SEDIMENTS INFILLING BURIED BEDROCK VALLEYS, SOUTHERN ONTARIO

Nature and Origin of Sediments Infilling
Buried Bedrock Valleys Adjacent to the
Niagara Escarpment, southern Ontario, Canada

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ABSTRACT

The Paleozoic bedrock surface of southern Ontario is dissected by an interconnected system of buried bedrock valleys that are infilled with thick successions of glacial, interglacial and fluvial sediments. These valleys can be several kilometers wide, reach depths of up to 250m and the coarse-grained units are known to host significant local and regional groundwater aquifers.

Two buried bedrock valleys located near the Niagara Escarpment in the Region of Halton were under investigation in the fall of 1999 for their potential to host additional municipal groundwater aquifers to supply drinking water to the towns of Milton and Georgetown. Detailed logging of sediment recovered from eleven continuously-cored boreholes, drilled within the Georgetown and Milton bedrock valleys, forms the basis for this study. Four distinct facies types were identified within the borehole cores including sand, gravel, fine-grained sediment and diamict (sand-rich, mud-rich and clast-rich). These four facies types were used to subdivide the cores into six stratigraphic units based on textural characteristics and stratigraphic position. These six units form a stacked succession of aquifers and aquitards within the valley infill with two stratigraphic units being identified as potential municipal aquifers.

The Georgetown buried bedrock valley contains narrow bedrock channel interpreted to have been fluvially incised, lying within a broader flat-bottom valley likely formed by glacial scouring of the bedrock. It is feasible that regional bedrock jointing created a zone of weakness that was later exploited by a drainage network. The valley infill sediments record the approach of the Laurentide Ice Sheet into southern Ontario during the Early to Mid-Wisconsin, and the subsequent overriding of the area during the Late Wisconsin period.

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CHAPTER ONE: INTRODUCTION

1.1 OVERVIEW

In southern Ontario, surficial Quaternary sediments are separated from underlying Paleozoic bedrock by a major unconformity that records a long period of non-deposition in eastern North America. An extensive channel network was eroded into the Paleozoic bedrock surface, probably during the late Tertiary, when a major fluvial system (the Laurentian Channel; Spencer, 1890; Straw, 1968) connected the drainage of the individual Great Lakes basins. During the past 2 million years, glaciers have repeatedly advanced and retreated across much of northern North America both eroding the landscape and depositing a thick blanket of interbedded glacial tills and interglacial gravels, sands, silts, and clays (Flint, 1967; Barnett, 1992; Eyles, 1997). Bedrock valleys formed excellent repositories for these Quaternary sediments as the deposits were protected from subsequent erosion by overriding ice, particularly during the Late Wisconsin (Eyles and Clark, 1988). Valley infill sediments thus contain a lengthy record of paleoenvironmental change during the Late Quaternary that is not preserved elsewhere (Eyles, 1997).

Bedrock valleys also served as topographic lows into which drainage was focussed over considerable periods of time and contain a relatively high proportion of coarse-grained, fluvial sediment interbedded with lacustrine silts and clays. These coarse-grained sediments form excellent subsurface aquifers and are used in several areas of southern Ontario as municipal drinking water sources (Bleuer et al., 1991; Eyles, 1997). However, due to limited outcrop exposure and poor subsurface data, the nature and stratigraphy of bedrock valley infills is not well understood, making prediction of aquifer geometry and characteristics extremely difficult.

This study focuses on the depositional origin and nature of sedimentary infills of two buried bedrock valleys in the Regional Municipality of Halton (Halton Region), west of Toronto, in southern Ontario. The two bedrock valleys lie close to the Niagara Escarpment and were recently drilled as part of the Halton Region groundwater exploration program.

1.2 BEDROCK TOPOGRAPHY

Throughout southern Ontario and the central Great Lakes states of the USA, Precambrian basement rocks of the North American craton are overlain by a thick succession of Paleozoic sedimentary rocks, and a relatively thin veneer of Quaternary glacial, fluvial and lacustrine deposits. The relatively flat-lying Paleozoic sedimentary rocks consist of interbedded carbonates, shales, and sandstones and were deposited predominately during the Ordovician and Silurian Periods (505-430Ma) when a shallow epeiric sea flooded the interior of the North American continent (Johnson et al., 1992; Nelson, 1998). Cratonic uplift and warping, related to orogenic activity on the eastern margin of North America, tilted the carbonate and clastic rocks (Johnston et al., 1992) and produced two intracratonic sedimentary basins, the Michigan and the Appalachian basins (Fig. 1.1). The Findlay-Algonquin Arch separates these two basins and forms a distinct northeast trending bedrock high in southern Ontario (Eyles et al., 1993).

The Paleozoic bedrock surface of northeastern North America was subaerially exposed during the Mesozoic and Cenozoic, and eroded by a variety of processes. Differential erosion of interbedded carbonates, sandstones and shales resulted in the carving of deep bedrock valleys in the relatively soft Ordovician shales, and the creation of bedrock highs such as the Niagara Escarpment in areas underlain by resistant Silurian carbonates (Karrow, 1989; Johnston et al., 1992). Much of the irregular bedrock topography is attributed to fluvial erosion during the Tertiary (Spencer, 1890; Straw, 1968) and subsequent glacial and fluvial erosion during the Quaternary (Straw, 1968; Karrow, 1973).

Irregular and channelized bedrock topography overlain by variable thicknesses of Quaternary sediment is characteristic of areas in the North-central USA as well as southern Ontario. The bedrock valleys of the North-central USA contain Quaternary sediments considerably older than those found in adjacent regions (Goldthwait, 1991; Gray, 1991).

1.2.1 Bedrock Valley Systems of North-central USA

In the Central Great Lakes region of the United States (Illinois, Ohio, Michigan and Indiana) a deep and extensive bedrock valley system, termed the Teays-Mahomet Bedrock Valley System (Fig. 1.2; Goldthwait; 1991) underlies a surficial cover of Quaternary sediment. The Teays-Mahomet valley system is over 400km long and shows

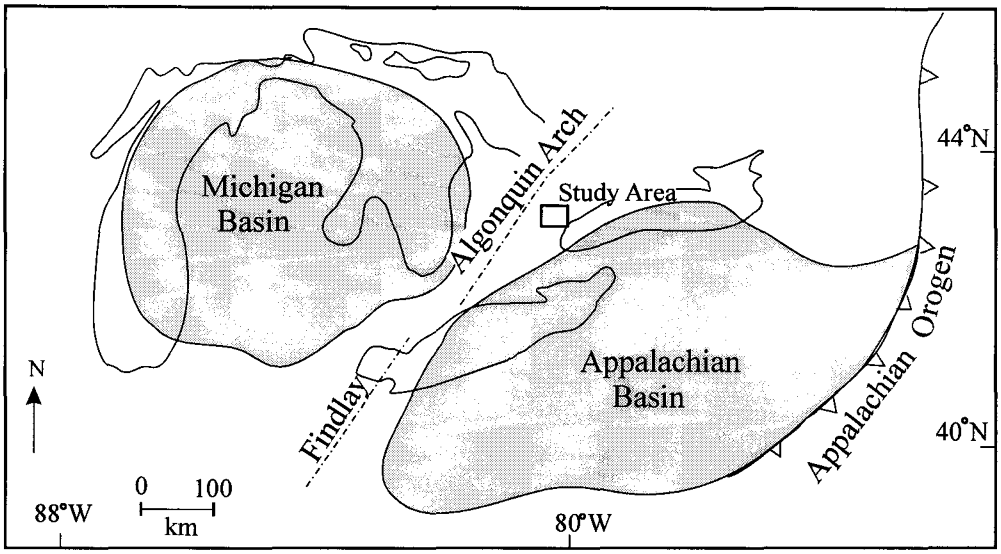

Figure 1.1- Paleozoic bedrock structures affecting southern Ontario. Map illustrating the position of the Michigan and Appalachian Sedimentary Basins separated by the Findlay-Algonquin Arch. Paleozoic rocks formed in the Appalachian Basin now underlie much of southern Ontario.

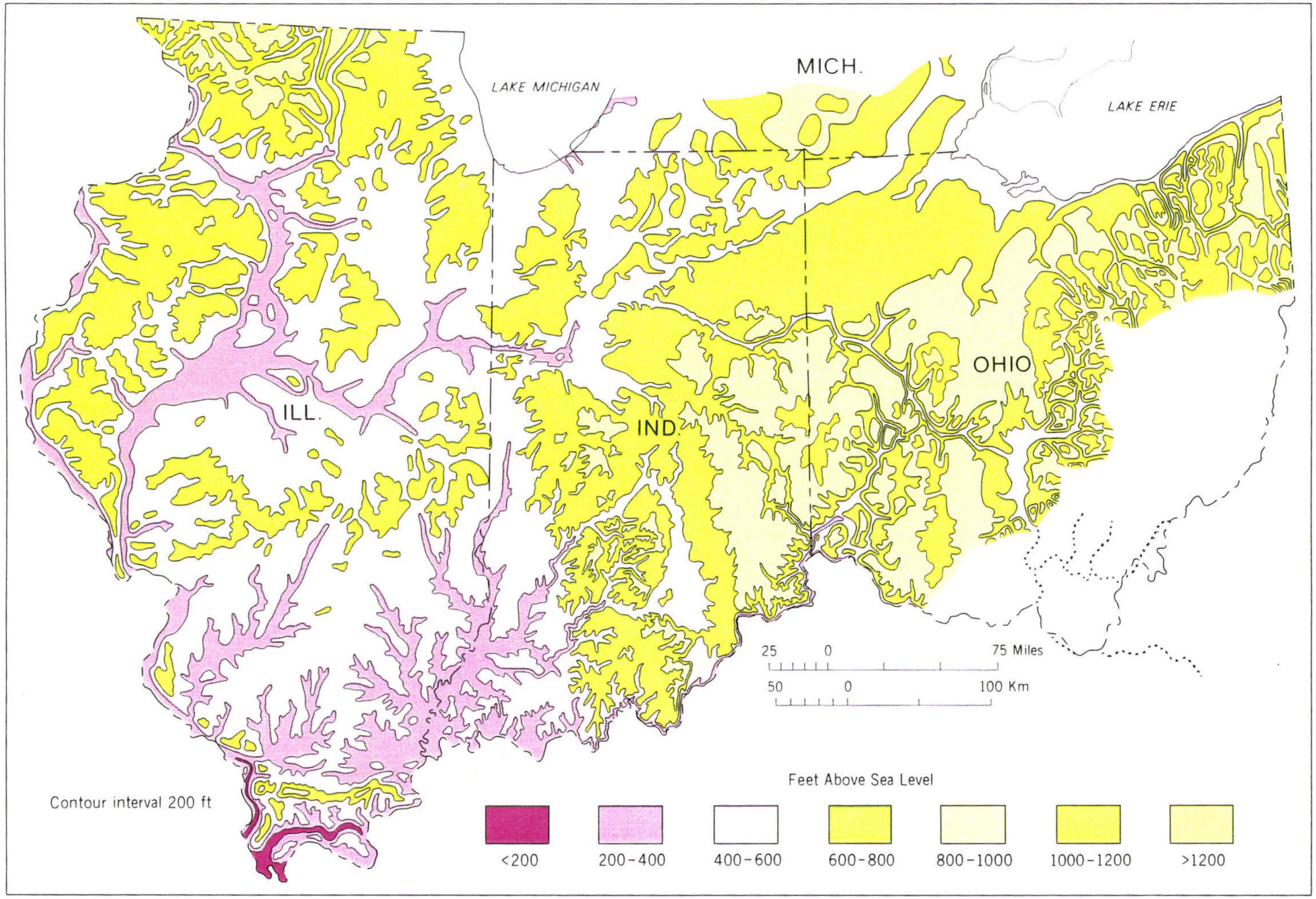

Figure 1.2- Regional bedrock topography showing Teays Valley system from West Virginia to Illinois (from Gray, 1991).

considerable spatial variability in terms of valley morphology, form and sedimentary infill. For example, sections of the Teays bedrock valley extending through Indiana are relatively straight, 60 to 90 m deep and up to 1.6km wide (Gray, 1991). This contrasts with the highly sinuous bedrock valley morphology identified in Ohio and West Virginia where valley widths up to 1km are mapped (Teller and Goldthwait, 1991). The valley floor of the Teays is irregular and does not maintain a uniform gradient; it is thought to have been fluvially incised, and subsequently modified by glacial erosion (Fig. 1.3; Gray, 1991; Teller and Goldthwait, 1991). In some areas of Ohio and Indiana the basal sediments of the Teays- Mahomet Valley bedrock contain Nebraskan-age glacial deposits considered to be more than 700,000 years old (Goldthwait, 1991).

1.2.2 Bedrock Valley Systems of Southern Ontario

The Teays-Mahomet Valley System has similarities in form and morphology to the buried bedrock valleys mapped across southern Ontario. Close to the end of the Tertiary period, an extensive river network, termed the Laurentian Channel System, is thought to have linked the drainage systems of the Great Lakes Basins. Several bedrock valleys eroded by this river system now underlie surficial sediments in southern Ontario (Spencer, 1890; Karrow, 1973; Eyles et al., 1985). Three main preglacial river channels (Fig.1.4) formed within south-central Ontario as part of the Laurentian Channel system including the main branch that linked Lake Huron (Georgian Bay) to Lake Ontario (Karrow, 1973; Eyles et al., 1985; Eyles, 1987) and the Dundas Valley that connected Lake Ontario and Lake Erie (Spencer, 1890). A third channel, the Erigan Valley, near St.

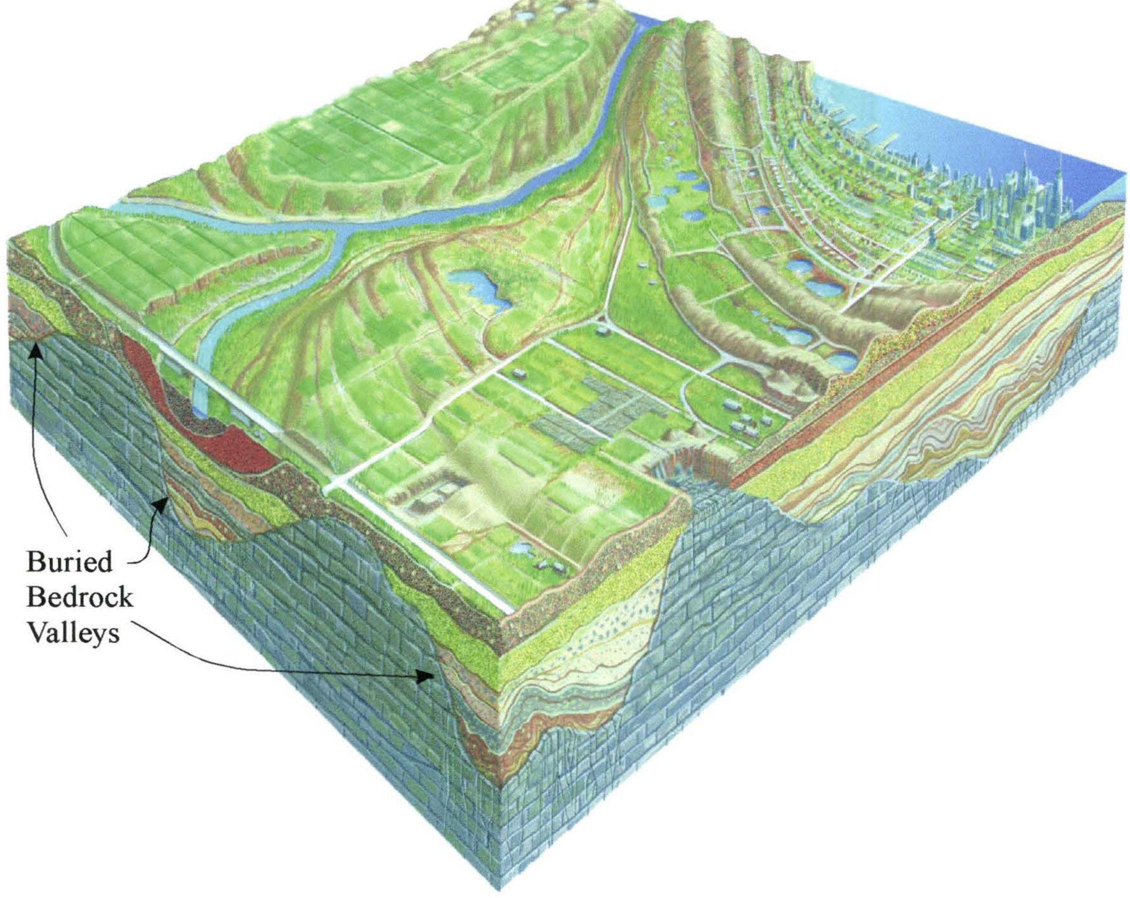

Figure 1.3- Schematic block diagram showing buried bedrock valleys and Quaternary sediment infill in the Central Great Lakes Region of the USA (from Evans, 2000).

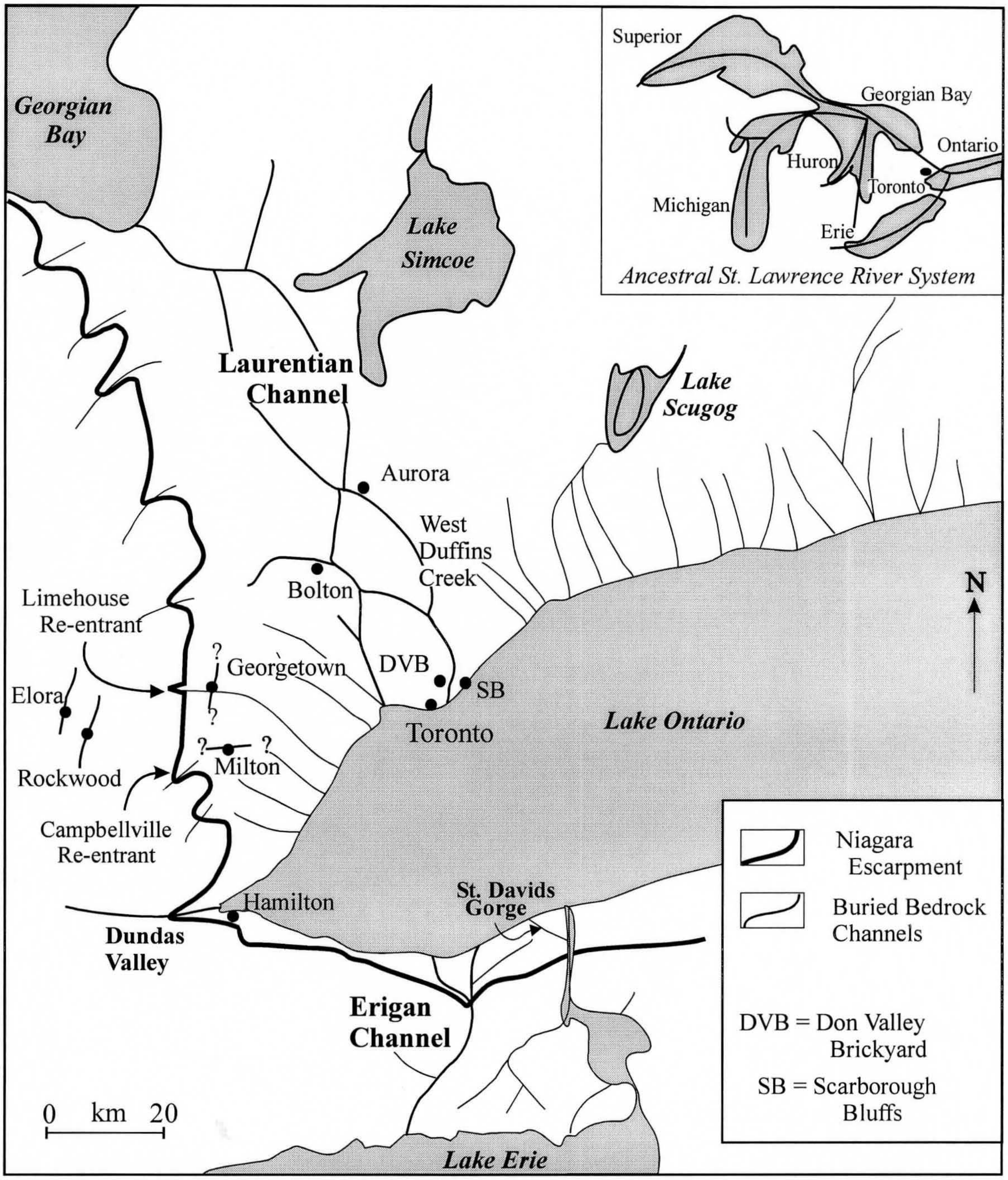

Figure 1.4- Location map showing major buried bedrock channels of southern Ontario including the Laurentian Channel, the Dundas Valley, the Erigan Channel and the Georgetown and Milton valleys. Smaller re-entrants cutting the edge of the Niagara Escarpment are also shown. Thick accumulations of Quaternary sediment are exposed at the Don Valley Brickyard and Scarborough Bluffs (modified from Eyles, 1997).

Catherines also formed a connection between the Lake Ontario and Erie basins (Fig. 1.4; Karrow, 1973; Flint and Lolcama, 1985). All three of these bedrock channels did not necessarily form at the same time, however, all three are now infilled with a thick complex of Quaternary sediment.

The Laurentian River Channel was first mapped by J.W.W. Spencer (1890) who interpreted it as the precursor of the modern day St. Lawrence River. This broad bedrock channel trends southeast from Georgian Bay to the Toronto area, and parallels the Niagara Escarpment (Fig. 1.4; Eyles et al., 1985). It is believed to have been fluvially incised, and later glacially modified to give the overdeepened "up and down" long profile that in places reaches sea level (Eyles et al., 1985). Quaternary sediments within the Laurentian Channel reach thicknesses of up to 150m and the basal sediments are of Illinoian age (Eyles, 1997). The bedrock channel has a composite width of over 20km and shows internal relief of up to 120-130m (Eyles et al., 1985). The overall depth of the Laurentian Channel is comparable to the Teays-Mahomet valley of the central Great Lakes area of the USA, although the basal sediments contained within the Laurentian Channel are much younger. This is most likely due to differential timing and extent of glacial ice advances across northern North America during the Quaternary.

