2006). Evanset al. (2006) suggest that subglacial deformation processes form part of a continuum that includes melt-out and lodgement processes and which vary both spatially and temporally according to changing substrate conditions. They introduced the term ‘traction till’ to describe the macroscopically structureless, homogenized diamicts resulting from these processes, the products of which are difficult, if not impossible, to discriminate. The diamicts of Unit 4 should therefore be considered as subglacial traction till deposits resulting primarily from deformation processes (Boulton and Hindmarsh 1987, Evans et al. 2006).

Clasts contained within the diamict of Unit 4a are of local provenance and were most likely derived from reworking of clast lags on local bedrock highs. The horizon of small clasts that discontinuously separates Unit 4 in the southern portion of the study area from the underlying deformed clays and silts of Unit 3 (Figure 2.5) is similar to those observed in the lower portion of the Catfish Creek Till in the Lake Erie basin (Lian et al. 2003). The clast horizons contained within the Catfish Creek Till have been interpreted as lags resulting from the squeezing of water saturated subglacial sediment upwards into cavities in the ice base (Hicock 1992, Lian et al. 2003). Similar coarse-grained deposits are found in late Wisconsin deposits in northern Sweden (Lindén et al 2008) and are interpreted as lag horizons or scour infills created by subglacial meltwater activity. Boyce and Eyles (2000) also describe coarse-grained interbeds within subglacial tills and suggest that they form as a result of active ground water discharge through the substrate that causes the preferential loss of fine-grained sediments. The clast horizon that lies between Unit 3 and 4 in the Vineland Quarry could have been generated by any of these processes.

The uppermost unit exposed in the Vineland Quarry (Unit 4b) is an extremely poorly sorted diamict that contains far-traveled clasts and common discontinuous sand stringers and lenses (Figure 2.6A). The presence of far-traveled clasts is indicative of sediment contribution from glacial sources and the melting out of debris from the overriding ice base (Hicock and Dreimanis 1992a, 1992b). The inclusion of poorly consolidated sand stringers into the diamict may either record episodic meltwater flow on the aggrading diamict surface or the deformation of sand-rich sediment inclusions (e.g. Menzies 1990, Norris 1998). Similar sand inclusions are described in the Northern Till of southern Ontario by Boyce and Eyles (2000) and ascribed to incorporation of sand into the deforming subglacial bed as glacial ice advanced over sand-rich outwash. Silty clay diamicts containing rounded and boudinaged sand interclasts are also reported from Pleistocene subglacial successions in North Norfolk, UK (Hart 2007, Lee and Phillips 2008, Waller et al. 2009) where sand clasts are interpreted as having been preserved due to cementation by pore ice during transport and deposition. Given that there is no evidence of sand-rich substrate materials in the Vineland region an origin for the sand stringers by winnowing of accumulating diamict is preferred. Overall, Unit 4b is interpreted as a subglacial till that records deposition from the deforming bed of a glacier and includes both glacially derived sediment and reworked substrate materials (Boulton 1986; Figure 2.8A). This unit should also be considered as a traction till (Evans et al. 2006) that records enhanced delivery and incorporation of glacially transported material into the resulting sediment. Units 4A and 4B together may also represent the A horizon, or zone of maximum sediment displacement, proposed in the model of glacier ice-bed interface presented by Boulton and Hindmarsh (1987: Figure 2.8B).

The complete succession of sediments exposed above bedrock in the Vineland Quarry passes upwards from undeformed lacustrine sediments (Units 1 and 2), through increasingly disrupted and deformed fine-grained sediments (Unit 3) into macroscopically homogenized deposits that incorporate sediment contributed directly from the overriding ice (Unit 4). The Vineland succession thus appears to record the full suite of deposits theorized to form as a result of the development of a subglacial deforming bed (Alley 1991, Boyce and Eyles 2000, Evans et al. 2006).

2.4 Discussion

The exposed sediments in the Vineland Quarry study area offer a unique opportunity to test theoretical models of subglacial deformation processes through detailed analysis of their characteristics and inferred depositional origin. The predominantly fine-grained sediments provide strong evidence of glaciolacustrine deposition followed by overriding, deformation and deposition under subglacial conditions. Facies transitions that pass from undisturbed laminated silts and clays through increasingly disturbed and deformed laminated fines to massive clay-rich diamicts are consistent with models of subglacial deformation proposed to result from variations in sediment displacement imposed by an overriding ice sheet (Figure 2.8A; Boulton and Hindmarsh 1987, Benn 1995, Evans et al. 2006, Cofaigh et al. 2010).

The progressive vertical increase in sediment deformation up-section, passing from an unaltered crudely bedded deposit to a fully homogenized deposit, can be directly related to the sediment displacement curve proposed by Boulton and Hindmarsh (1987)

(Figure 2.8A). The curve represents the theoretical displacement of sediments beneath an overriding ice mass. The sediments in the study area record a smooth progression from essentially undisturbed sediments of units 1 and 2 to the intensely deformed and macroscopically homogenized deposits of Unit 4 which form in the zone of maximum displacement (Figure 2.8). It is unusual to record such a smooth transition in a succession of subglacial deposits as spatial and temporal variability in subglacial conditions (the stable/deforming subglacial bed mosaic concept; Piotrowski et al. 2004) results in a variety of depositional processes operating as the sediment accumulates (Evans et al. 2006). The Quaternary sediments exposed at the Vineland Quarry show a remarkably consistent change in the intensity of sediment deformation up-section, and fully align with theoretical models describing subglacial deformation processes. This suggests that the deformation signature is the result of a single event that may have been relatively short-lived and could record rapid movement of ice across the area in a similar fashion to that proposed for ice marginal surges (Costello and Walker 1972, Boyce and Eyles 1991, Eyles et al. 2011). This interpretation, of rapid ice movement is consistent with the recent interpretations of other late glacial moraines fringing the Ontario basinand suggests that the Port Huron ice margin flowed rapidly out of the western Ontario basin, possibly as an ice surge, supported by a bed of soft, wet sediment (Clarke 1987, Evans et al. 2006, Eyles et al. 2011). Rapid ice movement and deforming bed conditions may have been promoted by the development of extensive proglacial lake bodies between the advancing ice margin and the topographic barrier of the Niagara Escarpment that allowed both the accumulation of easily deformed clay-rich sediments and the partial buoyancy of the ice margin.

Similar ice marginal environments are known to have existed elsewhere in the Great Lakes basins during the Quaternary and examples of subglacially deformed proglacial lacustrine sediments can be found farther afield in areas such as Scotland (Banham 1977, Golledge 2007), northern Venezuela (Mahaney et al. 2004), southwest Ireland (Cofaigh et al. 2010) and the state of Illinois in the United States (Johnson and Hansel 1990). A modern analog for this type of glacial setting can be identified in Antarctica where Ice Stream B flows rapidly over clay-rich subglacial debris (Alley et al. 1997, Eyles et al. 2011).

The succession of sediments exposed above bedrock at the Vineland Quarry appears to very closely conform to theoretical models describing subglacial deformation processes and may therefore serve as an appropriate ‘model’ to use for the interpretation of sediment packages elsewhere around the margins of the Great Lakes basins. In these lake margin settings, similar conditions to those experienced in the Vineland region may have developed in which water saturated fine-grained sediments were overridden by an ice margin. Using an appropriate terminology to describe such sedimentary successions is extremely important as the terminology should recognize the complexity and spatial/temporal variability of subglacial processes. We concur with the proposal of Evans et al. (2006) to use the non-process specific term of traction till to describe the deposits resulting from the continuum of subglacial deformation, lodgement and meltout.

2.5 Conclusion

The introduction of the deforming-bed model by Boulton and Jones (1979) can be viewed as a major paradigm shift in the study of subglacial processes and sediments (Murray 1997, Hart and Rose 2001, Lian and Hicock 2001). Recognizing the importance of subglacial sediment deformation as a means of facilitating ice movement has triggered a re-examination of how glacial beds control the overall dynamics of ice sheets, particularly the extensive Pleistocene ice sheets that covered large areas of North America and Europe (Piotrowski et al. 2004, Lee and Philips 2008, Stokes and Clark 2003, Clarke 2005). The identification of deformable beds beneath modern ice masses (Alley et al. 1986, Evans et al. 2006) has also stimulated research into the potential effects of climate and sea level change on current subglacial deformation processes and subsequent ice sheet behavior (Bentley 1997).

The field-based study presented here is a contribution to the literature describing deposits resulting from subglacial deformation processes. The sedimentary succession exposed in the Vineland Quarry shows clear evidence of the operation of subglacial deforming bed conditions in the form of up-section increases in the amount of attenuation and deformation of fine-grained substrate sediments that culminate in the formation of a macroscopically homogenized diamict identified here as a traction till (Figure 2.8). This interpretation of the sediment succession is consistent with the proposed theoretical models of sediment deformation due to overriding ice sheets (e.g. Boulton and Hindmarsh 1987). There is now widespread recognition of the importance and significance of subglacial deformation processes, but there are many questions yet to be answered regarding the spatial extent and variability of these processes as they operate under ice masses of different type and extent (Piotrowski et al. 2004). Subglacial successions resulting from the continuum of processes that include lodgement, melt-out and deformation are likely to be widespread around the Great Lake margins where the interplay of lacustrine and glacial processes has been complex. Recognition of the depositional signature of deformation processes is therefore important as an aid to the reliable reconstruction of past climate and environmental conditions.

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CHAPTER 3

QUANTITATIVE GEOMORPHOLOGICAL ANALYSIS OF DRUMLINS IN THE PETERBOROUGH DRUMLIN FIELD, ONTARIO, CANADA

Abstract

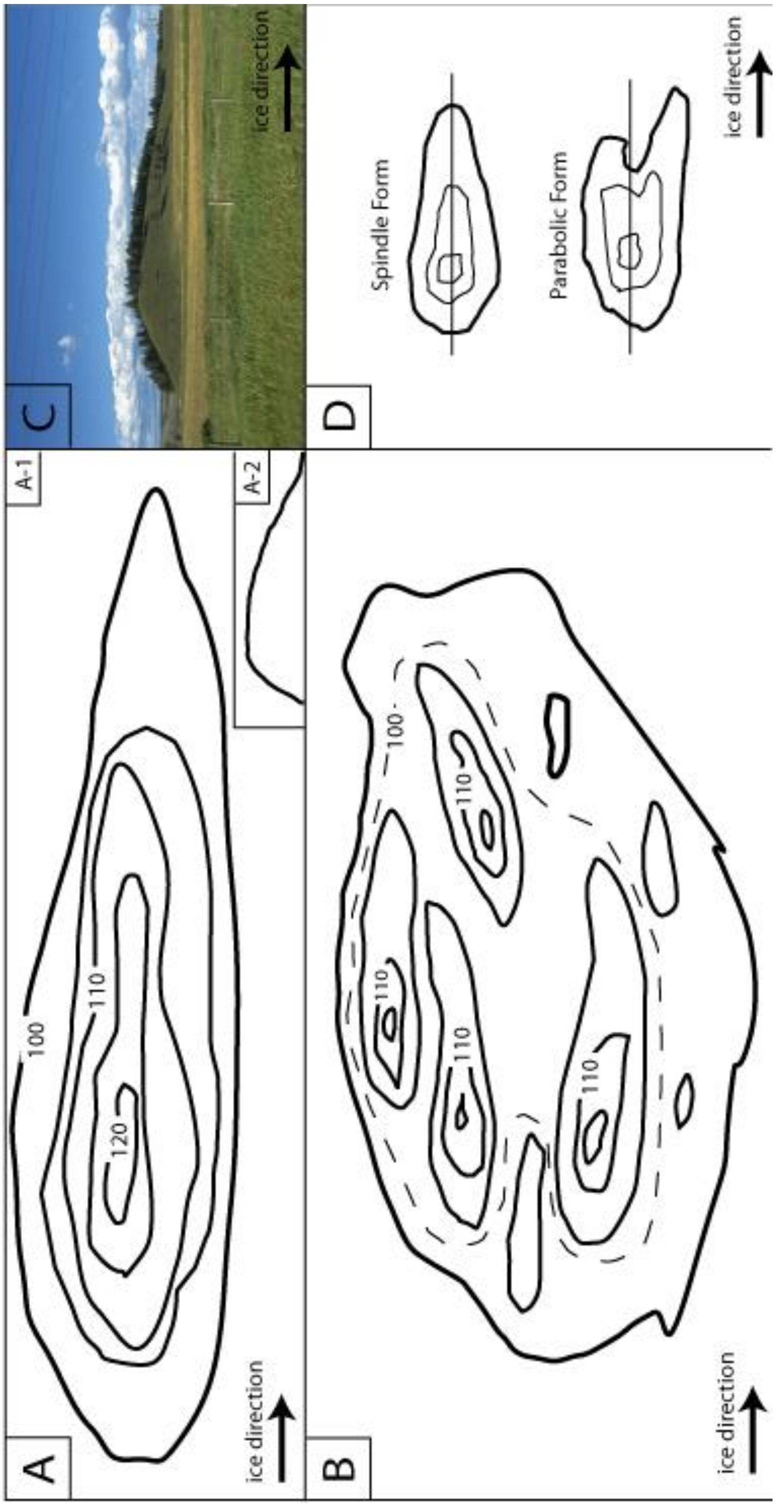
Drumlins are subglacial landforms interpreted to have formed by a variety of processes including incremental accumulation of till, erosion of previously deposited sediment, catastrophic meltwater floods and sediment deformation. In order to better constrain the subglacial conditions under which these landforms develop there is a need to obtain quantitative data on their morphologic characteristics and spatial distribution over broad regions. This paper explores a computational methodology that allows identification of drumlins and extraction of their morphological characteristics from existing topographic digital data. Spatial and non-spatial analysis of the form and distribution of drumlins across a portion of the Peterborough drumlin field in Ontario, Canada identifies drumlin characteristics such as size, elongation ratio and long axis orientation and shows that drumlins are not randomly distributed across the region and their form characteristics have distinct regional trends. Kernel density analysis is used to identify the regional trends in drumlin characteristics. Factors that appear to influence the form and distribution of drumlins in the study area include sediment thickness, length of time beneath the ice and direction of ice movement. The computational methodology

proposed here can be applied to other drumlin fields in order to better understand the relationship between the spatial variability of drumlin forms and the subglacial processes responsible for their formation.

3.1 Introduction

Drumlins are common landforms in previously glaciated regions commonly underlain by sedimentary bedrock and are broadly ascribed to formation by subglacial processes (Benn and Evans 2006). A widely accepted definition for the term drumlin is given by Menzies (1979: 315) as “a typically smooth oval-shaped hill of glacial material resembling an egg half-buried along its long axis with the blunter end pointing in the up ice direction” (Figure 3.1). The unique ‘half egg-shape’ morphology of drumlins allows them to be used as a tool for the identification of former subglacial terrains and permits reconstruction of glacier movement (Boulton and Hindmarsh 1987, Eyles 2006, Kerr and Eyles 2007). Drumlins occur occasionally as simple isolated features dotting the landscape, or as larger, more complex topographic highs containing multiple drumlin forms (Figure 3.1), but most commonly occur as groups or ‘swarms’ of drumlins comprising extensive drumlin fields.

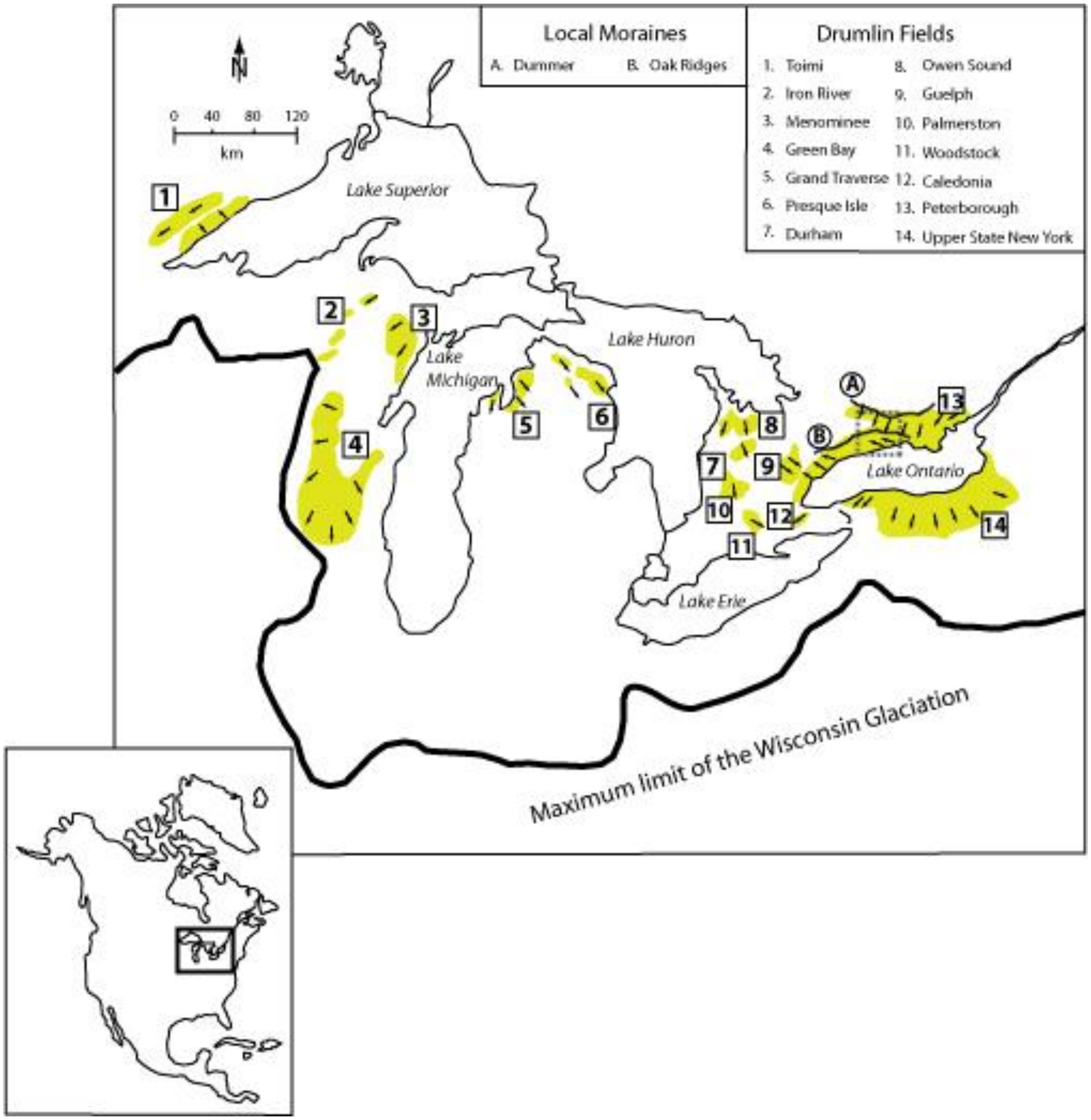
Figure 3.1: Schematic contour maps illustrating classic and 'complex' drumlin forms. Contour interval 5m. Ice flow direction from left to right. (A) Classic drumlin form (A-1 is a plan view; A-2 is a cross section). (B) Complex drumlin form. On a DEM, only landforms with multiple closed loop contours are accepted as potential drumlins. The dashed contour line represents an enclosing of numerous single drumlin. (C) Photo of a classic drumlin. (D) Contour map of the two predominant drumlin types in the study area.


A
A-1
A-2
100
110
120
ice direction
B
100
110
110
110
110
ice direction
C
ice direction
D
Spindle Form
Parabolic Form
ice direction

Numerous drumlin fields have been identified in glaciated regions of eastern North America (Figure 3.2) and are interpreted as the product of subglacial processes operating beneath the Laurentide Ice Sheet (LIS) during the Wisconsin glaciation. However, despite the widespread distribution of these landforms, the fundamental mechanism of drumlin formation remains one of the most controversial topics of debate among Quaternary scientists (Gravenor 1953, Trenhaile 1971, Crozier 1975, Shaw 1983, Boulton and Hindmarsh 1987, Menzies et al. 1997, Boyce and Eyles 1991, Shaw 2002, Boulton et al. 2009). There are many unanswered questions related to drumlin genesis that have implications for the understanding of large scale ice-sheet dynamics (Clarke et al. 2004, Evans et al. 2006, Clarke and Leverington 2005, Sharpe 2005, Johnson et al. 2010).

The wide range of geomorphic types of drumlins and variability of their internal sediment composition have promoted numerous theories to explain their origin including an accretionary origin, resulting from successive deposition of subglacial till beds (Menzies et al. 1997), erosional streamlining due to deformation of pre-existing glaciofluvial and glaciolacustrine sediments (Boulton and Hindmarsh 1987, Boyce and Eyles 1991, Knight and McCabe 1997, Benn and Evans 2006, Kerr and Eyles 2007), the infilling of cavities formed at the base of the ice sheet by catastrophic subglacial megafloods (Shaw, 1983), and the carving of pre-existing subglacial sediment through catastrophic subglacial megafloods (Shaw and Sharpe 1987, Shoemaker 1999, Fisher et al. 1999, Shaw 2002, Shaw 2010).

Figure 3.2: Principal drumlin fields (shaded) of the Great Lakes region of North America. Arrows illustrate ice-flow direction as indicated by drumlin form (adapted from Kerr and Eyles 2007).

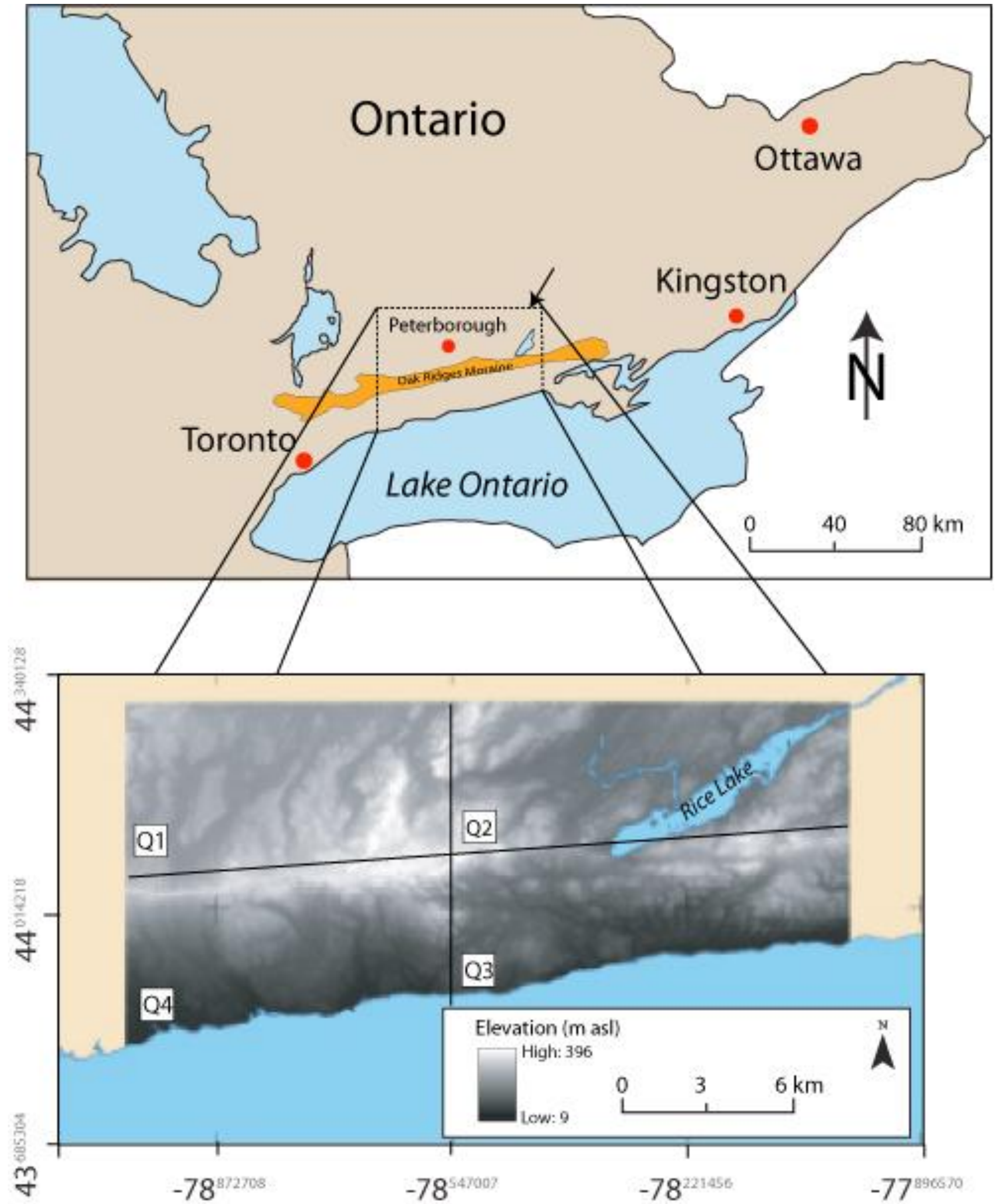

Local Moraines
A. Dummer
B. Oak Ridges
Drumlin Fields
1. Toimi
2. Iron River
3. Menominee
4. Green Bay
5. Grand Traverse
6. Presque Isle
7. Durham
8. Owen Sound
9. Guelph
10. Palmerston
11. Woodstock
12. Caledonia
13. Peterborough
14. Upper State New York
N
0 40 80 120
km
Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
Maximum limit of the Wisconsin Glaciation

In order to further understand mechanisms for the formation of these perplexing subglacial landforms, it is recognised that quantitative geomorphic data pertaining to drumlin form and spatial distribution are required, as these characteristics are directly controlled by processes and conditions at the ice base (Sharpe 2005, Clarke and Leverington 2005, Kerr and Eyles 2007, Clark et al. 2009, Hess and Briner 2009). The most common measure of drumlin morphology used to infer former subglacial conditions is the elongation ratio (length to width ratio, Clark et al. 2009) which has been used to gain insight on relative ice velocity (Briner 2007), time under ice, and ice-flow direction (Boyce and Eyles 1991, Clark 1994). The concept of using quantitative spatial analysis to explore drumlin data is not new (Chapman and Putnam 1943, Trenhaile 1971) and has recently been used to elucidate mechanisms of drumlin formation on a scale appropriate for the analysis of ice sheet behaviour (Knight, 1997, Briner 2007, Hess and Brinerr 2009, Clark et al. 2009). However, geomorphological studies of drumlin fields typically rely on qualitative descriptions of drumlin form and characteristics obtained from localized study areas, and rarely identify parameters that may be easily applied to the analysis of drumlin characteristics in other regions (e.g. Shaw and Sharpe 1987, Menzies and Brand 2007).

Recent advances in computing technologies and the availability of digital topographic data of appropriate resolution now allow application of effective quantitative techniques to the large-scale morphological analysis of surface landforms using criteria that may be digitally catalogued and analysed (Pike 2000). Quantitative geomorphic techniques have been used to describe erosional glacial features such as cirques (Aniya and Welch 1981, Federici and Spagnolo 2004), and non-glacial landforms such as sinkholes (Angel et al. 2004, Gutiérrez et al. 2008), but have rarely been used to analyse the spatial variability of drumlin morphology across entire drumlin fields (Knight 1997, Hättestrand et al. 2004, Briner 2007). These quantitative data will allow better understanding of the spatial relationships between different drumlin forms and conditions affecting their development across broad regions.

The primary objective of this study is to test a quantitative methodology that allows identification of spatial variance in the morphological properties of drumlins within a portion of the Peterborough drumlin field (PDF) of southern Ontario (approximately 125 km northeast of Toronto; Figure 3.3) and subsequently create insight to the nature of subglacial or substrate conditions that controlled this variability. Drumlins within the PDF have been described both qualitatively and semi-qualitatively and interpreted either as erosional ridges associated with catastrophic subglacial meltwater floods (Shaw and Sharpe 1987) or as geomorphological expressions of a deforming subglacial bed (Boyce and Eyles 1991). The size and extent of the PDF (approximately 5000 km^2) and availability of high resolution digital-elevation-model (DEM) data make this an ideal area for the quantitative study of drumlin morphology on a scale suitable to give further insight into the interpretation of the sub ice-sheet processes responsible for drumlin-field genesis. The quantitative methodology used will be applicable to the analysis of other drumlin fields where adequate digital data exists.

Figure 3.3: A) Location of study area (dashed box) within southern Ontario (B) shaded Digital Elevation Model of the study area with four quadrants (Q1,Q2,Q3,Q4) identified.