Buried bedrock valleys have been recognized in southern Ontario for over 100 years, but their detailed topographic characteristics and origin are still poorly understood. Geophysical analysis of parts of the Dundas buried bedrock valley located west of Hamilton, Ontario (Fig. 1.4) identified a broad, (up to 4.2km wide) relatively flat-floored bedrock valley with a steep sided 'V' shaped channel incised in its center (Edgecombe, 1999; Straw, 1968). Although the position of the bedrock surface has not yet been established for the full length of the valley, it is thought to lie over 200m below the ground surface (Straw, 1968; Karrow, 1987); boreholes drilled in the eastern parts of the Dundas valley near Hamilton penetrate 137m of Quaternary sediment without reaching bedrock. The form and infill of the valley suggest that a narrow channel was fluvially incised and the broad relatively flat-floored valley was the result of glacial modification.

Faulting of the underlying Paleozoic bedrock may also have played a significant role in the formation of the Dundas bedrock valley (Edgecombe, 1999). Lineaments identified on the bedrock surface, regional joint patterns, and other known faults in the Dundas-Hamilton region suggest that the orientation of the Dundas Valley is structurally controlled. It is possible that the position and orientation of the buried Dundas Valley is the result of glacial and fluvial exploitation of weaknesses in the bedrock surface created by faults (Eyles et al., 1997; Edgecombe, 1999).

Other bedrock valleys within southern Ontario are believed to have a similar "tectonic pre-design". Eyles and others (1997) used a bedrock topography map of southern Ontario produced by Karrow (1973) to identify the importance of regional joint set patterns in the formation of buried bedrock valleys (Eyles and Schiedegger, 1995). The orientation of buried channels, joints and modern day river channels suggest that there is a close relationship between orientations of bedrock joints, buried bedrock channels and postglacial river channels along the Niagara Escarpment, and in many instances bedrock valleys underlie, or lie close to, modern river valleys (Eyles and Scheidegger, 1995).

The irregular bedrock topography of northern North America is covered by a Quaternary sediment cover that is particularly thick in bedrock valleys where a long depositional record of glacial and interglacial cycles is preserved.

1.3 LATE QUATERNARY GLACIAL/ INTERGLACIAL RECORDS OF EASTERN NORTH AMERICA

Oxygen isotope analysis conducted on foraminifera found within deep sea cores provides convincing evidence that repeated glaciations have altered the Earth's landscape for over 2 million years and that North America has endured at least nine glacial/ interglacial cycles in the past 750,000 years (Fig. 1.5; Plint et al., 1992). Unfortunately, there is little preserved record of terrestrial deposition over this time period and the "classical" Quaternary glacial/interglacial sequence of eastern North America is based on the record of only four glacial/interglacial cycles (Table 1.1).

The oldest known Quaternary deposits in eastern North America are of Nebraskan age (Table 1.1), and are identified in the subsurface and in surficial outcrops found in southwestern Iowa, northern Missouri, eastern Nebraska, and northeastern Kansas (Fig. 1.6; Flint, 1967). Four pre-Illinoian tills have been identified within the Teays bedrock valley of Ohio, with the oldest till possibly of Nebraskan age (Teller, 1973; Norton et al, 1983; Teller and Goldthwait, 1991). These tills are interbedded with interglacial fluvial, deltaic and lacustrine deposits.

The Nebraskan glaciation was followed by the Aftonian interglaciation and subsequent Kansan glaciation (Table 1.1) when ice reached its most southerly extent in

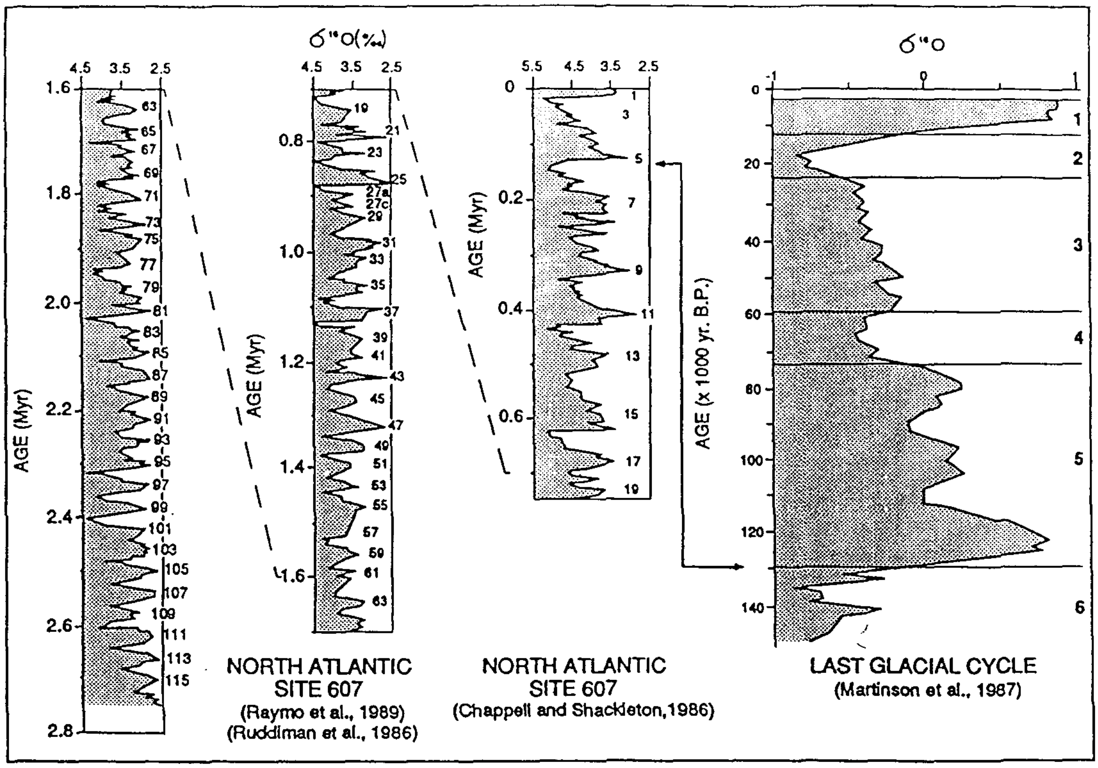

Figure 1.5- Oxygen isotope stratigraphy for the last 2.75 million years. Even numbers refer to major glacial stages and odd numbers refer to major interglacial stages of reduced global ice volume. At least nine major glacial/ interglacial cycles are recorded in the last 750,000 years (from Plint et al., 1992).

Age (yrs b.p.)	Epoch	Stage	Substage	Glacial Stage
7, 000	Holocene			
11, 500	Pleistocene	Wisconsin	Late Wisconsin	
12, 000				Twocreekean Interstade
13, 200				Port Huron Stade
14, 000				Mackinaw Interstade
15, 500				Port Bruce Stade
18, 000				Erie Interstade
25, 000				Nissouri Stade
53, 000			Mid-Wisconsin	
80, 000			Early Wisconsin	
130,000		Sangamonian Interglaciation		
		Illinoian Glaciation		
		Yarmouth Interglaciation		
		Kansan Glaciation		
		Aftonian Interglaciation		
		Nebraskan Glaciation		

Table 1.1- Late Pleistocene glacial and interglacial chronostratigraphy of southern Ontario (dates from Barnett, 1992; Berger and Eyles, 1994).

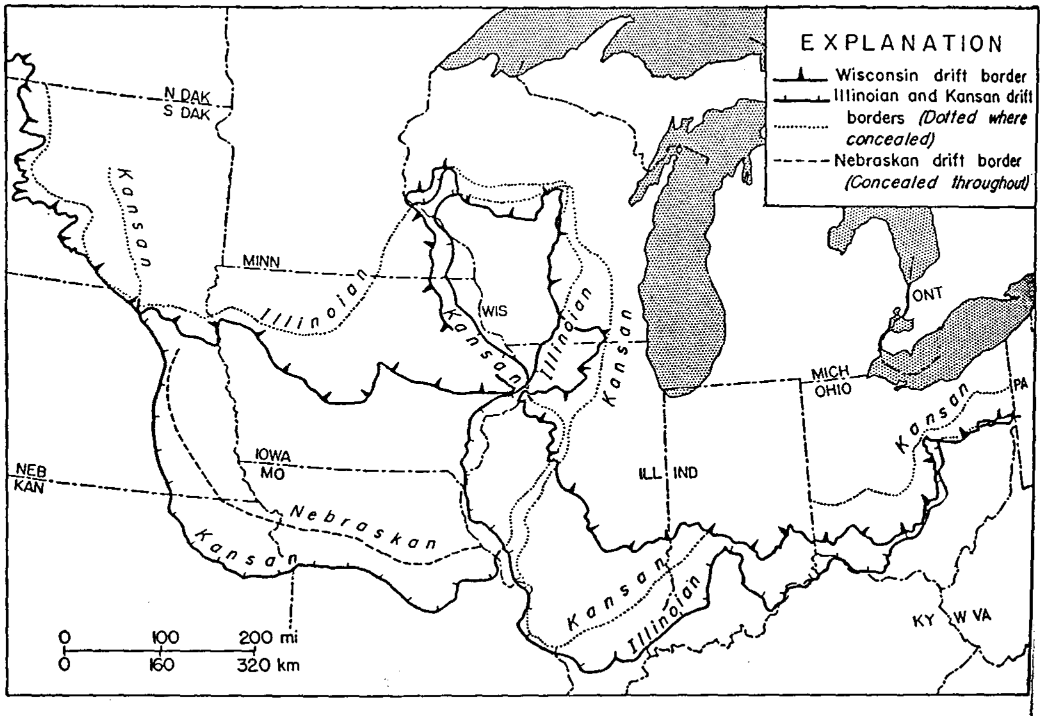

Figure 1.6- Map illustrating the location of maximum ice advance as evidenced by glacial tills deposited during the Nebraskan, Kansan, Illinoian and Wisconsin glaciations in the central USA states (from Flint, 1967).

eastern North America during the late Quaternary. Kansan-age tills are reported in Kansas and Missouri, but are not preserved farther north in the Dakotas, Montana or Canada (Flint, 1967). Ice advance during the subsequent Illinoian glacial stage, also extended as far south as Kansas and Missouri, as well as to the southern margins of Illinois and Indiana (Fig. 1.6; Flint, 1967).

The oldest Quaternary glacial deposits exposed in Ontario are of Illinoian age and are represented by the York Till which outcrops at the Don Valley Brickyard, near Toronto (Fig. 1.4). The Sangamonian interglacial period (130-80ka; Berger and Eyles, 1994) followed the Illinoian glaciation, and is recorded by the Don Beds which are also exposed in the Don Valley Brickyard (Eyles and Clark, 1988; Eyles and Schwartz, 1991; Eyles and Williams, 1992).

The most recent glaciation in North America was the Wisconsin glaciation (~80-10ka; Berger and Eyles, 1994) when the Laurentide Ice Sheet advanced as far south as Illinois, Indiana and northern Iowa (Fig. 1.6; Flint, 1967). The Wisconsin glacial stage is typically subdivided into 3 substages, the Early, Middle and Late Wisconsin, and into various stadial and interstadial episodes (Table 1.1). Sediments exposed in the Don Valley Brickyard, and the Scarborough Bluffs record a gradual cooling of climate beginning in the warm interglacial conditions of the Sangamonian Interglacial, and culminating in the cold stadial conditions of the Late Wisconsin (Eyles and Eyles, 1983; Eyles and Westgate, 1987; Eyles and Clark, 1988; Eyles and Williams, 1992).

During the Early to Mid-Wisconsin (50-25ka; Table 1.1; Berger and Eyles, 1994), sedimentation in the Great Lakes Basins was dominated by glaciolacustrine processes as advancing ice blocked lake outlets to the east and water levels were elevated to levels at times more than 90m higher than present day levels (Eyles and Eyles, 1983). During this time interbedded deltaic sands and muds (Scarborough Formation, Thorncliffe Formation; Eyles and Eyles, 1983, 1984; Eyles, et al., 1983, 1984; Eyles and Westgate, 1987; Rutka and Eyles, 1989; Eyles and Schwarcz, 1991; Eyles and Clark, 1992; Berger and Eyles, 1994) and fine-grained glaciolacustrine diamicts (Sunnybrook, Seminary and Meadowcliffe diamicts; Eyles and Eyles, 1983) were deposited around the northern margin of the Lake Ontario basin; these deposits are now exposed along the Scarborough Bluffs (Fig. 1.4). The amount and type of ice present in the Lake Ontario basin during the Early to Mid-Wisconsin period is highly debated. Karrow (1984), and Hicock and Dreimanis (1989), interpret diamicts exposed along Scarborough Bluffs as subglacial deposits indicating extensive glacial coverage. In contrast, Eyles and Clark (1988), and Eyles and Eyles (1983, 1984) interpret the same deposits as glaciolacustrine, formed in a lake basin in which only floating ice was present.

During the Late Wisconsin, the Laurentide Ice Sheet advanced across southern Ontario and reached its maximum extent during the Nissouri Stadial (22-18ka; Table 1.1) when it reached as far south as Wisconsin, Illinois, Ohio and Indiana (Fig. 1.6; Flint, 1967; Barnett, 1992). Nissouri Stadial ice was responsible for depositing the sand-rich Northern/ Newmarket subglacial till sheet which covers large areas of the Greater Toronto Area and the Halton Region (Eyles, 1997; Boyce and Eyles, 2000). The ice retreated out of southern Ontario during the Mackinaw Interstadial and a blanket of outwash gravel was deposited on the underlying till surface (Brookfield et al., 1982;

Boyce et al., 1995). Final advance of Late Wisconsin ice occurred during the Port Huron Stadial when the southern margin of the Laurentide Ice Sheet thinned and formed a series of sublobes each moving independently of the others. In south-central Ontario, the Ontario-Erie sublobe surged out of the basin now occupied by Lake Ontario, depositing a variety of subglacial, fluvial, and glaciolacustrine sediments which now make up the surficial Halton Till Complex (Karrow, 1967; Boyce et al., 1995). Complete withdrawal of the Laurentide Ice Sheet from eastern North America around 10ka marked the onset of the Holocene period (Barnett, 1992).

1.4 INFILL OF BEDROCK VALLEYS IN SOUTHERN ONTARIO

Borehole and geophysical data indicate that the main branch of the Laurentian Channel which extends from Georgian Bay southward to Lake Ontario (Fig. 1.4) contains interbedded glacial, lacustrine and fluvial deposits of Illinoian to Holocene-age (Eyles et al., 1985). The fluvially deposited Scarborough Formation can be traced from the Scarborough Bluffs and Don Valley Brickyard, near Toronto, north along the Laurentian Channel as far as the town of Bolton (Fig. 1.4) where it is overlain by the Thorncliffe Formation, the Northern Till and the Halton Till Complex (Eyles, 1997). Limited drill core data from the Dundas buried bedrock valley identifies a thick infill (up to 180m) of interbedded fluvial, lacustrine and glacial deposits, the oldest possibly being pre-Wisconsin age (Karrow, 1959; 1973; Edgecombe, 1999). Sedimentary infills of other bedrock valleys in southern Ontario are much less well understood as there are limited subsurface data and surface outcrop exposures.

1.5 AQUIFERS WITHIN BURIED BEDROCK VALLEYS

Buried bedrock valleys act as persistent topographic lows on the landscape that focus surface drainage and accumulate relatively large amounts of coarse-grained, predominantly fluvial, sediment. These coarse-grained deposits are often interbedded with fine-grained lacustrine deposits formed when valley floors were flooded or overridden by ice, and form effective subsurface aquifers (Howard and Beck, 1986). The best aquifers are commonly found in the deepest pasts of bedrock valleys where coarse-grained deposits are the thickest (Fig.1.7).

In a tributary to the Teays-Mahomet valley system of Indiana (Marion-Mahomet), coarse-grained facies of various fluvial and subaqueous fan environments thought to be of Wisconsin age form productive aquifers (Bleuer, 1991; Bleuer et al., 1991). Aquifer and aquitard relationships vary dramatically over relatively small distances in this buried bedrock valley and are directly related to a complex history of repeated fluvial incision and infilling produced by discordant movements of ice lobes (Bleuer et al., 1991). In some parts of the valley uninterrupted deposition of coarse-grained granular, outwash and braidplain sediments occurred, while in other areas thick clay aquitard facies were deposited under lacustrine conditions (Bleuer et al., 1991). Municipal water wells tap into portions of the buried valleys where the coarse-grained sediments are thick, extensive, and deep enough to ensure safe drinking water (~60m below ground surface), but shallow enough to be reached and pumped economically (Bleuer et al., 1991).

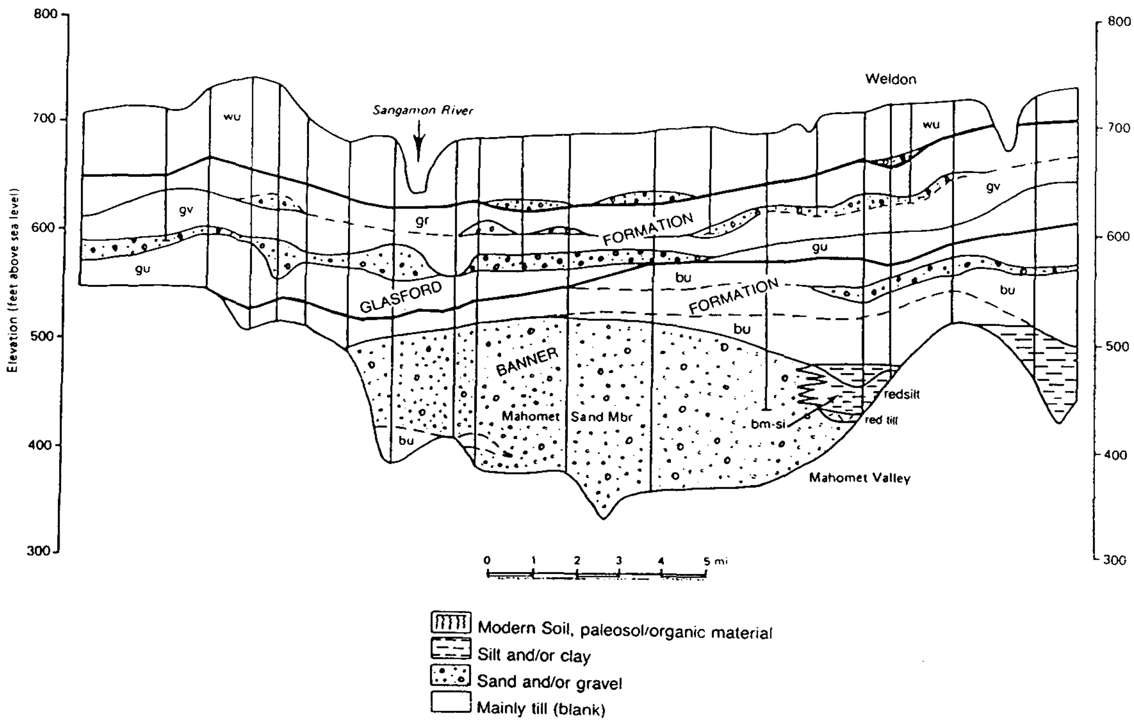

Figure 1.7 - Cross-section across the Mahomet Valley of east-central Illinois, USA showing the stratigraphy of Quaternary infill sediments. Coarse-grained sand and gravels form a productive bedrock aquifer at the base of the bedrock valley (from Kempton et al., 1991).

Several townships in southern Ontario rely on aquifers within buried bedrock valleys for their drinking water including Bolton and Aurora which extract water from the Laurentian Channel (Fig. 1.4; Eyles, 1997; Sharpe and Russell, 1999) and Georgetown and Milton which utilize aquifers in bedrock valleys adjacent to the Niagara Escarpment (Fig. 1.4; Holysh, 1997). The Milton and Georgetown buried bedrock valleys have been providing at least a portion of the municipal water supply to local communities for almost 50 years (Holysh, 1997); recent urban expansion has prompted the search for new groundwater resources in the bedrock valleys.

1.5.1 Aquifers within the Georgetown and Milton buried bedrock valley

The Regional Municipality of Halton began a search for additional municipal groundwater supplies east of the Niagara Escarpment in the fall of 1999. Groundwater exploration was focussed on locating aquifers within two buried bedrock valleys to supply drinking water to the growing towns of Milton, Georgetown and surrounding rural communities. Hydrogeological investigations involved the creation of a bedrock topography map of the region using the Ontario Ministry of the Environment and Energy (OMOEE) water well database which identified depth to bedrock in deep waterwells in the region (Fig.1.8). This bedrock topography map crudely identified the position of two buried bedrock valleys; one trending north-south near the town of Georgetown, and the second trending east-west just north of Milton. Although the bedrock topography map identified the presence of linear bedrock lows, the map had poor resolution and geophysical surveys were conducted to better define the valley forms. Shallow seismic

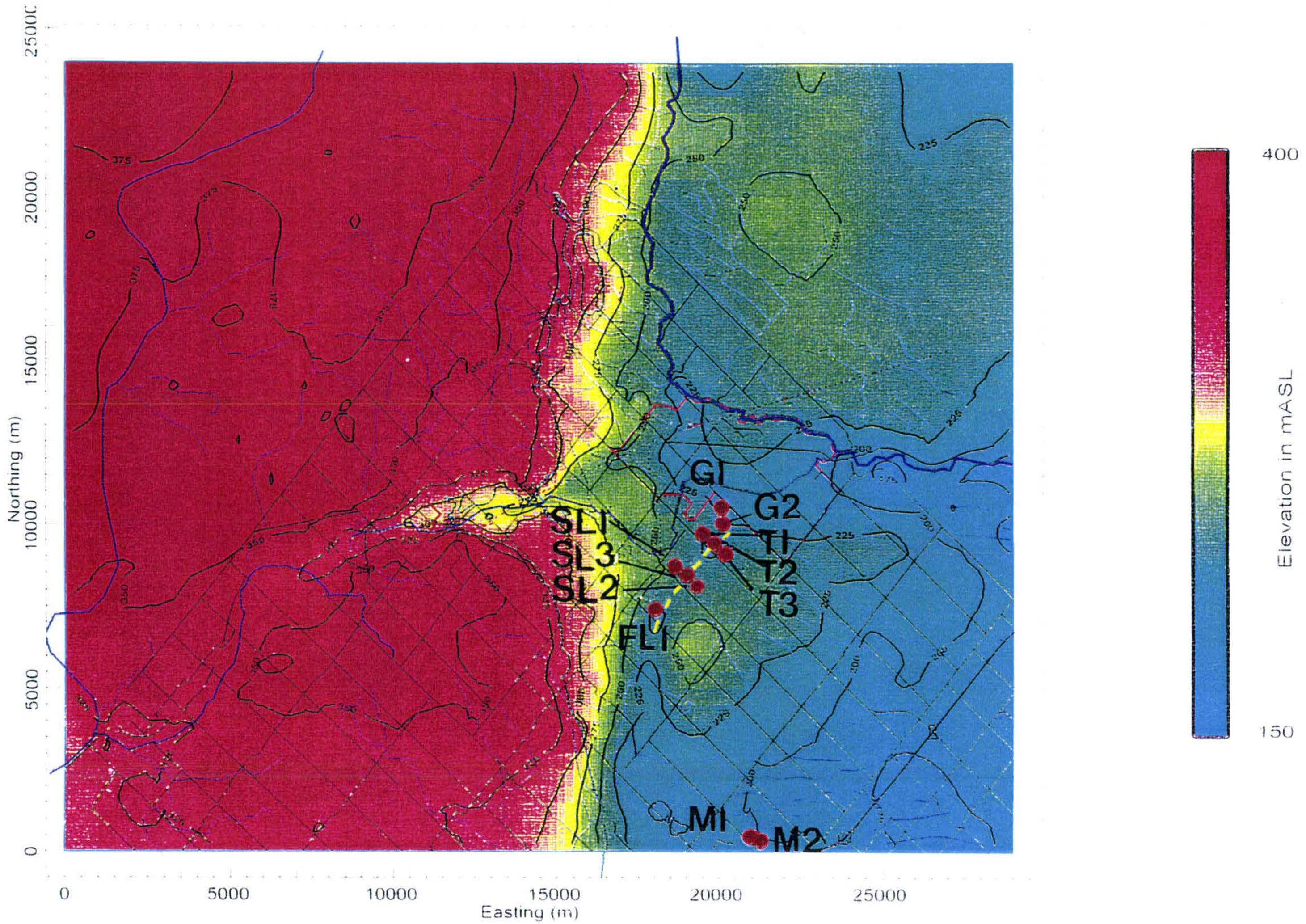

Figure 1.8- Bedrock topography map of the Georgetown area constructed from the Ontario Ministry of the Environment and Energy's water well database. Map shows the approximate location of the Georgetown buried bedrock valley (dashed yellow line). Red dots denote the locations of the eleven boreholes used for sedimentological investigations in this study (modified from Holysh, 1997).

reflection surveys run by GAPS (Geophysical Applications and Processing Services, Guelph ON) identified the location of the Georgetown buried bedrock valley, and its irregular valley floor topography.

Analysis of geophysical and water well data allowed selection of a series of drill targets in the Georgetown and Milton valleys along the strike of the bedrock valleys close to past productive deep water wells; borehole locations were selected in areas thought to be close to the deepest parts of the valley where the thickest accumulations of coarse-grained sediment should occur. Boreholes were continuously cored to allow detailed sedimentological analysis of the deposits infilling the bedrock valleys, and to aid in interpretation of results from hydrogeological tests such as pump tests. Four boreholes were initially drilled in the fall of 1999; two in the Milton area (M1, M2), and two in the Georgetown area (G1, G2; Fig. 1.8). One of the Milton boreholes (M2) intersected bedrock at roughly 70m (240') below surface, but pump tests determined the aquifers penetrated would be unproductive. The search for a new municipal groundwater supply for Milton was abandoned shortly after drilling of the M1 and M2 boreholes when a decision was made to pipe water in from Lake Ontario to the Milton Region. No subsequent boreholes were drilled in this area, and the focus of groundwater exploration moved to the Georgetown area. The initial two Georgetown boreholes (G1 and G2; Fig. 1.8) drilled did not reach the bottom of the bedrock valley and had low water yields; seven additional boreholes were drilled in the spring and fall of 2000, in an attempt to locate deeper parts of the Georgetown bedrock valley and productive groundwater resources. In the fall of 2000, a suitable aquifer was found in borehole SL3 (Fig. 1.8), and the Halton Region hope to add this new well to the existing municipal wells supplying the town of Georgetown (Holysh, 1997). Borehole SL3 contains over 60m of Quaternary sediments, and the producing aquifer lies within a 20m thick unit of variably sorted gravelly sands that overlies the impermeable bedrock surface.

1.6 AIMS OF THE STUDY

The aim of this study is to document the characteristics of sedimentary units infilling the Georgetown and Milton buried bedrock valleys of southern Ontario and to explain their depositional origin. Detailed sedimentological analysis of over 500m of Quaternary sediment extracted from eleven continuously-cored boreholes within the two buried bedrock valleys is the focus of this work and will allow interpretation of depositional processes and the reconstruction of changing paleoenvironmental conditions as the valleys infilled.

The study also aims to subdivide the valley infill deposits into distinct stratigraphic units on the basis of textural characteristics and relative position within the valley infill. This will allow identification of potential aquifers within the valleys, and assessment of their geometry and ability to form productive municipal groundwater sources, or serve as contaminant migration pathways should the groundwater become contaminated.

A final aim of this work is to better define the characteristics and form of the bedrock valleys using subsurface imaging techniques. Shallow seismic reflection surveys were therefore run over the Georgetown buried bedrock valley in an attempt to produce subsurface images of the bedrock surface and obtain more data on the nature of the infill stratigraphy.

1.7 ORGANIZATION OF THESIS

Chapter One provides an introduction to the thesis topic and includes discussion of buried bedrock valleys, their Quaternary infills, and the glacial history of eastern North America. Chapter two presents the sedimentological description and analysis of bedrock valley topography and valley infill deposits in the Georgetown and Milton bedrock valleys and summarizes their depositional history and potential to form municipal aquifers. This chapter is intended as the basis of a manuscript to be submitted for journal publication. The third chapter discusses the application, and limitations of shallow seismic reflection methods used in this study. The final chapter concludes and summarizes the main points of the study.

CHAPTER 2: NATURE AND ORIGIN OF SEDIMENTS INFILLING BURIED BEDROCK VALLEYS ADJACENT TO THE NIAGARA ESCARPMENT, SOUTHERN ONTARIO, CANADA.

2.1 INTRODUCTION

Southern Ontario is underlain by a Paleozoic bedrock surface dissected by an interconnected system of bedrock valleys and covered by variable thicknesses of Quaternary age glacial and interglacial sediment (Straw, 1968; Barnett, 1992; Eyles et al., 1997). Bedrock valleys can be up to several kilometers wide (Eyles et al., 1985; Gray, 1991) and over 250m deep (Eyles, 1997) and are infilled with relatively thick successions of coarse-grained gravels and sands of fluvial origin, poorly sorted glacial tills and diamicts, and fine-grained lacustrine silts and clays (Eyles et al., 1985; Barnett, 1992; Eyles et al., 1997). These deposits preserve a lengthy and detailed record of changing environmental conditions; the oldest Quaternary deposits known in southern Ontario are preserved in buried bedrock valleys (e.g. Don Valley Brickyard; Eyles et al., 1985; Eyles and Schwartz, 1991; Eyles, 1997).

Buried bedrock valleys also host significant local and regional aquifers (Howard and Beck, 1986) as they formed persistent topographic lows on the landscape into which surficial drainage was focussed over long periods of time (Eyles et al., 1997) and their infills contain a relative abundance of coarse-grained fluvial sand and gravel. Interbedded fine-grained lacustrine silts and clay-rich diamicts form confining aquitards for these aquifers. In several areas of southern Ontario, aquifers contained within the sedimentary infill of buried bedrock valleys provide a valuable municipal groundwater source for rural communities (White, 1975; Holysh, 1995). These aquifers also serve as significant contaminant migration pathways in urban areas (Edgecombe, 1999).

Similar bedrock valley infills occur in several regions of northern North America including Illinois, Michigan, Ohio and Indiana (Bleuer, 1991; Kempton et al., 1991; Teller and Goldthwait, 1991). These valley infills contain a record of older Quaternary depositional events than those preserved in Ontario, and also host significant aquifers (Bleuer et al., 1991; Gray, 1991).

Despite the importance of buried bedrock valleys as repositories of lengthy depositional records and productive municipal aquifers, relatively little is known about the actual form and geometries of the buried valleys or the sedimentary characteristics of their infills. This is primarily due to the lack of outcrop exposure and limited amount of drillcore or geophysical data available. Regional scale bedrock topographic maps, based on the Ontario Ministry of Energy and the Environment (OMOEE) water well database have been used to identify the general position and orientation of buried bedrock valleys in southern Ontario (Holysh, 1995; Eyles et al., 1997), but the resolution of the waterwell database is insufficient to allow determination of their exact form. Waterwell databases and construction reports also provide limited information on the nature of sediments infilling these valleys but data are commonly restricted to the shallow subsurface, and do not provide enough detail to accurately discriminate between stratigraphic units.

This paper describes the characteristics of over 500m of sediment recovered from eleven continuously-cored boreholes, each up to 75m in length, recently drilled along two bedrock valleys in southern Ontario (Fig. 2.1). The two valleys lie adjacent to the Niagara Escarpment, near the towns of Milton and Georgetown and are informally named the Milton and Georgetown bedrock valleys. The Regional Municipality of Halton drilled the boreholes in their search for new municipal groundwater sources for the town of Georgetown (Halton Hills) and its surrounding rural communities. The cored sediments identify a stacked succession of aquifers and aquitards that may be similar to infills of other buried bedrock valleys in southern Ontario, some of which underlie industrialized urban areas such as Hamilton and Toronto (Fig.2.1; Karrow, 1963; 1987; Greenhouse and Karrow, 1989). Understanding the characteristics, origin and form of the buried valleys and their sedimentary infills has significance for the reconstruction of late Quaternary environmental change in southern Ontario and for groundwater exploration programmes and remediation strategies, both locally and on a more regional scale.

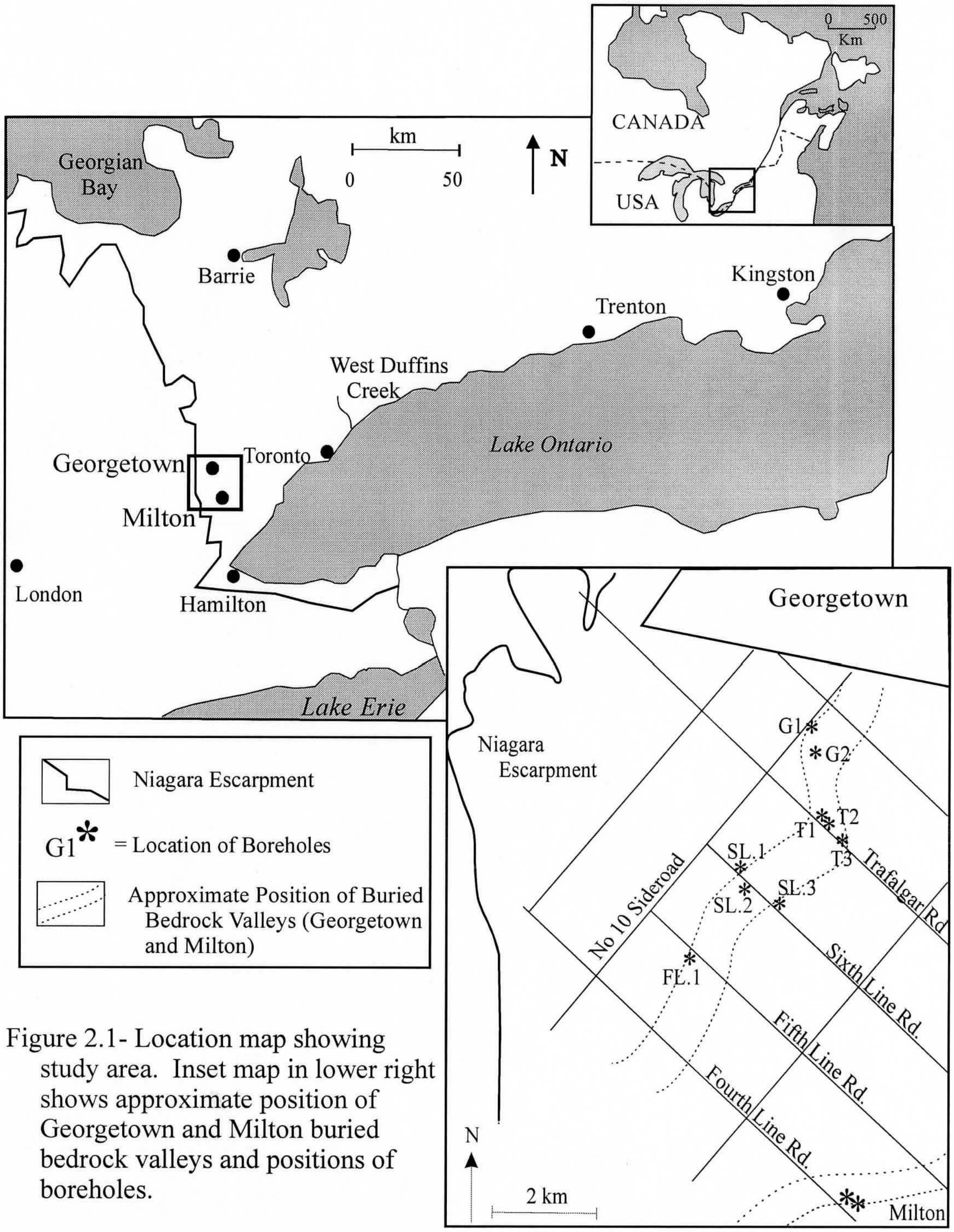

Figure 2.1- Location map showing study area. Inset map in lower right shows approximate position of Georgetown and Milton buried bedrock valleys and positions of boreholes.

2.2 GEOLOGICAL BACKGROUND

2.2.1 Bedrock Geology

Southern Ontario is underlain by gently dipping (<0.5 degrees to the south; Johnston et al., 1992) Paleozoic sedimentary rocks of Upper Cambrian to Middle Devonian age which unconformably overlie Precambrian basement (Fig. 2.2). The Paleozoic sediments were deposited in a tropical sea that covered southern Ontario between 570 to 91Ma and consist of deep-water shales interbedded with shallow water dolomites, limestones, and sandstones (Johnson et al., 1992; Eyles, 1997). These rocks are buried by a variable thickness of Quaternary sediment across most of southern Ontario but outcrop in the east between Trenton and Kingston and along the Niagara Escarpment (Fig. 2.2). In the Toronto-Hamilton region, areas lying to the north and east of the Niagara Escarpment are underlain by the Georgian Bay Shale and the Queenston Shale; areas to the south and west of the Escarpment are underlain by the Lockport Dolomite (Fig. 2.2). The Queenston Shale consists of red argillaceous shale interbedded with green siltstone, sandstone and limestone (Costello and Walker, 1972; Johnson et al., 1992); this shale lies at the base of the Escarpment and is found at the base of many bedrock channels within the study area (Holysh, 1997). The highly fractured Lockport Dolomite forms a 'cap rock' at the top of the Niagara Escarpment succession and acts as a major groundwater recharge zone for aquifers both above and below the Escarpment (Holysh, 1997).

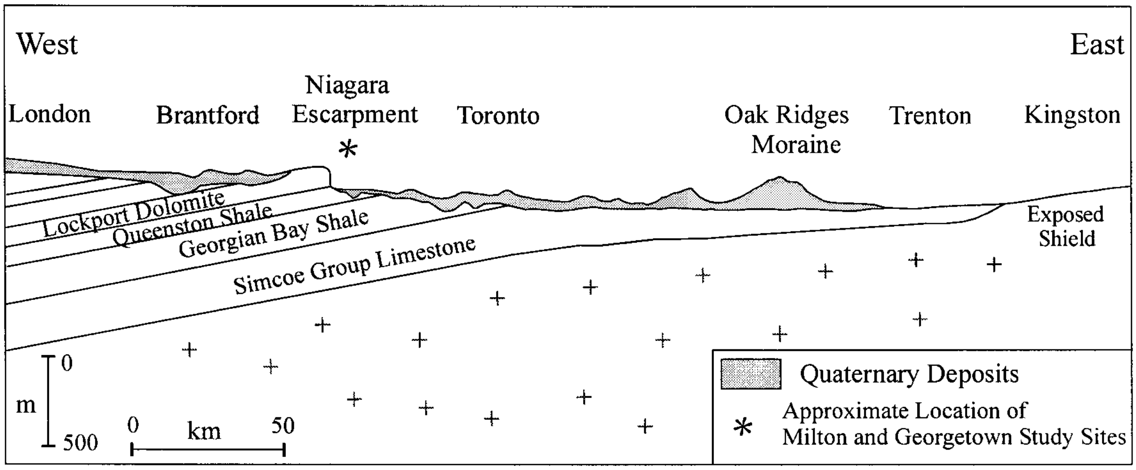

Figure 2.2- West-East cross-section through underlying geology of southern Ontario (modified from Eyles and Clinton, 1998).

2.2.2 Bedrock Surface Topography

A major unconformity separates Paleozoic rocks from overlying Quaternary deposits across southern Ontario. This unconformity was formed in part during an episode of late Tertiary erosion when a large interconnected river system, termed the Laurentian River Channel System, carved valleys into the exposed Paleozoic bedrock surface of the Great Lakes region (Fig. 2.3; Spencer, 1890; Straw, 1968; Karrow, 1973). Three major elements of this system affect the bedrock topography of southern Ontario; a channel that links Georgian Bay directly to Lake Ontario in the vicinity of Toronto, a second channel that forms the Dundas Valley re-entrant at the western end of Lake Ontario, and a third channel, the Erigan Channel near St. Catherines, which connects the Lake Ontario and Erie basins (Fig. 2.3; Eyles, 1997). All three of these channels are infilled with a thick succession of Quaternary sediments. A number of smaller bedrock channels, termed re-entrants (e.g. Limehouse and Campbellville re-entrants; Fig. 2.3) dissect the exposed edge of the Niagara Escarpment and are thought to have formed during the late Quaternary (Straw, 1968). These re-entrants extend to the east of the Niagara Escarpment as buried bedrock channels infilled by Quaternary sediments. The Limehouse re-entrant trends E-W and underlies the town of Georgetown where it cross-cuts the NNE-SSW trending Georgetown bedrock valley (Holysh, 1995). A similar NNE-SSW orientation is shown by the Elora and Rockwood bedrock valleys, which lie 20km to the west of Georgetown (Fig. 2.3; Greenhouse and Karrow, 1994; Holysh,

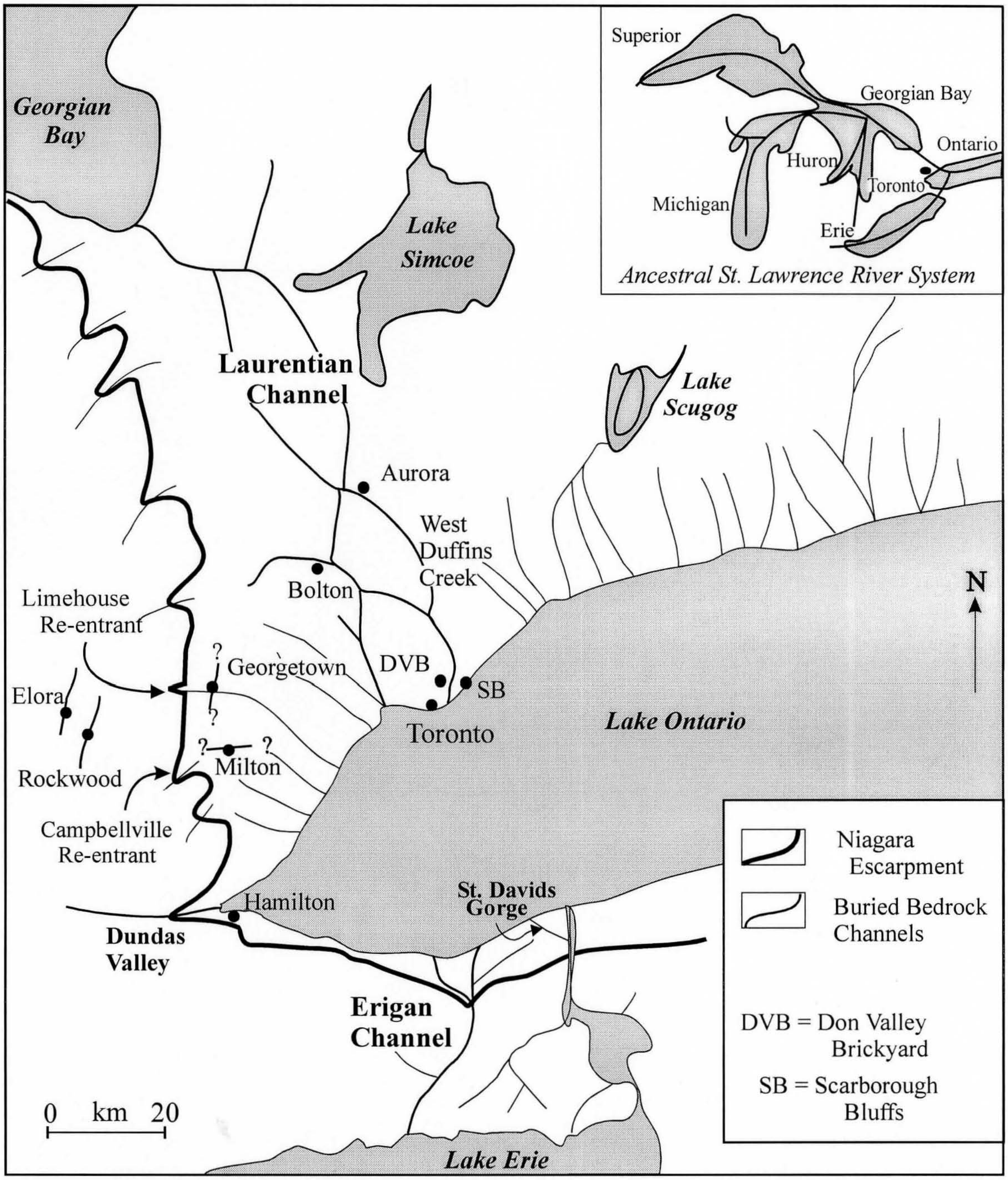

Figure 2.3- Location map showing major buried bedrock channels of southern Ontario including the Laurentian Channel, the Dundas Valley, the Erigan Channel and the Georgetown and Milton valleys. Smaller re-entrants cutting the edge of the Niagara Escarpment are also shown. Thick accumulations of Quaternary sediment are exposed at the Don Valley Brickyard and Scarborough Bluffs (modified from Eyles, 1997).