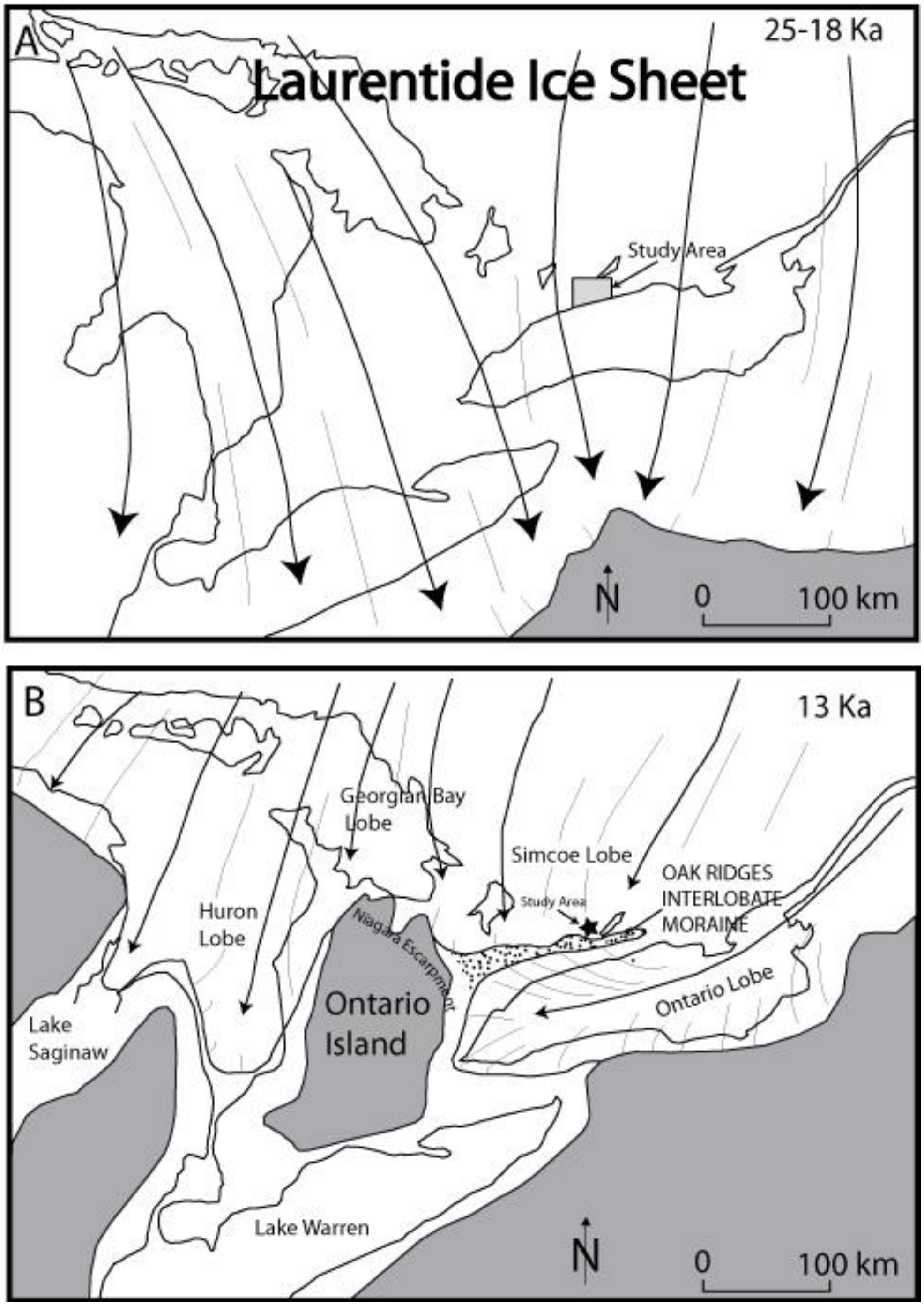

Ontario
Ottawa
Kingston
Peterborough
Oak Ridges Moraine
Toronto
Lake Ontario
0 40 80 km
N
Rice Lake
Q1
Q2
Q3
Q4
Elevation (m asl)
High: 396
Low: 9
0 3 6 km
N
44 340128
44 014218
43 685304
-78 872708
-78 547007
-78 221456
-77 896570

3.2 Study Area

The PDF of southern Ontario contains approximately 3000 drumlins and stretches across a broad geographic region from the shores of Lake Ontario in the south to the Dummer Moraine north of the city of Peterborough (Figure 3.3). Southern Ontario was last glaciated during the late Wisconsin between 25,000 and 12,000 BP, and the PDF is thought to record subglacial conditions during the concluding stages of the Wisconsin glaciation at approximately 13,000 BP (Karrow 1984). The orientation of drumlins within the northern and eastern parts of the PDF records southward flow of the Simcoe lobe of the Laurentide Ice Sheet (LIS), whereas drumlins in the south-western part of the field record northwestward movement of the Ontario lobe as it flowed out of the Ontario basin (Figure 3.4; Chapman and Putnam, 1943, 1966, 1984, Boyce and Eyles 1991, Boyce et al. 1995).

The two notable moraines within and immediately adjacent to the study area, the Dummer Moraine lies to the northeast and the Oak Ridges Moraine crosses the area from west to east (Figure 3.2). Some of the earliest published studies of the Dummer Moraine suggest it formed as a terminal moraine (Loken and Leahy 1964, Chapman and Putnam 1966) representing a major still-stand position of the Laurentide Ice Sheet. More recent studies argue that the Dummer Moraine was deposited due to differences in drainage conditions between Precambrian substrates to the north and Paleozoic substrates to the south which would represent a much shorter duration event (Gadd 1980). There is currently no consensus regarding the origin of the Dummer Moraine (Schulmeister 1989).

Figure 3.4: Ice cover and flow directions in southern Ontario at 25-18Ka (A) and 13 Ka (B). Study area marked by box. (A) during the maximum late Wisconsin extent of the Laurentide Ice Sheet the Newmarket and Kettleby Tills were deposited (B) during the Port Huron Stadial the Oak Ridges Interlobate Moraine formed and Halton Till was deposited. Note ice flow out from the Ontario basin to the northwest at this time (adapted from Howard et al. 1999).

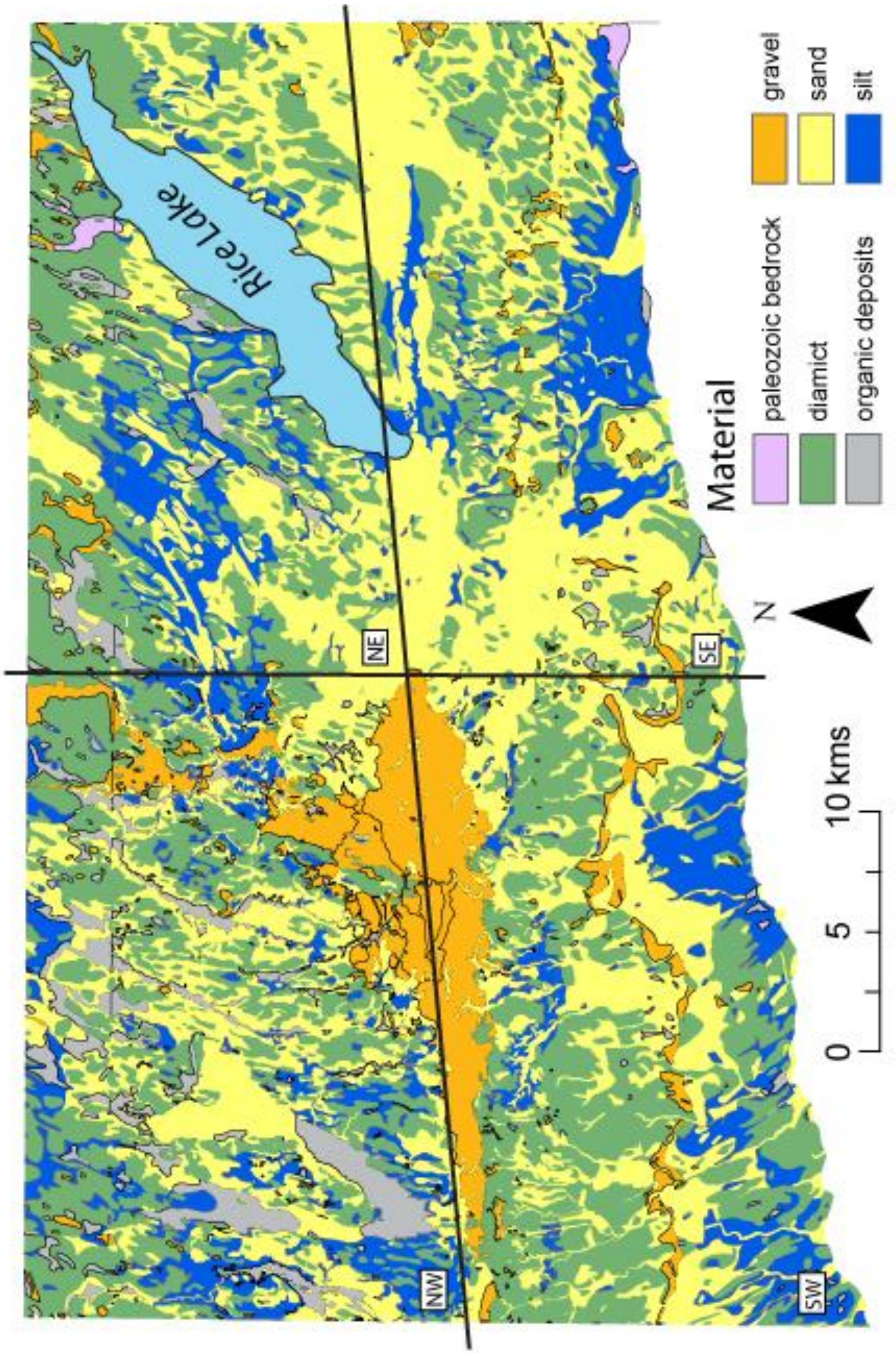

A
25-18 Ka
Laurentide Ice Sheet
Study Area
N
0
100 km
B
13 Ka
Georgian Bay Lobe
Simcoe Lobe
Study Area
OAK RIDGES INTERLOBATE MORAINE
Huron Lobe
Niagara Escarpment
Ontario Island
Ontario Lobe
Lake Saginaw
Lake Warren
N
0
100 km

The Oak Ridges Moraine is located within the central portion of the study area and, because of the relatively coarse-grained sediment it contains, forms an important ground water recharge zone (Bradford 2008). The Oak Ridges Moraine is considered to have formed as an interlobate feature (Chapman and Putnam 1943, Gravenor 1957, Howard et al. 1995) recording a complex depositional history of subglacial, ice-marginal and proglacial lacustrine conditions between the Ontario and Simcoe lobes of the Laurentide Ice Sheet.

The portion of the PDF selected for this study covers an area of approximately 2000 km^2 and includes the southern part of the Dummer Moraine, the eastern section of the Oak Ridges Moraine and Rice Lake (Figure 3.3). This area was selected for study because it contains drumlins that show a variety of forms, record a range of ice-flow directions, and probably developed on different substrate types. Currently exposed at surface include sediments (diamict, gravel, sand, silt, organics) and Paleozoic bedrock (Figure 3.5). A similar portion of the PDF was used by Boyce and Eyles (1991) in their study of drumlins which combined both quantitative and qualitative techniques. In order to facilitate comparative spatial analysis of drumlin form, the study area has been subdivided into four geographic quadrants (Figure 3.3). The boundaries between each of the quadrants were placed arbitrarily to create four areas of approximately equal area regardless of substrate type, sediment thickness or surface elevation.

The Quaternary surficial sediments in the study area are underlain by Ordovician limestone and shale bedrock that dips gently to the southwest (Liberty 1969). The bedrock surface slopes gently toward Lake Ontario and is dissected by a broad, elongate

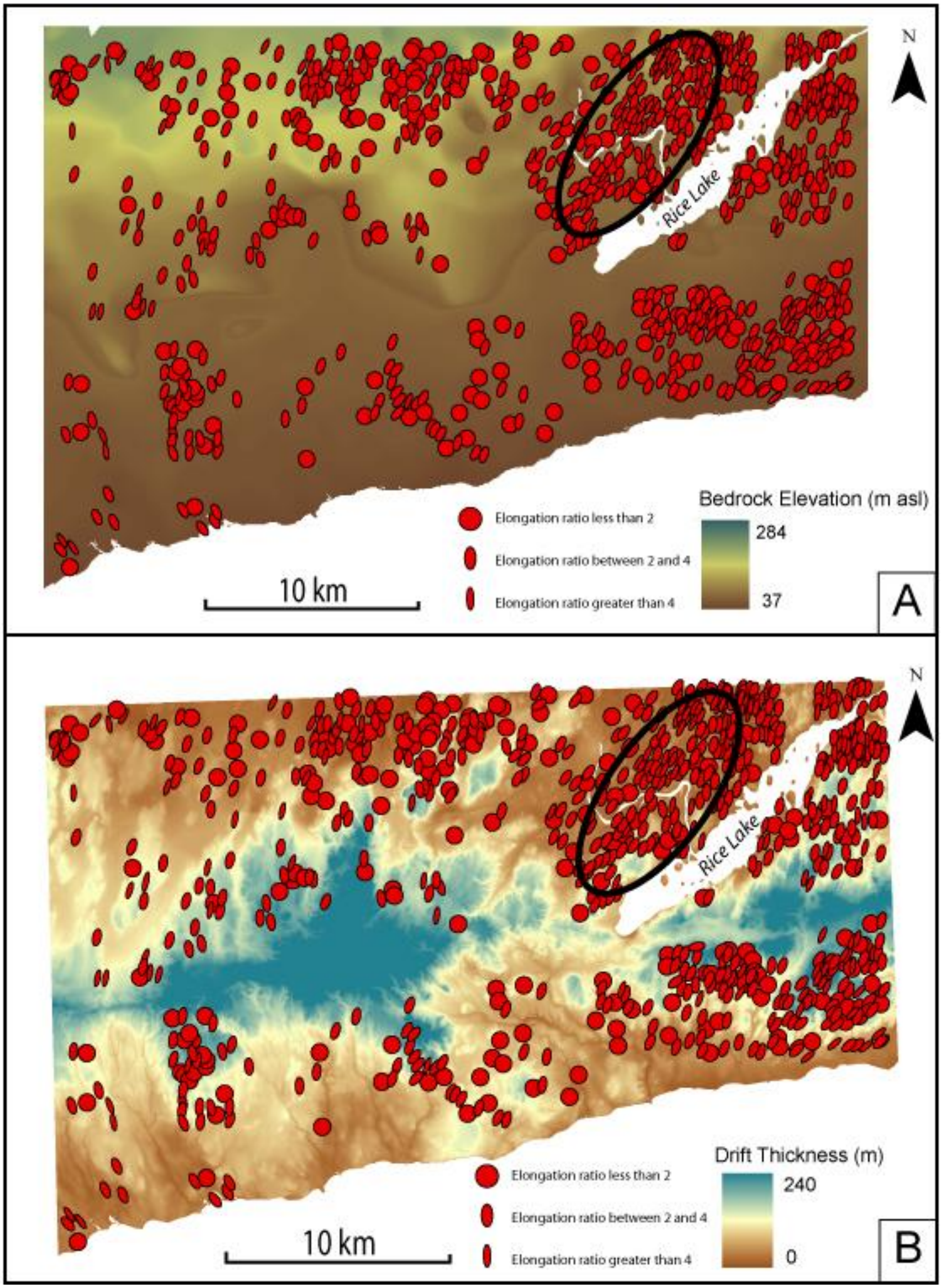
Figure 3.5: Map of substrate materials across the study area. Data obtained from the Ontario Geological Survey of Canada.


Rice Lake
NE
SE
NW
SW
N
0
5
10 kms
Material
paleozoic bedrock
diamict
organic deposits
gravel
sand
silt

bedrock low, trending northeast-southwest, that underlies the area of Rice Lake (Figure 3.6; Russell et al. 2003). In the eastern portion of the study area, drift thickness increases southward from approximately 10 m or less in the area immediately south of the Dummer Moraine, to 80 m closer to the shores of Lake Ontario (Duckworth 1979). In the western part of the study area, drift thickness reaches upwards of 200 m in the area of the Oak Ridges Moraine (Figure 3.6).

The southern part of the study area is veneered by subglacial diamict and sand comprising the Halton Till, which was deposited by the Ontario lobe of the LIS and consists of subglacial diamict interbedded with sands (Eyles and Meulendyk 2008). North of the Oak Ridges Moraine surficial sediments comprise the Newmarket Till on the western flank of the Oak Ridges Moraine and the Kettleby Till to the east (in proximity to the Dummer Moraine). The Newmarket Till is a compact stony, sandy silt till (Gwyn and Cowan 1978) deposited by the last major southward advance of the Simcoe Lobe ice during the Port Huron Stade (Karrow 1984). The Kettleby Till is a finer-grained, highly calcareous silty clay to clay till (Karrow et al. 1995) deposited subsequent to the Newmarket Till by a minor re-advance of the Simcoe lobe across the study area (Patterson and Cheel 1997).

Figure 3.6: Study area maps depicting potential geologic controls on drumlin distribution. (A) A bedrock topography map created using Ontario Geological Survey bedrock topography data with drumlin distribution. (B) Drift thickness map of study area also with drumlin distribution. Drift thickness is calculated using Ontario Geological Survey bedrock topography and OGDE DEM data.


N
Rice Lake
Bedrock Elevation (m asl)
284
37
Elongation ratio less than 2
Elongation ratio between 2 and 4
Elongation ratio greater than 4
10 km
A
N
Rice Lake
Drift Thickness (m)
240
0
Elongation ratio less than 2
Elongation ratio between 2 and 4
Elongation ratio greater than 4
10 km
B

3.3 Data Aquisition

3.3.1 Data sources

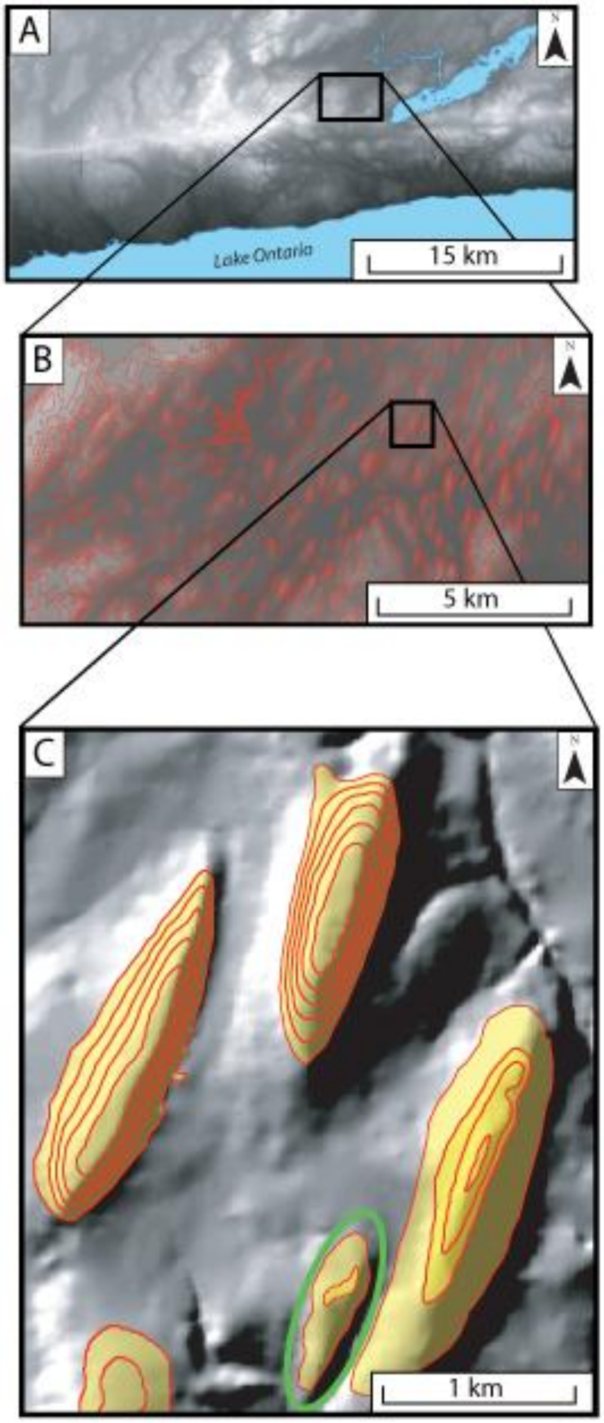
The dataset used for this quantitative study of the PDF was the Ontario Geospatial Data Exchange (OGDE) digital elevation model (DEM). The DEM dataset has a spatial resolution of 10 meters, meaning that each cell within the raster is 10 metres in both length and width. The vertical accuracy of the data is approximately 10 metres and the horizontal accuracy is approximately 5 metres. This database resolution and accuracy is appropriate for the study of drumlins within the PDF as they range in length between 55 and 2215 m (Table 3. 1). Landforms identified on the DEM with relief of less than 20 m were not included in the drumlin database due to resolution issues and potential inaccuracies in identification (van Boxel et al. 2004). Ontario Geological Survey data was used to determine the surface geology and drift thickness of the study area (Figure 3.6; Gravenor 1953, OGS 2010). Printed topographic maps were also referred to in order to validate the automated landform identification process used with the DEM data.

All morphologic and geologic data obtained were imported to ESRI shapefiles which are compatible with ESRI ArcView 3.2 and ESRI ArcGIS 9.1 software. All statistical analyses were conducted in SPSS 11.0 and spatial statistic analyses in SPLUS 3.0.

Table 3.1: Drumlin parameters calculated.

	Minimum	Maximum	Mean	Standard Deviation
All Drumlins *(n=812)*				
Area (km2)	0.01	1.7	0.17	0.18
Perimeter (km)	0.12	8.8	1.8	0.95
Elongation	1	19	2.9	3.1
NE Quadrant *(n=345)*				
Area (km2)	0.01	1.3	0.18	0.13
Perimeter (km)	0.15	5.7	1.9	0.79
Elongation	1.1	19	3.5	4.2
NW Quadrant *(n=183)*				
Area (km2)	0.01	0.9	0.16	0.18
Perimeter (km)	0.4	7	1.7	1
Elongation	1.1	6.7	2.5	1.1
SE Quadrant *(n=181)*				
Area (km2)	0.01	1.3	0.15	0.21
Perimeter (km)	0.12	6.4	1.9	0.98
Elongation	1	7.2	2.7	1.1
SW Quadrant *(n=103)*				
Area (km2)	0.05	1.7	0.15	0.22
Perimeter (km)	0.36	1.7	8.79	1.2
Elongation	1.1	5.9	2.4	2.1

Figure 3.7: Steps in the delineation of drumlins from a DEM. From top to bottom: (A) a DEM of with areas of high elevation lighter in colour with Lake Ontario to the south; (B) a sample of the contour polylines created using the DEM; (C) is a representation of closed loop polygons that have been created based on the contour lines. All closed loop contour lines are reclassified as a polygon. The small polygon circled in the southern region of the figure was identified as a sink where the contour values decrease towards the center of the polygon. This polygon would be disregarded and not used for further analysis.


A
N
Lake Ontario
15 km
B
N
5 km
C
N
1 km

3.3.2 Drumlin identification

The first stage of drumlin identification from the OGDE DEM data involved inputting the data (Figure 3.7A) into a Geographic Information Systems (GIS) program (ESRI ArcGIS 9.1, ESRI 2010) to generate contours (Figure 3.7B), a standard GIS practice. Computer-based contouring of digital elevation data has been demonstrated to be equally reliable to that conducted by experienced geologists with differences in accuracy being negligible (Bishop and Shroder 2004) and the automated process is considerably more time efficient. The contour interval used in this study was 10 meters, consistent with the resolution of the original DEM.

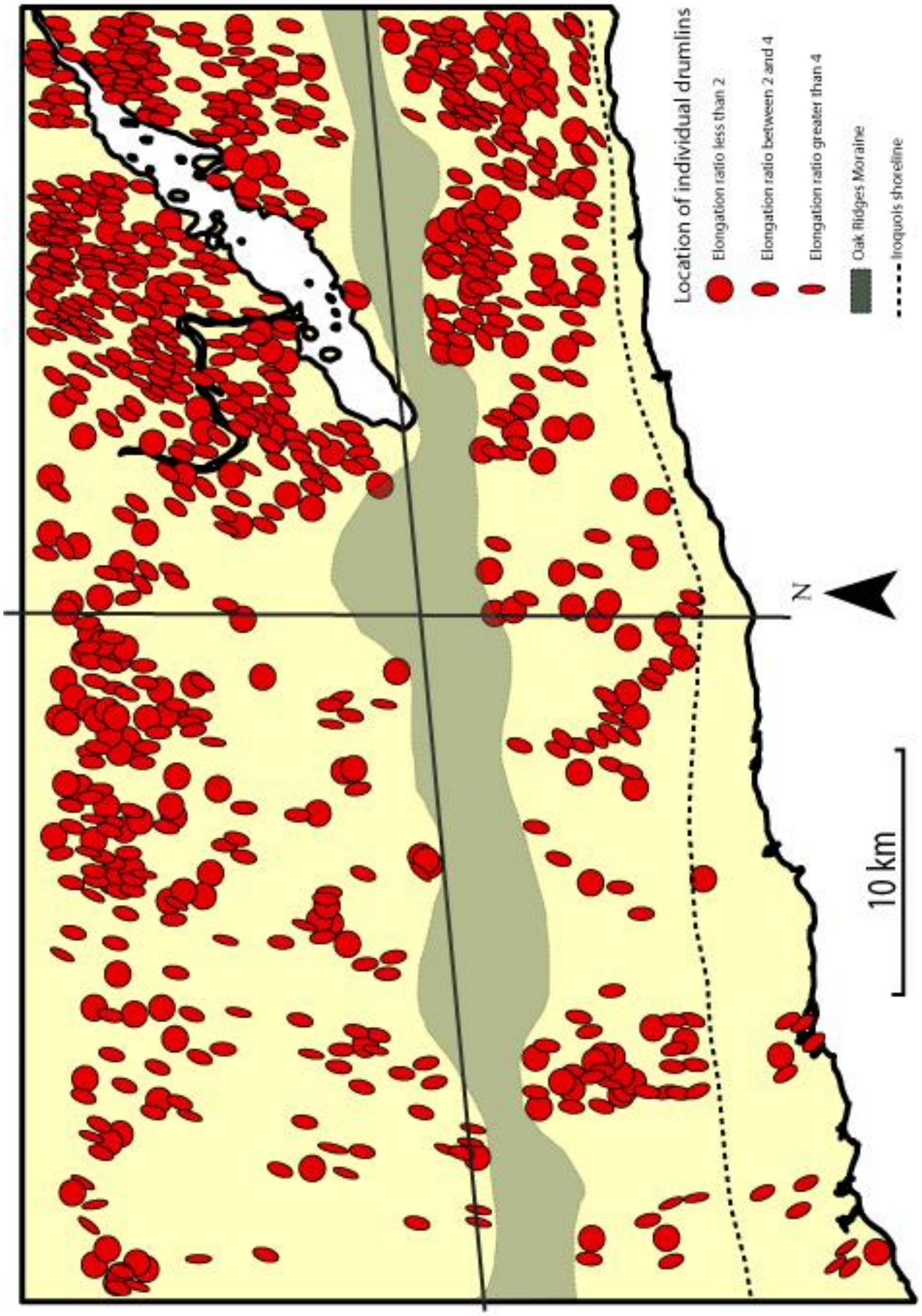
Once contours had been generated from the DEM, a GIS was used to build a topology that could identify relationships between individual spatial elements (Fürst and Hörhan 2009). In this study the topology was used to create polygons from the contour file by identifying all closed-looped contours (Figure 3.7C). The building of topology in GIS ensures that all data integrity rules are defined and enforced (i.e., that there are no gaps between polygons and no overlapping of features), and ensures the management of shared features (i.e., constrains how features share geometrical elements such as adjacent polygons). Polygons were only created within the boundaries of a closed-loop contour. All other contour lines (i.e., those that did not connect to form closed loops) were removed from the data set.

An ArcView script was then created to select and delete all polygons that represented single enclosed contours and isolated low-relief topographic features. This step, while possibly deleting a small number of drumlins with low relief, cleaned up the data by eliminating thousands of small remnant polygons that may represent undulating topography in hummocky terrain. Remaining polygon groups were then checked within the GIS environment to confirm that the form identified was a peak (i.e. a positive relief landform) and not a sink (i.e. a negative relief landform; Figure 3.7C). This last step eliminated any inverted closed contour depression in the database such as a pond or gully.

The resulting group of polygon files were then visually inspected and edited to remove obvious non-drumlin forms, such as simple, but extensive elevated plateaux. With the last non-drumlin forms eliminated from the database, the 812 polygon files remaining were considered to represent drumlins for the purposes of this study (Figure 3.8).

Significant variability in drumlin shape and form has the potential to complicate the results of any drumlin morphological study and consistency in recognition and documentation of drumlin characteristics from the DEM data was an essential component of the landform identification process. Visual inspection of the resultant forms shows that the vast majority appeared to be an elongate oval drumlin form. However, there are a few exceptions with the variations include spindle shaped, two-tailed shaped drumlins (Shaw 1983, Clark et al. 2009). Drumlins tend to form in swarms and display similar characteristics and orientation to their neighbours (Benn and Evans 2006) However, the larger complex forms may show several areas of enclosed contours within one peripheral contour (Figure 3.1). In this study, each of the smaller series of enclosed contours were

Figure 3.8: Distribution of drumlins (red ellipses) within study area. Drumlins are categorized by elongation ratio (Elongation Ratio = Length divided by width).

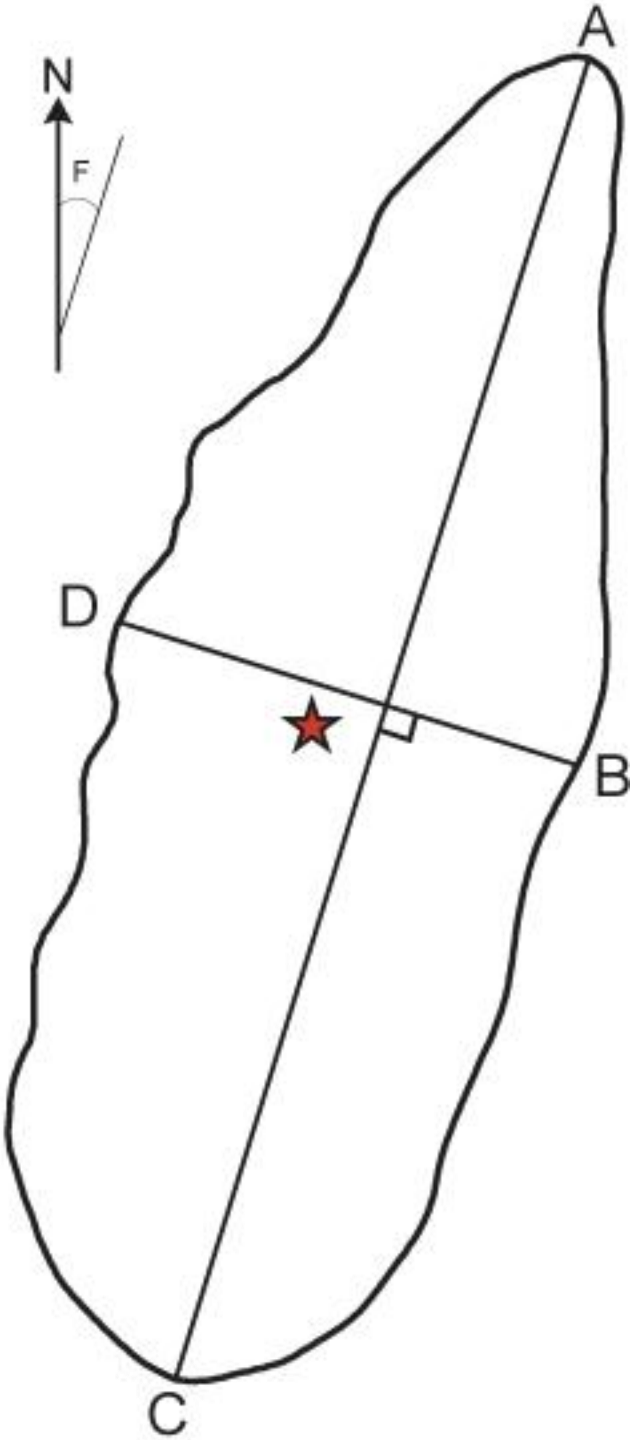

Location of individual drumlins
Elongation ratio less than 2
Elongation ratio between 2 and 4
Elongation ratio greater than 4
Oak Ridges Moraine
Iroquois shoreline
N
10 km

analysed individually to ensure that only one topographical high was recorded for each drumlin. In the automated process of drumlin identification, the GIS program seeks the highest value single enclosed contour to represent the highest point on the drumlin.

3.3.3 Calculation of morphological attributes of the drumlins

Each drumlin digitized as a polygon in the database was assigned a unique code number. The morphological attributes of each drumlin were then calculated through the use of ArcView scripts including width (W), length (L), area (A), perimeter (P), geometric center and long-axis azimuth. Length was calculated, and is defined, as the longest straight line that can be drawn through the polygon (Figure 3.9). Drumlin width was determined to be the line of longest length inscribed in the drumlin perpendicular to the length line. Length and width measurements were then used to calculate the Elongation Ratio (ER = L/W) for each drumlin. An elongation ratio of one indicates a circular object with increasing ER values indicating more elongate forms. Drumlins were then classified into elongate (ER >4), intermediate (ER = 2 to 4) and ovoid (ER <2) types according to their elongation ratio (Figure 3.8). In order to analyse the spatial distribution of drumlins across the PDF, the geometric center of each drumlin was calculated within ArcView as the mathematical center of the irregular polygon. The long axis orientation of the drumlins was also determined by measurement of the polygon azimuth, which was recorded as a uniaxial direction of between 0^o and 180^o (Figure 3.9).

Figure 3.9: Schematic plan view of drumlin showing dimensions measured for form analysis. Line A-C represents the length (long axis) of the drumlin defined as the longest straight line possible within the polygon; D-B represents the width of the drumlin and is defined as the longest straight line possible within the polygon perpendicular to the long axis; the compass direction of the long axis is represented by F and defines the uniaxial drumlin orientation; the star represents the geometric center of the drumlin. Area and perimeter are automatically calculated at the creation of the polygon attribute table.


N
F
A
D
B
C

3.4 Results and Analysis

In order to better understand the morphological variability of drumlin types within the study area and to identify any preferential spatial arrangement of morphological types both non-spatial and spatial analyses were conducted. Non-spatial analytical methods address questions concerning drumlin form such as ‘What is the mean elongation value of drumlins within the study area?’, while spatial methods address questions of spatial relationships between drumlin types such as ‘Do drumlins in the northeastern section of the map tend to be more elongated than those in the southwestern section?’ Non-spatial data analysis includes ‘classic’ statistical parameters such as the mean, standard deviation and long axis azimuth of calculated parameters. Spatial analysis (also known as spatial statistics) examines the geographic relationship of the individual drumlin polygons to each other and their relative position within the study area.

3.4.1 Non-spatial analysis

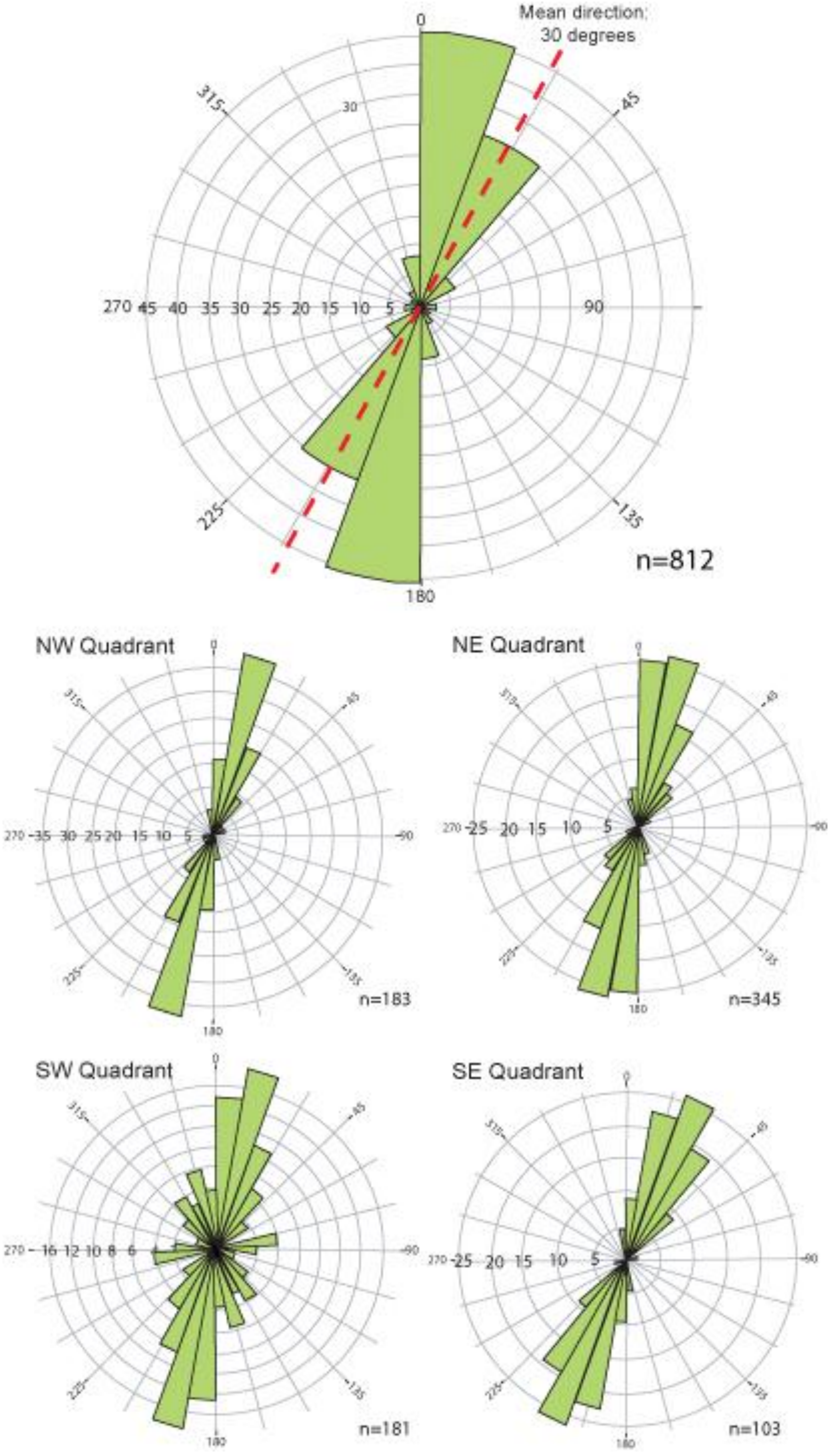
Non-spatial analysis of data describing the morphological characteristics of drumlins within the entire study area provides information about the overall characteristics of drumlins within the field and identifies maximum, minimum and standard deviation values for individual morphological parameters (Table 3.1). Drumlins range from 55 to 2220 m in length and between 0.01 and 1.7 km^2 in area. The mean elongation ratio of 2.9 is comparable to mean values obtained from numerous other drumlin studies (Clark et al., 2009). In this study, the long axis orientation of drumlins was analysed only as a uniaxial trend due to a limitation of the computational method that did not have a reliable unidirectional identifier. Examination of uniaxial orientation data for the whole study area shows that the overall long axis trend of drumlin direction is fairly consistent at 30°/210° (Figure 3.9), and agrees with ice-flow directions from northeast to southwest as previously recognised from field studies (e.g. Karrow 1967, Barnett 1992).

3.4.2 Spatial analysis

Comparison of the drumlin forms within each of the four equally sized quadrants of the study area (Figure 3.3) shows that each quadrant contains drumlins with distinct morphological characteristics and suggests a spatial control on the development of drumlin forms. Average elongation ratios calculated for each of the four quadrants of the study area range from a high of 3.5 in the northeast, where drumlins are predominantly elongate, to a low of 2.4 in the southwest, where drumlins are predominantly ovoid (Table 3.1; Figure 3.7). Drumlin long axis orientation is relatively consistent within each of the four quadrants, with the greatest amount of dispersion shown by drumlins within the southwestern quadrant (Figure 3.10).

Spatial analysis of the distribution of drumlins within the study area identifies whether or not drumlins occur in a random or an orderly fashion. Nearest Neighbour Analysis (NNA) is the study of the spatial distribution of objects (in this case drumlins) in order to discern any regularity in spacing by comparing the actual pattern of occurrence with a theoretical random pattern (Bailey and Gatrell 1995). The use of NNA allows for the classification of data as dispersed, random or clustered (Trenhaile 1971).

Figure 3.10: Rose diagrams illustrating drumlin long axis orientations for entire study area (large upper diagram) and individual quadrants (see Figure 3.3 for location of quadrants). The long axis azimuth of drumlin polygons were not assigned an absolute direction but a bidirectional trend. The trend of the drumlin orientation data for the entire study area (30° to 210°) is represented by the red dashed line. Drumlin orientations within individual quadrants of the study area show patterns different to the trend of the entire study area. Values obtained using Rock ware Rockworks software.


Mean direction:
30 degrees
0
45
90
135
180
225
270
315
270 45 40 35 30 25 20 15 10 5
30
n=812
NW Quadrant
270 35 30 25 20 15 10 5
n=183
NE Quadrant
270 25 20 15 10 5
n=345
SW Quadrant
270 16 12 10 8 6
n=181
SE Quadrant
270 25 20 15 10 5
n=103

NNA of the geometric center of drumlins within the study area shows a distinctly clustered pattern and indicates that there is a less than 1% likelihood of the clustered pattern resulting from random chance. Further testing for spatial randomness of these data using Multi-Distance Spatial Cluster Analysis (Ripley's K-function) illustrates a statistically significant pattern of clustering at a 99% confidence interval (Figure 3.11; Ripley 1981). This indicates that the observed spatial pattern of drumlin distribution is statistically different from that expected from a random spatial pattern.

3.4.3 Kernel estimation

Kernel estimation is an effective method for visualizing the distribution of event density over time and/or space but is underutilized in geomorphological data analysis (Cox 2007). In this study, it is used to visualize variability in the concentration of drumlins across the study area. Kernel estimation creates a map of density values in which the density at each location reflects the concentration of points representing the geometric centres of the landforms in question. The distance of influence of the kernel, or area included in the density analysis, is determined by the user and is referred to as the bandwidth (Figure 3.12). Density highs represent areas in which there is a relatively high concentration of drumlins and density lows represent areas of relatively sparse drumlin distribution. This provides a qualitative interpretation of relative clustering or spatial concentration of drumlin forms. Kernel estimations of drumlin distribution also show that drumlins are not randomly distributed across the study area but are most highly

Figure 3.11: K-function estimate for drumlin polygons. The green and orange lines represent 'simulation envelopes' to show an upper and lower limit to expected values (with a 99% confidence interval) if complete spatial randomness on drumlin distribution is assume. The K-function value lies above the envelopes at distances up to 50km illustrating a clustering of the data and implies a lack of a random spatial pattern.

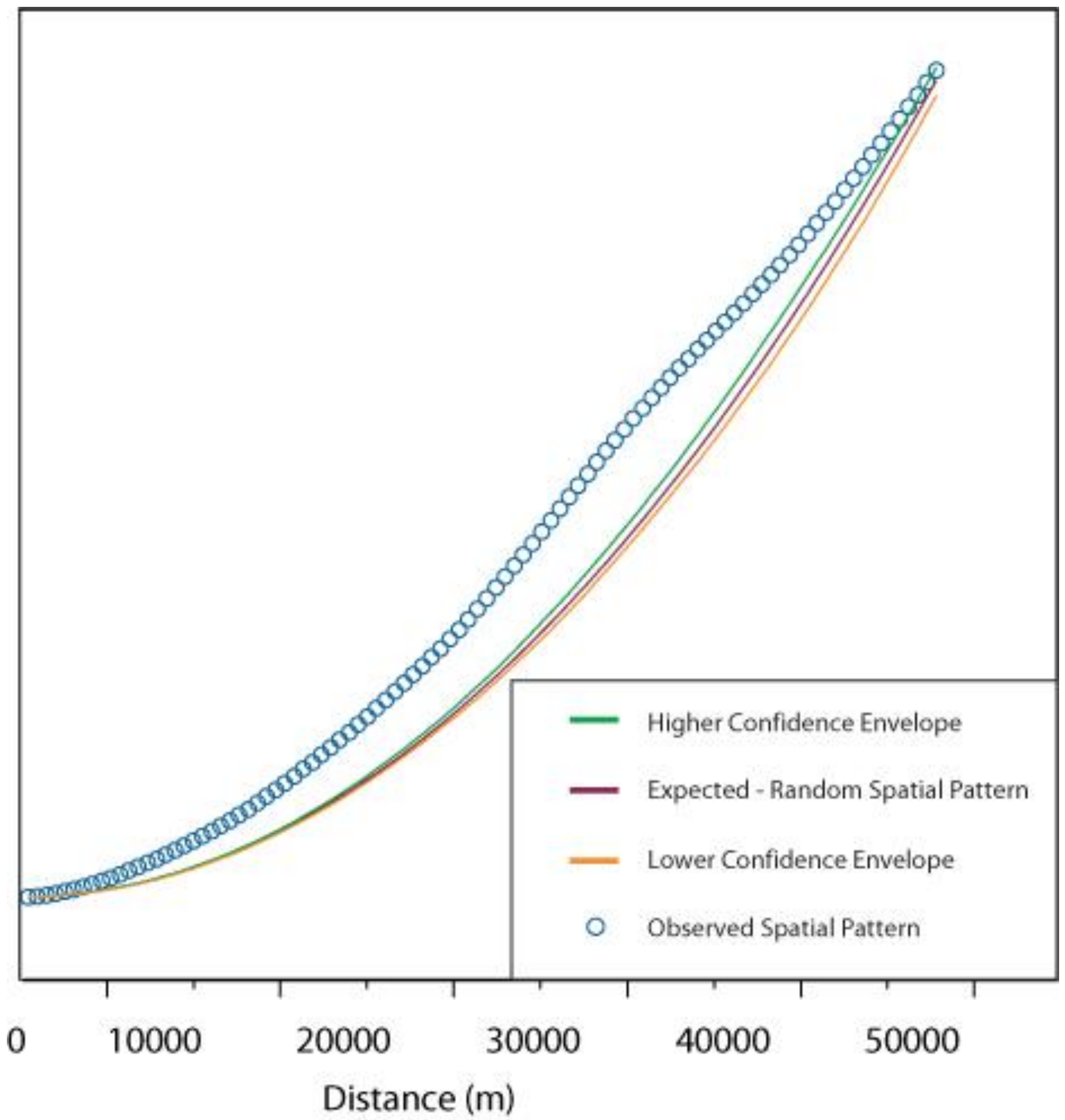
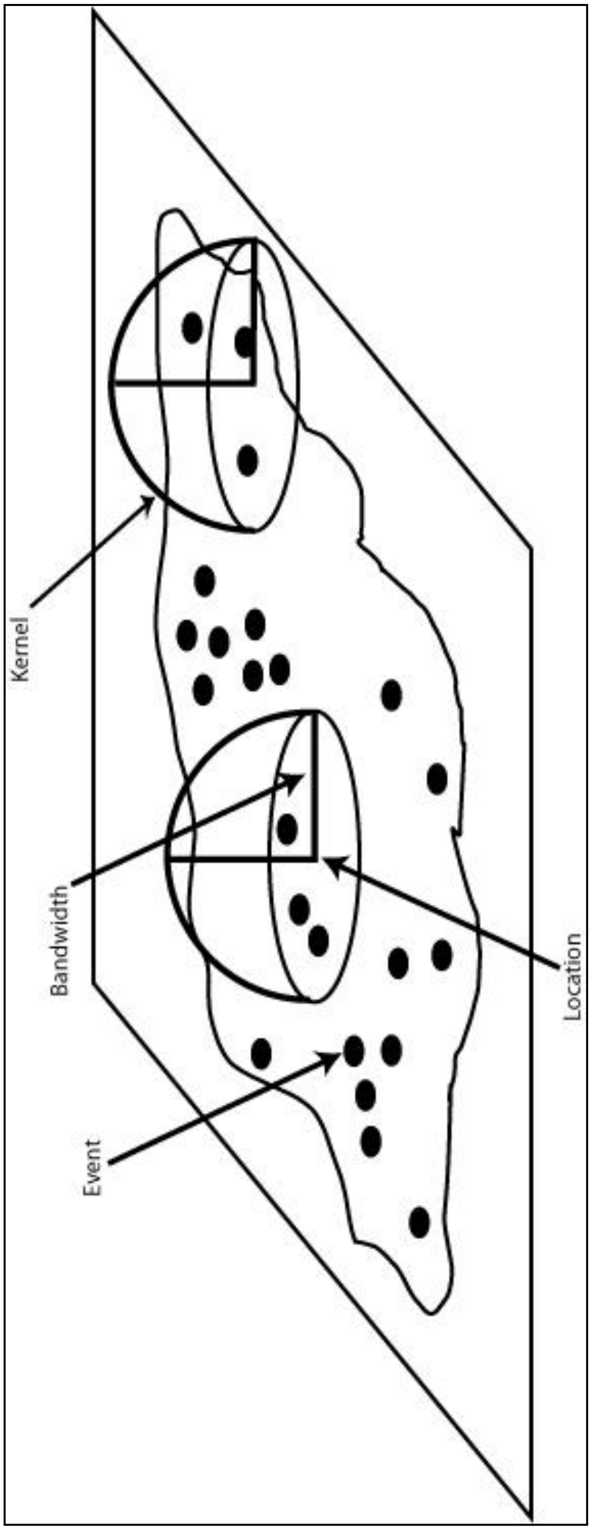

Higher Confidence Envelope
Expected - Random Spatial Pattern
Lower Confidence Envelope
Observed Spatial Pattern
0
10000
20000
30000
40000
50000
Distance (m)

Figure 3.12: Schematic diagram to show method of kernel estimation. A ‘kernel’ is moved through a study area and all events (e.g. drumlins) within the kernel are counted. This is done at user set intervals throughout the study area and the result is a continuous surface illustrating event (e.g. drumlin) concentrations. The bandwidth is set by the researcher and determines the size of the kernel. The location is the point in space where the value obtained will be recorded.

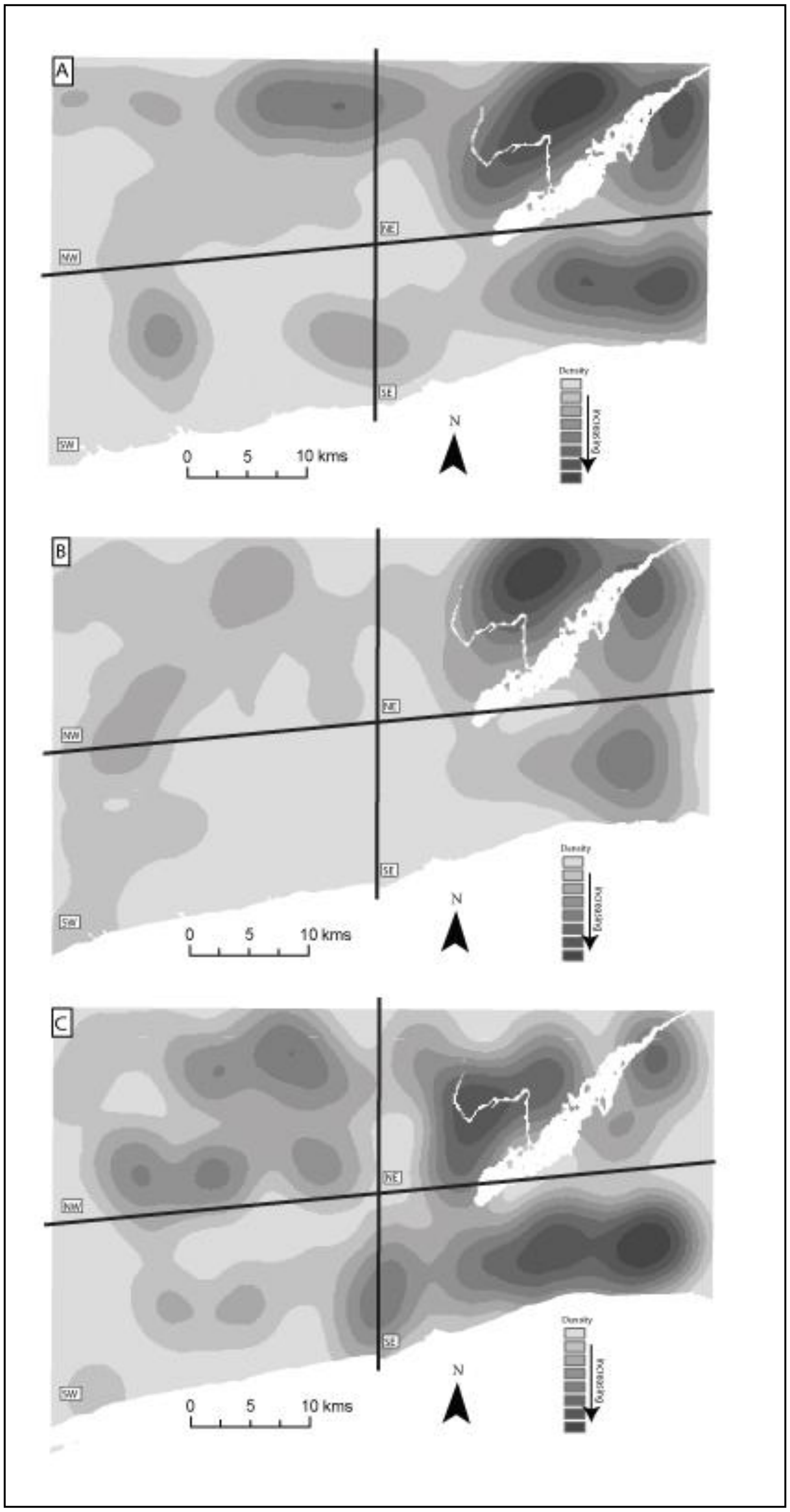

Kernel
Bandwidth
Location
Event

concentrated in the northeast quadrant (Figure 3.13A). Kernel density maps of drumlins with specific morphological attributes were also created using only drumlins possessing the top quintile of values for that attribute (Figure 3.13). These maps show that drumlins with the highest elongation values are most highly concentrated in the northeast quadrant (Figure 3.13B) and that pockets of relatively large drumlins are concentrated in the eastern half of the study area (Figure 3.13C). The southwestern quadrant of the study area contains relatively few large drumlins.

3.4.4 Summary: Spatial distribution of drumlin forms within the PDF

Quantitative analysis of the form and spatial distribution of drumlins within the PDF identifies a number of distinctive patterns that may reflect spatial variability in processes and conditions responsible for their formation. Drumlins are not randomly distributed across the study area but are ‘clustered’ in the northeast quadrant. This part of the study area also contains the greatest concentration of large, elongate drumlins. Drumlins are not present on top of the Oak Ridges Moraine and are rare in areas south of the Lake Iroquois shoreline (Figure 3.8). Drumlins in the south tend to be slightly smaller on average than those in the northern sections, with a greater size range and predominantly ovoid forms (Figure 3.13). The clustering of less elongated drumlins in the areas closer to Lake Ontario is consistent with results previously presented by Boyce and Eyles (1991) who determined length:width ratios of drumlins in a similar portion of the PDF. The average elongation ratio of 2.9 calculated for drumlins in the study area is

Figure 3.13: Maps to illustrate kernel estimation of drumlin distribution across the study area. (A) Kernel estimation of all drumlins across the study area. (B) Kernel estimation of drumlins with the highest elongation ratios (top quintile). (C) Kernel estimation of drumlins with the highest area values (top quintile).


A
NE
NW
SE
SW
0 5 10 kms
N
Density
increasing
B
NE
NW
SE
SW
0 5 10 kms
N
Density
increasing
C
NE
NW
SE
SW
0 5 10 kms
N
Density
increasing

similar to that identified in previous studies in Upper State New York (Kerr and Eyles 2007), in Poland (Wysota 1995), in Denmark (Jørgensen and Piotrowski 2003) and the Arran and Woodstock Drumlin Fields in Ontario, Canada (Harry and Trenhaile 1987, Piotrowski 1987). This value is identical to the mean elongation ratio of 2.9 determined in a review of all documented drumlin forms (n=37,043) by Clark et al. (2009).

The average preferred long axis orientation of drumlins in the study area (30°/210 °) is also consistent with other studies documenting ice-flow direction in the region (Shaw and Sharpe 1987, Boyce and Eyles 1991). However, there is some variation in long axis orientation of drumlins within different quadrants. Drumlin long axis orientation in the southwestern quadrant shows greater directional variability and an average orientation of approximately 330°/150° (Figure 3.10). This has been interpreted by others to record flow of the Ontario Lobe out of the basin towards the northwest during the Port Huron stadial (Boyce and Eyles 1991).

3.5 Discussion

This study applies a quantitative methodology using GIS tools to identify distinctive patterns in the distribution and form (size, elongation and orientation) of drumlins in a portion of the PDF, patterns that reflect spatial variability in the conditions responsible for drumlin formation. Few studies have related the specific morphological variable of drumlin size to glacial processes or substrate characteristics (Miller 1972, Mitchell 1994). However, the largest drumlins in the study area are concentrated in the northeast quadrant, an area of relatively low drift thickness (Figure 3.6).

The creation of drumlins with variable elongation ratios has been attributed to a number of factors including differences in drift thickness, drainage conditions, time, and ice velocity (Clark et al. 2009, Hess and Briner 2009). The availability of substantial amounts of sediment beneath an ice margin is considered by many to induce the formation of deforming bed conditions and the generation of streamlined (‘classical’) drumlin forms (Boulton and Hindmarsh 1987, Knight 1997, Stokes and Clark 2002). However, in their study of drumlins in upper New York State, Kerr and Eyles (2007) argue that streamlined drumlin forms are most common in areas of thin sediment cover where glacial erosion has removed much of the pre-existing sediment. In the PDF study area, the most elongate drumlin forms occur in areas of relatively thin drift cover and their development may similarly reflect substantial glacial erosion of pre-existing sediment.