1997); these bedrock valleys are thought to have formed southward-flowing tributaries to the W-E trending Dundas buried bedrock valley (Karrow, 1973). The Milton valley also trends approximately W-E and may form an eastward continuation of the Campbellville re-entrant located west of Milton (Fig. 2.3; Barnett et al., 1993).

Controls on the form and orientation of bedrock valleys in southern Ontario have been widely debated (Spencer, 1890; Straw, 1968; Eyles and Scheidegger, 1995; Eyles et al., 1997) and range from simple fluvial and glacial erosion processes (Karrow, 1973) to those involving exploitation of crustal weaknesses created by tectonic stresses (Eyles et al., 1993; Eyles and Scheidegger, 1995; Eyles et al., 1997). It should be noted that the orientation of many bedrock valleys in southern Ontario is similar to that of regional jointing patterns and buried bedrock structures (Eyles et al., 1997). The Laurentian River Channel, for example, as it passes southward from Georgian Bay toward Toronto, follows the boundaries of underlying Proterozoic basement terranes (Eyles, 1997). Modern river valleys commonly lie above buried bedrock valleys (Goldthwait, 1991), and appear to have the same orientation as regional joint or fracture systems in the underlying basement rocks (Eyles et al., 1993).

It is not known exactly when the extensive bedrock valley systems of southern Ontario were carved. Buried bedrock valleys are commonly referred to as "preglacial" and often assumed to have formed during the late Tertiary (Spencer, 1890; Karrow, 1973). However, not all bedrock valleys in southern Ontario are this old. The St. David's Gorge near Niagara Falls is thought to date back only to the Sangamonian interglacial period (Fig. 2.3; Hobson and Terasmae, 1969; Flint and Lolcama, 1985) and many of the smaller 're-entrant' valleys that dissect the Niagara Escarpment probably formed during the Late Wisconsin to Holocene (Straw, 1968; Barnett et al., 1998).

2.2.3 Quaternary Depositional Record

During the Quaternary, the Paleozoic bedrock surface of southern Ontario was repeatedly overridden and exposed by successive advance and retreat of the Laurentide Ice Sheet (Barnett, 1992). Glacial and fluvial erosion of the Paleozoic rocks contributed to formation of the large unconformity that separates the Paleozoic bedrock from overlying Quaternary sediments. Few sediments are preserved from the time period prior to the beginning of the Wisconsin period (~115ka; Barnett, 1992); those sediments that are preserved are found in topographic lows on the bedrock surface such as buried bedrock valleys and lake basins (Eyles et al., 1985). The Don Valley Brickyard in Toronto (Fig. 2.3) lies within the Laurentian River and hosts sediments from the penultimate glaciation (Illinoian; 190-135ka; Barnett, 1992) and the last interglacial period (Sangamon; ~125ka; Berger and Eyles, 1994).

During the Early to Mid-Wisconsin (Fig. 2.4; 80ka- 25ka; Berger and Eyles, 1994), the Laurentide Ice Sheet margin fluctuated significantly in its position across southern Ontario. Tills and glaciolacustrine diamicts were deposited during episodes of ice advance (stadials) when ice blocked lake outlets and water levels were elevated up to

Age (y.b.p.)	Epoch	Glacial Stage	Substage	Glacial Stade/ Interstade	Associated Deposits
7, 000	Pleistocene	Wisconsin	Late Wisconsin	Post Iroquois and Pre-Lake Ontario Events	
11, 500				Twocreekean Interstade	Shoreline formation Glaciolacustrine deposition
12, 000				Port Huron Stade	Halton Till Complex Wentworth Till
13, 200				Mackinaw Interstade	Outwash Sands and Gravels
14, 000				Port Bruce Stade	?
15, 500				Erie Interstade	
18, 000				Nissouri Stade	Northern/ Newmarket Till
25, 000			Mid-Wisconsin		Thorncliffe Formation Meadowcliffe Diamict Seminary Diamict
53,000			Early Wisconsin		Sunnybrook Diamict
80,000					

Figure 2.4; Chronostratigraphy of the Wisconsin glacial stage in southern Ontario identifying glacial stade and interstade events and deposits (dates from Barnett, 1992; Berger and Eyles, 1994).

90 m higher than present day levels (Eyles and Eyles, 1983). Fluvial and deltaic sands and gravels formed during ice margin retreat and lake level lowering (interstadials). The bedrock valleys of southern Ontario contain an excellent record of these events, as stadial and interstadial deposits were protected from subsequent erosion by overriding glaciers, especially in those valleys oriented perpendicular to the direction of ice flow (Eyles, 1997). The Scarborough Bluffs on the north shore of Lake Ontario (near Toronto) lie within a branch of the Laurentian River Channel and expose Early to Mid- Wisconsin age sediments including stadial deposits of the Sunnybrook, Seminary, and Meadowcliffe diamicts, and interstadial deltaic deposits of the Scarborough and Thorncliffe Formations (Fig. 2.4; Eyles et al., 1985; Eyles and Clark, 1987; Eyles and Westgate, 1987; Hicock and Dreimanis, 1989; Martini, 1990).

The Laurentide Ice Sheet completely covered most of southern Ontario during the Late Wisconsinan period as a series of sublobes that flowed along the Great Lakes basins coalesced. The Huron- Simcoe and Ontario-Erie sublobes deposited extensive subglacial till sheets across southern Ontario, including the sandy Northern Till (Fig. 2.4; Boyce and Eyles, 2000; Eyles, 1997; Boyce et al., 1995) and equivalent Newmarket Till (Barnett et al., 1998; Sharpe et al., 1999; Pugin et al., 1999) as they advanced from the north during the Nissouri Stadial between 25 and 18 ka (Fig. 2.5).

As temperatures warmed during the Mackinaw Interstadial (13.3ka; Fig. 2.4, 2.6) ice withdrew from southwestern Ontario and an extensive blanket of coarse-grained sand and gravel outwash was deposited (Boyce et al., 1995). Subsequent readvance of the

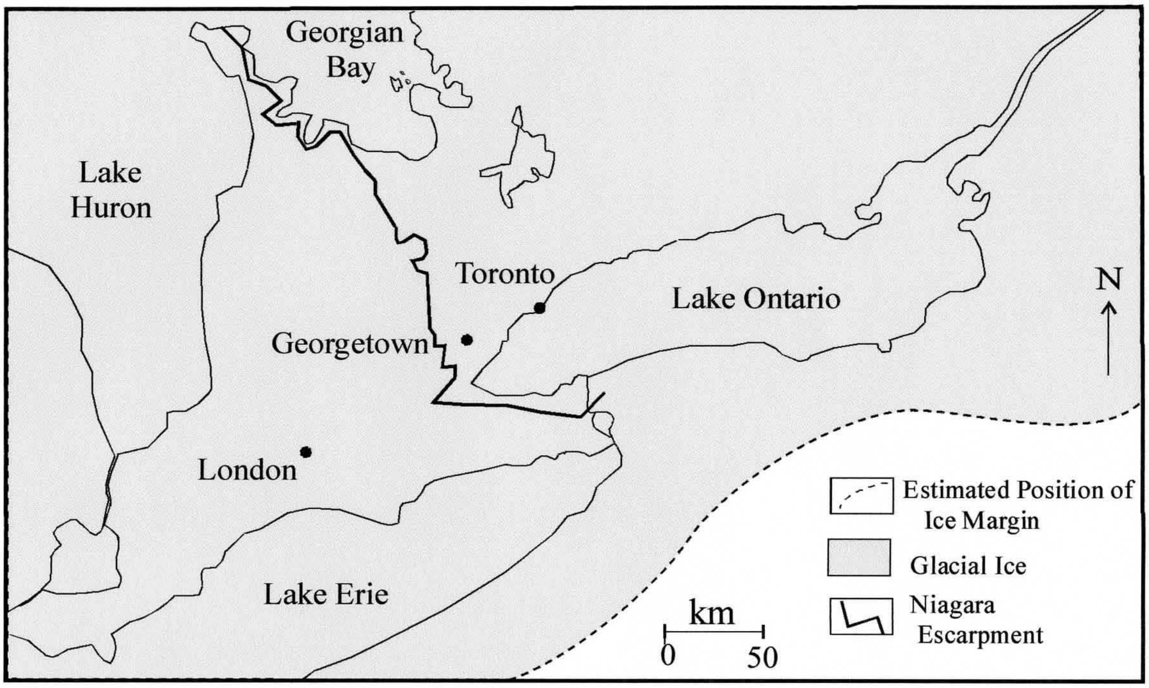

Figure 2.5; Reconstructed paleoenvironmental conditions across southern Ontario during the Nissouri Stadial (25-18ka; modified from Chapman and Putnam, 1984).

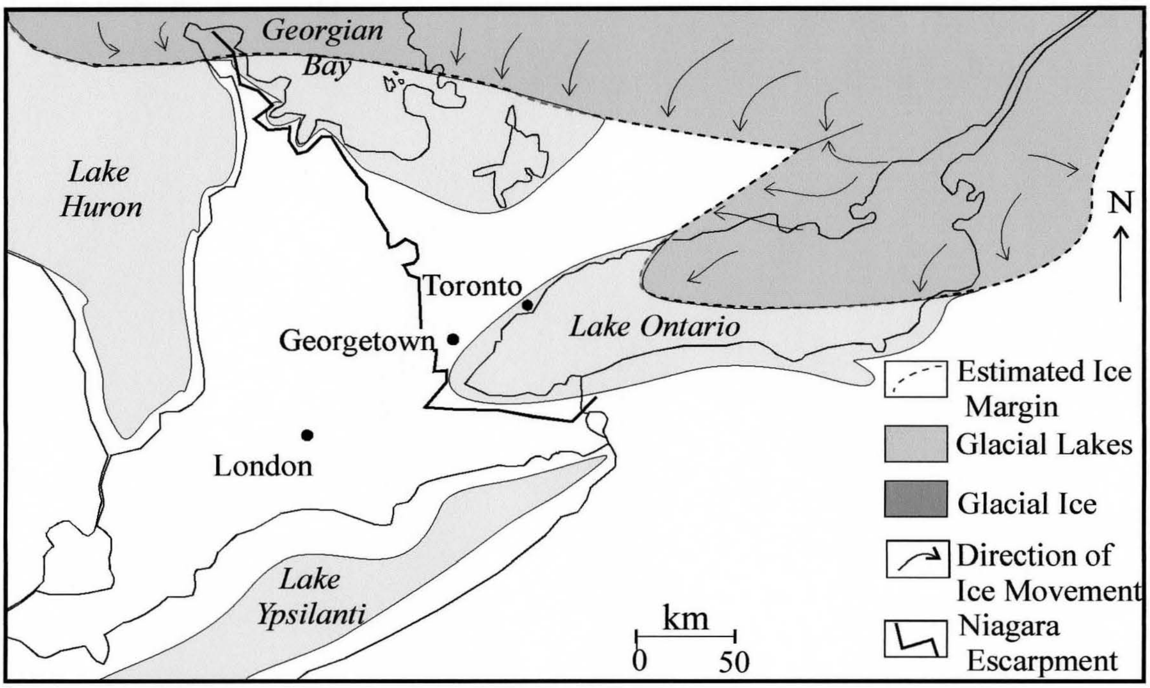

Figure 2.6- Reconstructed paleoenvironmental conditions across southern Ontario during the Mackinaw Interstadial (14-13.2ka). Note subaerial exposure of large areas of southern Ontario during ice withdrawl to the east (modified from Chapman and Putnam, 1984)

Ontario-Erie sublobe during the Port Huron Stadial (13ka; Fig. 2.4) allowed ice to flow from the Lake Ontario basin, northwestward toward the Niagara Escarpment (Fig. 2.7), where it overrode the Milton-Georgetown area and the Escarpment. This ice lobe flowed rapidly over previously deposited fine-grained lacustrine deposits near the Lake Ontario shoreline (Chapman and Putnam, 1984) and deposited the mud-rich subglacial tills and interbedded sands referred to as the Halton Till Complex (Fig. 2.4). The Halton Till Complex covers the area south of the Oak Ridges Moraine and east of the Niagara Escarpment (Boyce et al., 1995). Where the rapidly moving Port Huron ice overrode the Niagara Escarpment and incorporated clasts of dolostone, a coarse-grained subglacial till, the Wentworth Till was formed (Eyles, 1997) and is mapped as an equivalent of the Halton Till to the west of the Niagara Escarpment. By 12ka ice fully retreated from the area and a relatively deep and extensive lake, Lake Iroquois, formed in the Lake Ontario basin.

This history of ice advance and retreat, lake formation and drainage, has allowed a relatively thick succession of interbedded glacial, fluvial and lacustrine sediments to accumulate in topographic lows created by the buried bedrock valleys of southern Ontario. The Quaternary sediments infilling the valleys should therefore include a variety of stadial deposits, including diamicts equivalent to the 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.

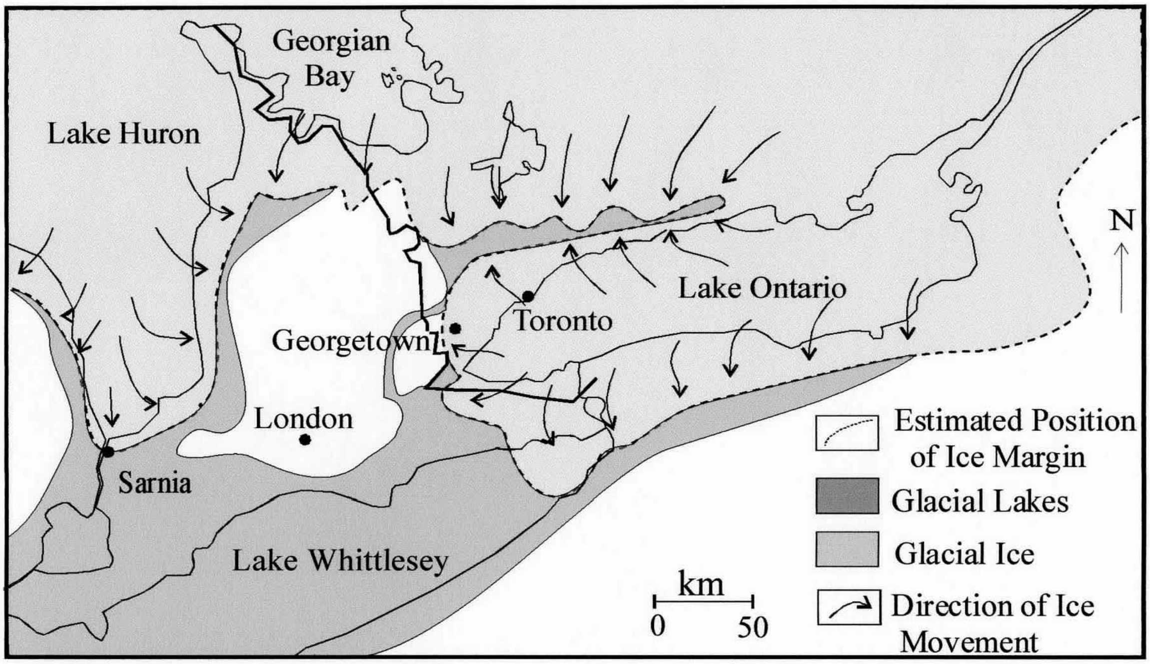

Figure 2.7- Reconstructed paleoenvironmental conditions across southern Ontario during the early stages of the Port Huron Stadial (13-12ka). Note readvance of Ontario lobe across the study area (modified from Chapman and Putnam, 1984).

2.3 STUDY AREA AND METHODOLOGY

Eleven continuously cored boreholes were drilled between the fall of 1999 and fall of 2000 in the Milton-Georgetown area (Fig. 2.1) by the Regional Municipality of Halton as part of a groundwater exploration program. Drilling sites were selected based on their proximity to existing deep and productive water wells, information from the OMOEE water well database, and shallow seismic refraction and reflection surveys (Holysh, 1997; IWS, 1989). These three sources of data allowed identification of the approximate position of two buried bedrock valleys adjacent to the Niagara Escarpment in the Halton region, herein named the Milton bedrock valley and the Georgetown bedrock valley (Fig. 1.8, 2.1; Holysh, 1997). Two cores were taken from within the Milton bedrock valley, which lies north of the city of Milton (cores Milton 1 and 2 [M1, M2]; Fig. 2.8a). The remaining nine cores were taken from the Georgetown buried valley, just south of the town of Georgetown in the Halton Hills area (cores Georgetown 1, and 2, [G1, G2], Trafalgar 1-3 [T1-3], Sixth Line 1-3 [SL1-3] and Fifth Line 1 [FL1]; Figs. 2.9-2.12 respectively). The Georgetown and Milton bedrock valleys lie less than 5km east of the Niagara Escarpment. Identification of the bedrock/ Quaternary sediment contact in the cored boreholes indicates that the bedrock valleys are deeply incised into the underlying Queenston Shale and have up to 35m of relief; channel margins are steep with local slopes of up to 40 degrees (Fig. 2.8a). Valley widths are estimated to be between 700 and 1500m (Fig. 2.13; IWS, 1989; Holysh, 1997).

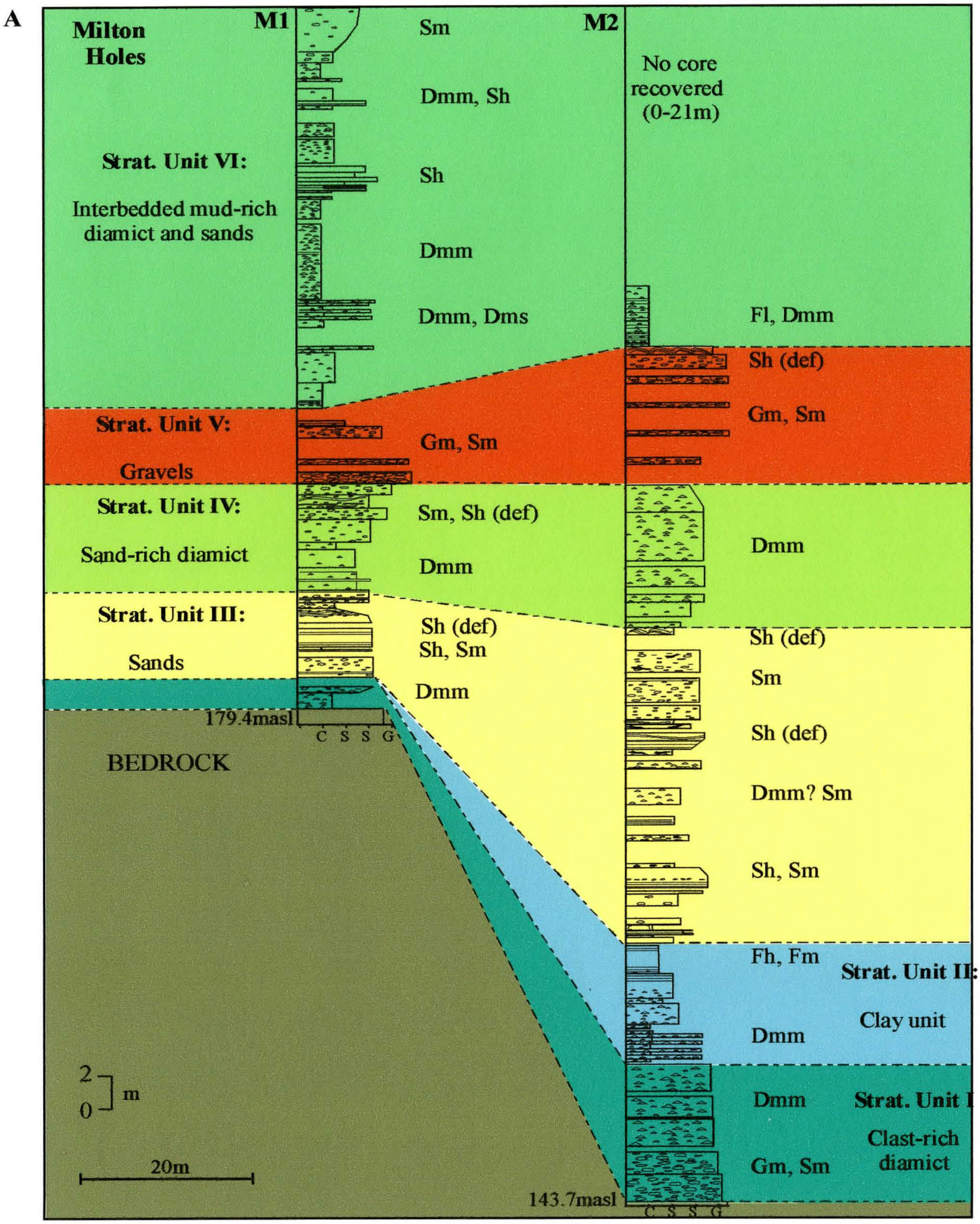

Figure 2.8A- Sediment logs of Milton boreholes (M1 and M2). Refer to fig. 2.1 for location of boreholes and fig.2.8b for legend and lithofacies codes. The two boreholes are approximately 40m apart.

B

KEY

Symbols

Diamicts

Gravels

Clay Clasts

Sand Lenses

Bedding

Laminated

Deformed

Rippled

Cross Bedded

Contacts

Planar Tabular

Gradational

Grain Size

C - Clay S - Silt S - Sand G - Gravel

Lithofacies Codes

DIAMICT, D

Dm- matrix supported
D-m- massive
D-s- stratified

SANDS, S

Sr rippled
St trough cross-bedded
Sh horizontal laminations
Sh (def) deformed laminations
Sm massive

FINE-GRAINED (MUD), F

Fl laminated
Fl (def) deformed laminations
Fm massive
F-d with dropstones

GRAVELS, G

Gm massive

Figure 2.8B- Symbols and lithofacies codes used on sediment logs. Width of sediment log is proportional to grain size. Lithofacies codes modified from Eyles and Eyles (1983).

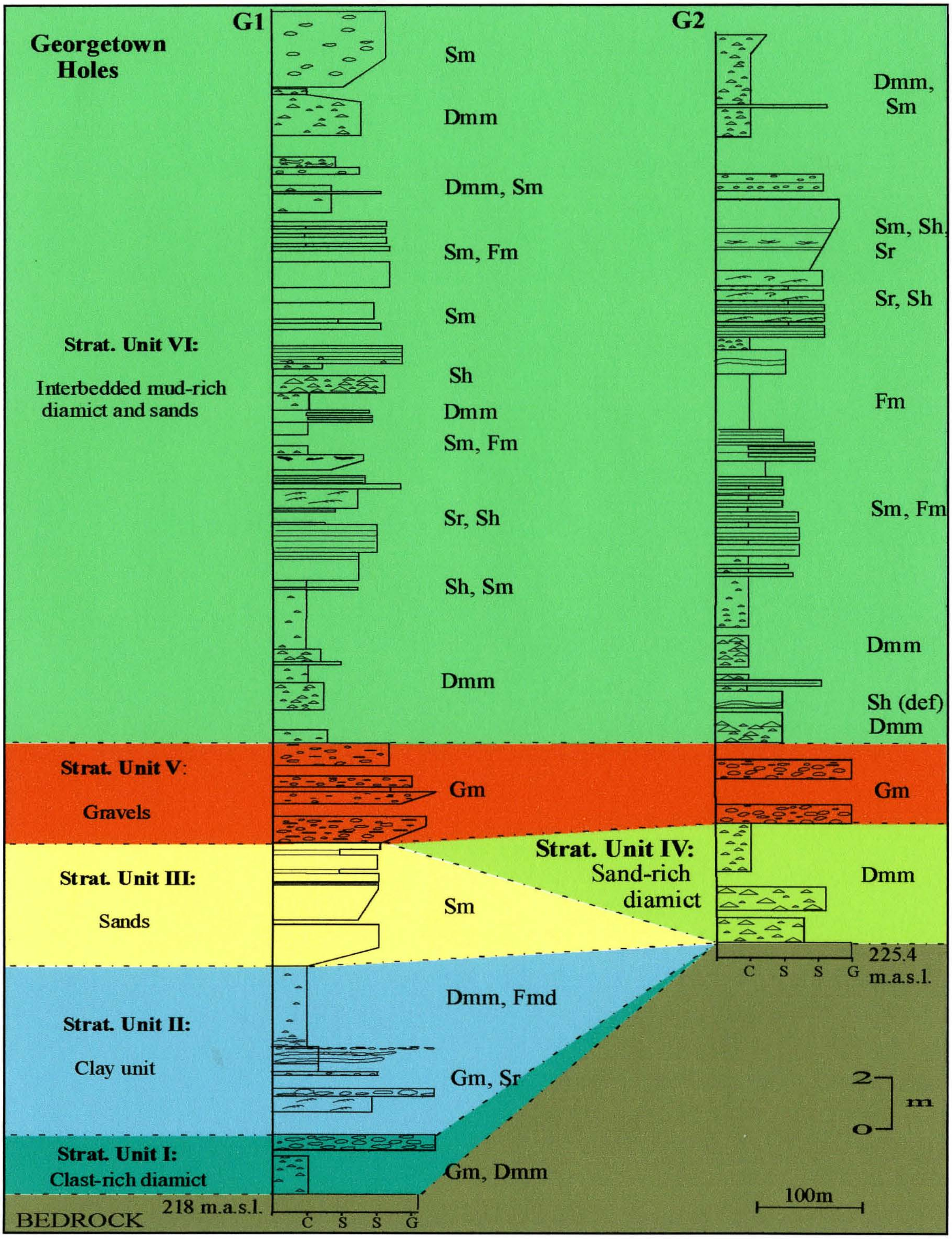

Figure 2.9- Sediment logs from the Georgetown boreholes (G1 and G2). The two boreholes are approximately 400m apart. Refer to fig. 2.1 for location of boreholes, and fig. 2.8B for legend and lithofacies codes.

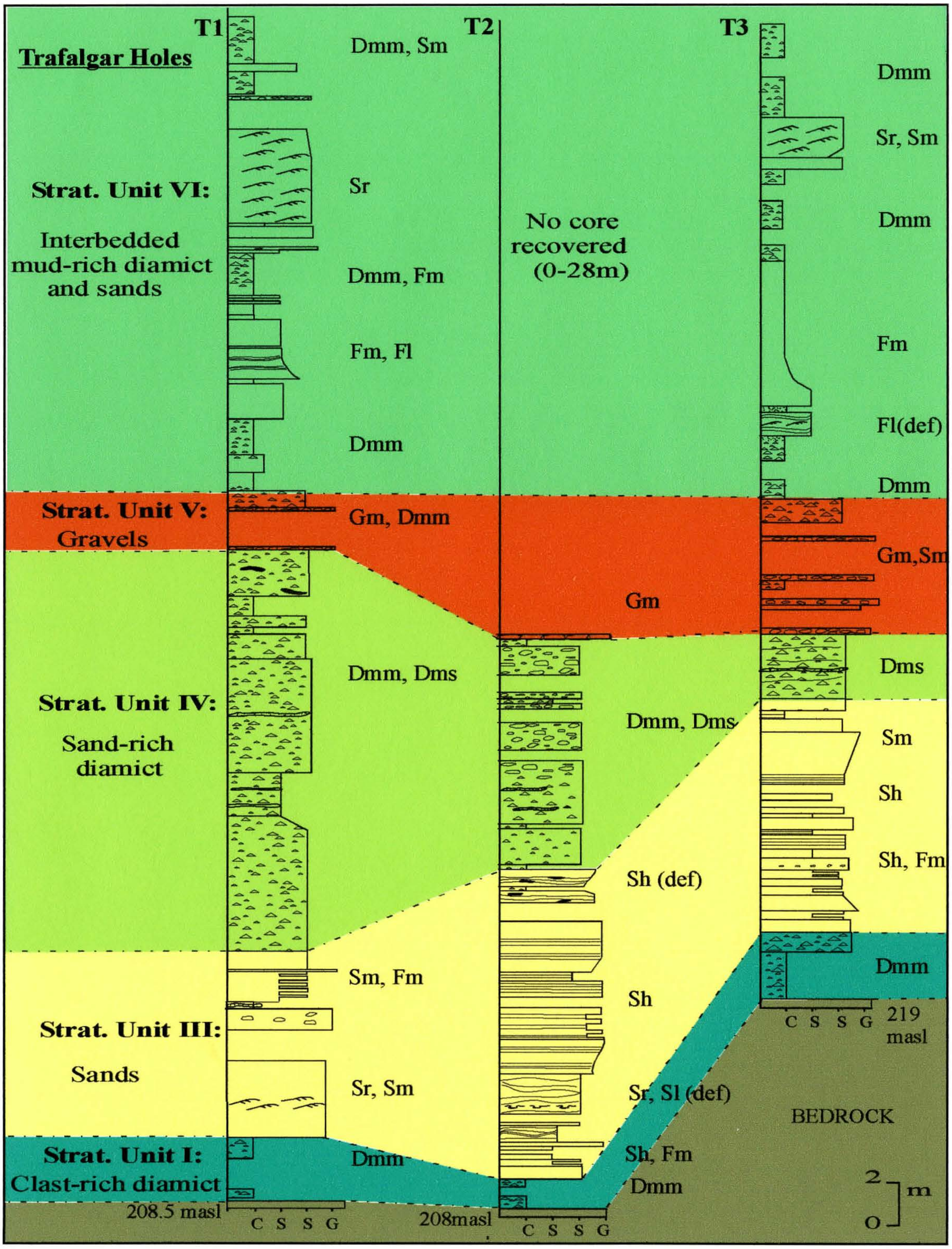

Figure 2.10- Sediment logs from the Trafalgar Road boreholes (T1, T2, T3). Boreholes T1 and T2 are 200m apart, and T2 is 350m from T3. Refer to fig. 2.1 for locations of boreholes, and fig. 2.8 for legend and lithofacies codes.

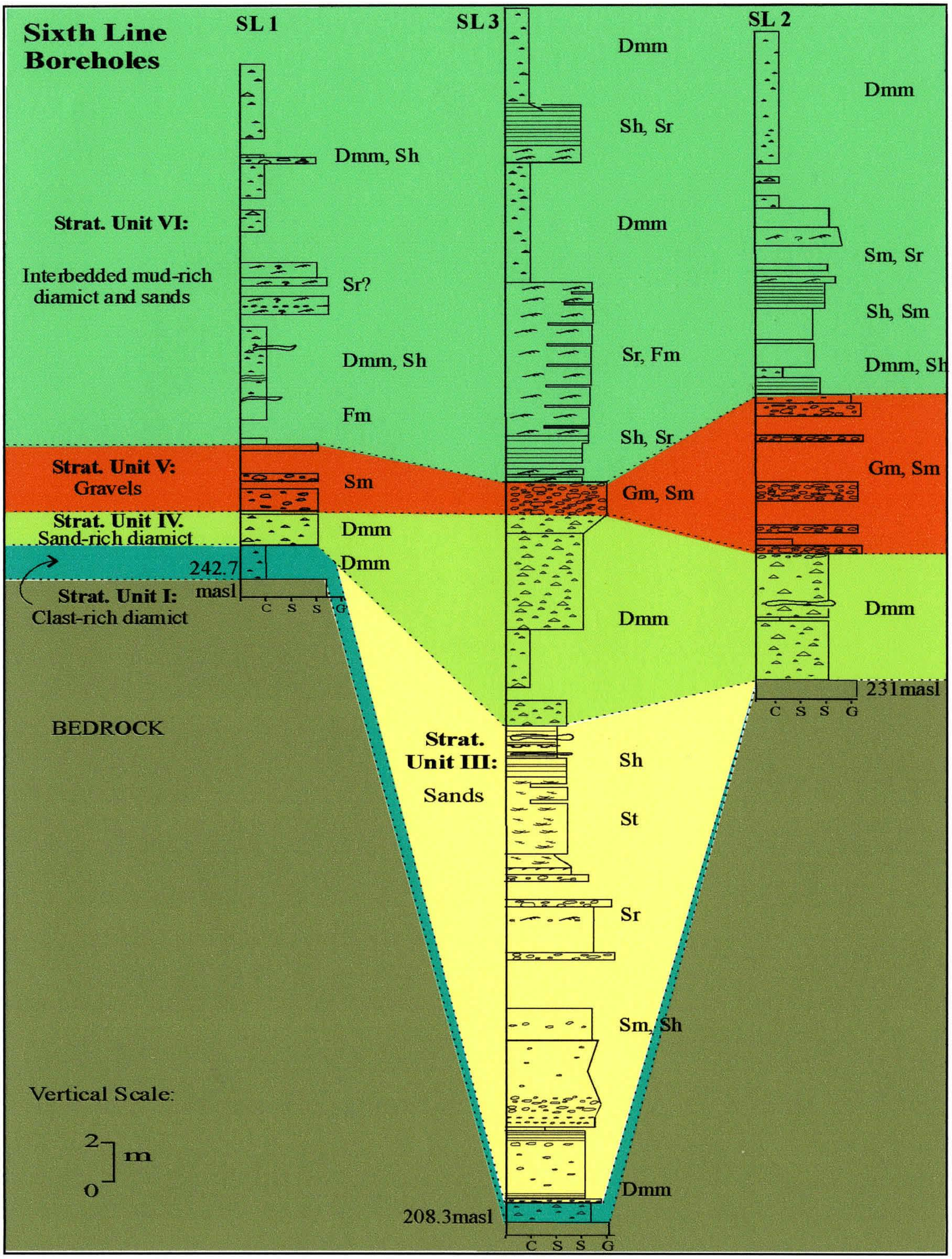

Figure 2.11- Sediment logs from the Sixth Line Road boreholes (SL1, SL2, and SL3). Boreholes SL1 and Sl3 are 200m apart, Sl3 and Sl2 are 700m apart. Refer to fig. 2.1 for location of boreholes, fig. 2.8b for legend and lithofacies codes.

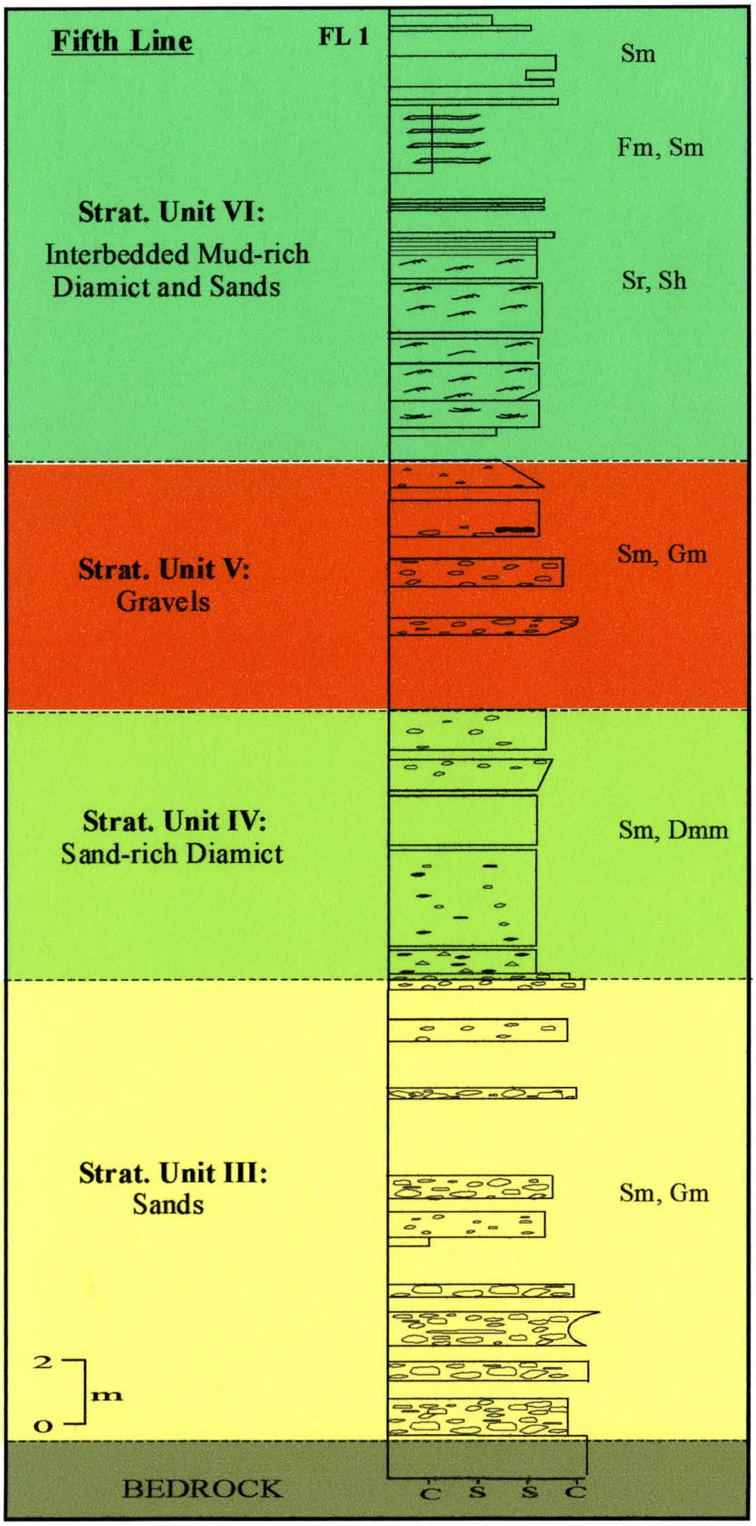

Figure 2.12- Sediment log from the Fifth Line Road borehole (FL1). Refer to fig. 2.1 for location of borehole, and fig. 2.8 for legend and lithofacies codes.

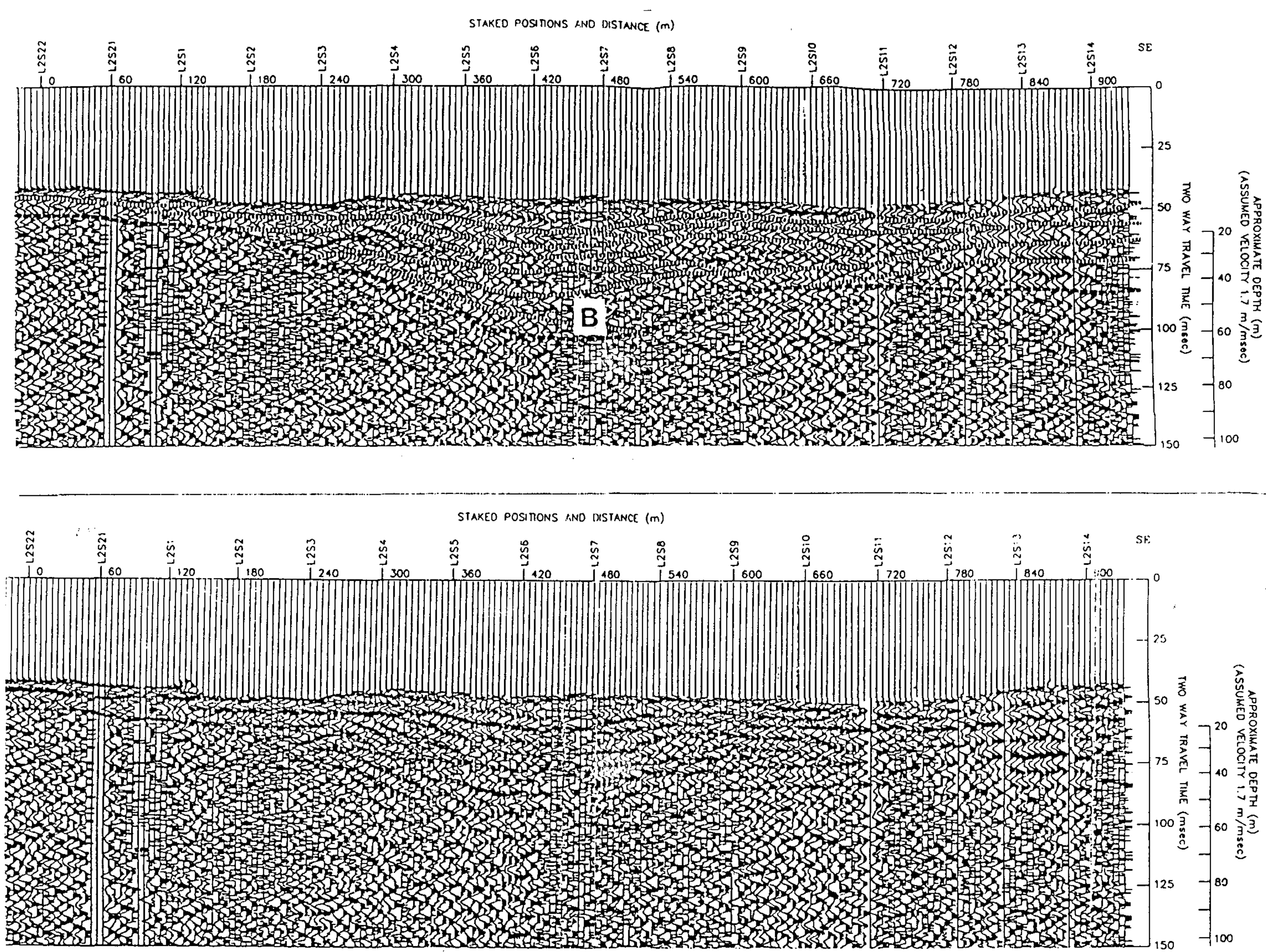

Figure 2.13-International Water Supply (1989) seismic reflection survey transect of the Sixth Line Road. Top section is IWS's interpreted result, the bottom section is the final section with no interpretation. "B" represents bedrock.

Boreholes were drilled using a PQ coring technique that uses a diamond drill bit to "continuously" core the unconsolidated sediment. Core was retrieved using a 7.6cm (3") diameter, core barrel in 1.5m (5ft) intervals, depending on drilling conditions (shorter intervals were used where core recovery was low). Good core recovery was obtained in the fine-grained silt and clay units, but sand and gravel units did not core well due to the 'wash out' of coarse material during drilling.