Drainage conditions at the ice base are also considered to affect the development of different drumlin forms (Knight and McCabe 1997, Boulton et al. 2009). Units of well drained subglacial sediment are relatively resistant to subglacial deformation and provide resistant cores around which sediment may be streamlined to form drumlins. Hence, drumlins should be most abundant on coarse and relatively well drained substrates (Boulton and Hindmarsh, 1987). In the PDF study area, it is difficult to evaluate the influence of substrate type and drainage conditions on the development of drumlins as many units of surficial sediment were deposited subsequent to ice retreat or in ice marginal environments. Consequently, few drumlins can be identified in the large area of gravel and sand that forms part of the interlobate Oak Ridges Moraine (Figure 3.6). Shoreline erosion and deposition during post glacial flooding of the area by Lake Iroquois has also modified drumlin forms in the southern quadrants (Briner 2007, Eyles and Meriano 2010).

The spatial distribution of drumlin forms has also been related to the amount of time available for drumlin development. The formation of less elongate drumlins has been related to relatively short residence times below the ice (Boulton and Hindmarsh 1987, Boyce and Eyles 1991) reflecting lesser amounts of time in which elongation and streamlining processes could operate. Elongate drumlins are most common in the northeastern quadrant of the study area, an area that would have been covered by ice and affected by subglacial processes for longer periods of time than areas to the south. The transition from elongate drumlin forms in the northeast to more rounded forms in the south of the PDF was also noted by Boyce and Eyles (1991) who ascribed this change in drumlin morphology to differences in subglacial residence times. However, drumlins in the northwestern quadrant of the study area, an area that would have experienced similar subglacial residence times to the northeast quadrant, do not show the same high degree of elongation (Figure 3.13).

Changes in drumlin form and elongation within a drumlin field have also been ascribed to spatial variations in ice sheet dynamics. It has been hypothesized that ice sheet velocity impacts the morphology of drumlins formed under subglacial conditions, with faster moving ice producing drumlins with higher elongation ratios (Chorley 1959, Stokes and Clark 2002, Briner 2007). This change in ice sheet dynamics could be caused by numerous factors ranging from climatic to geologic controls (Cuffey and Marshall 2000, Marshall et al. 2000). The location of streams of fast moving ice within an ice sheet has been related to underlying bedrock troughs or areas of particularly soft sediment that predispose an area to particularly rapid ice-flow (Stokes and Clarke 2003). Drumlin-like forms have been identified beneath the modern Rutford Ice Stream in the Antarctic (Smith et al. 2007, Gudmundsson and Jenkins 2009).

The most elongate drumlins within the PDF study area lie within a broad bedrock low in which Rice Lake now sits. The area characterised by the most elongate drumlin forms may therefore delineate the former location of a fast flowing zone of ice, or ice stream (Figure 3.8; Stokes and Clark 2002). Boyce and Eyles (1991) inferred the existence of such an ice stream but were not able to delineate its boundaries. Fine-grained lacustrine sediment deposited within the bedrock low prior to ice advance may also have facilitated rapid ice movement (Stokes and Clark 2003). The zone of elongated drumlins may be used to identify a former fast flowing ice stream at least 10 km to15 km wide although the eastern boundary of the ice stream may lie outside of the study area (Figure 3.6). This former ice stream is on scale consistent with modern ice streams documented in the Antarctic (Alley et al. 1986) such as the West Antarctic Ice Steam (Engelhardt et al. 1990), paleo ice streams such as a Late Weichselian ice stream within the Scandinavian Ice Sheet (Jørgensen and Piotrowski 2002) and Irish Ice Streams in north central Ireland (Knight and McCabe 1997).

The average preferred long axis orientation of drumlins in the study area (30°/210°) is consistent with other studies documenting ice-flow direction in the region (Shaw and Sharpe 1987, Boyce and Eyles 1991). However, the southwestern quadrant shows a preferred drumlin long axis orientation of approximately 330°/150° that may be interpreted to indicate an ice-flow direction trending in a southeast to northwest direction (Figure 3.10; Liberty 1969, Boyce and Eyles 1991). These data support the idea that sediments in the southwestern quadrant may have been reworked by the last surge of the Ontario Lobe of the Laurentide Ice Sheet which travelled out of the Lake Ontario basin toward the northwest (Boyce and Eyles 1991). This short-lived advance of the ice margin may have also reworked previously deposited glacial sediments to create drumlin forms with low elongation ratios close to the shore of Lake Ontario (Möller, 2004).

3.6 Conclusions

The computational geomorphological techniques described in this paper have been used to conduct a quantitative analysis of the form and spatial distribution of drumlins across a portion of the Peterborough Drumlin Field. A number of factors may account for the spatial variability of drumlin forms across the study area including residence time below the ice, ice velocity, variations in ice-flow direction and reworking and modification by post-glacial geomorphic processes. However, the distribution of elongate drumlin forms across the study area appears to coincide with the location of a broad bedrock low that may have facilitated the development of a zone of fast flowing ice (ice stream). Elongated drumlins in this area may therefore be used to delineate the position of a former ice stream and can contribute data to aid in the reconstruction of former ice sheet dynamics. Similar quantitative studies of drumlin fields in other regions are now required to allow comparative analysis of patterns of drumlin forms in different physiographic settings and identification of characteristics most critical to the reconstruction of former glacial processes.

This paper outlines a computational methodology that may be used to quantitatively analyse the form and spatial distribution of drumlins within a drumlin field. Such quantitative analysis of landforms creates a systematic and reproducible protocol for their identification and description which allows direct comparison of data between different study sites. If applied more widely, this methodology could facilitate the compilation of a large database of drumlin morphological characteristics covering extensive formerly glaciated areas. The ultimate aim of such a large scale study would be to use the spatial variability of drumlin characteristics to better understand mechanisms responsible for their formation and to reconstruct processes and conditions operating at the base of former ice sheets (e.g. Boulton and Hindmarsh 1987, Boyce and Eyles 1991, Benn and Evans 2006, Clark et al. 2009).

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CHAPTER 4

SPATIAL ANALYSIS OF DRUMLINS WITHIN THE ARRAN, GUELPH, AND GALT DRUMLIN FIELDS OF SOUTHERN ONTARIO

Abstract

Reconstruction of former ice conditions and glacier dynamics in previously glaciated terrains requires understanding of the processes and controls on the development of subglacial landforms such as drumlins. This paper presents a quantitative analysis of the spatial distribution of drumlins identified from digital elevation model (DEM) data within three drumlin fields in southern Ontario (the Arran, Galt and Guelph drumlin fields) and a field description of a partially excavated drumlin within the Guelph drumlin field. Drumlins are identified and their morphological parameters documented using a computer-based process that allows direct comparison of forms within and between individual fields. Statistical analysis of the morphological characteristics and spatial distribution of drumlins within each of the three drumlin fields, using kernel density and nearest neighbour analysis, indicates that drumlins of particular types show distinct patterns of clustering. These patterns of clustering appear to be are related to several different factors including length of time under ice, bedrock topography, and ice velocity. Sediments exposed in one drumlin within the Guelph drumlin field show a relatively undisturbed older fluvial or glaciofluvial crudely stratified sands draped by a

thin veneer of coarse grained deformation till. This stratigraphy is similar to that described from modern drumlins in Iceland and is consistent with models of drumlin formation by subglacial deformation processes. The methodology of drumlin analysis presented in this paper can be applied to the study of any drumlin field with an adequate coverage of digital spatial data. The ability to consistently identify and characterize drumlin morphology and distribution will allow more objective and systematic comparison of these landforms both within and between drumlin fields and will enhance understanding of the spatial controls on the development of these enigmatic landforms.

4.1 Introduction

Drumlins are subglacial landforms, commonly found in glaciated landscapes previously shaped by actively moving temperate glaciers (Briner 2007, Knight 2010, Spangnolo et al. 2010). Classically shaped drumlins are streamlined asymmetric hills aligned parallel to the inferred paleodirection of ice flow that have a blunt, steep side facing up glacier (stoss-side) and a more gently sloping, tapered side (lee side) facing down glacier (Piotrowski 1987). Drumlins most commonly range in size between 250 and 1000 m long, and 120 to 200 m wide (Clark et al. 2009), and tend to cluster in groupings referred to as drumlin fields or swarms (Lesemann and Brennand 2009).

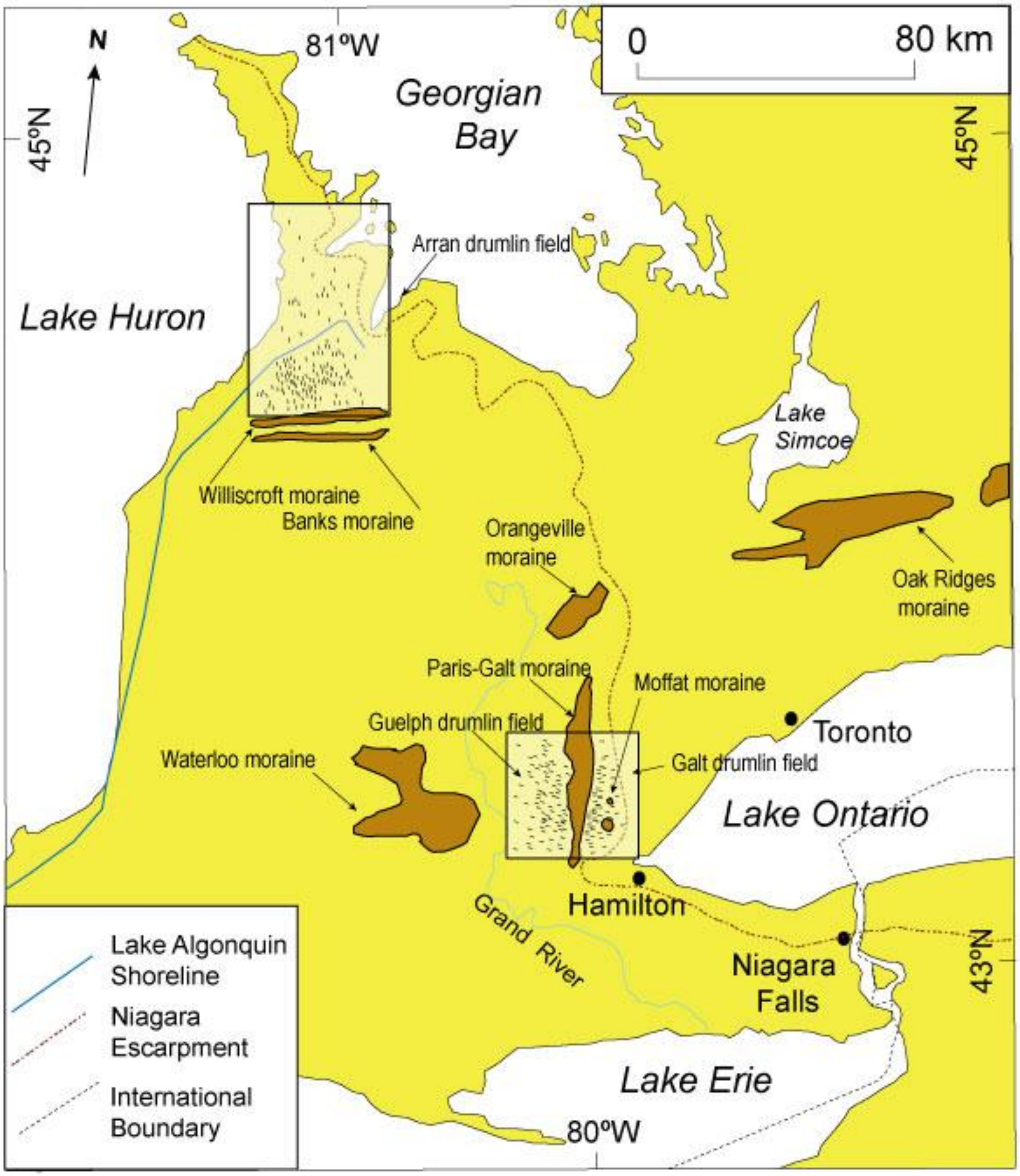
The consistency of form and orientation of individual drumlins within a drumlin field allows drumlins to serve as a valuable tool for the reconstruction of previous ice movement (Boyce and Eyles 1991, Knight 2010). However, despite extensive qualitative investigations of drumlin fields (Spangnolo et al. 2010), the genesis of drumlins is controversial and is vigorously contested within the literature (Shaw and Sharpe 1987, Boyce and Eyles 1991, Shaw 2002, Clark et al. 2009, Fowler 2010). Understanding drumlin genesis is important because of the valuable information these landforms can provide regarding former subglacial conditions and large scale ice sheet dynamics. However, the current lack of consensus regarding drumlin genesis and the processes controlling their spatial distribution prevents effective knowledge translation to the field of ice sheet dynamics.

The most widely accepted theory of drumlin genesis involves subglacial deformation of water-saturated sediment (Boulton and Hindmarsh 1987, Lee and Phillips 2008, Evans 2011). This model of drumlin formation proposes that ice advancing over a relatively thick succession of heterogenous sediment, will deform and remobilize water-saturated fine-grained sediments (silts and clays), forming a slurry at the ice base. Coarser-grained sediments overridden by the ice are better drained and less easily deformed and become streamlined, or ‘boudinaged’, into drumlinized forms (Boulton and Hindmarsh 1987). An alternate model involves drumlin formation by catastrophic subglacial meltwater floods, and theorizes the erosion and/or deposition of sediment into drumlinized forms as a result of subglacial sheet floods (Shaw 1983, 2002, 2010). Each of these models involves quite different drumlin forming processes that will vary spatially and should be reflected in the form and distribution of drumlins within either a single drumlin field, or between geographically distinct drumlin fields.

The spatial distribution of drumlin types has been attributed to various factors including substrate type and thickness, ice velocity, and length of time under the ice (Hess and Briner 2009, Knight 2010). Hence, analysis of the spatial distribution of drumlin types within or between fields has the potential to enhance understanding of the processes involved in drumlin genesis and former ice sheet dynamics (Clark et al. 2009, Hess and Briner 2009). Unfortunately, few quantitative data are available to compare drumlin types and their spatial distribution within or between individual drumlin fields. Many previous drumlin studies are based upon qualitative observations (e.g. Shaw 1983, Shaw and Sharpe 1987), although there is a now a trend toward utilization of more quantitative approaches to the study of these enigmatic landforms (e.g. Kerr and Eyles 2007, Clark et al. 2009, Smith et al. 2007, Hess and Briner 2009, Knight 2010).

This paper presents a quantitative analysis of the spatial distribution of drumlins within three drumlin fields in Southern Ontario (the Arran, Galt and Guelph drumlin fields) and a qualitative description of an excavated drumlin within one of the fields (Figure 4.1). In this study drumlins are identified using a methodology created within a Geographic Information System (GIS) that utilizes existing, widely available digital topographic data. This methodology is similar to that successfully applied to a portion of the Peterborough drumlin field in Southern Ontario (Maclachlan and Eyles, submitted). Once identified, the drumlins are characterized according to their morphological attributes (e.g., length, width, elongation ratio) and analyzed using quantitative methods that show the distribution and clustering of drumlins with specified morphological attributes within each of the fields.

Figure 4.1: Map of the study area showing location and extent of the Arran, Guelph and Galt drumlin fields (boxed and highlighted areas) and major physiographic features (adapted from Eyles 2002).


N
81ºW
45ºN
Georgian Bay
0 80 km
45ºN
Arran drumlin field
Lake Huron
Lake Simcoe
Williscroft moraine
Banks moraine
Orangeville moraine
Oak Ridges moraine
Paris-Galt moraine
Moffat moraine
Guelph drumlin field
Toronto
Waterloo moraine
Galt drumlin field
Lake Ontario
Hamilton
Grand River
Niagara Falls
43ºN
Lake Algonquin Shoreline
Niagara Escarpment
International Boundary
Lake Erie
80ºW

This study augments the results of the quantitative analysis of drumlin form and distribution with qualitative sedimentological data from a freshly excavated drumlin in order to better evaluate the mechanism of drumlin formation and its potential relationship to ice sheet dynamics. The methodology presented here can be replicated elsewhere to describe and analyse the spatial distribution of drumlins in any drumlin field where adequate digital data exist.

4.2 Study Area

The Arran, Galt, and Guelph drumlin fields (Figure 4.1) were selected for study because they formed in relatively close geographic proximity to one another as a result of separate advance phases of the southern margin of the Laurentide Ice Sheet (LIS) during the late Wisconsin. The Guelph and Galt drumlin fields are adjoining fields separated by the Paris-Galt moraine (Figure 4.1) and are often referred to as a single field (Costello and Walker 1972, Barnett 1992). These drumlin fields collectively cover an area of approximately 1,000 km^2 and lie approximately 75 km southwest of Toronto (Figure 4.1; Trenhaile 1975). The Arran drumlin field covers an area of approximately 1000 km^2 and lies 200 km northwest of Toronto (Figure 4.1; Kor and Cowell 1998).

Two major Late Wisconsin ice lobes of the LIS that affected the lower Great Lakes basins, the Ontario ice lobe and the Georgian Bay ice lobe, are thought to be responsible for the formation of the three drumlin fields under investigation (Barnett 1992). The Arran drumlin field formed beneath the Georgian Bay ice lobe as it moved over the relatively thin Quaternary sediment cover overlying bedrock south of Georgian

Bay (Figure 4.1). The Guelph and Galt drumlin fields, while separated by a relatively small distance, are believed to have been created by two separate ice advance events during the Port Huron stadial (Figure 4.2). Quantitative analysis of drumlins within these fields should show significant variance over a small geographic area (Costello and Walker 1972, Trenhaile 1975) and may allow more accurate reconstruction of past ice movements.

4. 2.1 Arran drumlin field

The Arran drumlin field is bounded by Lake Huron and Georgian Bay to the west, east and north, and by the Niagara Escarpment to the northeast (Figure 4.1). The area is underlain by an extensive till plain with drift thicknesses that range from almost zero in the north, where the bedrock can be exposed at the surface, to over 50 m towards the southern extent of the study area where the Williscroft and the Banks end moraines are located (Figure 4.3; Gwyn and Cowan 1978). Both end moraines were formed as ice withdrew during the Late Wisconsin Port Huron Stadial, the last major ice advance to affect the study area, when the Georgian Bay ice lobe flowed into the area from the north.

Figure 4.2: Late glacial history and deposits in southern Ontario. **A.** Time distance diagram showing extent of influence of ice lobes formed along the southern margin of the Late Wisconsin Laurentide Ice Sheet and relevant subglacial deposits (tills), drumlin fields and end moraines. **B, C.** Schematic diagrams to show ice cover and flow directions in southern Ontario at 25-18Ka and 13 Ka respectively. Study areas shown by shaded boxes. (adapted from Howard et al. 1999).

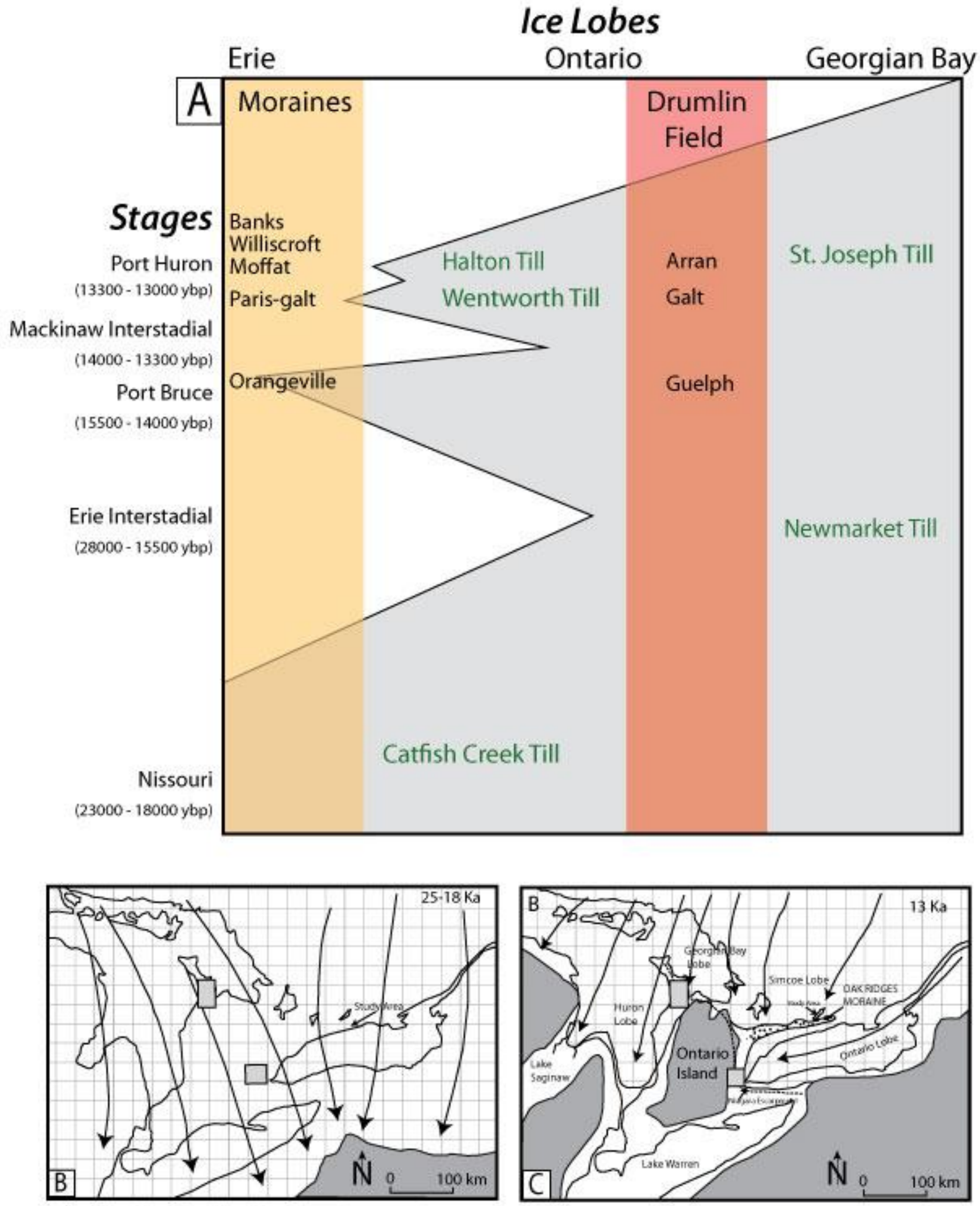
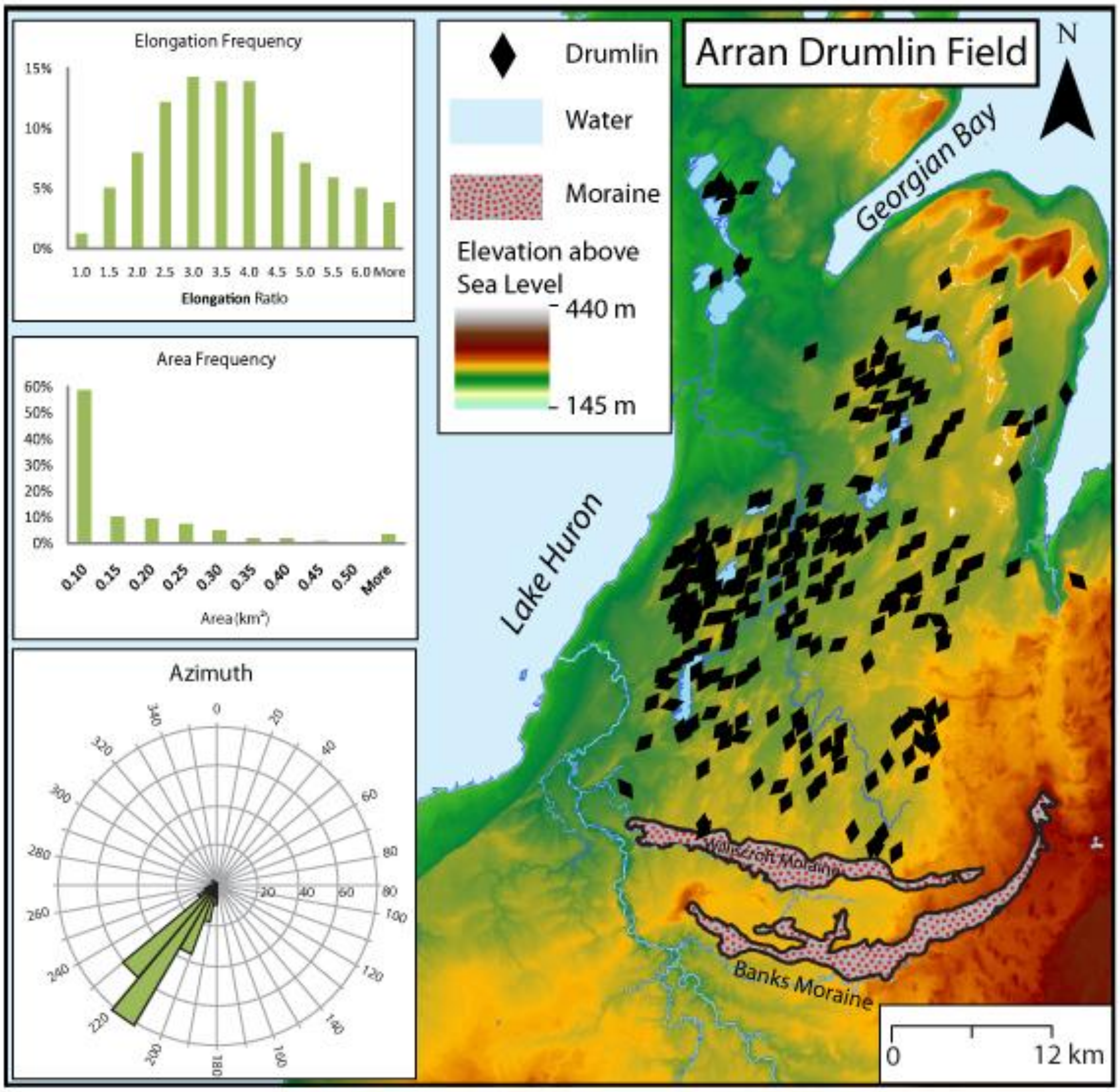

Ice Lobes
Erie
Ontario
Georgian Bay
A
Moraines
Drumlin Field
Stages
Port Huron
(13300 - 13000 ybp)
Mackinaw Interstadial
(14000 - 13300 ybp)
Port Bruce
(15500 - 14000 ybp)
Erie Interstadial
(28000 - 15500 ybp)
Nissouri
(23000 - 18000 ybp)
Banks
Williscroft
Moffat
Paris-galt
Orangeville
Halton Till
Wentworth Till
Catfish Creek Till
Arran
Galt
Guelph
St. Joseph Till
Newmarket Till
25-18 Ka
Study Area
0
100 km
B
13 Ka
Georgian Bay Lobe
Simcoe Lobe
OAK RIDGES MORAINE
Study Area
Huron Lobe
Lake Saginaw
Ontario Island
Ontario Lobe
Niagara Escarpment
Lake Warren
0
100 km
C

Figure 4.3: Right: Coloured DEM of the Arran drumlin field showing the distribution and trend of drumlin long axes (diamond symbol). Diamond long axes trend in the same direction as drumlin long axes as determined from analysis of DEM data.

Left: Summary morphological data (elongation ratio, area and long axis azimuth) for drumlins identified in the Arran field.


Elongation Frequency
15%
10%
5%
0%
1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 More
Elongation Ratio
Area Frequency
60%
50%
40%
30%
20%
10%
0%
0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 More
Area (km²)
Azimuth
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
20 40 60 80
Drumlin
Water
Moraine
Elevation above Sea Level
440 m
145 m
Arran Drumlin Field
N
Georgian Bay
Lake Huron
Banks Moraine
0
12 km

4.2.2 Guelph and Galt drumlin fields

The Guelph and Galt drumlin fields cover an extensive till plain bounded by the Niagara Escarpment to the east (Figure 4.1). The area is underlain by a sandy to silty sand till (Wentworth Till; OGS 2011) deposited beneath the Ontario ice lobe as it flowed in a north-westerly direction out from the Ontario basin between 15,000 and 13,000 years ago (Costello and Walker 1972, Trenhaile 1975, Barnett 1992). The Guelph and Galt drumlin fields are differentiated by their geographic location to the west and east of the Paris-Galt moraine respectively and also by slight changes in drumlin orientation (Figures 4.4, 4.5). The physical separation of the two drumlin fields by the Paris-Galt moraine suggests that they formed as a result of two distinct phases of ice advance, with the Guelph field pre-dating the Galt field. The Paris-Galt moraine represents the westward extent of minor advances of the Ontario ice lobe during retreat and is traditionally interpreted as an ice-contact moraine deposited approximately 13,000 - 14,000 y.b.p. (Figure 4.2; Trenhaile 1971, Costello and Walker 1972, Gwyn and Cowan 1978, Barnett 1992). This was probably concurrent with formation of the drumlins of the Galt drumlin field (Trenhaile 1975). The small Moffat moraine lies within the Galt drumlin field and may overlie drumlins within sections of the field (Figure 4.1; Straw 1968). Sediments within the Moffat moraine are similar to those of the Paris-Galt moraine and are believed to have been deposited during a minor readvance of the Ontario lobe as it receded toward the east (Straw 1968, Trenhaile 1975).