Over five hundred meters of drillcore were logged under laboratory conditions, noting details of sedimentary structures, grain, matrix and clast characteristics, as well as the nature of the contacts between individual beds (Appendix 1). Five distinct lithofacies types were identified in the cores including sands, gravels, sand-rich diamicts, clay-rich diamicts, and clays. These facies types were then grouped into six distinct stratigraphic units (SU I through VI) with SU I at the base of the succession, and SU VI at the top. Stratigraphic units were identified by grouping facies types with similar textural characteristics in stratigraphic order.

Grain size analysis was conducted on 14 sediment samples. Samples were chosen as either being representative of a particular facies type (e.g. SU VI; SL2, 4.72m; Table 2.1), or as representative of an end member of a facies that showed a broad range of textural characteristics (e.g. SL3; 1.83m; Table 2.1). Samples were dried, weighed, disaggregated using a mortar and pestle and sieved, using the methodology outlined in Folk (1974). Textural data obtained from this study and by previous workers are presented in Table 2.1.

Description	Location	Gravel	Sand Coarse	Sand Medium	Sand Fine	Silt/ Clay	Source	Sorting
Stratigraphic Unit VI								
Halton Till	Traf. 3; 11.3m	5.4	0.3	15.4	65	14	This study	Poorly sorted
Halton Till	Traf. 1; 19.8m	0.5	0.6	0.1	57.8	41	This study	Poorly sorted
Halton Till	6th Line2; 4.7m	9.8	12.3	10.5	45.9	21.6	This study	Poorly sorted
Halton Till	6th Line3; 1.8m	50.7	0	1	36	12.3	This study	Very poorly sorted
Halton Till	6th Line3; 8.5m	10.5	0.2	4.2	42.5	40.9	This study	Poorly sorted
Halton Till	Hamilton/ Galt		15-43% sand		24-65%silt	20-56% clay	Karrow, 1963	
Halton Till	Hamilton/ Cambridge		20% sand		49% silt	31% clay	Karrow, 1987*	
Halton Till	Bolton Area	<12	10-55% sand		35-70%silt	10-45%clay	White, 1972	
Stratigraphic Unit IV								
Northern Till	Traf. 1; 26.8m	18.6	34.1	9.3	19	19	This study	Very poorly sorted
Northern Till	6th Line2; 29.0m	36.2	19.2	7.3	29.6	7.6	This study	Very poorly sorted
Northern Till	6th Line2; 29.9m	41.2	19.2	9.4	19.7	10	This study	Very poorly sorted
Northern Till	6th Line2; 28.0m	10.3	4.3	17.2	46.3	22	This study	Very poorly sorted
Northern Till	North York	13-20	46-54%sand		30-39%silt	7-20% clay	White, 1972	
Stratigraphic Unit III								
Sands	T.W. 5; 21.0m	13	40	16	15	16	Peto-MacCallum	Very poorly sorted
Sands	T.W. 5; 22.86m	63	17	5	4	11	Peto-MacCallum	Poorly sorted
Sands	6th Line3; 50.9m	0.8	15.7	65	17.1	1.3	This study	Mod'ly well sorted
Sands	6th Line3; 52.1m	58.7	30.2	7.7	3.3	0.2	This study	Very poorly sorted
Sands	6th Line3; 55.8m	8	9.5	5.8	62.7	13.9	This study	Poorly sorted
Stratigraphic Unit I								
Lower Diamict	Traf. 2; 51.2m	27.2	6.9	7.3	37.4	21.1	This study	Very poorly sorted
Lower Diamict	6th Line3; 57.3m	50.7	0	1	36	12.3	This study	Very poorly sorted

Karrow, 1987* - average grain sizes

Table 2.1; Grain size analysis conducted in this study and others (Karrow, 1963; White, 1972; Karrow, 1987; Holysh, 1995).

Seven samples taken from fine-grained facies (including fine-grained diamicts) were also subject to micropaleontological analysis using methods outlined in Rutka and Eyles (1989). Samples were examined for the presence of micro-crustaceans, specifically ostracod fauna, which live in freshwater lacustrine environments. Different ostracod species thrive in different types of lacustrine environments and by identifying the presence of ostracods and their species it was hoped that detailed paleolimnological information including water depth and temperature could be obtained. Unfortunately, no ostracod species were found in any of the samples examined. However, only small samples were available for analysis and the absence of ostracods in the samples analyzed in this study does not exclude the possibility that ostracods exist in these deposits.

2.4 BURIED BEDROCK VALLEY TOPOGRAPHY

The elevation of the bedrock/ sediment contact identified from boreholes in the two buried bedrock valleys studied shows considerable topographic relief (Fig. 2.8a). Boreholes M1 and M2, outside Milton, are 40m apart, and show a difference in bedrock surface elevation of over 32m, giving a slope angle on the bedrock surface of approximately 40° (Fig. 2.8a). Bedrock surface topography identified from wells in the Georgetown valley on the Sixth Line Road show minimum slope angles of between 5° (SL2 to SL3; Fig. 2.11) and 10° (SL1 to SL3; Fig. 2.11).

Water well data and geophysical surveys conducted in the area suggest that the Georgetown valley consists of a narrow meandering channel incised within a much broader valley. The eleven boreholes drilled are interpreted to have intersected various parts of the broad valley, including the steep-sided and narrow channel walls (e.g. SL2; Fig.2.11), the deepest parts of the channel (thalweg; e.g. SL3; Fig.2.11), and the broader valley outside the incised channel (e.g. SL1; Fig.2.11)

The irregular bedrock topography identified from the Milton and Georgetown wells is comparable to that documented by geophysical investigations of bedrock valleys found in the Elora and Rockwood area, 20km west of Georgetown (Fig. 2.3). The Elora and Rockwood bedrock valleys are 'V' shaped, roughly 150m wide and up to 70m deep (Greenhouse and Karrow, 1994). Slope angles on the valley sides of the Elora and Rockwood valleys are estimated at between 5 and 30 degrees, although resolution of the steep-sided valley walls using geophysical methods is difficult (Greenhouse and Karrow, 1994). The depth, orientation and cross-sectional form of the valleys in the Elora/ Rockwood area (trend NNE-SSW) are very similar to those of the Georgetown valley except that no broader valley exists, only the narrow, incised, steep-sided channel. The bedrock form of the Dundas Valley is almost identical to that of the Georgetown valley, only on a larger scale. The Dundas Valley has an estimated depth of nearly 300m, is infilled with over 180m of Quaternary sediment and is likely the deepest bedrock valley in southern Ontario (Karrow, 1973). Geophysical surveys have shown that the floor of the Dundas Valley is broad and flat but contains a narrow incised channel in the center, interpreted to represent an incised fluvial channel lying within a broader, glacially-scoured valley (Edgecombe, 1999).

2.5 VALLEY INFILL SEDIMENTS: FACIES DESCRIPTIONS

The Georgetown and Milton cores contain a wide variety of facies types. Sediments encountered within the cores include gravels, rippled, massive and cross-bedded sands, laminated and massive silts and clays, and sand-rich, mud-rich and clast-rich diamicts (Figs. 2.8a-2.12).

2.5.1 Sand Facies

Sand facies constitute approximately 40% of the core thickness logged. Grain size varies from very fine-grained to very coarse-grained, but the majority of sands are fine to medium-grained (Table 2.1). Sands are very poorly to moderately well sorted, contain varying amounts of fines (0.2-16%; Table 2.1) and occasional well-rounded pebbles of limestone, dolostone or shale, mostly less than 3cm diameter. Silt and clay clasts occur within the sands in beds where clays overlie, underlie or are interbedded with sands (M2, G1, T1, T2; Fig. 2.8a, 2.9, 2.10). Sands range from medium to dark brown in colour, and individual bed thickness varies from a few centimeters to 6m (SL3; Fig. 2.11).

Sand facies occur as massive (Sm; Fig. 2.14a), horizontally laminated (Sh; Fig. 2.14b) and rippled (Sr; Fig. 2.14c,d) units. Massive sands are most common and bed thicknesses range from a few centimeters to 2m (G1; Fig. 2.9). Horizontally laminated and rippled facies occur in beds between 0.5 and 4m thick; particularly thick beds (up to 4m) of rippled sand occur towards the top of cores G2, T1 and T3 (Fig. 2.9, 2.10). Ripples are asymmetrical with amplitudes ranging from 1 to 2cm and commonly have microfaulted or deformed foresets. Climbing ripples are seen in core G1 with the angle of climb less than 10 degrees.

Sand facies indicate deposition by both traction currents and sediment gravity flow processes. Massive sands are usually attributed to turbidite deposition representing the rapidly deposited structureless Bouma A division (Walker, 1992). A turbidite origin is also supported by the presence of small silt clasts in massive sand facies (e.g. G2, M2; Fig. 2.8a, 2.9) which originate as rip-up clasts, eroded from the substrate as the flow moves downslope. Most of the massive, coarse-grained sands described here are interpreted as turbidite deposits; however, the absence of structure in some of the massive sand beds may be due to disturbance caused by drilling rather than depositional mechanism.

Horizontally laminated and rippled sands form by traction current deposition under either high or low energy regimes (Collinson and Thompson, 1982). The relatively fine-grained nature of horizontally laminated and rippled sands and the predominance of climbing ripple forms suggest deposition by relatively low energy traction currents in an

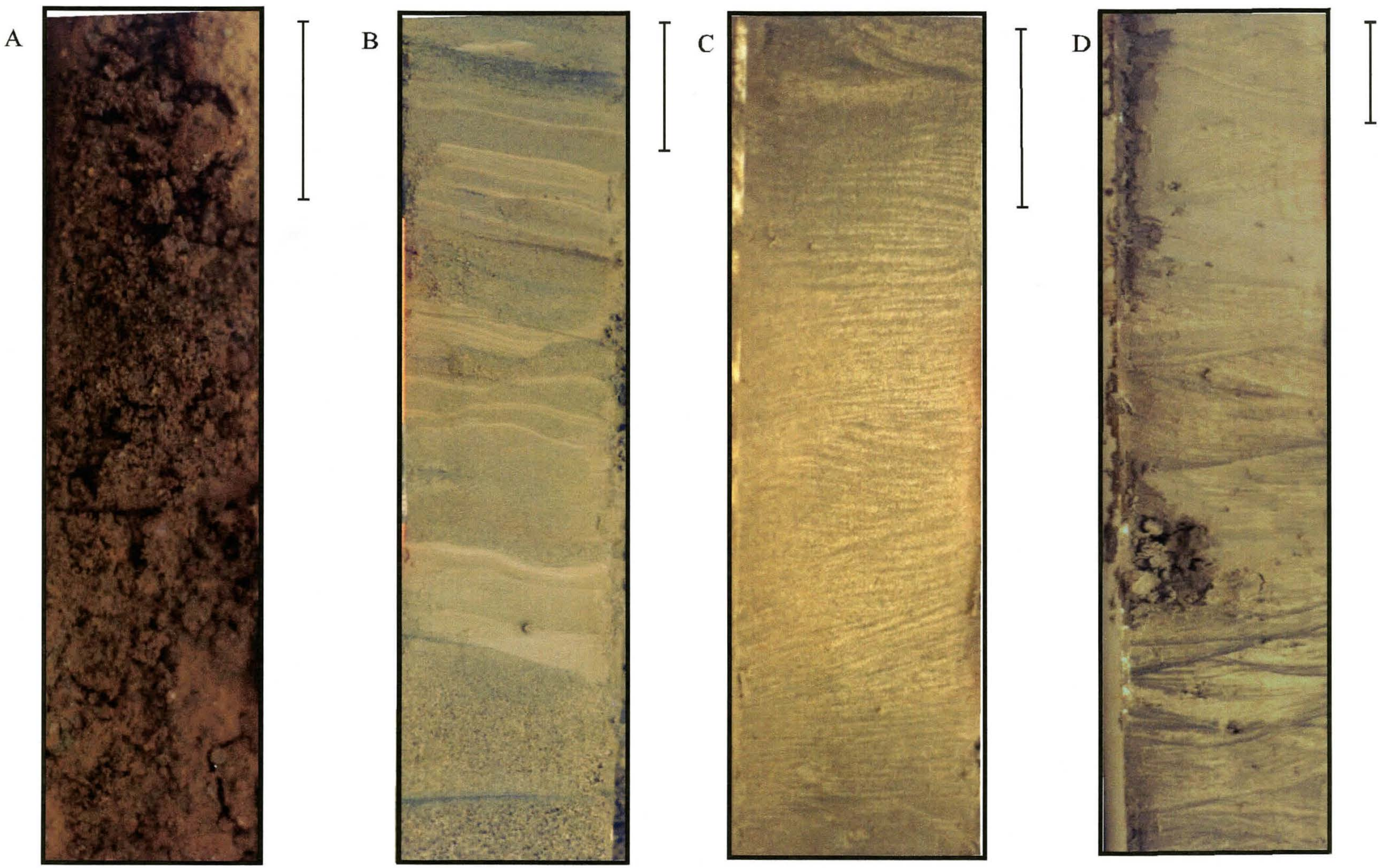

Figure 2.14- Sand facies. A. Coarse-grained poorly sorted massive sands (FL1; 35.1m). B. Fine-grained laminated silty sands (T2; 43.1m). C. Fine-grained rippled sands (SL4; 39.4m). D. Fine-grained cross-bedded sands (SL4; 40.5m). Scale bar to the right is 5 cm.

environment supplied with large volumes of fine-grained bedload and suspended sediment (Walker, 1992).

2.5.2 Gravel Facies

Gravels contain clasts that vary in size from small granules (0.2-0.4mm), to cobbles greater than the diameter of the core (>10cm). Clasts are poorly sorted, and composed of locally-derived limestone, dolostone and shale, and far-traveled granite, gneiss, gabbro and tonalite ('Shield' material; Fig. 2.15a). Clasts composed of 'Shield' material are predominately well rounded to subangular, and those of local derivation have more angular forms. Matrix material is lost from many cores but where present consists of coarse to very coarse-grained sand (Fig. 2.15b, c). Poor core recovery of gravel facies means that the amount and thickness of gravel logged in the cores should be viewed as a minimum only. It was not possible to determine the nature of internal structures, grading or bed contacts for these facies.

Gravel facies are most commonly deposited by high velocity traction currents or by coarse-grained sediment gravity flows (Collinson and Thompson, 1982). The poorly sorted nature of the cored gravels suggests they were deposited fairly rapidly and close to their source area; the loss of internal structure prohibits a more detailed interpretation (Leeder, 1982). Gravel facies are interpreted here as bedload deposits formed in a high-

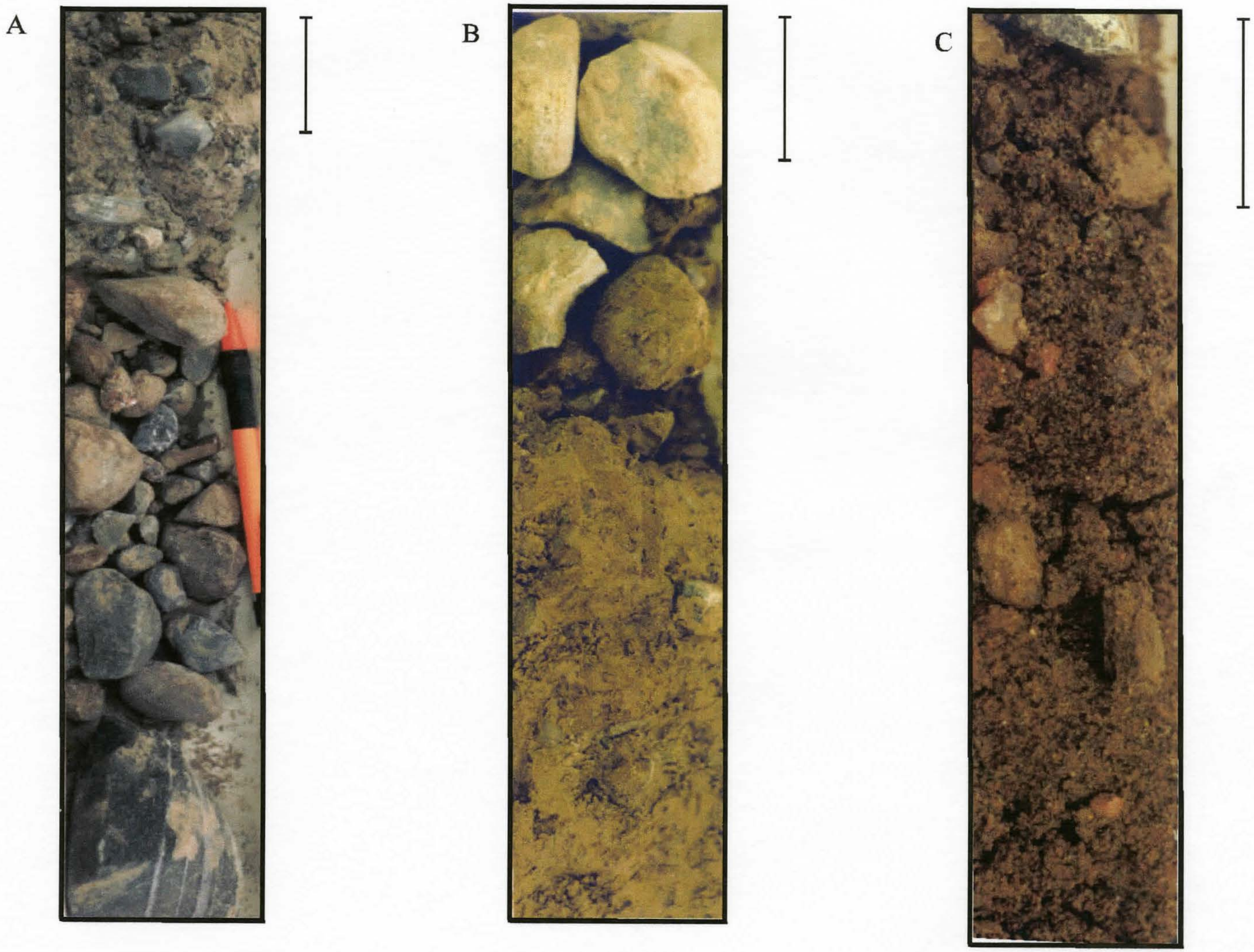

Figure 2.15- Gravel facies. A. Large well-rounded clasts of local and shield material(M2; 26.2m). B. Large well-rounded clasts of local origin (T3; 25.3m). C. Very coarse-grained and poorly sorted sand and gravel (FL1; 18.9m). Scale bar to the right is 5cm.

energy fluvial system and probably represent stacked longitudinal bar deposits (Miall, 1997).

A relatively thick (1.5-8m; M2, SL3; Fig.2.8a, 2.11) gravel horizon occurs at approximately the same stratigraphic position, above sand-rich diamict and below fine-grained diamict, in all cores examined (Figs.2.8a-2.12). As there is only one gravel bed of this thickness in the cores it was used to correlate between boreholes in the study area.

2.5.3 Fine-grained Facies

Fine-grained facies are predominantly gray in colour and are composed of variably interbedded silts and clays. These facies have abrupt contacts with underlying and overlying facies, which most commonly are sands (M1, T1-3, SL1-3; Figs. 2.8a, 2.10, 2.11). Textural analyses of fine-grained facies indicate between 12 to 41% silt/clay content (percent weight of total sample; Table 2.1).

Massive (Fm), laminated (Fl; Fig. 2.16a,b) and deformed (Fl def; Fig. 2.16c) silt and clay beds range in thickness from a few centimeters to 10m (T3; Fig. 2.10). The majority of clay and silt beds are massive (Fm) and occasionally contain small (<2cm), angular clasts of shale. Laminated facies consist of horizontal laminae of silt and clay which occur as distinct silt/ clay couplets in cores M1 and M2 (Fig. 2.8a; Fig. 2.16a). Core M2 is the only core to contain graded bedding in fine-grained laminated facies

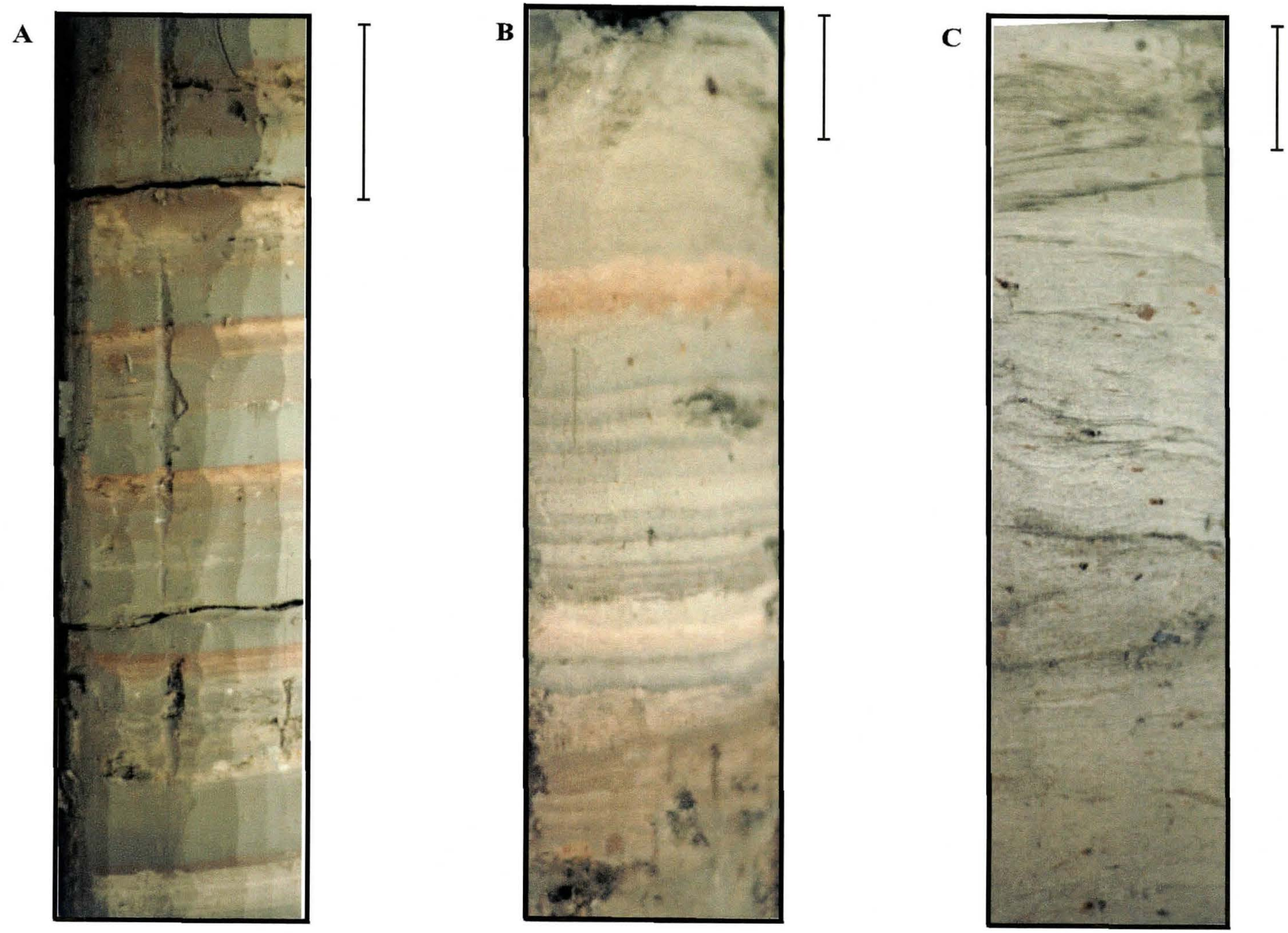

Figure 2.16- Fine-grained facies. A. Laminated silts and clays showing graded beddding (clay to silt) and ocassional white silt clasts (M1; 23.2m). B. Laminated silt and clay (M2; 61.9m). C. Deformed laminations in silt bed with very small (<0.5cm) red shale clasts (M2; 60.2m). Scale bar to right is 5cm.

(Fig.2.16b). Deformed laminae are either microfaulted (Fig. 2.16c) or show small scale (few centimeters), irregular convolutions.

Fine-grained facies accumulate in low energy depositional environments such as lakes when sediment settles out of suspension as flow velocities decrease upon entering a quiet body of water (Boggs, 1987; Collinson and Thompson, 1982). Massive facies accumulate either under conditions of rapid and continuous supply of fine-grained suspended sediment or form by post-depositional destruction of structure by bioturbation, plant roots or soil-forming processes (Boggs, 1987; Collinson and Thompson, 1982). Bioturbation was noted in a few cores.

Laminated fine-grained facies are formed when slight changes in the texture of sediment supplied or fluctuations in flow velocities cause subtle changes in the grain size of accumulating sediment (Eyles and Eyles, 1983; 1992; Eyles and Clark, 1988). The grading observed in some laminated facies (e.g. 21m in M2; Fig.2.9a) suggest that some of these facies were deposited by dilute turbidity flows (Collinson and Thompson, 1982; Walker, 1992).

2.5.4 Diamict Facies

Diamicts are poorly sorted admixtures of clasts, sand, silt and clay (Eyles and Eyles, 1983). In the cores examined, diamicts are matrix supported and contain at least 10% fines (silts and clays). Three distinct types of diamict can be recognized in the cores according to their textural composition; clast-rich diamicts, clay-rich diamicts and sand-rich diamicts.

2.5.4.1 Clast-rich Diamicts

Clast-rich diamicts have the same distinctive red colour as the Queenston Shale bedrock that they overlie (Fig. 2.17). These diamicts are massive and contain a predominantly fine-grained, but sand-rich, matrix (36-37.4% fine sand; Table 2.1) and very abundant, well-rounded to angular shale clasts (27.2 to 50.7% by weight; Table 2.1) ranging in size from 1-4cm. Individual bed thickness varies from <1m (M1) to 8m (M2; Fig. 2.8a).

2.5.4.2 Sand-rich Diamicts

Sand-rich diamicts are brownish red with a very poorly sorted matrix of fine- to medium-grained sand and mud (Fig. 2.18; Table 2.1). They contain abundant poorly sorted clasts (10-41% by weight; Table 2.1) that range in size from 0.5-10cm (Fig. 2.18a). Well-rounded to subrounded clasts are composed predominantly of shale, limestone, and dolostone, although clasts of granite, basalt, and/or gneiss are also present. Individual bed thickness varies from 2m to 10m (T1, SL1; Fig. 2.10, 2.11).

Figure 2.17- Clast-rich diamict containing abundant small shale clasts (Sl1; 23.8m). Scale bar to right is 5cm.

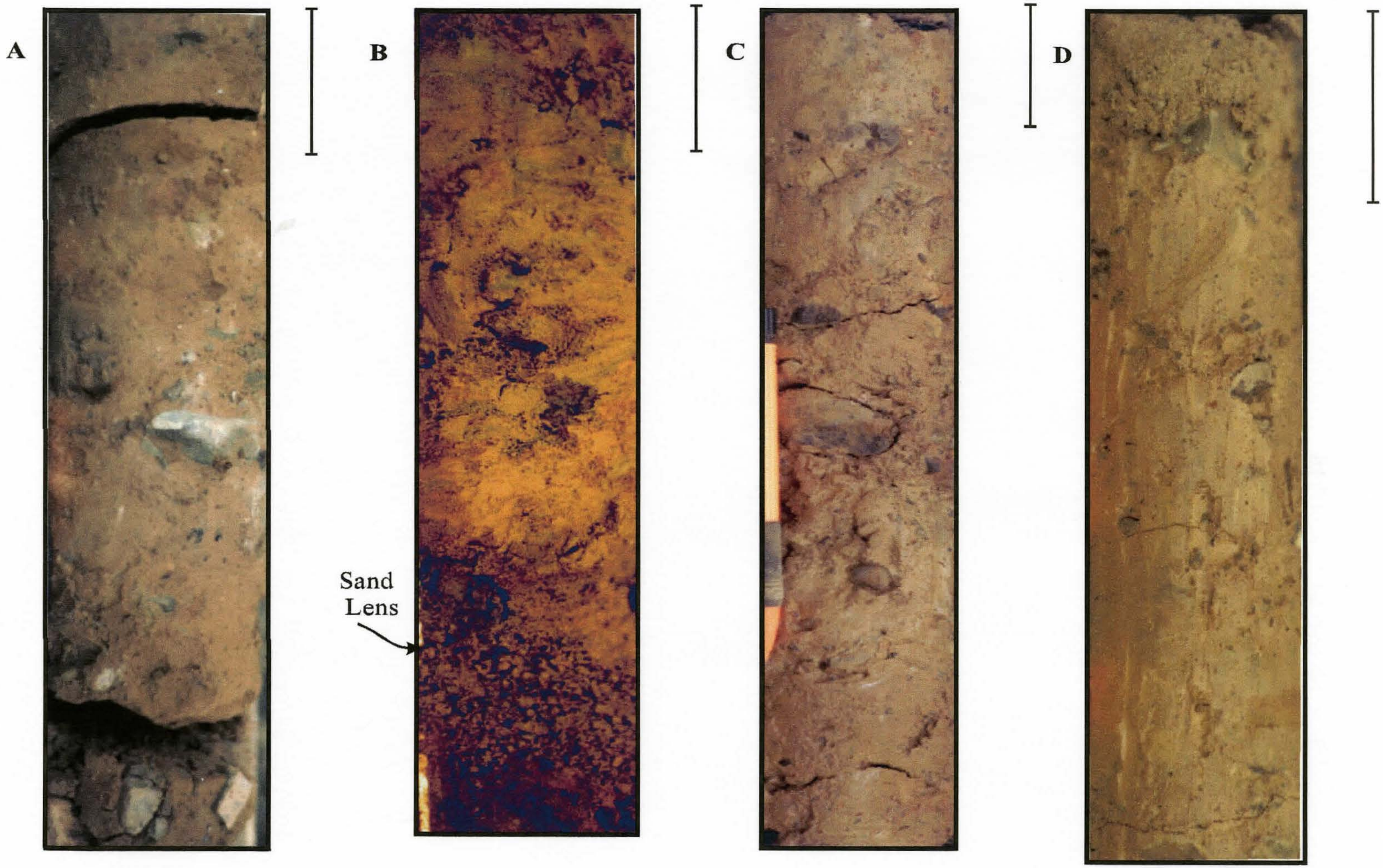

Figure 2.18- Sand-rich diamict facies. A. Sand-rich diamict containing abundant poorly sorted clasts of local composition (M2; 32m). B. Sand-rich diamict with poorly sorted, coarse-grained sand lens (lower part of photo; T3; 26.5m). C, D. Sand-rich diamict with poorly sorted, well-rounded clasts (both SL1; 22.9m). Scale bar to right is 5cm.

Sand-rich diamicts are predominantly massive, but in some cores show crude matrix stratification consisting of thin (2-5cm wide; Fig. 2.18b), fine- to medium-grained sand interbeds (T1-3, SL2; Fig. 2.10, 2.11).

2.4.4.3 Mud-rich Diamicts

The third type of diamict logged in the cores is characterized by a mud-rich, gray or brown matrix (Table 2.1) containing sparse to abundant clasts (Fig. 2.19). Bed thickness varies from a few centimeters up to 8m (SL2; Fig. 2.11). Clasts are well rounded to subrounded (Fig. 2.19c) and are composed predominately of shale although dolostone, limestone, and a variety of igneous and metamorphic types, typical of Shield sources are also common. Clast sizes range from 0.5-6cm and average 0.5-1cm in diameter. Mud-rich diamicts are dense, cohesive and predominately massive (Dmm; SL2; Fig. 2.11). Crude stratification in some mud-rich diamicts is formed by thin horizontal interbeds of sand, clay or gravel (Dms; SL1, FL1; Fig. 2.11, 2.12, 2.19a).

Diamicts can form by a variety of processes, in a wide range of depositional environments (Eyles and Eyles, 1992). Hence, interpreting the depositional origin of diamict facies can be difficult, particularly when using only drill core data, as large-scale features often seen in field outcrops and useful for paleoenvironmental interpretation, are not apparent. In order to constrain the type of depositional environment in which a diamict formed, the origin of facies associated with the diamict must be determined. In

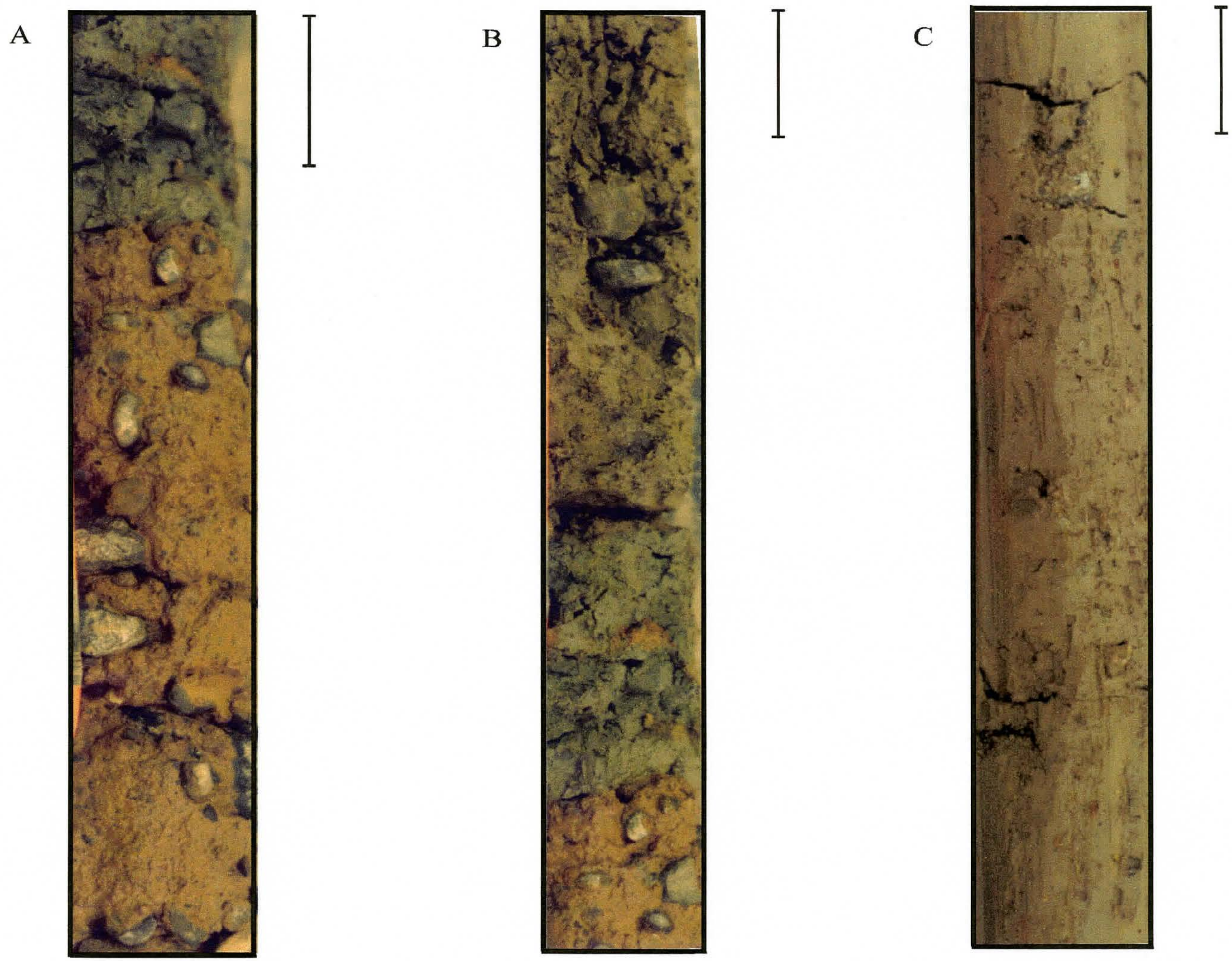

Figure 2.19- Mud-rich diamict facies. A. (T3; 19.2m) and B. (T3; 18.8m) mud-rich diamicts with abundant poorly sorted clasts of local material. C. (SL1; 5.5m) Massive mud-rich diamict with sparse clasts. Scale bar to right is 5cm.

the cores examined, diamicts are associated with gravel, sand and fine-grained facies interpreted to be of fluvial and lacustrine origin. It is therefore most likely that the diamict facies described in this study originated either as subglacial deposits (lodgment and deformation tills; Boulton and Hindmarsh, 1987; Boyce and Eyles, 1991; Boyce et al., 1995) glaciolacustrine deposits (Eyles and Eyles, 1982) or subaerial debris flow deposits (Lawson, 1982).

2.6 STRATIGRAPHIC UNITS

Individual facies types identified in core were grouped into distinct packages or 'stratigraphic units' according to their textural characteristics and the stratigraphic position in which they occur. Six distinct stratigraphic units (SU I –VI; Fig. 2.8a) were identified within the Milton and Georgetown cores, with SU I at the base of the succession and SU VI at the top; not all stratigraphic units could be identified in every borehole (Fig. 2.20). SU I consists of shale- and sand-rich diamicts and gravels, and lies unconformably on top of the Queenston shale bedrock. SU II conformably overlies SU I, and is composed of laminated clays with interbeds of gravel and sand. Thick, massive and rippled sand beds characterize SU III, which is unconformably overlain by SU IV, a red sand-rich diamict unit. SU V is a thick unit of sand and gravel that lies unconformably on top of SU IV, and unconformably below SU VI, a complex stratigraphic unit composed of interbedded clay, mud-rich diamict and sand. These six stratigraphic units are interpreted to represent a range of glaciofluvial, subglacial and

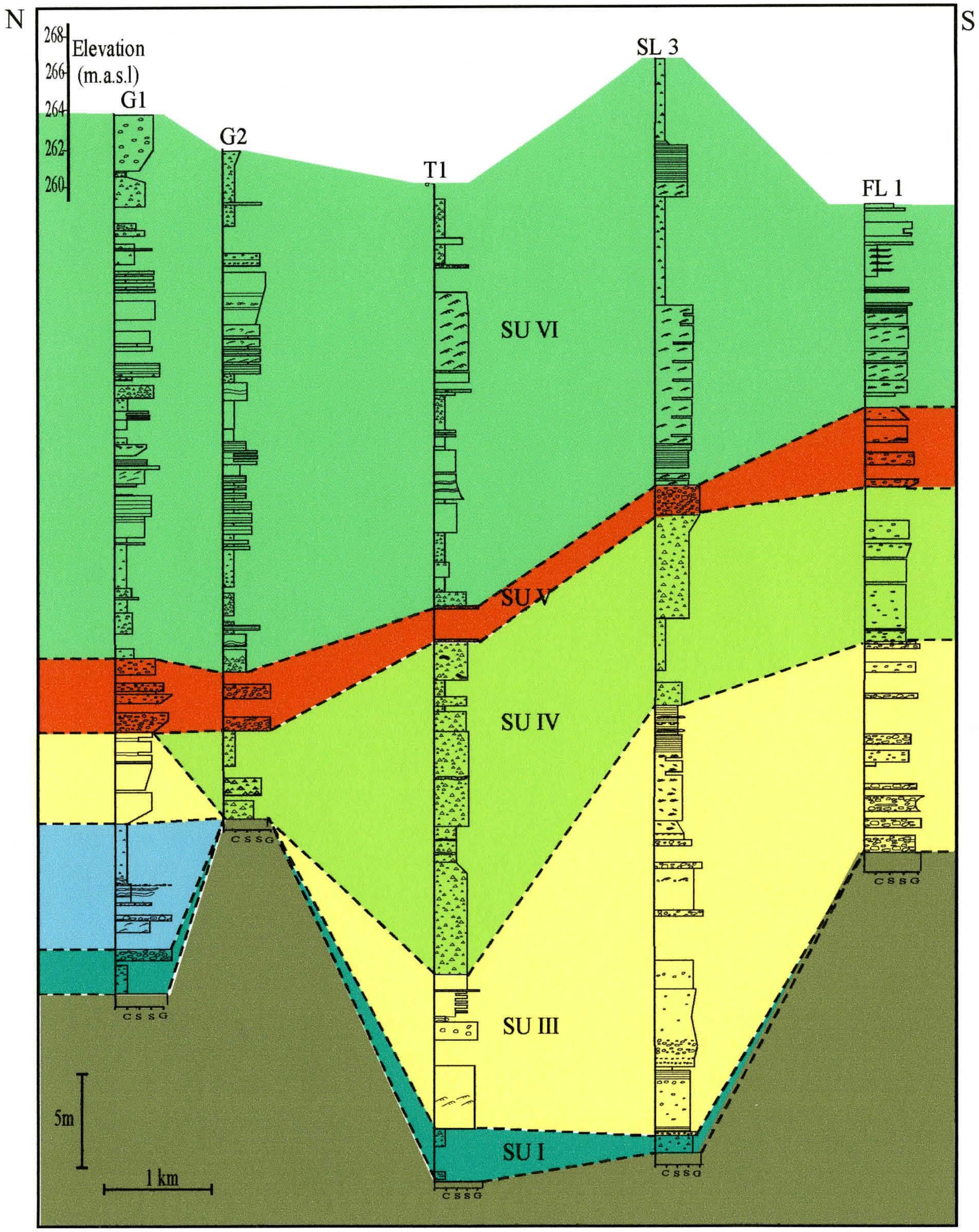

Figure 2.20- North-South cross-section along the strike of the Georgetown bedrock valley. Approximate length of section is 7km. Refer to fig. 2.1 for borehole locations.

glaciolacustrine deposits formed at the fluctuating margin of the Laurentide Ice Sheet during the Wisconsin. Descriptions of each of the stratigraphic units and interpretation of their depositional environments are presented below.

2.6.1 Stratigraphic Unit I (Clast-rich diamicts and gravels)

Stratigraphic Unit I (SU I) consists of red clast-rich diamicts and poorly sorted gravels that unconformably overlie the Queenston shale bedrock. SU I occurs at the base of six of the eleven cored holes and ranges in thickness from 2m to over 7m in boreholes M2 (Fig. 2.8a) and G1 (Fig. 2.9). The thickness of SU I may be underestimated as drilling frequently ceased when red weathered shale, assumed to be bedrock, was encountered.

Gravels only occur in SU I at the base of the deepest bedrock valley (Milton valley M1; Fig. 2.8a). These gravels are interpreted to be of fluvial origin, deposited by a river flowing eastward in the steep-sided bedrock valley away from the Niagara Escarpment.

Clast-rich diamicts associated with gravels in the steep-walled bedrock valley near Milton (e.g. T1, T2; Fig.2.10) probably originated by a combination of fluvial and mass flow processes. Well-rounded clasts in the diamicts support a fluvial origin for some of the materials, while mass wasting processes explain the poorly sorted nature of the deposits and the presence of angular shale clasts derived from locally exposed bedrock. Steep slopes of up to 40 degrees identified within these valleys would allow a variety of subaerial mass flow processes, including debris flows and slides, to occur (Boggs, 1987).

Not all clast-rich diamicts found in SU I lie on the deepest parts of the valley floors. Bedrock intersected by boreholes at intermediate depths (between 30 and 43m; e.g. SL3; Fig.2.11) is interpreted to represent the broader form of the valley floor outside the deepest parts of the channel, and is also overlain by clast-rich diamicts. In contrast to the diamicts found in incised valley floor positions, these diamicts only contain angular shale clasts and are interpreted to be the product of in situ weathering of the Queenston Shale bedrock.