Figure 4.4: Right: Coloured DEM of the Galt drumlin field showing the distribution and trend of drumlin long axes (diamond symbol). Diamond long axes trend in the same direction as drumlin long axes as determined from analysis of DEM data.

Left: Summary morphological data (elongation ratio, area and long axis azimuth) for drumlins identified in the Galt field.

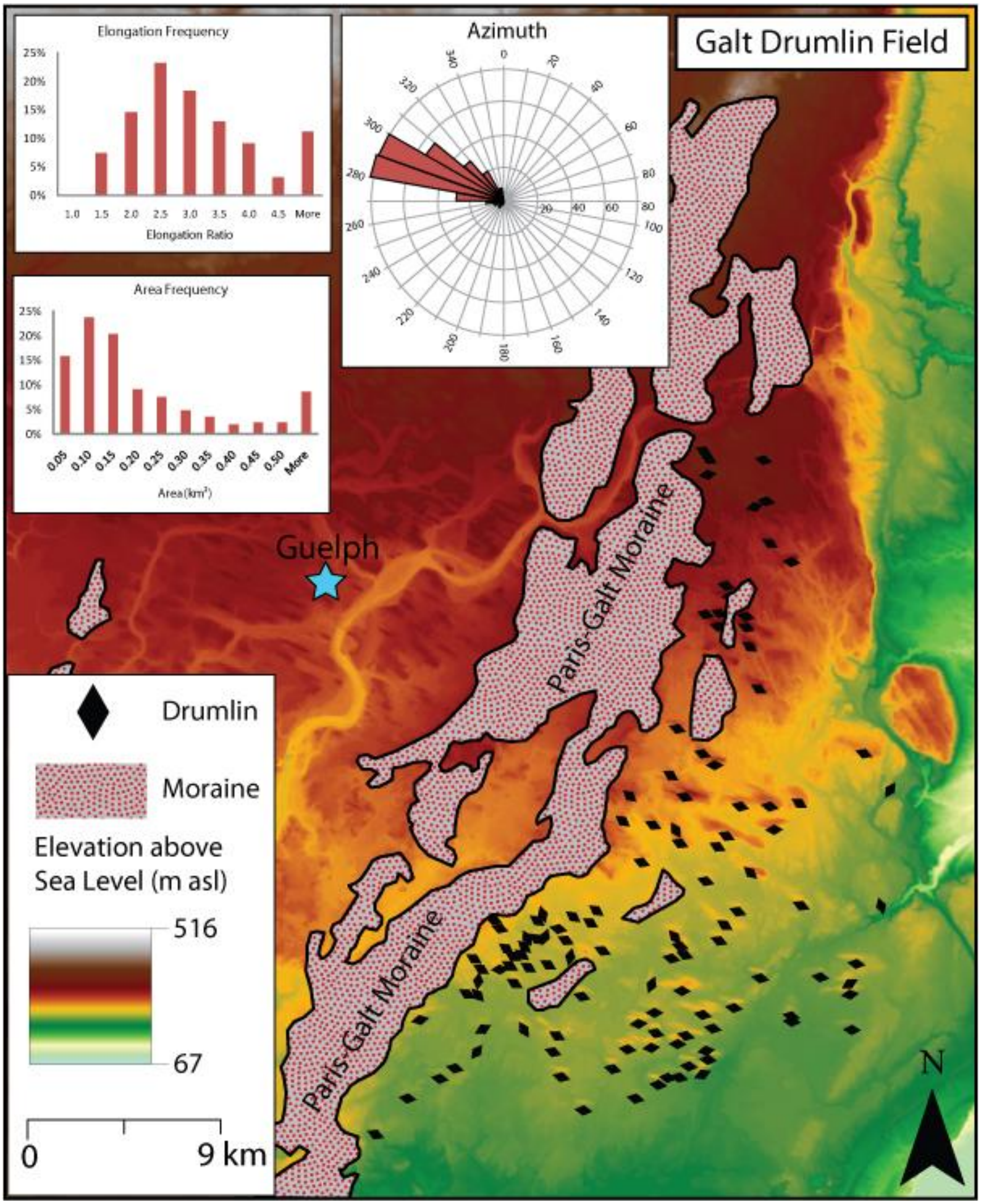
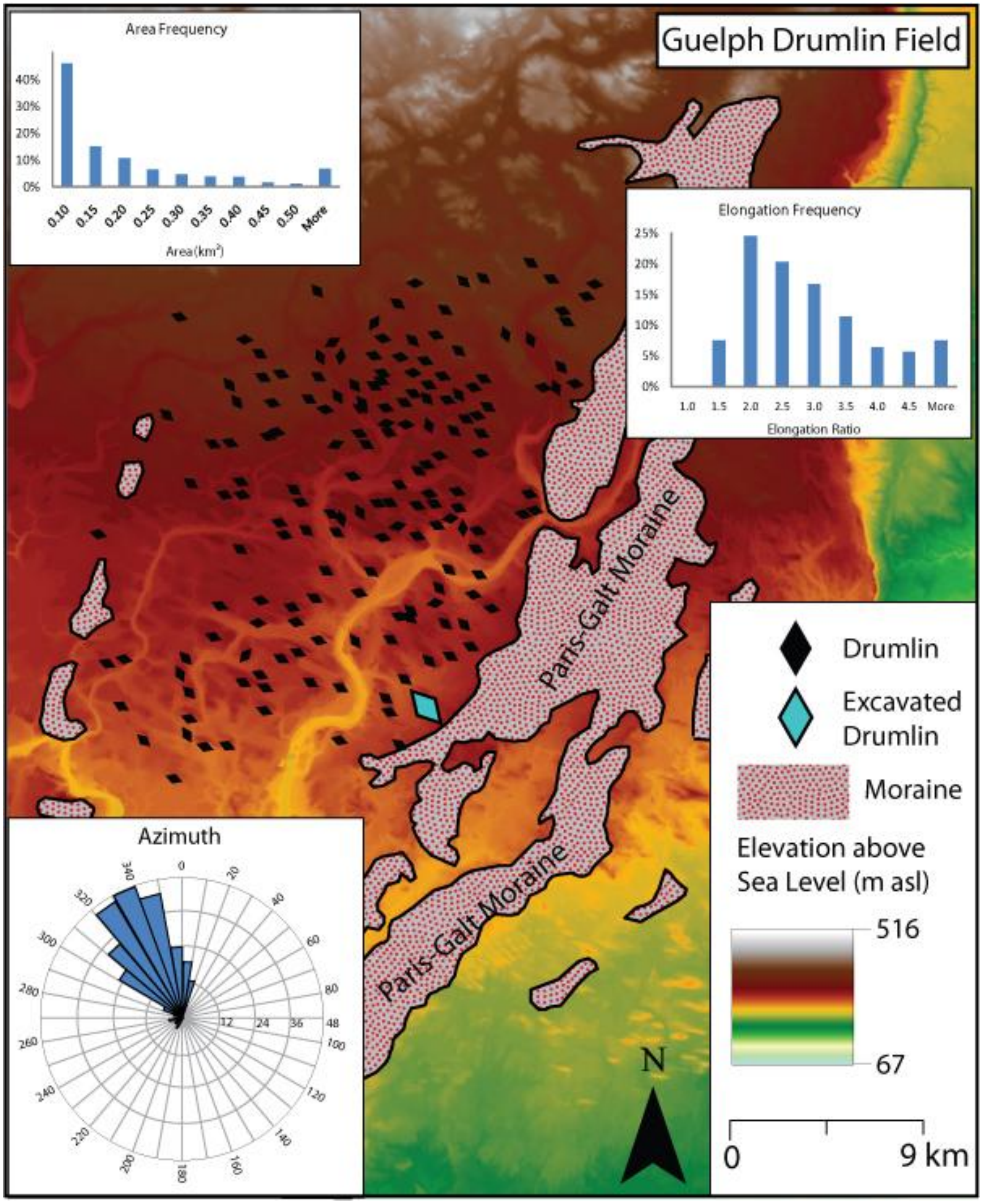

Elongation Frequency
25%
20%
15%
10%
5%
0%
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
More
Elongation Ratio
Area Frequency
25%
20%
15%
10%
5%
0%
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
More
Area (km²)
Azimuth
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
20
40
60
80
Galt Drumlin Field
Guelph
Paris-Galt Moraine
Paris-Galt Moraine
Drumlin
Moraine
Elevation above Sea Level (m asl)
516
67
0
9 km
N

Figure 4.5: Right: Coloured DEM of the Guelph drumlin field showing the distribution and trend of drumlin long axes (diamond symbol). Diamond long axes trend in the same direction as drumlin long axes. The location of the partially excavated drumlin examined in the field study is highlighted in blue.

Left: Summary morphological data (elongation ratio, area and long axis azimuth) for drumlins identified in the Guelph field.


Guelph Drumlin Field
Area Frequency
40%
30%
20%
10%
0%
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
More
Area (km²)
Elongation Frequency
25%
20%
15%
10%
5%
0%
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
More
Elongation Ratio
Paris-Galt Moraine
Paris-Galt Moraine
Drumlin
Excavated Drumlin
Moraine
Elevation above Sea Level (m asl)
516
67
Azimuth
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
12
24
36
48
N
0
9 km

A partially excavated drumlin was found in the south-east section of the Guelph drumlin field, in the Aberfoyle Quarry located west of Highway 401 near the intersection of Highway 401 and Highway 6, approximately 25 km west of Hamilton, Ontario (Figure 4.5). The internal structure and sediment exposed within the drumlin was photographed and described in the field. Observations and interpretations of depositional processes made from this partially exposed drumlin will be used to enhance interpretations made from the quantitative spatial data.

4.3 Data Sources

The Ontario Geospatial Data Exchange (OGDE) Digital Elevation Model (DEM) data used to identify drumlins in this study are freely available to the majority of universities in Ontario. The DEMs are created by the Ontario Ministry of Natural Resources through the compilation of existing topographic contour data interpolated using ANUDEM 4.6.3 software. The spatial resolution of the dataset is 10 m with a vertical accuracy of 10 m, and a horizontal accuracy of approximately 5 m. Using the methodology presented below, landforms identified as potential drumlins but with a vertical relief of less than 20 m, were not included in the analysis due to the limited resolution of the elevation data and the potential for inaccuracies in their identification (van Boxel et al. 2004). Printed topographic maps were used to validate the automated landform identification derived from the DEM data.

In order to evaluate substrate controls on drumlin form and distribution, surface geology and bedrock elevation data were obtained for each of the study areas from the Ontario Geological Survey (OGS 2010). Drift thickness data were determined using a simple raster calculation of:

$$\mathrm{RASTER}_{DT} = \mathrm{DEM} - \mathrm{RASTER}_{BE}$$

Where RASTER_{DT} is the calculated drift thickness raster, the DEM is the digital elevation model and the RASTER_{BE} is the bedrock elevation (Figures 4.6, 4.7). All morphologic and geologic data obtained were imported to ESRI shapefiles, which are compatible with ESRI ArcView 3.2 and ESRI ArcGIS 9.3 software. All statistical analyses were conducted in SPSS 11.0 and the *R* Stats Package.

4.4 Methods

The automated methodology for drumlin identification and analysis presented here is organized into three stages: (1) Data Identification; (2) Data Exploration; and (3) Data Analysis. Data identification includes the recognition of drumlin landforms from the DEM data and their subsequent visualization. Data exploration involves investigation of the data using standard statistical packages that facilitate the identification of relationships through examination of graphs or diagrams. Data analysis includes the exploration of factors that may control drumlin distribution and the spatial relationships between morphological characteristics within a single drumlin field. Determination of drumlin distribution focuses on identifying the type of point pattern exhibited by the drumlins within the study area. A clustered pattern represents a distinctly non-random distribution of events, a dispersed pattern is one which exhibits a uniform distribution,

Figure 4.6: Drift thickness map of the Arran drumlin field study area. Drumlins shown by yellow diamonds. Bedrock topography data used to create this map was obtained from the Ontario Geological Survey. Inset chart shows plot of relationship between drift thickness and elongation ratio of drumlins in the Arran field.

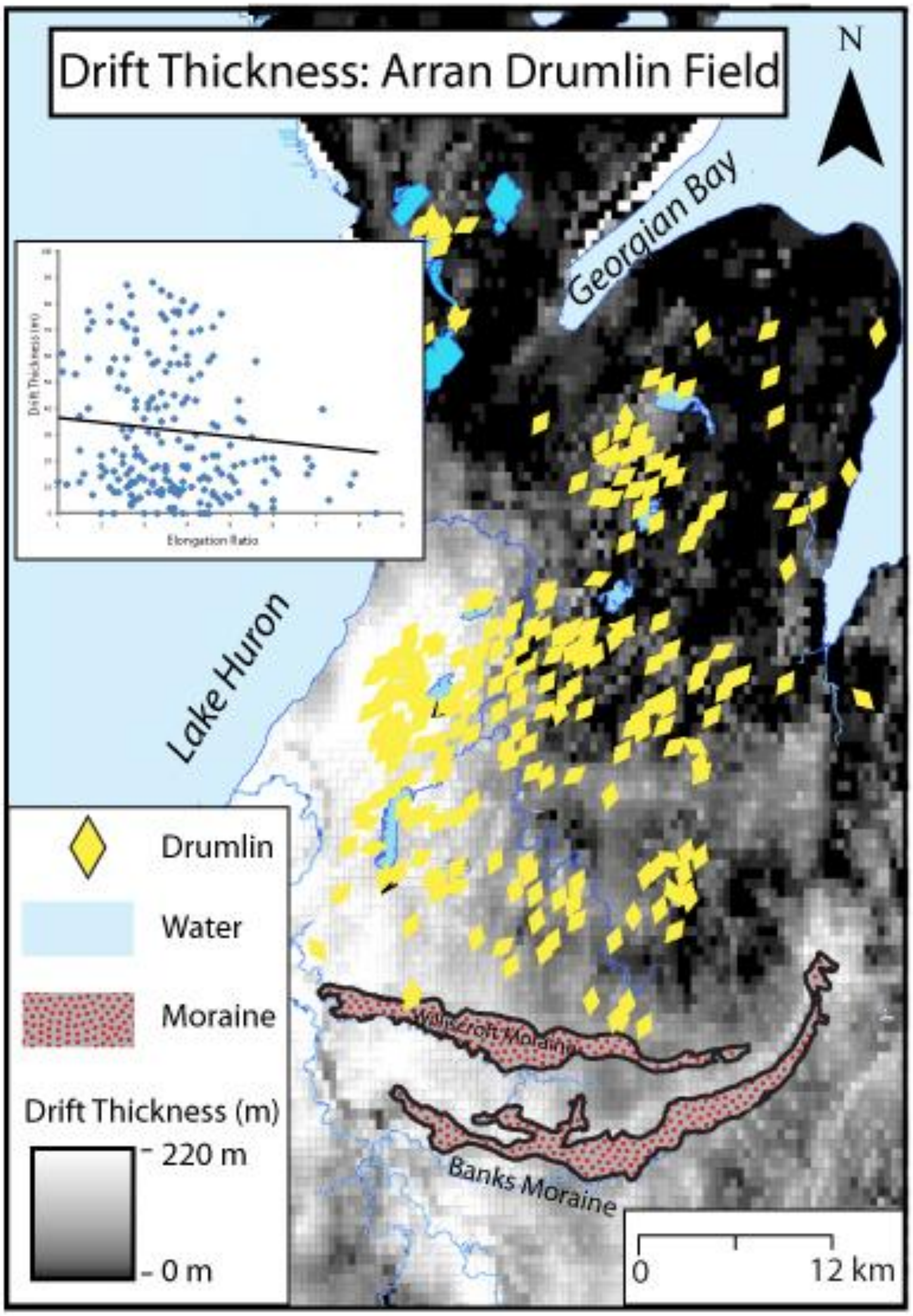
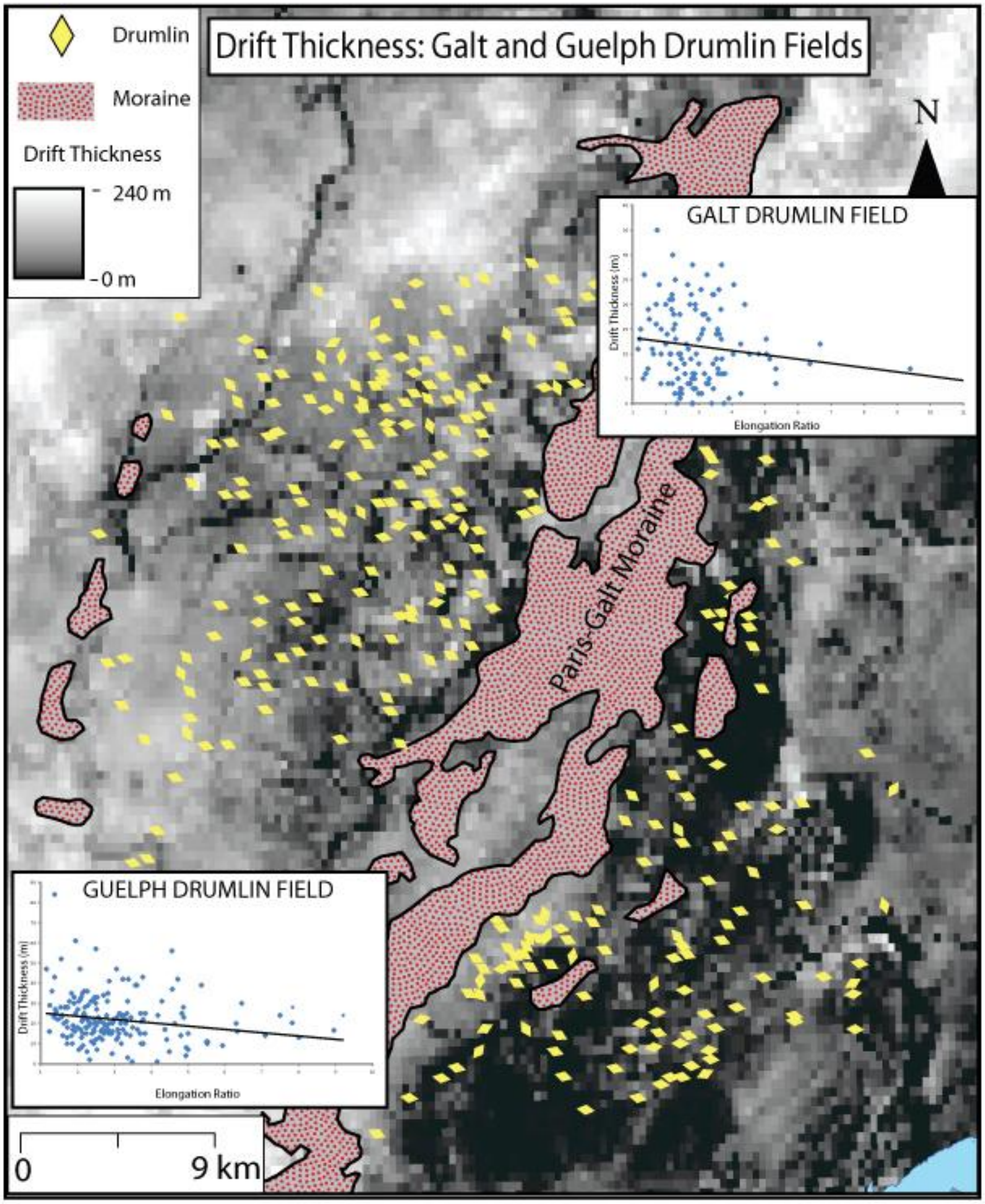

Drift Thickness: Arran Drumlin Field
N
Georgian Bay
Lake Huron
Drift Thickness (m)
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
Elongation Ratio
Drumlin
Water
Moraine
Drift Thickness (m)
220 m
0 m
Wawcroft Moraine
Banks Moraine
0
12 km

Figure 4.7: Drift thickness map of the Guelph and Galt drumlin fields study area. Drumlins shown by yellow diamonds. Bedrock topography data used to create this map was obtained from the Ontario Geological Survey. Inset charts show plots of relationship between drift thickness and elongation ratio of drumlins in the Guelph (left) and Galt (right) fields.


Drift Thickness: Galt and Guelph Drumlin Fields
Drumlin
Moraine
Drift Thickness
240 m
0 m
N
GALT DRUMLIN FIELD
Drift Thickness (m)
Elongation Ratio
Paris-Galt Moraine
GUELPH DRUMLIN FIELD
Drift Thickness (m)
Elongation Ratio
0
9 km

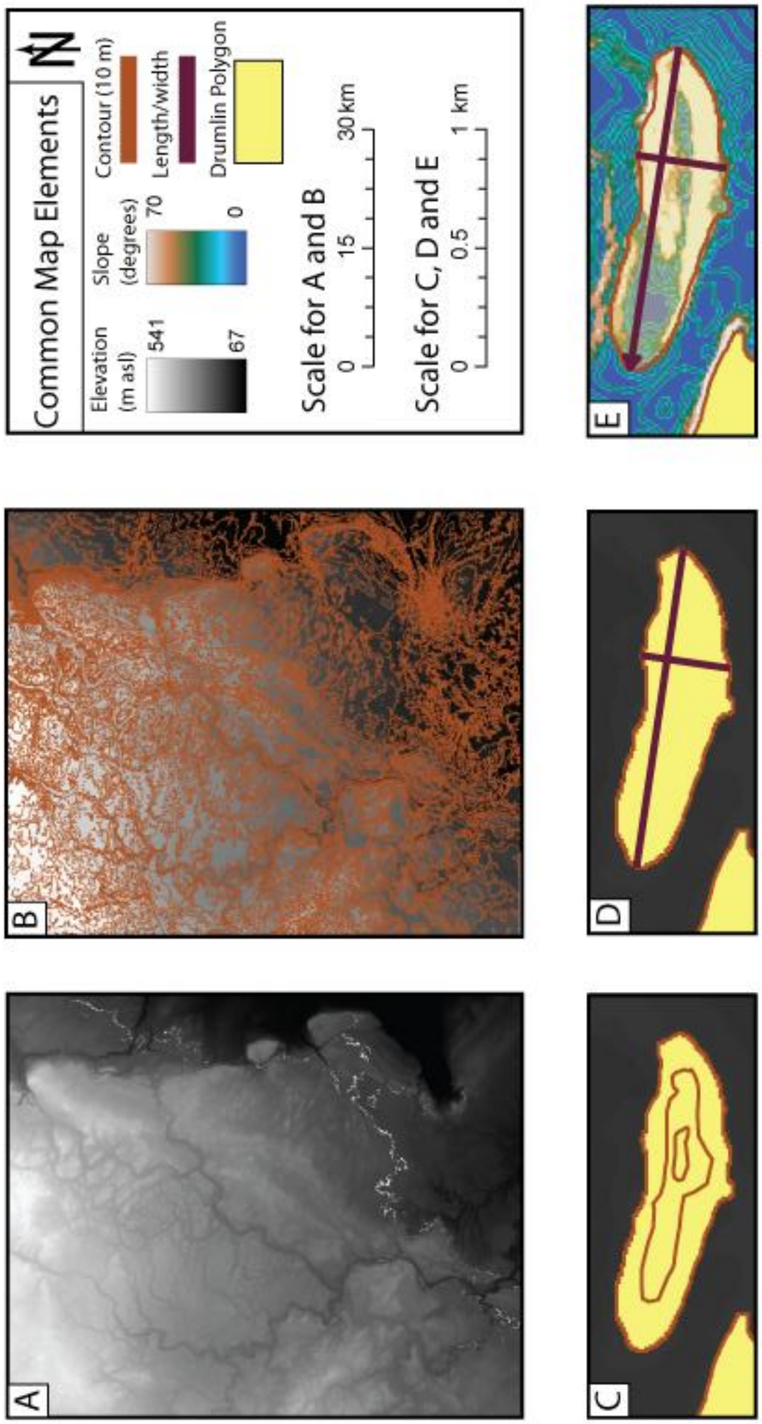
and a random distribution displays no dominant trend towards either clustering or dispersion (O'Sullivan et al. 2010).

4.4.1 Data identification

The initial step in the automated identification of drumlins from an OGDE DEM requires conversion of the DEM data from a ‘floating point’ data set to a file that can be used within the Geographic Information System (GIS) program, ArcGIS 9.3, to generate contours (Figure 4.8A). Computer-based contouring of digital elevation data has been found to be equally reliable to contouring by experienced geologists, with differences in accuracy being negligible (Figure 4.8B; Shroder 2008). The advantage of the automated process is that it is considerably more time efficient.

Once contours have been generated from the DEM, a GIS is used to build a topology to identify relationships between individual spatial elements (Furst and Horhan 2009). In this study, the topology was used to create polygons from the contour file by identifying all closed-loop contours that could potentially represent drumlins. The building of topology in GIS ensures that all data integrity rules are defined and enforced (i.e., that there are no gaps between polygons and no overlapping of features), and ensures the management of shared features (i.e., constrains how features share geometrical elements such as adjacent polygons). Polygons that may represent drumlins were only created within the boundaries of a closed loop contour. All other contour lines (i.e., those that did not connect to form closed loops) were removed from the data set (Figure 4.8C).

Figure 4.8: Illustration of the methodology used to identify drumlins from digital data. (A) The DEM used in the Galt drumlin field study area; (B) 10 m contours created from the DEM; (C) closed loop polygons are isolated to identify individual drumlins; (D) drumlin parameters such as length, width and geometric center are calculated and assigned; (E) azimuth of drumlin long axis is established on the basis of slope calculations (the steeper slope of the drumlin points up-glacier).


Common Map Elements
Elevation (m asl)
541
67
Slope (degrees)
70
0
Contour (10 m)
Length/width
Drumlin Polygon
Scale for A and B
0
15
30 km
Scale for C, D and E
0
0.5
1 km
A
B
C
D
E

The resulting dataset of closed loop contours can contain numerous small non-drumlin forms such as ponds, depressions, or surface irregularities in undulating, hummocky terrain. A filter can be applied to remove these small non-drumlin forms that deletes all polygons created by an isolated single enclosed contour and topographic features less than 10m in height (Figure 4.8D). This process may delete a small number of low-relief drumlins; however, it also cleans the data by eliminating thousands of small remnant polygons that are likely to represent the low relief undulating topography common in glaciated terrain. Another potential shortcoming resulting from this step is the ‘shortening’ of the drumlin polygons. It is possible that some of the identified drumlins will have a shorter length and a less elongated shape due to the lower relief down-ice 'tail' of the drumlin being prematurely truncated by this process. The potential for some truncation of each mapped drumlin is an unavoidable by-product of the automated landform identification process.

The polygon group remaining after this process was filtered a second time to ensure that the inner contours had higher elevation values than those surrounding them, and a positive landform was represented rather than a negative landform, such as a pond or valley. These latter forms were classified as sinks (negative relief forms) and eliminated from the dataset. The remaining group of polygon files were then visually inspected, checked against printed topographic maps, and edited to remove obvious non-drumlin forms, such as simple, but extensive elevated plateaus. The remaining forms were considered to represent drumlins for the purposes of this study if they met the criteria of having a minimum length of 250 m, a minimum width of 50 m, and a minimum relief of 10m.

Inconsistencies in what is considered as 'typical drumlin morphology' add to the difficulty of creating an automated process for the recognition of drumlins from digital elevation data. Accurate recognition and documentation of drumlin morphological characteristics from the DEM data was essential for the exploration and discussion of results. The automated process described above identifies a simple, ‘classical’ drumlin, through recognition of a discrete series of closed loop contours on a topographic map. While it is possible that larger and more complex drumlin forms may show several areas of enclosed contours within one peripheral bounding contour (Knight 2010, Maclachlan and Eyles submitted), in this study each individual series of enclosed contours within the larger boundary were analysed individually. This method allows the smaller constituent parts of larger complex drumlins to be analysed and ensures that morphological parameters for individual drumlin forms are consistently recorded. Only one topographic high is recorded for each identified drumlin and is identified from the highest value enclosed contour.

To augment the morphology and spatial distribution data obtained from the DEM, a field study was conducted on a partially excavated drumlin within the Aberfoyle Quarry in the Guelph drumlin field (Figure 4.9). This study allowed the identification of sediment characteristics and unit geometries within the excavated drumlin, data that can be used to enhance observations, discussions and conclusions made from the digital data.

4.4.2 Data exploration

The data exploration step involves the generation of data that describe the morphological characteristics of the drumlins. These data can then be used to identify and analyse spatial variability of drumlin forms within and between drumlin fields.

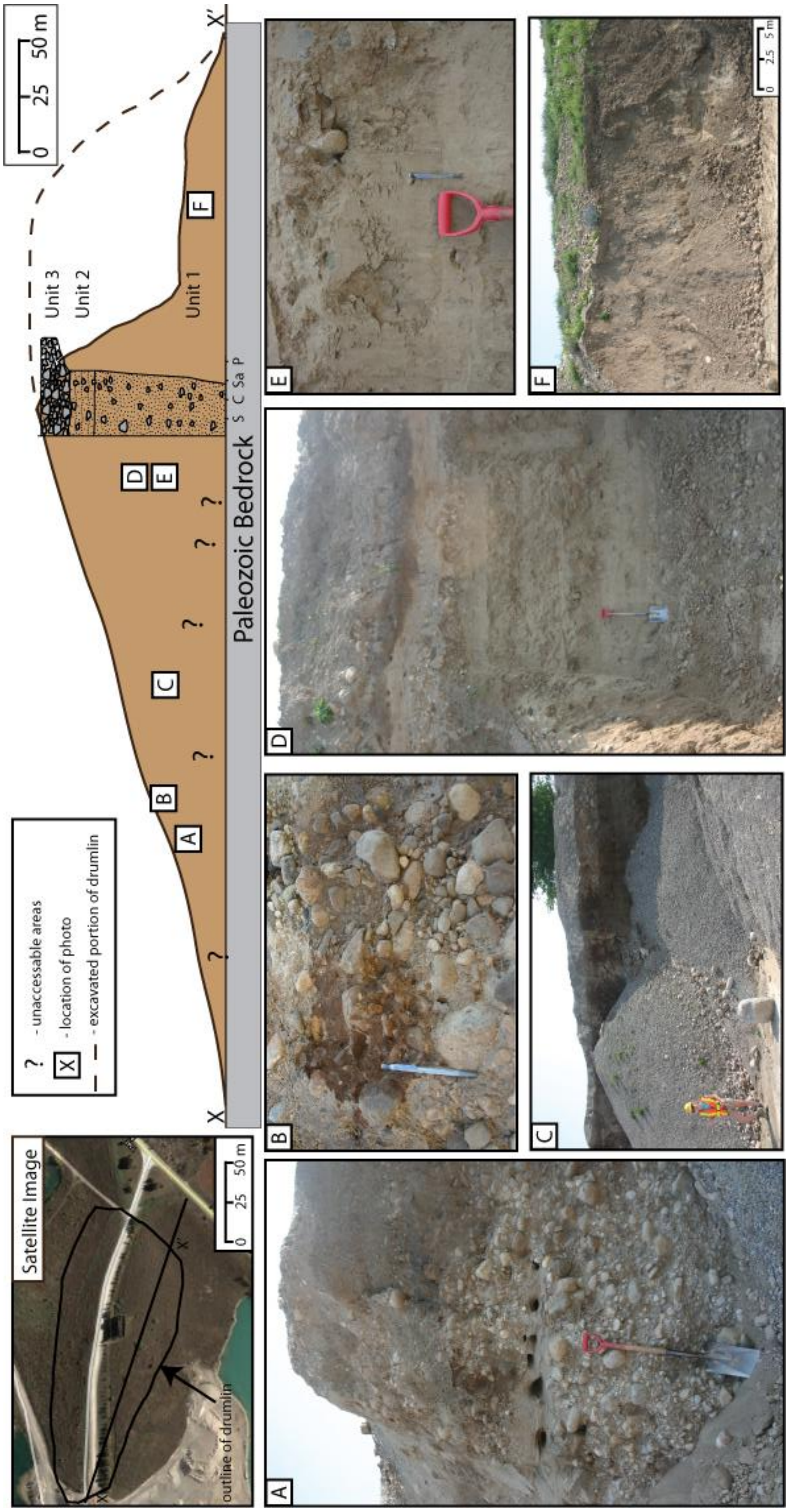
4.4.2.1 Descriptive statistics: morphological analysis

Morphological analysis of the drumlins identified from the DEM data requires that each drumlin identified is assigned a unique numeric identifier. The morphological attributes of each drumlin are then recorded using a series of processes available within ArcView 3.2 and ArcGIS 10. The descriptions and definitions of drumlin attributes used in this study can be found in Table 4.1. To determine the direction of the drumlin long axis azimuth line the slope values of the DEM are used (Figure 4.8C). The azimuth direction is calculated by assigning a compass direction to the length line (the longest line that can be drawn through the drumlin). As 'classic' drumlins have a steeper slope facing the up-ice direction (stoss-side; Clark et al. 2009) each length line is then assigned a direction based on the relative slope values identified at each end of the azimuth line with the azimuth direction always pointing from the steepest toward the gentler slope. The azimuth direction of the identified drumlins can therefore be used to infer former ice flow directions (Clark et al. 2009).

Table 4.1: Description of the drumlin variables calculated from the digital elevation data.

Attribute	Definition
Length	Calculated as the longest straight line that can be drawn through the polygon (drumlin)
Width	Calculated as the longest straight line that can be drawn perpendicular to the length of the polygon (drumlin)
Area	The area contained within the outside closed contour line that defines the external margin of the polygon (drumlin)
Perimeter	The perimeter of the closed contour line that defines the external margin of the polygon (drumlin)
Geometric Center	The calculated center of the polygon (drumlin) taking into account all vertices
Long Axis Azimuth	The compass direction of the polygon (drumlin) length line

Figure 4.9: Schematic cross section through partially excavated drumlin in the Guelph drumlin field and photographs of exposed sediment (locations marked by labelled boxes on cross section). Upper left: satellite image of the drumlin obtained from Google Earth. (A-B) Clast rich medium to coarse grained sandy diamict of Unit 3. (C) Contact between Units 2 and 3 visible in the upper right portion of the photo. (D) Units 1 through 3 in a freshly exposed outcrop. (E) Fine to medium crudely stratified sands of Unit 1. (F) poorly exposed sediment of Unit 1 at the stoss end of the drumlin. Question marks on cross section are located in areas where drumlin sediment was covered by slumped material.


Satellite Image
0 25 50 m
outline of drumlin
X
X'
? - unaccessable areas
X - location of photo
- excavated portion of drumlin
0 25 50 m
Unit 3
Unit 2
Unit 1
Paleozoic Bedrock
S C Sa P
?
A
B
C
D
E
F
0 2.5 5 m

The elongation ratio (ER) of drumlins is considered to be another important morphological parameter that can be used to assist in the reconstruction of former glacial conditions (Boyce and Eyles 1991, Hart 1999, Clark et al. 2009). It has been suggested that the elongation ratio may be a useful proxy for the reconstruction of ice sheet velocity as elongate drumlins tend to form preferentially beneath streams of fast-flowing ice (Briner 2007). To calculate ER, length and width measurements are used (ER=L/W). An ER value represents the circularity of an object with the object being more circular, and less elliptical, as the value trends closer to one.

All measured variables of drumlin form and morphology from each of the study areas, including length, width, area, azimuth and ER, are summarized using descriptive statistics including minimum, maximum, mean, skewness and standard deviation values, and are presented in Table 4.2.

4.4.2.2 Kernel estimation

Examination of the spatial distribution of drumlins, whether they are clustered, dispersed or random, will help determine what factors are controlling their formation. An effective and underutilized technique to visually explore relationships and clustering of geomorphological data is kernel estimation (Cox 2007). In this study, kernel estimation is used as an exploration tool to visualize the distribution of drumlins within each drumlin field and to identify any areas of clustering (Figures 4.10 - 4.13). For this reason kernel estimation is commonly conducted prior to more quantitative methods of cluster detection as the results of kernel estimation can guide the selection of areas for further analysis (Cox 2007).

Kernel estimation is a technique that can be used with any point pattern to create a continuous surface that represents the relative concentration, or density, of the feature the points represent. In this study, the geometric centre of each drumlin (Table 4.1) is the feature the points are representing. Kernel estimation works by counting the number of events within a user specified distance (the bandwidth) from a centre point which moves through the study area at an interval equal to the size of each raster cell being created. The centre point is assigned a value based upon the number of events within the bandwidth to create a continuous surface. There is no 'ideal' bandwidth (Cox 2007) but statistical packages (such as the open-source and freely available *R*) use simple methodologies to help determine a bandwidth that is suitable for any particular application. In this study, the most appropriate bandwidth was found to be 2 km for the Arran drumlin field and 1.2 km for both the Arran and Guelph drumlin fields. The raster surface produced by the process is transcribed to a map. The resulting map provides visual representation of drumlin clustering within the study area and helps identify regional patterns of drumlin distribution. Kernel density analysis was used to identify both the overall clustering of drumlins within the fields (Figures 4.10, 4.11), and the clustering of only those drumlins with a high elongation value (within the top 25% of ER values; Figures 4.12, 4.13). This provides a visual representation of the distribution of drumlins with high elongation ratio values, a variable which has been linked to particular sub-ice sheet conditions (Clark et al. 2009).

Table 4.2: Descriptive statistics of each the Arran, Galt and Guelph drumlin fields.

		Min	Max	Mean	Standard Deviation	Skewness
GALT *n=178*	Length (m)	267	3794	862	511	2.1
	Width (m)	92	1267	324	201	1.9
	Area (km^2)	0.03	2.3	0.22	0.31	3.8
	Azimuth	186	356	293	25	-1.3
	Elongation	1.03	11.6	2.9	1.4	2.0
GUELPH *n=249*	Length (m)	282	2875	793	426	1.7
	Width (m)	95	986	312	155	1.3
	Area (km^2)	0.05	1.1	0.18	0.18	2.1
	Azimuth	0	359	285	105	-2.2
	Elongation	1.06	9.7	2.8	1.3	2.0
ARRAN *n=301*	Length (m)	254	2487	776	504	0.95
	Width (m)	67	1014	226	152	1.9
	Area (km^2)	0.01	1.3	0.14	0.17	3.4
	Azimuth	143	314	216	18	1.2
	Elongation	1.01	8.4	3.6	1.4	0.7

Figure 4.10: Coloured DEM with overlay map showing kernel estimation of drumlin distribution across the Arran drumlin field.

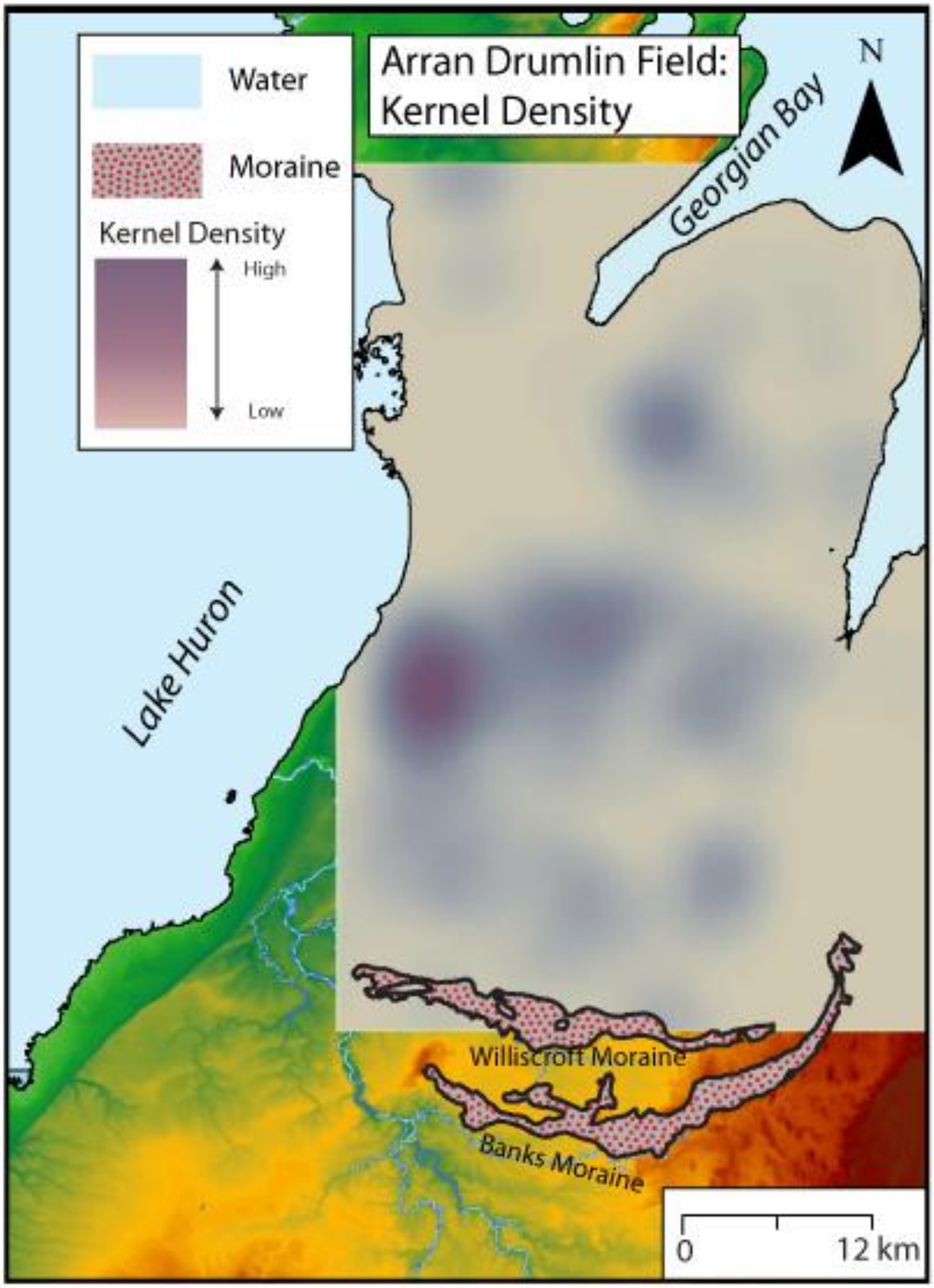

Water
Moraine
Kernel Density
High
Low
Arran Drumlin Field:
Kernel Density
Georgian Bay
N
Lake Huron
Williscroft Moraine
Banks Moraine
0
12 km

Figure 4.11: Coloured DEM with overlay map showing kernel estimation of drumlin distribution across the Guelph and Galt drumlin fields.

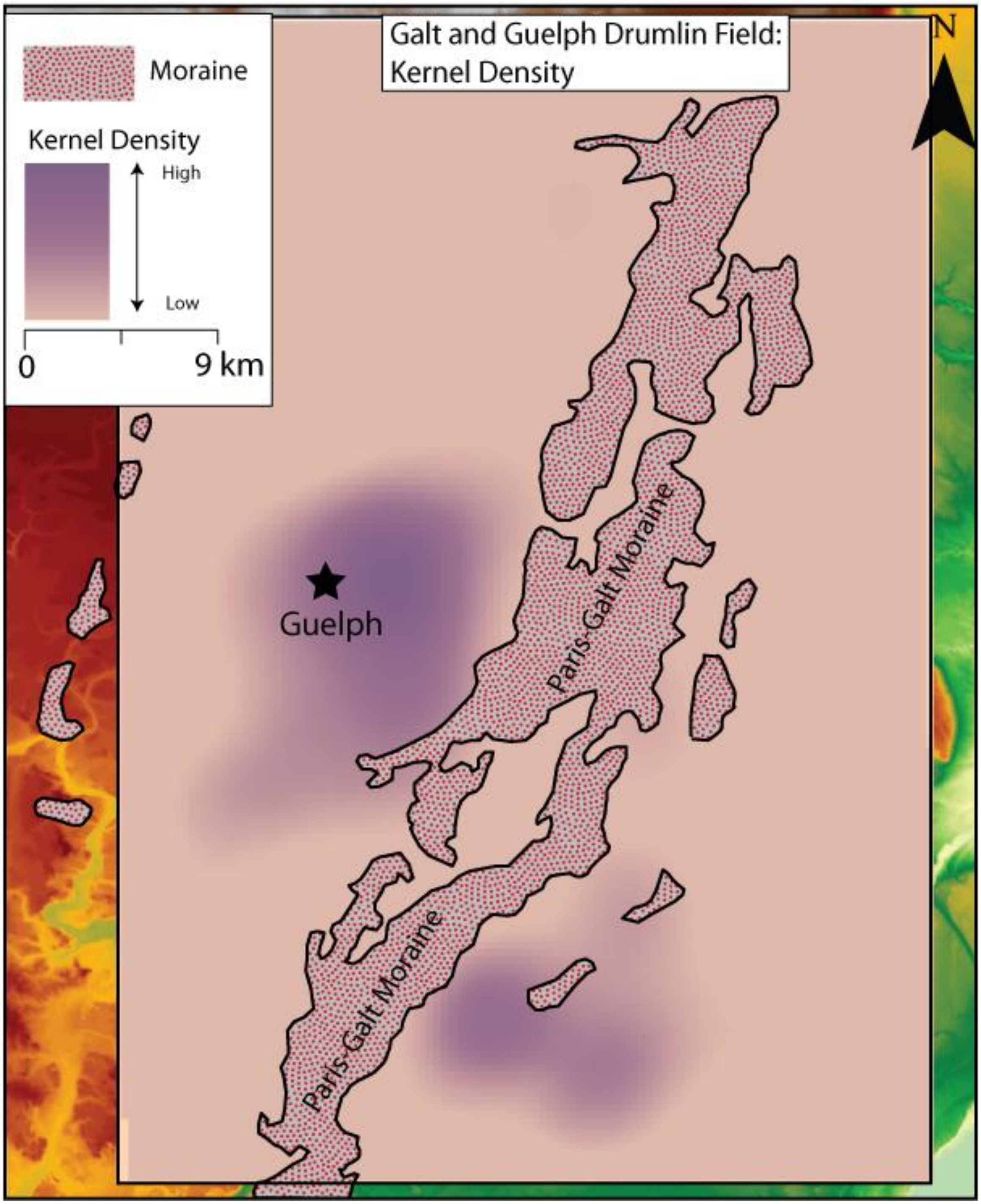

Galt and Guelph Drumlin Field:
Kernel Density
Moraine
Kernel Density
High
Low
0
9 km
N
Guelph
Paris-Galt Moraine
Paris-Galt Moraine

Figure 4.12: Coloured DEM with overlay map showing kernel estimation of the distribution of the most elongated drumlins (the upper 25% of ER values within the study area) in the Arran drumlin field.

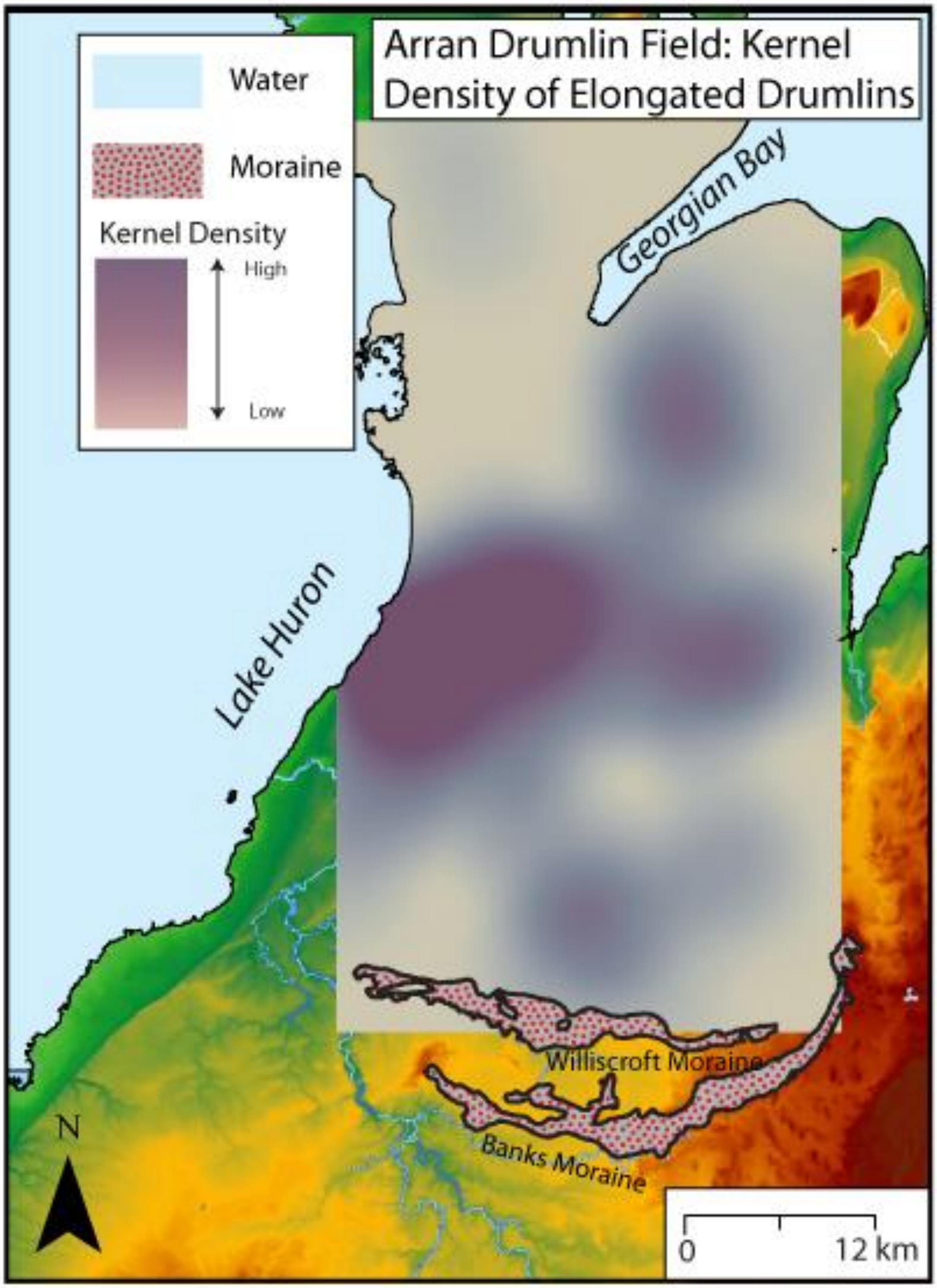
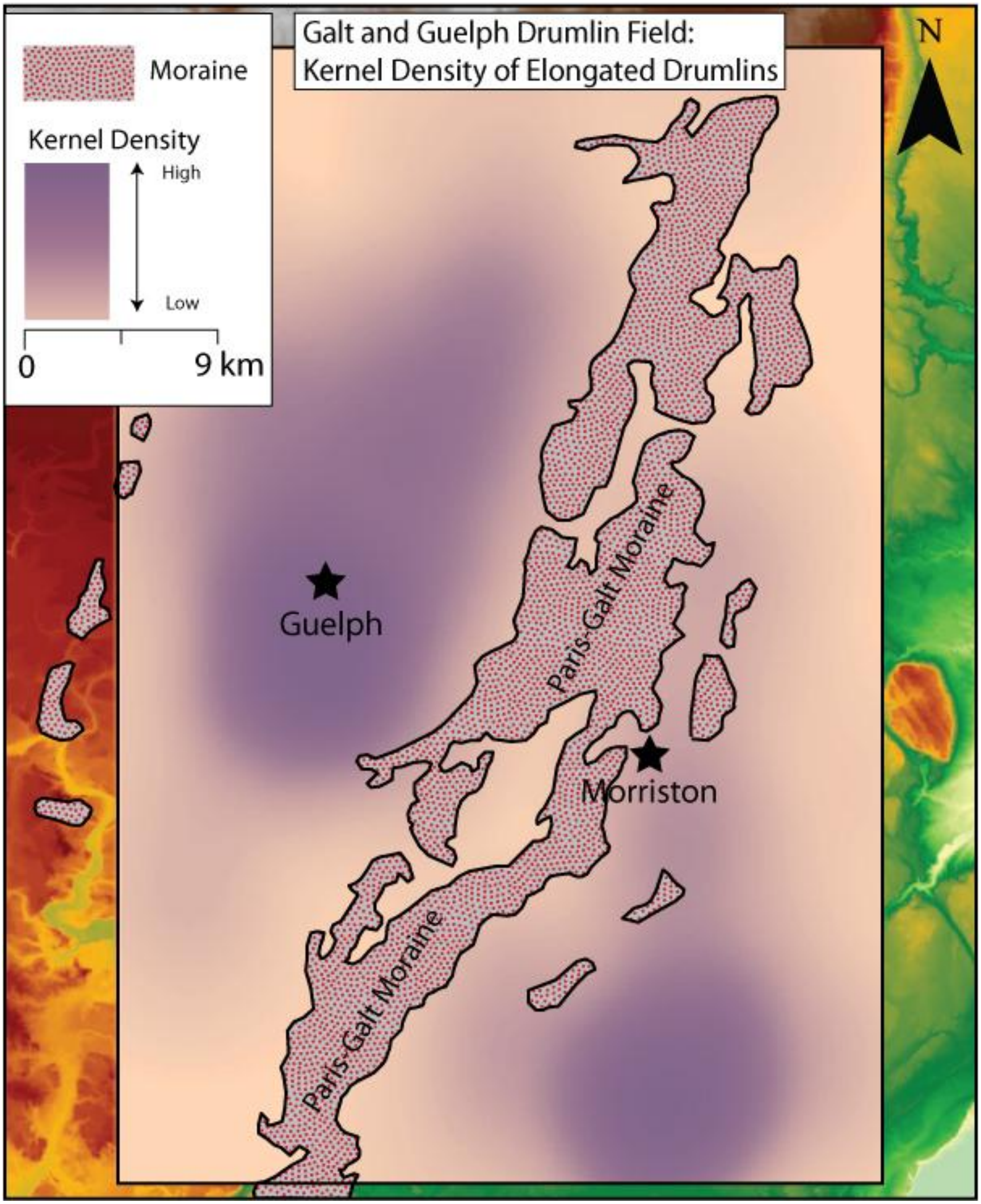

Arran Drumlin Field: Kernel Density of Elongated Drumlins
Water
Moraine
Kernel Density
High
Low
Georgian Bay
Lake Huron
Williscroft Moraine
Banks Moraine
N
0
12 km

Figure 4.13: Coloured DEM with overlay map showing kernel estimation of the distribution of the most elongated drumlins (the upper 25% of ER values within the study area) in the Guelph and Galt drumlin fields.


Galt and Guelph Drumlin Field:
Kernel Density of Elongated Drumlins
Moraine
Kernel Density
High
Low
0
9 km
N
Guelph
Morriston
Paris-Galt Moraine
Paris-Galt Moraine

4.4.3 Data analysis

Three methods of spatial point pattern analysis were conducted on each of the study areas to explore the spatial distribution of drumlin forms. In order to identify regional distribution patterns *nearest neighbour analysis* and *Ripley's K-function* (also referred to as multidistance spatial cluster analysis) were used. The *G-statistic* was used for identification of the spatial distribution of extreme values (both high and low) of individual variables within the overall dataset. This technique allowed the exploration of clustering of both high and low elongation ratio values, in a similar fashion to kernel density estimation, but with a statistically significant output

4.4.3.1 Nearest neighbour analysis

One of the classic techniques used in point pattern analysis is nearest neighbour analysis, where the distance between each data point and the nearest neighbouring point is used to determine if a point pattern is random, regular or clustered (Getis and Ord 1992). The results provide a ratio (*R)* of the observed distance between events (d_{OBS}) and the expected average distance between events(d_{EXP}); assuming a hypothetical random distribution:

$$R = \frac{d_{OBS}}{d_{EXP}}$$

A calculated value of less than one means that the pattern is more clustered than random, whereas a value greater than one indicates that the data are more dispersed than random. The corresponding *Z-score*, calculated using the standard deviation, is a measure of statistical significance of the analysis. The default null hypothesis for nearest neighbour calculations is one of spatial randomness. A Z-score of less than -1.96 means the null hypothesis can be rejected with the negative value indicating clustering. A Z-score of more than 1.96 also means the null hypothesis can be rejected with the positive value indicating dispersion (Sprinthall 2003).

4.4.3.2 Ripley's K-function

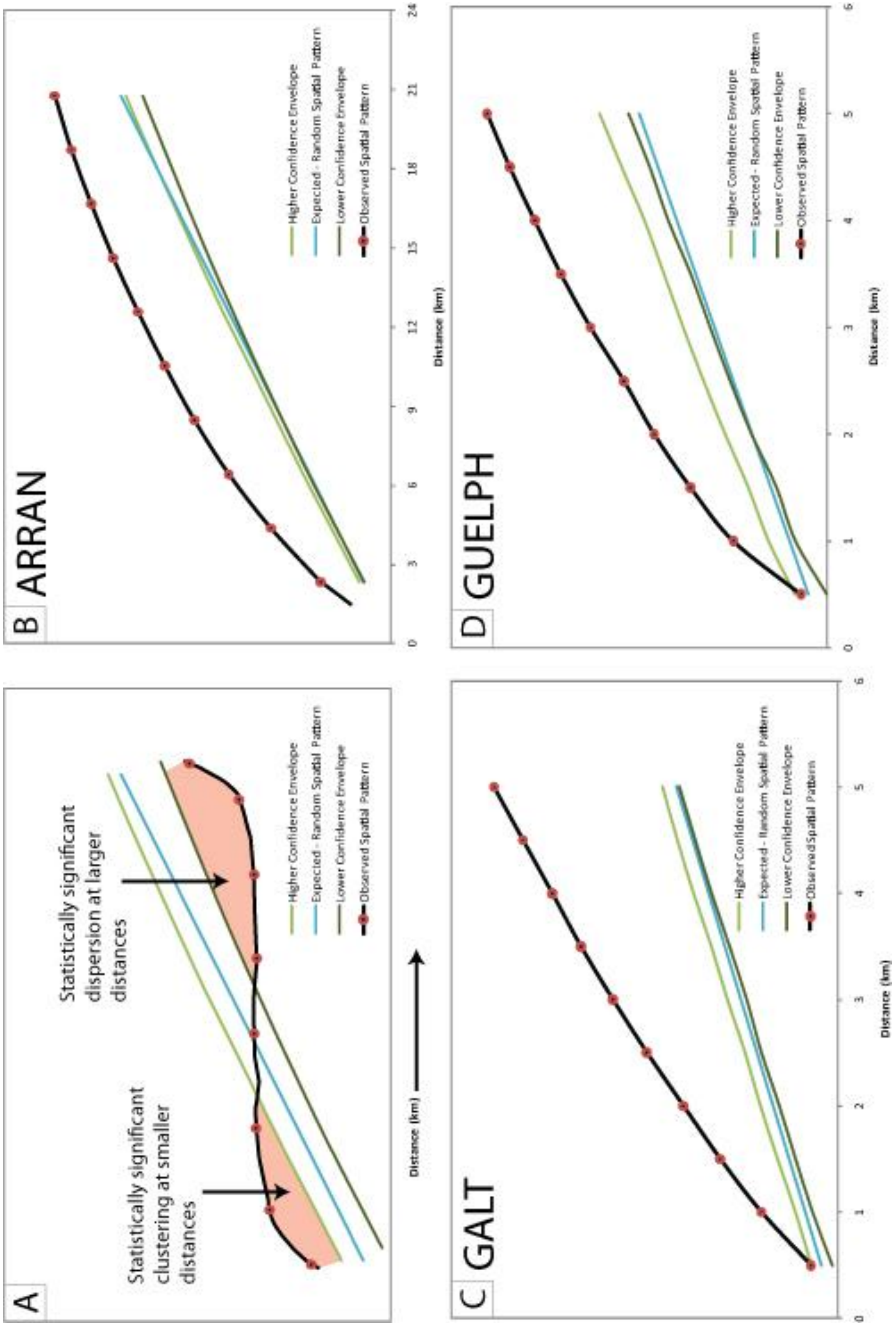
The calculation of Ripley's K-function is a second method that may be used for the analysis of point patterns. While nearest neighbour analysis is important for identifying clustering, randomness, or dispersion, Ripley's K-function compares the spatial relationship of the observed data to that expected if it was random (Ripley 1981). The comparison determines the extent of clustering or dispersion at various spatial scales. When the observed data value is higher than the expected value created by a theoretical random distribution of points for an assigned distance between points, the distribution is considered to be more clustered than random. If the observed data value is lower than the expected value, then the distribution is considered to be more dispersed than random (Figure 4.14A). The distribution is defined as *L(d)* and is computed by:

$$L(d) = \sqrt{\frac{A \sum_{i=1}^{n} \sum_{j=1, j \neq 1}^{n} k(i,j)}{\pi n(n-1)}}$$

where *A* represents the study area size, π is a constant and n is the number of points used in the analysis. Within the overall equation, *k(i, j)* measures the number of events (points) *(j)* residing within a distance *(d)* of all *(i)* points. The value for *k(i, j)* is zero when the distance between *i* and *j* is greater than *d*, and it is a value of one when the distance between *i* and *j* is less than or equal to *d*. At any certain distance *(d)* for a random point pattern distribution, the value calculated for *L(d)* should be approximately equal to that of *d*. Any pattern that is more clustered than random at a specific distance *(d)* will have a calculated *L(d)* value higher than the expected value. If the *L(d)* value is less than the expected value for a certain distance then the pattern would be considered to be more dispersed than random (Figure 4.14).

Ripley's K-function analysis is increasingly being used in ecological studies of the distribution of plant communities (Hasse 1995, Grau 2002, Blanco et al. 2008), geographical and epidemiological studies of melioidosis distribution in urban area (Corkeron et al. 2010), and in economic geology to determine the spatial distribution pattern of economic deposits such as nickel (Mamuse et al. 2010). The technique is applied here in the study of drumlin distribution to allow quantitative analysis of the relative distribution of drumlins within each field over a range of spatial scales.

Figure 4.14: K-function estimates for drumlin polygons. (A) Illustration explaining how the K-function is graphed. The green lines represent a ‘simulation envelope’ that show the upper and lower limits of expected values (with a 99% confidence interval) if complete spatial randomness on drumlin distribution is assumed. An observed value above the simulation envelope occurs when data distribution is clustered and a value below the simulation envelope occurs when the data distribution is dispersed. (B-D) For each of the three studied drumlin fields the K-function values lie above the simulation envelopes. This shows that in each drumlin field, data (drumlins) are clustered rather than randomly distributed.


A
Statistically significant clustering at smaller distances
Statistically significant dispersion at larger distances
Distance (km)
Higher Confidence Envelope
Expected - Random Spatial Pattern
Lower Confidence Envelope
Observed Spatial Pattern
B ARRAN
0
3
6
9
12
15
18
21
24
Distance (km)
C GALT
0
1
2
3
4
5
6
Distance (km)
D GUELPH
0
1
2
3
4
5
6
Distance (km)

4.4.3.4 G-statistics

A third statistical technique was applied to analyse the clustering of high or low values within data describing the elongation ratios of drumlins. In contrast to nearest neighbour analysis that identifies general spatial relationships between data points, the Getis Ord General G statistical function (*G-statistic)* is used to search for spatial heterogeneity within specific data sets (Getis and Franklin 2010). The *G-statistic* separates clusters with high values from those with low values and is defined as:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} x_i x_j}{\sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j}, \forall j \neq 1$$

where x_i is the value at location *i*, x_j is the value at location *j*, finally, $w_{i,j}$ is the spatial relationship based upon distance. The expected value for *G* (E[G]) is defined as:

$$E[G] = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j}}{n(n-1)}, \forall j \neq i$$

Simply, a relatively high value of *G* indicates a tendency for high values to be clustered, while a low value indicates a clustering of low values. In each case the clustering is not likely to be occurring by random chance. This is confirmed using the following equation:

$$V[G] = E[G^2] - E[G]^2$$

where *V* represents the calculated variance to determine the typical amount *G* is likely to differ from the expectation E[G]. This allows for the comparison of the observed values with those of the expected values.

4.5 Results and Analysis

4.5.1 Morphological characteristics

The morphological characteristics of drumlins identified in the Arran, Guelph and Galt fields are summarized in Table 4.2. Overall, the drumlins range from 254 m to 3794 m in length, 67 m to 1267 m in width and have an average elongation ratio (ER) of 3.1. The Arran drumlin field contains more elongated drumlins (mean ER=3.6) than those in either the Guelph (mean ER=2.8) or the Galt (mean ER=2.9) drumlin fields (Table 4.2). The maximum ER value is higher in the Galt drumlin field (max ER=11.6) than either the Arran (max ER=8.4) or the Guelph drumlin fields (max ER=9.7). The largest drumlins, identified by both the mean and maximum values of area, width and length, reside in the Galt drumlin field.

The morphological attributes of the drumlins identified in the Arran, Guelph and Galt drumlin fields appear to be broadly consistent with those recorded from other drumlin fields in Ontario and elsewhere. Drumlins within the Woodstock drumlin field have an estimated ER of 2.7 (707 drumlins; Piotrowski 1987), the drumlins of Peterborough County have an estimated ER of 3.16 (898 drumlins; Crozier 1975) and an overall Southern Ontario average of 3.33 is estimated from 60 randomly selected drumlin fields around the province (Trenhaile 1971). Clark et al. (2009) calculated an overall average ER of 2.9 for 37,043 drumlins identified within Britain.

The drumlins in the Arran drumlin field are relatively elongated with ER values ranging from a minimum of 1.01 to a maximum of 8.4 and averaging 3.6 (Table 4.2). Drumlins in this field have an average area of 0.14 km^2 (Table 4.2). Harry and Trenhaile (1987) used topographic maps to visually estimate the mean length and width of the drumlins within the field to be 1150 m and 280 m respectively. These values are both slightly larger than the results obtained from this study with averages of 776 m for length and 226 m for width (Table 4.2). The average ER value of 3.8 calculated by Harry and Trenhaile (1987) is also slightly greater than the value obtained in this study. Drumlins in the Arran field have long axis azimuths that lie within a range of values between 143° and 314° with a mean value of 216° (Figure 4.3, Table 4.2). The azimuth values showed greatest variability within the southern portion of the drumlin field (Figure 4.3, Table 4.2).

Drumlins of the Galt drumlin field show a broad range of ER values extending from a minimum of 1.03 to a maximum of 11.6 (Table 4.2), with the average ER of 2.9 representing a more ovoid drumlin shape than the average of 3.1 reported by Trenhaile (1975). The average area of the Galt drumlins is 0.22 km^2 (Figure 4.4). This value is larger than that obtained by Trenhaile (1975) who reports a mean drumlin area of approximately 0.12 km^2 for the Galt field. The long axis azimuth of drumlins within the Galt field ranges between 186° and 356°, with a mean value of 293° (Figure 4.4; Table 4.2).

The Guelph drumlin field is characterized by drumlins with slightly lower elongation ratios than those of the Galt field, averaging 2.8 with a range of ER values from 1.06 to 9.7, and with an average area of 0.18 km^2 (Figure 4.5; Table 4.2). The average area calculated for drumlins within the Guelph drumlin field (0.18 km^2) is similar to that recorded by Trenhaile (1975) of 0.12 km^2. For the Guelph drumlin field the range of drumlin long axis azimuths was between 181° and 359°, with a mean of 285° (Figure 4.5; Table 4.2). In both the Guelph and Galt drumlin fields the long axis azimuth values become less consistent in a westward (down-ice) direction (Figures 4.4, 4.5).

4.5.2 Spatial distribution of drumlins

Statistical analysis of the distribution of drumlins determines if the occurrence of the landforms is dispersed, random or clustered, and at what distances, if any, clustering occurs. The degree and potential for clustering of various morphological characteristics of the drumlins can also be assessed through statistical analyses.

4.5.2.1 Kernel density analysis

The results of kernel estimation analyses conducted for each drumlin field provide a visual representation of the spatial variability of drumlin occurrence. This first step in exploration of drumlin distribution allows a qualitative visual assessment of clustering prior to more detailed exploration and analysis of the data.

Kernel estimation analyses of the three drumlin fields (Figures 4.10, 4.11) show distinct areas of clustering. The Arran drumlin field shows several distinct areas of drumlin clustering (Figure 4.10) with the largest cluster lying along the western edge of the field, close to Lake Huron, near the ancient Lake Iroquois shoreline (Figure 4.1). Both the Guelph and Galt drumlin fields exhibit clustering but, unlike the Arran drumlin field, the clustering is limited to a single area within each field, close to the Paris-Galt moraine (Figure 4.11).

Kernel density analysis is not limited to exploration of drumlin distribution but can also be used to visualize the clustering of morphological variables. By analysing the clustering of drumlins with the top 25% of elongation values, the distribution of the more elongated drumlins may be visualized. Elongation ratio is the drumlin variable most often reported (Boyce and Eyles 1991, Kerr and Eyles 2007, Clark et al. 2009) to be directly related to former ice conditions, and the visualization of areas containing highly elongated drumlins is therefore important. Within the Arran drumlin field, the largest concentration of elongated drumlin lies in the western portion of the study area close to the shore of Lake Huron and approximately 10 km north of the Williscroft moraine (Figure 4.12). The highest concentration of elongated drumlins within the Guelph drumlin field lies near the southern extent of the drumlin field, approximately 8 km west (down-ice) from the Paris-Galt moraine (Figure 4.13). Most of the elongated drumlins within the Galt drumlin field are concentrated approximately 11 km east (up-ice) of the Paris-Galt moraine (Figure 4.13).

4.5.2.2 Nearest neighbour analysis results

The results of nearest neighbour analysis of drumlins within all three drumlin fields shows the drumlins to be clustered, with a less than 1% likelihood of the clustering pattern resulting from random chance (Table 4.3). The nearest neighbour analysis for the Arran drumlin field (*R Score = 0.78)*, the Guelph drumlin field (*R Score = 0.54)*, and the Galt drumlin field (*R Score = 0.54)* show values of less than one, indicating a clustered pattern. These results also indicate that drumlins within the Arran field are more clustered than those in the Galt and Guelph fields. This result contradicts a previous study of drumlin distribution within the Arran field that found there was no statistically significant clustering of drumlins (Harry and Trenhaile 1987). Early studies of the Wingham, Guelph, and Peterborough drumlin fields also concluded that the distribution of drumlins within these fields was random (Trenhaile 1971, 1975). The difference in interpretation of drumlin distribution within these various fields is perplexing but may be due to the utilization of different methodologies to identify drumlins, and also to the sensitivity of the quantitative tools applied to discriminate the complex spatial distribution patterns.

4.5.2.3 Ripley's K-function results

Ripley's K-function is also used to analyse the relative distribution of drumlins within a field. For each of the three study areas examined the results indicate a 99.9% likelihood that the drumlins are clustered at all distances (Figure 4.14). The graphical results of this test (Figure 4.14) show that the observed spatial pattern of drumlin distribution for each of the three fields plots above the expected spatial random pattern and the higher confidence envelope, indicating significant clustering of the drumlins. If the observed spatial pattern was below the line identifying the expected random pattern and outside the lower confidence envelope, the pattern would be considered significantly dispersed. Any

Table 4.3: Nearest neighbour distance results of each the Arran, Galt and Guelph drumlin fields.

Drumlin field	Nearest Neighbour	Z-score	Confidence
Galt	0.54	-16.32	99%
Guelph	0.54	-14.73	99%
Arran	0.78	-6.46	99%

results lying within the confidence envelop do not exhibit a statistically significant spatial pattern of either clustering or dispersion (Yamanda and Rogerson 2003).

The results of the Ripley's K-function analysis from all three drumlin fields concur with the results of nearest neighbour analysis and demonstrate an overall tendency for clustering of drumlins at varying spatial scales (Figure 4.14). Clustering is shown to occur over distances of up to, and beyond, 20 km in the Arran drumlin field (Figure 4.14B). In the Galt drumlin field clustering occurs at all distances up to, and beyond, 5 km (Figure 4.14C) and the Guelph field also shows clustering at all distances up to 5 km (Figure 4.14D). The distances at which clustering occurs can be used to evaluate spatial variability in the processes responsible for drumlin formation beneath large ice sheets.

4.5.2.4 G-Statistic results

Once clustering of drumlins within each of the three drumlin fields has been established it is possible to identify areas of spatial clustering of either high (hot spots) or low (cold spots) values of particular variables within each drumlin field using G-Statistic analysis. In this study, the clustering of drumlins with either high or low elongation ratios was examined (Figures 4.15, 4.16). In the Arran field the 'hot spot' of elongated drumlins occurs in the western portion of the study area, just east of the Lake Algonquin paleoshoreline (Figure 4.1) and approximately 15 km north (up-ice) of the local moraine complex that marks the southern end of the drumlin field. In the south-western part of the drumlin field, 3 km north of the Banks and Williscroft moraine complex, a 'cold spot' of less elongate (more ovoid) drumlins occurs (Figure 4.15). Within the Galt drumlin field

Figure 4.15: Coloured DEM of the Arran drumlin field showing results of G-statistic calculations for drumlin ER values. The G-statistic separates clustering of high and low values within a dataset. The resulting map identifies areas of clustering of both elongated (red dots) and ovoid (blue dots) drumlins with the field.

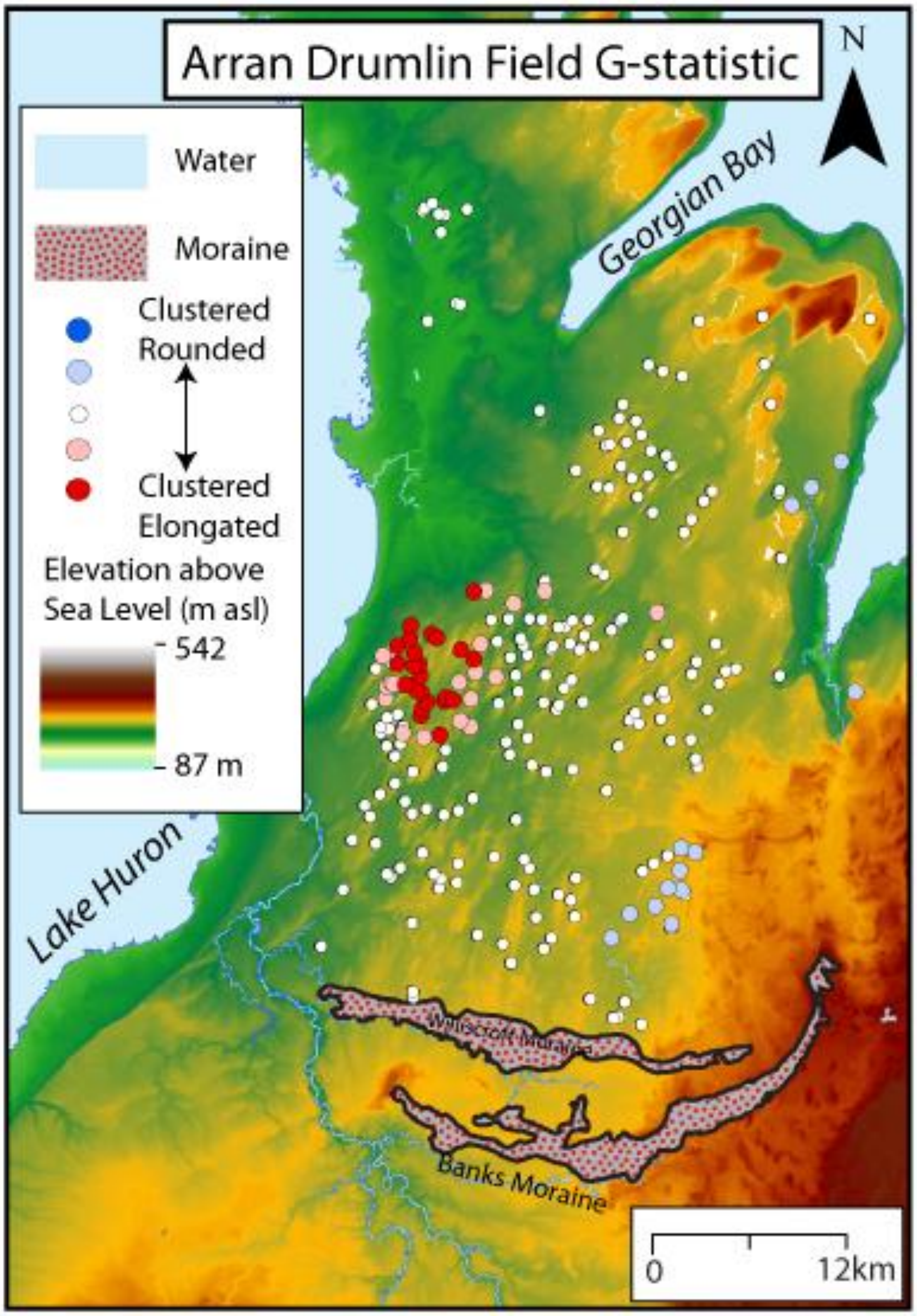
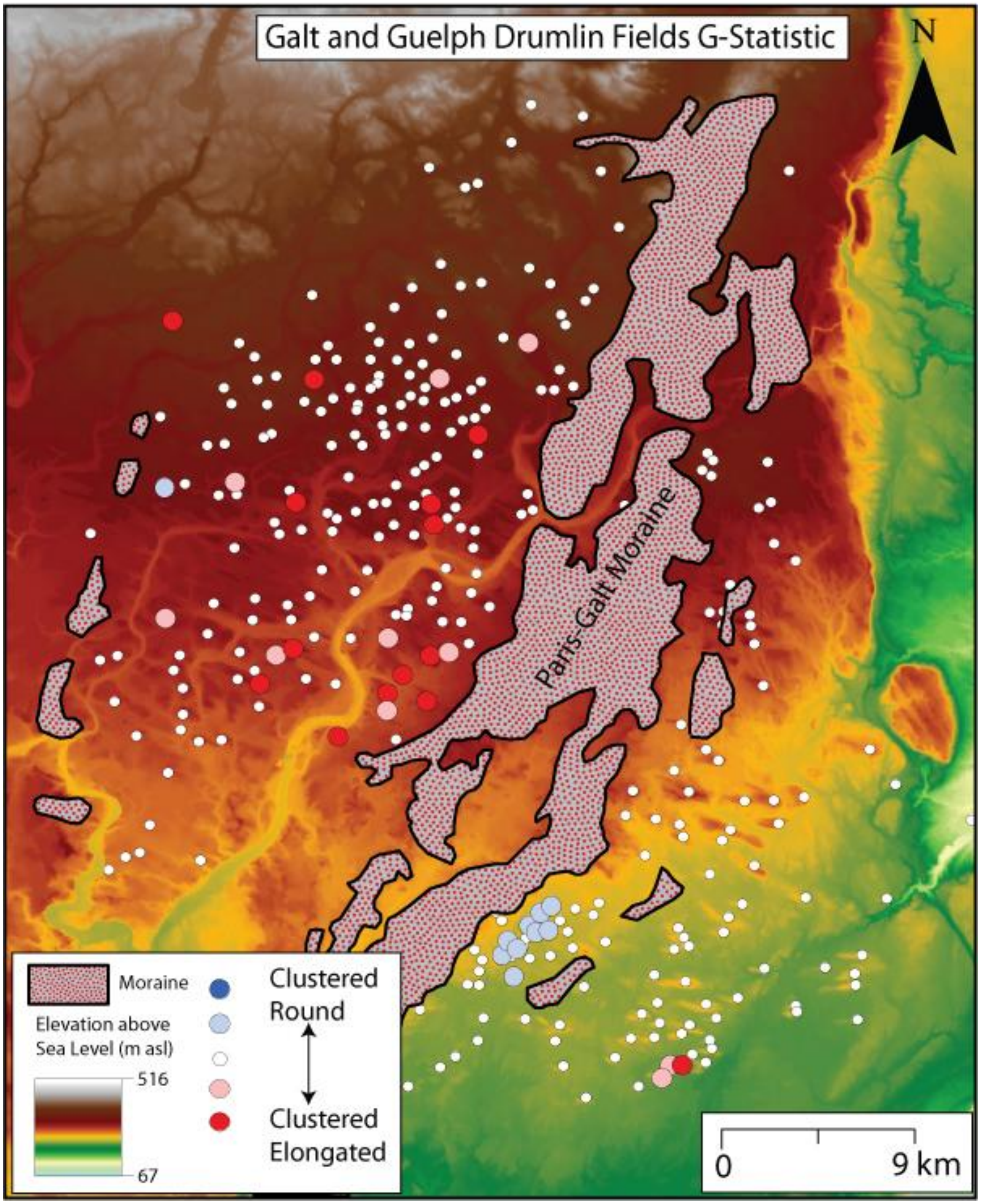

Arran Drumlin Field G-statistic
N
Water
Moraine
Clustered Rounded
Clustered Elongated
Elevation above Sea Level (m asl)
542
87 m
Georgian Bay
Lake Huron
Wiscroft Moraine
Banks Moraine
0
12km

Figure 4.16: Coloured DEM of the Guelph and Galt drumlin fields showing results of G-statistic calculations for drumlin ER values. The G-statistic separates clustering of high and low values within a dataset. The resulting map identifies areas of clustering of both elongated (red dots) and ovoid (blue dots) drumlins with the fields.


Galt and Guelph Drumlin Fields G-Statistic
N
Paris-Galt Moraine
Moraine
Elevation above Sea Level (m asl)
516
67
Clustered Round
Clustered Elongated
0
9 km

likelihood that the drumlins are clustered at all distances (Figure 4.14). The graphical results of this test (Figure 4.14) show that the observed spatial pattern of drumlin distribution for each of the three fields plots above the expected spatial random pattern and the higher confidence envelope, indicating significant clustering of the drumlins. If the observed spatial pattern was below the line identifying the expected random pattern and outside the lower confidence envelope, the pattern would be considered significantly dispersed. Any results lying within the confidence envelop do not exhibit a statistically significant spatial pattern of either clustering or dispersion (Ripley 1981).

4.6 Field Observations

The results of spatial statistical tests described above show that the spatial distribution of drumlins within the three studied drumlin fields exhibit various levels of clustering in terms of both drumlin occurrence and drumlin morphology, specifically ER. To relate the morphological data to the processes responsible for the formation of drumlins, identification of the internal structure and composition of drumlins is required. Unfortunately, very few drumlins have been excavated and relatively little is known about their internal composition, particularly in the three fields under investigation. Only one partially excavated drumlin was identified within the Aberfoyle Quarry in the eastern portion of Guelph drumlin field, approximately 1 km west of the Paris-Galt moraine (Figure 4.5). The drumlin is excavated at an oblique angle to the long axis exposing the down-ice (lee-side) portion more fully than the up-glacier (stoss) portion (Figure 4.9).

Three distinct stratigraphic units can be recognized within the partially excavated drumlin (Figure 4.9). The lowermost unit, Unit 1, consists of approximately 4 m of crudely stratified fine to medium sand draped directly over the low relief limestone bedrock. This unit contains scattered subrounded to rounded clasts of local limestone and dolostone ranging in size up to 5 cm diameter (Figure 4.9E). Unit 2 is approximately 1 m thick and consists of predominately structureless with some crude stratification medium sand containing subrounded to rounded clasts of local bedrock varying in size from 1 to 10 cm diameter. Clasts have no apparent preferred long axis orientation. Unit 2 is capped by a discontinuous, 20-40 cm thick horizon of silty sand with climbing ripples containing a small number of rounded to subrounded limestone/dolostone clasts up to 3 cm diameter (Figure 4.9D). Unit 3, the uppermost layer exposed in the drumlin, is a 1.5 m thick, laterally continuous, well consolidated unit of clast-rich, medium to coarse grained sandy diamict containing subrounded to rounded limestone and dolostone clasts 1 mm to 25 cm diameter (Figure 4.9B). Clast long axis orientation is approximately parallel to the drumlin long axis. The limited exposure and extensive removal of material on the stoss side of the drumlin make it impossible to confidently ascertain full details of the internal structure along the entire drumlin long axis (Figure 4.9F). However, an exposure through the lateral edge of the drumlin in the down-ice direction reveals a sharp planar contact between Unit 1 and Unit 3 and an absence of Unit 2 (Figure 4.9C). Unit 3 thickens and Unit 1 appears to taper out in the down-ice direction (Figure 4.9A).

The core of the partially excavated drumlin exposed in the Aberfoyle Quarry, consisting of Unit 1 and Unit 2, is interpreted as proglacial outwash composed of crudely stratified sands containing clasts of variable size (Caputo et al. 2008). These sediments are similar to those described from the cores of several other drumlins in Ontario (Figure 4.9D: Trenhaile 1975, Shaw and Kvill 1984, Karrow 1984, Kerr and Eyles 2007). The uppermost unit (Unit 3, sandy diamict) of the exposed drumlin is interpreted as an erosively-based overconsolidated deformation till, created by the overriding and incorporation of previously deposited coarse-grained fluvial/glaciofluvial deposits. Similar diamict facies have been described in the upper parts of drumlins in the Peterborough drumlin field (Boyce and Eyles 1991) and erosional drumlins from various areas in the United States of America, Iceland and Ireland as reported by Hart (1997). The overall composition and structure of the exposed part of the drumlin is consistent with sedimentary successions described as glacitectonite (Evans et al. 2006), a term used to describe sediment that has undergone deformation induced by ice but that retains a portion of its original structural characteristics (Evans et al. 2006, Maclachlan and Eyles 2011). The lower units within the exposed drumlin (Units 1 and 2; Figure 4.9) are interpreted as outwash sediments that have been overridden and moulded by overriding ice. The upper veneer of coarse, sandy diamict represents the sediment mobilized as part of a deforming bed at the ice base (Boulton and Dobbie 1998). Drumlins recently exposed at the base of the Múlajökull glacier in Iceland (Johnson et al. 2010) show a similar stratigraphic succession to that observed in the Aberfoyle Quarry drumlin.

Sedimentological analysis of the partially excavated drumlin suggests that the drumlin formed as a result of subglacial erosion and deformation of pre-existing outwash sediments in a similar manner to that proposed by Boulton and Hindmarsh (1987), Boyce and Eyles (1991) and Johnson et al. (2010). Relatively undisturbed older sediments (Units 1 and 2) are draped with more highly deformed outwash and an erosionally-based veneer of subglacial deformation till (Unit 3).

4.7 Discussion

This study has demonstrated that clustering of drumlins occurs on a range of spatial scales in each of the three drumlin fields under investigation and identifies the potential for influences upon the distribution of drumlins beyond random chance (Clark et al. 2009, Hess and Briner 2009, Fowler 2010, Greenwood and Clark 2010). Past research into the morphological variability of drumlins has identified a number of factors that may be controlling drumlin morphology and spatial distribution including drift thickness, differences in time under ice, bedrock conditions, ice sheet dynamics, and substrate type (Clark et al. 2009, Hess and Briner 2009, Phillips et al. 2010). The most commonly cited morphological variable used to compare drumlins within a field is elongation ratio (ER), which has been positively correlated to the formation of drumlins on both relatively thin (Boyce and Eyles 1991, Kerr and Eyles 2007, Clark et al. 2009, Phillips et al. 2010) and relatively thick drift cover (Stokes and Clark 2002, Greenwood and Clark 2010). In this study, a comparison of drift thickness values and elongation ratios shows a weak negative correlation between the two variables. The Arran (Figure 4.7), Galt, and Guelph drumlin fields (Figure 4.8) each exhibit a negative relationship between the ER and drift thickness, with ER showing a tendency to increase as drift thickness decreases. This relationship is similar that reported by Boyce and Eyles (1991) and Kerr and Eyles (2007) for the Peterborough and the New York State drumlin fields respectively, and has been used to infer that the most elongate drumlins develop in areas of thin drift cover.

An increased duration of subglacial sediment deformation has also been linked to the production of drumlins with high ER values. It has been suggested that ER decreases toward the former position of the ice margin due to the shorter duration of subglacial conditions in these areas (Stokes and Clark 2002). This concept of downstream decrease in drumlin elongation was reported from research in the Peterborough drumlin field (Boyce and Eyles 1991) and the M'Clintock Channel paleo-ice stream bed on Victoria Island in the Canadian Arctic (Clark and Stokes 2001).

Factors related to former ice sheet dynamics that may control drumlin creation and distribution include preferential development of drumlins beneath fast-flowing ice streams (Boyce and Eyles 1991, Larter et al. 2009, Hess and Briner 2009, Phillips et al. 2010, Stokes et al. 2011), or beneath decelerating ice streams (as reported in the Irish Sea; Van Landeghem et al. 2009). Fast-flowing ice streams, or fast moving areas of ice within the larger ice body are noted to preferentially develop in areas associated with elongate bedrock lows (Bradwell et al. 2008, Phillips et al. 2010, Pingree et al. 2011). Drumlin formation has also been linked to ice sheet velocity which is in turn impacted by bedrock topography (Krabbendam et al. 2011, White et al. 2011). Research has also shown that ice velocity can affect the morphology of drumlins, with a positive correlation between the speed of the ice and higher elongation values (Dyke and Morris 1988, Stokes and Clark 2002, Briner 2007).

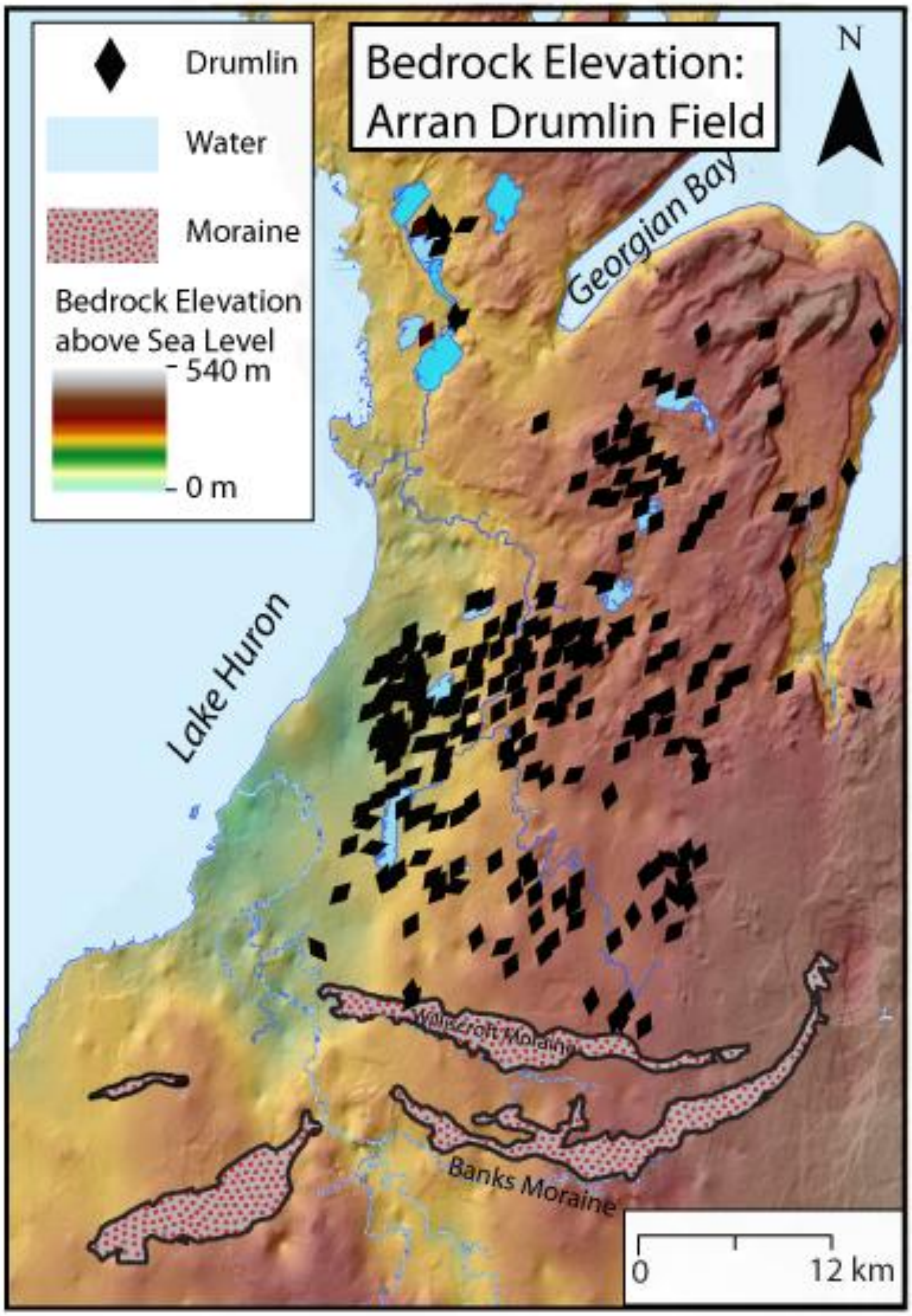
Some models of drumlin formation suggest that the morphology and spatial distribution of drumlins is related to substrate type and the rheological characteristics of the materials of which they are formed (e.g. Boulton and Hindmarsh 1987). Investigating the relationship between drumlin form, distribution and substrate type required comparison of the drumlin database created for each of the three drumlin fields with surficial geology maps published by the Ontario Geological Survey (OGS 2011). All of the data were compared using ArcGIS 10 and, with the exception of 6 drumlins located in the northern reaches of the Arran field (and outside of the OGS map area), each of the drumlins identified in this study are located on diamicton substrates with 'low-medium permeability' (clayey-sand or sand-clay mixture; OGS 2011). The field evidence presented here from the exposed drumlin core in the Guelph drumlin field is consistent with these data and suggests that at least some of the drumlins formed as a result of erosion and subglacial deformation of previously deposited fluvial/glaciofluvial sediments. Unfortunately, the resolution of the available surficial sediment data is insufficient to establish a more reliable and meaningful relationship between drumlin form and substrate type in all three drumlin fields. Given the wide range of factors that can influence the development of drumlins each of the three drumlin fields under investigation will be discussed separately below.

4.7.1 Controls on drumlin development within the Arran field

The description and analysis of drumlin distribution within the Arran drumlin field is complicated by the erosion of an unidentified number of drumlins in the western portion of the field by wave action in paleolake Algonquin (Figure 4.1, Straw 1968). However, a number of interesting distribution patterns can be identified. The most elongated drumlins in the Arran field are clustered in the north western portion of the drumlin field in an area of regionally low drift thickness that is truncated by the Lake Algonquin shoreline (Figures 4.12, 4.15). There appears to be an overall trend toward increasing ER values as drift thickness decreases. While this negative relationship between ER values and drift thickness does exist in each of the three study areas, it is most pronounced in the Arran drumlin field where drift thickness ranges from almost zero in the north to over 500 m in the southern part of the field.

Immediately west of, and partially underlying this area of high ER values, is a regional bedrock low that trends north to south, roughly parallel to the Lake Algonquin shoreline (Figure 4.17). The identification of a clustering of elongate drumlins in the western portion of the Arran field proximal to a north-south trending bedrock low may indicate the former location of a fast-flowing ice stream within the Georgian Bay ice lobe. In the southern part of the Arran drumlin field close to the end moraines, a small clustering of ovoid drumlins with relatively low elongation ratios occurs in an area of relatively high drift thickness (Figures 4.6, 4.17). The presence of ovoid drumlins close to the terminal margin of the field is consistent with the conclusions of past studies (e.g. Boulton and Hindmarsh 1987, Boyce and Eyles 1991, Stokes and Clark 2001, Stokes and

Figure 4.17: Bedrock topography map for the Arran drumlin field study area. Map created using data obtained from the Ontario Geological Survey. Note area of low bedrock elevation to the east of the Lake Huron shoreline.


Drumlin
Water
Moraine
Bedrock Elevation above Sea Level
540 m
0 m
Bedrock Elevation: Arran Drumlin Field
N
Georgian Bay
Lake Huron
Walscroft Moraine
Banks Moraine
0
12 km

Clark 2002) that propose a short residence time under the ice leads to a less defined (more ovoid) drumlin form.

4.7.2 Controls on drumlin development within the Galt and Guelph fields

The formation of the Guelph drumlin field beneath the Ontario lobe of the Laurentide ice sheet preceded development of the Galt drumlin field (Trenhaile 1975). The ice responsible for the Galt field would have overridden components of the eastern part of the Guelph drumlin field (Trenhaile 1975). Previous studies of these drumlin fields suggested that drumlins were distributed randomly (Trenhaile 1971, Trenhaile 1975, Harry and Trenhaile 1987) but the quantitative analysis presented here indicates that both the Guelph and Galt drumlin fields show significant clustering of drumlins (Figures 4.11, 4.14, 4.16).

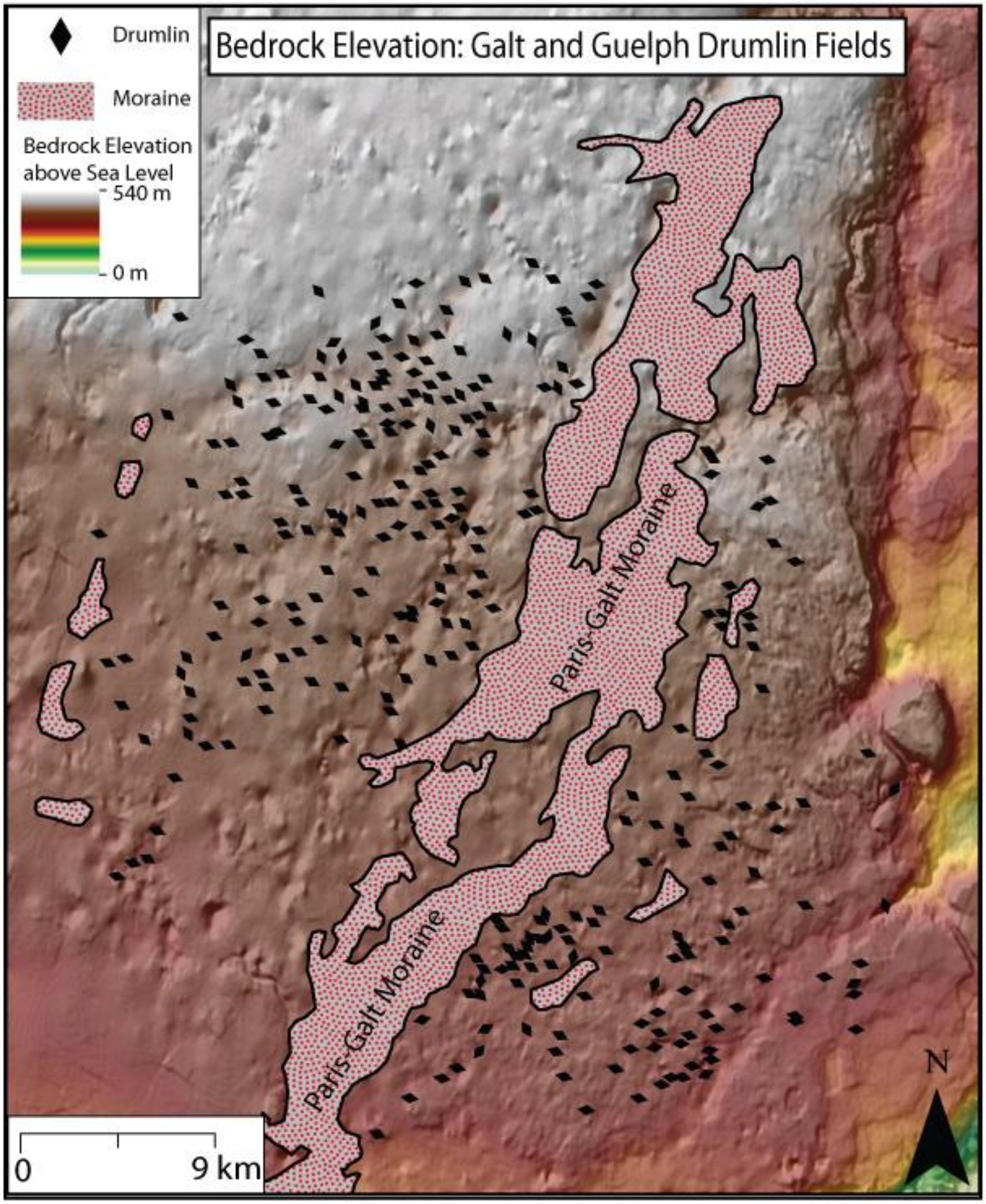
4.7.2.1 Galt drumlin field

The Galt drumlin field shows similar spatial patterns of drumlin distribution to those identified in the Arran drumlin field. However, unlike the Arran drumlin field bedrock topography has a consistently low relief throughout the study area with a slight net increase in elevation from the southeast to the northwest that does not appear to be reflected in the changing morphology of drumlins (Figure 4.17). As with the Arran drumlin field there is a weak negative correlation between drift thickness and drumlin ER (Figure 4.6). The most significant variance in drumlin form across the field is in the distribution of elongate and ovoid forms. A cluster of elongated drumlins is located in the eastern portion of the study area and a cluster of ovoid drumlins lies close to the terminus of the ice advance responsible for the formation of the Galt drumlin field and the Paris-Galt moraines (Figure 4.13; Costello and Walker 1972). This suggests that the length of time beneath the ice has influenced drumlin morphology in the Galt field, with more elongate forms developing in areas covered by ice for longer time periods (Boulton and Hindmarsh 1987, Boyce and Eyles 1991, Clark and Stokes 2001, Stokes and Clark 2002).

4.7.2.2 Guelph drumlin field

The Guelph drumlin field shows the least significant spatial distribution patterns of the three study areas. Unlike the Arran and Galt fields there is no significant clustering of ovoid drumlins within the Guelph drumlin field and a relatively inconsistent distribution of elongated drumlins (Figure 4.16). A single grouping of elongated drumlins lies just west of the Paris-Galt moraine in the southernmost section of the drumlin field (Figure 4.16) in the area that experienced the longest duration of subglacial conditions. As with the Galt drumlin field there are no significant changes in bedrock topography (Figure 4.18) within the field and there is an overall weak negative correlation between drift thickness and drumlin elongtion consistent with all study areas. Analysis of the distribution of drumlins within the Guelph drumlin field is complicated by the post depositional reworking of sediments during the secondary advance of the ice sheet which deposited the Paris-Galt moraine. This advance most likely resulted in truncation of the easternmost portion of the drumlin field (Trenhaile 1975). There is additional evidence of post-depositional erosion of drumlins caused by glaciofluvial processes associated with

Figure 4.18: Bedrock topography map for the Guelph and Galt drumlin fields study area. Map created using data obtained from the Ontario Geological Survey. Note relatively consistent elevation of bedrock beneath the two drumlin fields. Niagara Escarpment is shown at far right.


Drumlin
Moraine
Bedrock Elevation above Sea Level
540 m
0 m
Bedrock Elevation: Galt and Guelph Drumlin Fields
Paris Galt Moraine
Paris Galt Moraine
N
0
9 km

ice advance at the time when the Galt drumlin field was formed (Eynon and Walker 1974, Chapman and Putman 1966, 1984). Post-depositional modification of many of the drumlins within the Guelph field either by subsequent overriding by glacial ice or erosion by glaciofluvial processes makes the interpretation of spatial patterns of drumlin form difficult. However, it is significant that the partially excavated drumlin within this field is composed of similar sediment to modern drumlins that have formed as a result of subglacial deformation processes in Iceland (Johnson et al. 2010). This suggests that similar processes may have been responsible for the development of drumlins in southern Ontario.

4.8 Conclusions

The computational analyses of drumlin form and distribution discussed in this paper have been used to examine the spatial distribution of drumlins across three drumlin fields in southern Ontario: the Arran, the Guelph, and the Galt drumlin fields. A number of factors may account for the spatial variability of drumlin morphological characteristics within these fields but several important conclusions can be reached:

- Drumlins within each of the drumlin fields are not randomly distributed and show significant clustering both in terms of their overall distribution and their morphological characteristics. Drumlins in each of the three study areas show a weak negative correlation between drift thickness and drumlin elongation.
- The Galt and Arran drumlin fields show spatial variability in drumlin elongation that is consistent with the length of time under the ice being a major factor

influencing drumlin morphology. The longer the time spent beneath the ice, the more elongate the drumlin forms.

- The Arran drumlin field shows a clustering of drumlins with high ER values that is coincident with an elongate bedrock low. These elongate drumlins may record the former position of a fast flowing ice stream focussed along the bedrock low.
- Sediments within the Guelph drumlin field indicate the presence of relatively undisturbed older fluvial/glaciofluvial sediments draped with a thin veneer of coarse-grained sediment deposited as deformation till. This stratigraphy is similar to that described from modern drumlins in Iceland (Johnson et al. 2010) and is consistent with models of drumlin formation by subglacial deformation processes (Alley et al. 1986, Boulton 1986, Boyce and Eyles 1991).

This study applies a quantitative methodology to identify the location, form and patterns of distribution of drumlins within three drumlin fields in southern Ontario. The methodology can be applied to the study of any drumlin field with an adequate coverage of digital spatial data. The ability to consistently identify and characterize drumlin morphology and distribution will allow more objective and systematic comparison of these landforms both within and between drumlin fields that may ultimately lead to enhanced understanding of the spatial controls on the development of these enigmatic landforms.

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CHAPTER 5
SUMMARY AND CONCLUSIONS

The objective of the research conducted for this thesis is to explore the Quaternary sedimentological and geomorphological record of selected areas of southern Ontario in order to more thoroughly understand the subglacial processes and depositional history that the sediments and landforms record. The integration of field documentation of subglacial sediment characteristics with analysis of glacial landform distribution using existing spatial digital data within a Geographic Information System (GIS) allows exploration of the relationships between glacial landforms (specifically drumlins), and regional glacial sediments and processes. The results of this work will assist in the more accurate interpretation of glacial depositional histories in the region and in the reconstruction of former local and regional ice sheet characteristics.

This thesis explores the sedimentological and geomorphological record of southern Ontario by; 1) analysing a suite of recently exposed sediments within the Vineland Quarry in Vineland, Ontario that is determined to be the product of subglacial deformation of glaciolacustrine sediment (Chapter 2); 2) identifying drumlins and assessing and quantifying their morphology and spatial distribution within the Arran, Galt, Guelph, and Peterborough drumlin fields from pre-existing digital data (Chapters 3 and 4); and 3) exploring the relationship between sedimentology and geomorphology within the Guelph drumlin field through the analysis of a partially excavated drumlin (Chapter 4).

The methodological contribution of this thesis is the creation and documentation of a computational system that may be used to identify and determine the morphological characteristics of drumlins using existing digital data within GIS (Chapters 3 and 4). An important implication of using this computational methodology to identify drumlins is that it allows for the comparison of drumlin attributes between drumlin fields. This was not possible using qualitative data previously available. Ultimately this computational methodology will allow data comparisons to be made between drumlin fields within Ontario and in other previously glaciated regions where adequate digital data are available. Given the continuous creation, archiving and availability of digital geographic data, the production of a repeatable methodology to identify, analyse and compare the data increases their intrinsic value.

Analysis of the sedimentary succession exposed in Vineland, Ontario increases overall understanding of the nature of late Quaternary subglacial processes that operated in the region (Chapter 2). The field-based study is a contribution to the literature on subglacial sedimentology as the sediment package records a complete transition from bedrock erosion to the ice-bed contact and most likely records the final advance of the Ontario Lobe of the Laurentide Ice Sheet. The succession shows clear evidence of the results of subglacial deformation of previously deposited fine-grained sediments. Sediments show evidence of increasing up-section deformation passing from *in situ,* undeformed lacustrine sediment overlying bedrock to highly deformed lacustrine facies and macroscopically homogenized diamict at the top of the section. The interpretation of this succession as having originated by subglacial deformation of pre-existing sediment is consistent with proposed theoretical models of sediment deformation due to overriding ice sheets (Figure 1.1; Boulton 1996). The terminology used to describe the sediment is that of Evans et al. (2006), a non-process specific classification system in which the term 'glacitectonite' is used to describe sediment deformed by subglacial processes but retaining a portion of the original structural characteristics, and 'traction till' describes the sediment macroscopically homogenized due to the overriding ice. The Vineland succession is unique in that it records the full continuum of processes ascribed to subglacial deformation in a single location and provides valuable field evidence with which to substantiate theoretical models.

Geographic Information Systems and non-traditional statistics such as kernel estimations are currently underutilized in glacial geomorphology (Napieralski et al. 2007, Cox 2007). The research presented in this thesis outlines a methodology that may be used to identify drumlins from pre-existing, and widely available, digital data that facilitate large scale analysis and comparison of landforms within drumlin fields (Chapter 2). This methodology allows for examination of the geomorphology of any area possessing adequate digital data with appropriate coverage and resolution. Utilization of a standardized method of landform identification and measurement creates quantitative data that can be accurately compared within and between drumlin fields. Analysis of the Arran, Galt and Guelph drumlin fields showed a significant amount of clustering of drumlins that contrasts with previously published results which depicted the distribution as random (Harry and Trenhaile 1987, Trenhaile 1971, Trenhaile 1975). Kernel density analysis was used to visualize areas of clustering and relate these to potential controls on drumlin distribution such as drift thickness, bedrock topography, time under the ice, and substrate type. These results show that all of the controls can influence the distribution of drumlins within a field but that the factors affecting drumlin distribution do vary between drumlin fields. While these results support the conclusions reached by others (e.g. Boyce and Eyles 1991) the additional information presented here consolidates some of the connections made between drumlins, substrate conditions and glacier dynamics.

Three themes have recently emerged in drumlin research; field mapping, sedimentary and ice-bed processes, and glacier dynamics (Knight 2010). This thesis incorporates research that addresses each of the three themes: (1) Field mapping and morphometry is the primary focus of the thesis and incorporates analysis of non-spatial properties of drumlins, such as elongation ratio and uniaxial direction, as well as spatial properties of drumlin fields that may be used to test for evidence of clustering and spatial controls on the distribution of drumlin types within and between drumlin fields; (2) Sedimentary and ice-bed processes are explored directly through analysis of a succession of subglacially deformed sediments in Vineland, Ontario and within a partially excavated drumlin within the Guelph drumlin field; (3) Glacier dynamics are discussed through consideration of the effects of ice streaming and variable ice flow velocities on drumlin morphology.

5.1 Methodological Contributions: Summary and Assessment

The methodological contribution of this thesis is the creation and documentation of a computational system that may be used to identify and determine the morphological characteristics of drumlins using existing digital data within GIS (Chapters 3 and 4). An important implication of using this computational methodology to identify drumlins is that it allows for the comparison of drumlin attributes between drumlin fields. This was not possible using qualitative data previously available. Ultimately this computational methodology will allow data comparisons to be made between drumlin fields within Ontario and in other previously glaciated regions where adequate digital data are available. Given the continuous creation, archiving and availability of digital geographic data, the production of a repeatable methodology to identify, analyse and compare the data increases their intrinsic value.

The identification and analysis of drumlins from existing digital data within a GIS produced exciting results and also identify areas for potential expansion and improvement. In its current form the methodology can be used to effectively locate individual drumlins and identify their morphological characteristics but there are limitations which can be improved upon with new techniques and the availability of higher resolution data.

Currently all drumlins with an elevation of more than 20 m are identifiable but drumlins with lower elevation (less than 20 m) are excluded. These smaller drumlins have been hypothesized to exist preferentially within areas of relatively thick sediment cover where the landforms have little time to form subglacially (Boyce and Eyles 1991). Exclusion of these drumlins from the spatial analysis is a limitation of the computational methodology and may bias the results presented here. A secondary limitation to the methodology is the potential loss of data regarding the morphological attributes of each form. In particular, the lower relief drumlin 'tail' may be artificially shortened which may in turn reduce the elongation ratio, an important parameter related to conditions of drumlin formation (Spagnolo et al. 2011). The underrepresentation of drumlins of low elevation and elongation ratio may result in a misinterpretation of the significance of variables that account for drumlin formation. These limitations are directly relatedto the resolution of the data and will be minimized when higher resolution data are available.

Future development of the methodology should also include enhanced definition of the morphological characteristics of drumlins and inclusion of bathometric data when relevant. For example, bathymetric data from Rice Lake would enhance the spatial coverage of data in the Peterborough drumlin field (Chapter 3). Additional morphological parameters that could be identified include the elevation of the drumlin at the highest point, and identification of slope and aspect characteristics to provide additional data regarding drumlin three-dimensional form.

5.2 Future Directions

The research presented in this thesis presents a methodology that integrates sedimentology with geomatics, an approach to the analysis of glaciated terrains that can be used in other regions of Canada and elsewhere. Additional and more extensive regional analyses of subglacial deposits and landforms using a similar approach will allow the isolation of specific controls on their development. This in turn will enhance understanding of subglacial processes and their spatial distribution, particularly those that operated under large ice sheets such as the LIS. Quantitative analysis and comparison of data from a large number of drumlin fields can be also used to more effectively evaluate theoretical models of drumlin formation.

Future directions for research on subglacial landforms and sediments will involve many sub-disciplines within the Earth sciences. There is considerable potential and value for research in the following areas:

- The utilization of geophysics and remote probes (e.g. Hart et al. 2006) to explore the processes involved in drumlin formation beneath modern glaciers and the ice conditions responsible for their creation.
- The application of techniques such as GPR and borehole geophysics to explore the internal structure of drumlins. Geophysical techniques may also be used to assess the spatial variability of subglacial sedimentary successions and their relationship to surface landforms and factors such as

drift thickness, and bedrock topography, factors that do appear to exert some control on glacial landform development.

- Analysis of the sedimentology of drumlins and surrounding subglacial deposits in other regions of Ontario in order to better understand the complex subsurface stratigraphies that host important groundwater resources in glaciated terrains.
- Exploration of the Livingstone drumlin field on the Athabasca Plains in northern Saskatchewan to develop and expand upon the methodologies discussed in this thesis. This could be carried out using data recently released through the 'Saskatchewan Orthophoto Program 2011' which provides accurate orthorectified aerial photography and elevation data covering the entire province of Saskatchewan (Saskatchewan Geospatial Imagery Collaborative 2011). These new data can be used to further explore the spatial variability and genesis of drumlins within the Livingston drumlin field which have previously been attributed to subglacial meltwater flooding (Shaw 1983, Shaw and Kvill 1984) and subglacial deformation (Boulton 1987).
- Further exploration of the potential for the use of kernel estimation as a tool in drumlin research and, more generally, in glacial geomorphology. There are two possible areas of focus for such a study: (1) testing the effect of changing the kernel to be more elliptical in shape and varying the orientation of the kernel long axis to determine if, and how, the shape of

the kernel relative to the orientation of drumlins within a field affects the identification of high density area, and (2) the use of spatial analysis including kernel estimation, in conjunction with specified parameters that are hypothesized to affect the spatial distribution and spatial variance of morphology of drumlins (e.g. drift thickness, time under ice), to create predictive drumlin susceptibility maps. These maps can then be compared to the actual distribution of drumlins within a field. Research similar to this has been applied in karstic landscapes to determine sinkhole susceptibility (Galve et al. 2009).

- Investigation of the spatial variability of the 3-dimensional characteristics of drumlin fields. The research reported in this thesis is primarily 2-dimensional in nature (surface form and spatial distribution) and there is considerable potential for future analysis of 3-dimensional spatial attributes of drumlin fields such as variability in slope characteristics and drumlin volume. These 3-dimensional attributes can then be compared to parameters that may control the formation of drumlins such as bedrock topography and drift thickness.

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