2.6.2 Stratigraphic Unit II (Laminated clays with sand and gravel interbeds)

SU II consists of a fining-upward succession of massive and laminated clays interbedded with thin sand-rich diamicts, sands and gravels; sand-rich diamicts and gravels are restricted to the base of SU II and are similar to those found in SU I below. Fine-grained facies show a progressive change from silty-clays with very few clasts at the base of the unit, into massive and finely laminated clays with scattered clasts towards the top (Fig. 2.8a). SU II is between 7 and 8m thick, and only occurs in two holes (M2, Fig. 2.8a; G1, Fig. 2.9).

The predominance of fine-grained facies in SU II suggests deposition under lacustrine conditions formed when local base levels rose and the bedrock valley floors were flooded. Sand-rich diamicts and thin sand and gravel beds interbedded with silts and clays at the base of SU II are interpreted to represent material slumping into the lake from the steep valley walls. Flooding of the valleys may be related to advance of an ice margin into the area, supplying abundant meltwater, blocking drainage and causing isostatic depression of the substrate. Clasts contained within the upper clays may represent ice-rafted debris released from an advancing ice margin.

2.6.3 Stratigraphic Unit III (Sands)

SU III is composed of horizontally laminated, rippled and massive sands and most commonly forms a coarsening upward succession, passing from fine-grained silty sand at the base into medium- to coarse-grained sand at the top (e.g. G1, T2; Fig. 2.9, 2.10). However, a distinctive fining-upward succession occurs in SL3 (Fig. 2.11), which lies in a deep part of the Georgetown valley close to the Escarpment. Clasts within SU III are mostly restricted to thin gravel horizons, although scattered clasts are noted throughout the upper part SU III in M2 (Fig. 2.8a). Stratigraphic Unit III varies in thickness between 5m (M1; Fig. 2.8a) and 23m (SL 3; Fig. 2.11) and is found in 8 of 11 cores examined in this study. The 3 boreholes that do not contain SU III are relatively shallow holes that intersect the bedrock surface on the flanks of the bedrock valley (G2, SL1, SL2; Fig. 2.9, 2.11).

The sands of SU III are interpreted as fluvial deposits formed by sandy braided rivers, flowing southward along topographic lows created by the bedrock valleys, possibly from an ice margin advancing from the north. The sands are thickest in the middle of the deep bedrock valleys (e.g. M2; Fig. 2.8a), and thin towards the valley margins (e.g. M1; Fig. 2.8a). Progradation of the sediment source area is suggested by the crude coarsening-upward succession shown by SU III in most cores. The underlying fine-grained sediments of SU II are interpreted to have been deposited in water ponded in front of an advancing ice margin; the sands of SU III may have been deposited pro-glacially as sand-rich rivers built out into the bedrock valley lows. The fining upward succession preserved in SL3 (Fig. 2.11), which lies in the deepest part of the Georgetown valley may record subsequent flooding of the valley floor as advancing ice disrupted drainage.

2.6.4 Stratigraphic Unit IV (Sand-rich diamict)

Stratigraphic Unit IV consists of a red, massive to crudely stratified sand-rich diamict that contains abundant locally-derived and far-traveled clasts. Thin (1-5cm) sand interbeds occur within the diamict in 5 of 11 cores (M1, T1, T2, T3, SL2; Fig. 2.8a, 2.10, 2.11). SU IV is identified in all boreholes and varies between 2 (SL 1; Fig. 2.11) and 20m in thickness (T1; Fig. 2.10).

The sand-rich diamicts of SU IV have similar characteristics to the Newmarket Till (Barnett et al., 1998; Sharpe et al., 1999; Pugin et al., 1999) and Northern Till (Boyce et al., 1995; Eyles, 1997; Boyce and Eyles, 2000) described from surface outcrops. The Newmarket and Northern tills are interpreted as subglacial deposits formed by lodgement and deformation processes below the ice base (Karrow and Ocheitti, 1989; Boyce and Eyles, 2000). The presence of sandy interbeds and lenses within SU IV of cores M1, T1-3, and SL2 (Fig. 2.8a, 2.10, 2.11) suggests localized meltwater deposition with incorporation and deformation of the underlying sands (SU III) within a slurry at the ice-bed contact (the deforming bed of Boulton and Hindmarsh, 1987; Boulton, 1996). Outcrop exposures of the Northern Till in West Duffins Creek near Toronto (Fig. 2.1), show boulder pavements and sandy interbeds within the diamict (Boyce and Eyles, 2000). The Northern Till is interpreted to have been deposited during the Nissouri Stadial (25-18 ka) when the Laurentide Ice Sheet reached its maximum extent and covered the entire Great Lakes region (Fig.2.6; Barnett; 1992; Boyce and Eyles, 2000).

Within the study area, SU IV is found in 10 of 11 boreholes studied and infills the remaining lows within the bedrock valleys essentially 'flattening out' the depositional topography; it has a consistent upper surface elevation of between 231 and 245 m.a.s.l. in the Georgetown area (Table 2.2). The till is thickest within the valleys, and thins toward the valley margin. SU IV is absent in one borehole (G1; Fig. 2.9), and may have been eroded prior to deposition of overlying gravel. Deposition of stratigraphic units overlying SU IV does not appear to have been influenced by the bedrock channel topography; units SU V and SU VI essentially form a blanket of sediments across the area (Table 2.2).

Table 2.2: Elevations (m.a.s.l) of the upper surface of Stratigraphic Units in each of the cored boreholes.

Strat. Unit	**Borehole**										
	G1	G2	T1	T2	T3	SL1	SL3	SL2	FL1	M1	M2
SU VI	264	262	260	259	258	267	266	263	260	215	215
SU V	236	235	238	/	238	248	243	244	247	193	191
SU IV	/	232	235	231	232	245	241	237	239	185	183
SU III	232	/	218	222	230	/	231	/	231	182	175
SU II	227	/	/	/	/	/	/	/	/	/	157
SU I	220	/	210	208	221	243	/	/	/	177	151

/ Stratigraphic Unit not present within the borehole

2.6.5 Stratigraphic Unit V (Gravels)

Stratigraphic Unit V consists of poorly sorted, locally derived and far-traveled (Shield) gravels interbedded with coarse-grained sand. It is found within all the cores examined and provides an excellent 'marker' horizon that can be laterally correlated between boreholes. The thickness of SU V varies from 1.5m (SL 3; Fig. 2.11) to 8m (M2; Fig. 2.8a) and has an upper surface elevation of between 235 and 248 m.a.s.l. in the Georgetown area (Table 2.2).

The lateral extent, thickness, and textural characteristics of SU V suggest that these gravels represent fluvial deposits. Their stratigraphic position overlying the sand-rich subglacial-deposits of SU IV (interpreted as the Northern / Newmarket Till) suggest they were deposited as ice withdrew from the area during the Mackinaw Interstade between 14 and 13.2 ka (Barnett, 1992). These gravels are similar in texture and composition to the Mackinaw Interstadial gravels described from surface outcrops in the Toronto area (Boyce et al., 1995). The gravels have a sheet-like geometry with considerable lateral extent and an undulating, erosive base (Table 2.2). This suggests SU V was deposited as a gravelly braided fluvial system that formed an extensive outwash (sandur) plain.

2.6.6 Stratigraphic Unit VI (Mud-rich diamict interbedded with sands)

SU VI is the most complex and variable of all the stratigraphic units identified in core and lies directly above SU V and below the ground surface. It is found in all boreholes and is by far the thickest stratigraphic unit of the six identified, ranging from 16m (FL1; Fig. 2.12) to 26m (T1; Fig. 2.10). SU VI includes mud-rich diamicts, massive and laminated clays and rippled sands (Fig. 2.10a,c, 2.11). Individual facies constituents do not show any lateral continuity between boreholes (e.g. Fig.2.8a) and do not allow stratigraphic subdivision of this complex unit.

SU VI is interpreted as a complex of ice marginal lacustrine, fluvial and subglacial deposits formed during the rapid advance of ice northward from the Lake Ontario basin during the Port Huron Stadial (13.2- 12ka). These deposits are equivalent to the Halton Till Complex exposed in outcrop and described in the literature (Karrow, 1963; Barnett, 1992; Boyce et al., 1995; Boyce and Eyles, 2000). The extreme facies variability shown by this till complex is probably due to spatial changes in depositional processes and environments close to an ice margin.

Many of the boreholes studied show a crude coarsening upward succession in SU VI (e.g. M1, G1, G2; Figs. 2.8a, 2.9). The basal part of the unit consists of laminated clays and/or mud-rich diamicts with few clasts (M1; Fig. 2.8a). These facies suggest deposition either under glaciolacustrine conditions or by subglacial reworking of previously deposited lacustrine sediments (Boyce and Eyles, 1991; Eyles and Eyles, 1992). As ice moved northwestward out of the Lake Ontario basin ponding of water in front of the advancing glacier makes either of these two scenarios possible.

Diamict facies at the base of SU VI coarsen upward into silty-sands, which become coarser-grained with gravel interbeds toward the surface. This crude coarsening upward trend may record the advance of ice from the southeast into an ice- proximal lake ponded between the ice and the Niagara Escarpment. Progressively coarser-grained sediment would be introduced as the ice advanced and finally overrode the area.

A coarsening upward succession in SU VI is not evident in all cores. It is likely that streams draining the area to the north, and/or the Escarpment to the west, would create localized sediment sources and add variability to the overall coarsening-upward trend. Several thick units of rippled, fine-grained sand within the Halton Till Complex appear to be of deltaic origin (T1, T3, SL3, FL1; Fig. 2.10, 2.11, 2.12). The fine-grained nature of these deposits suggests they are supplied from a different sediment source area to that responsible for depositing the overall coarsening-upward succession of SU VI. The sands of SU VI also contrast with the coarser-grained and more poorly sorted sands of SU III. The sands of SU III were probably supplied by a regional drainage system flowing from the north, while the sands of SU VI originated from local sediment sources. The localized nature of the sediment source areas for SU VI makes prediction of sand body geometries within SU VI (the Halton Till Complex) extremely difficult.

2.7 DISCUSSION

2.7.1 Formation of Bedrock Valleys

The orientation of the buried bedrock valleys in the Milton/ Georgetown area is comparable to those of other bedrock valleys in southern Ontario (Karrow, 1973; Greenhouse and Karrow, 1994; Eyles et al., 1997). Eyles et al., (1997) identified preferred orientations for buried bedrock valleys that matched regional joint set orientations of 22° and 104°. The trends of the Georgetown bedrock valley (15-30°), and the trend of the Milton valley (approximately 90°), are consistent with these values and suggest that the development of the bedrock valleys may have been influenced by bedrock jointing patterns (Scheidegger, 1980; Eyles, et al., 1993; Eyles and Scheidegger, 1995).

The Georgetown valley appears to consist of two components; a narrow, deeply incised central channel within a broader, relatively flat-floored valley. The narrow, incised component has a similar form to the Rockwood and Elora bedrock valleys (Greenhouse and Karrow, 1994) and is infilled with fluvial and colluvial sediments suggesting the operation of fluvial, rather than glacial processes. The broader, flat-floored component of the Georgetown valley widens above this incised channel and is overlain by red coloured, sand-rich diamicts of SU IV. The predominance of shale clasts in SU IV derived from the underlying bedrock, suggests that glacial ice was responsible for eroding and widening the initial narrow, fluvially-incised bedrock valley and subsequently infilled it with subglacial till. This two-component valley form consisting of a narrow fluvially-incised channel lying within a broader glacially-scoured valley, is very similar to the Dundas buried bedrock valley (Edgecombe, 1999).

2.7.2 Depositional History of Valley Infill Sediments

In the Milton/ Georgetown area, the deepest parts of the bedrock valleys are infilled with relatively coarse-grained fluvial and colluvial sediments (SU I) formed by rivers flowing along the valley floors and mass flow processes operating on the steep valley walls. Subsequent ponding of water in these valleys allowed localized deposition of fine-grained silts and clays characteristic of SU II. These deposits, together with overlying rippled, laminated and massive sands of SU III, record deposition in fluvial and lacustrine environments prior to the advance of ice into the area, probably during the Nissouri Stadial (25-18ka; Barnett, 1992). SU II and III indicate flooding of the valley floors and may be equivalent to Mid-Wisconsin lacustrine and glaciolacustrine deposits of the Thorncliffe Formation exposed along the Scarborough Bluffs (Fig. 2.3) that formed when water depths were at least 90m deeper than at present (Eyles and Eyles, 1983).

The sand-rich diamicts of SU IV are interpreted as subglacial tills equivalent to the Newmarket/ Northern tills described from surface outcrops (Boyce et al., 1995; Boyce and Eyles, 2000) and were probably deposited during the Nissouri Stadial (25-18ka). The Laurentide Ice Sheet subsequently retreated from southern Ontario during the Mackinaw Interstadial, (14-13.5ka; Fig. 2.6) and deposited a blanket of fluvial outwash gravel (SU V) across the area. These interstadial gravels overlie the Northern Till and, at the Woodbridge site near Toronto (Fig. 2.3) gravel-filled ice-wedge casts penetrate up to 1.5m into the underlying till surface (Westgate, 1979; Boyce et al., 1995). These ice-wedge casts are interpreted as periglacial features formed during cold but ice-free interstadial conditions. Interstadial gravels similar to those described in this study have also been mapped northwest of Toronto (Boyce et al., 1995), and east of Toronto in the Bowmanville area (Brookfield et al., 1982). In all of these areas, the coarse-grained sand and gravel deposits lie between two Late Wisconsin tills and provide evidence for widespread ice withdrawl and subaerial exposure during the Mackinaw Interstadial.

The Halton Till Complex (SU VI) overlies the Mackinaw Interstadial gravels and is interpreted to have been deposited during the Port Huron Stadial (12-13.5ka; Barnett, 1992) when the Ontario-Erie sublobe of the Laurentide Ice Sheet surged rapidly out of Lake Ontario across the study area. Drumlins and flutes developed across the surface of the Halton Till Complex indicate that the ice sheet flowed out of the Lake Ontario basin (Karrow, 1967; Boyce et al., 1995), covering the Toronto area and parts of the Niagara Peninsula (Fig. 2.7; Barnett, 1992). This till complex is interpreted to record rapid advance of the ice margin into ponded proglacial lakes and the production of fine-grained subglacial and glaciolacustrine diamicts; interbedded sand facies were probably deposited by local fluvial systems flowing into the ponded lakes from the north and west.

Sediments within the Elora and Rockwood buried bedrock valleys (Fig. 2.3) are of comparable age to those within the Georgetown and Milton bedrock valleys. The Elora bedrock valley contains at least four tills, with the oldest till interpreted as the Catfish Creek Till deposited during the Nissouri Stadial (Fig.2.4; Greenhouse and Karrow, 1994). Interbedded lacustrine clays and tills (Maryhill Till, Tavistock Till; Greenhouse and Karrow, 1994) deposited during the Port Bruce Stadial, and the Port Stanley Till/ Wentworth Till deposited during the Port Huron Stadial form the remainder of the valley infills (Greenhouse and Karrow, 1994).

2.7.3 Geometry of Aquifer/ Aquitards

Each of the stratigraphic units identified in the cores from the Georgetown and Milton bedrock valleys either form aquifers (units capable of retaining or transmitting large quantities of water) or aquitards (low permeability units) as their identification is based primarily on textural characteristics. The most productive aquifers are produced by thick and laterally extensive coarse-grained units that lie in topographic lows (Howard et al., 1997). Hence, in the Georgetown and Milton valleys the subsurface geometry and form of potential aquifers can be established from examination of the regional distribution of relatively coarse-grained stratigraphic units such as SU I, SU III, and SU V (Fig. 2.21).

In the southeastern part of the Halton Region, the upper weathered surface of the Queenston Formation forms an effective aquifer and is frequently used for water supply (Holysh, 1997). Coarse-grained facies of SU I found in the lowest reaches of the bedrock valleys (Fig. 2.21) have the potential to act as reasonable aquifers as they form thin, but spatially continuous permeable units lying on the bedrock surface (M2, SU I; Fig. 2.8a). SU I facies found on bedrock highs are less suitable as they contain more fine-grained matrix material, and have a limited areal extent.

SU II is predominantly fine-grained and consists of clays with thin interbeds of sand, sand-rich diamict and gravel. It may serve as a significant aquitard in the deeper parts of the bedrock valleys but has limited areal extent and is unlikely to affect groundwater movement on a regional scale.

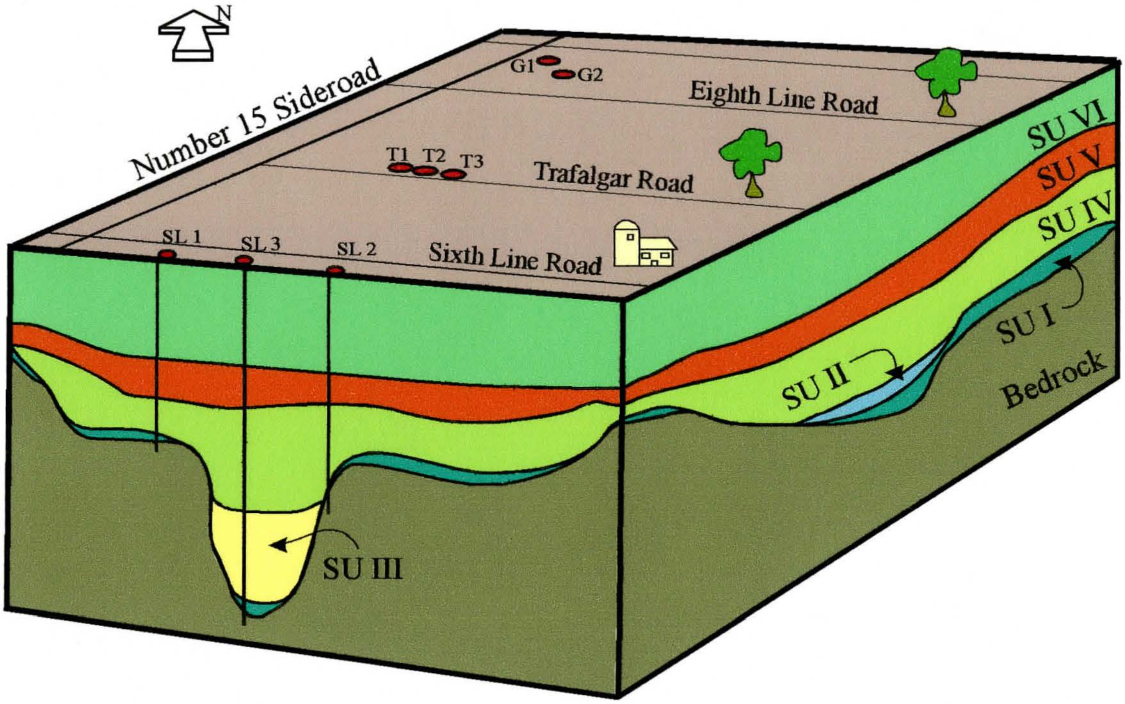

Figure 2.21- Schematic block diagram showing geometry of stratigraphic units (SU I to SU VI) infilling the Georgetown and Milton buried bedrock valleys. SU I, SU III, and SU V are predominately coarse-grained units that may host productive aquifers. See figure 2.1 for borehole locations. (Not to scale).

Due to the restricted areal extent of SU II, sands of SU III commonly overlie gravels and clast-rich diamicts of SU I (Fig. 2.21). This forms a thick and extensive horizon of permeable materials overlying bedrock and it is likely that SU I and III together host productive aquifers, especially at the base of deep bedrock valleys, where SU III is thickest (e.g. SL3; Fig.2.11).

The Northern Till, SU IV, is found in 10 of the 11 boreholes studied. It is laterally continuous across the study area, and infills pre-existing topography to form a relatively thick cover over bedrock valleys, and a thinner veneer across valley margins (Fig. 2.21). SU IV does not occur in borehole G1 (Fig. 2.9), but its absence may be due to fluvial erosion following deposition of the diamict (Fig. 2.21). Although SU IV shows some textural variability and is sand-rich in places, it may be considered as an effective regional aquitard. Howard et al., (1997) describe the Northern Till as an impermeable till that should be considered as a regional aquitard. However, sheet-like sand and gravel interbeds contained within the till create a higher than expected hydraulic conductivity for this unit (Gerber and Howard, 1996; Howard et al., 1997; Boyce and Koseoglu, 1997; Eyles and Boyce, 1997).

The laterally continuous, coarse-grained sands and gravels of SU V have the potential to form a significant regional aquifer. Hydraulic conductivities of Mackinaw Interstadial sediments range from $5x10^{-5}$ to $6x10^{-6}$ m/s in the Duffin's Creek area, north of Toronto, values consistent with those of productive regional aquifers (Gerber and Howard, 1999). However, the stratigraphic top of SU V lies close to the ground surface (e.g. FL1; Fig. 2.12) making it highly susceptible to surface water contamination and reducing its suitability as a municipal groundwater resource. North of Toronto, Mackinaw Interstadial sediments and overlying coarse-grained sediments of the Oak Ridges Moraine are protected by a thick layer of Halton Till and do serve as a municipal groundwater source (Howard et al., 1997).

The uppermost stratigraphic unit (SU VI: the Halton Till Complex) is continuous across the study area but has variable thickness and it is too shallow to be considered as a suitable aquifer. Sandy interbeds within the fine-grained diamicts of the Halton Till Complex act as excellent groundwater migration pathways and compromise its function as a regional aquitard (Howard and Beck, 1986; Eyles and Boyce, 1997; Boyce et al., 1995; Gerber and Howard, 1996). Howard and Beck (1986) conducted major and minor-ion geochemical analysis of subsurface waters beneath the Halton Till complex north of Toronto and determined that the till is "relatively permeable" (Howard and Beck, 1986: p.946) and allows for a significant amount of surface water infiltration. The complex interbedding of fine and coarse-grained units within SU VI makes shallow aquifers susceptible to surface contaminants including road salt, pesticides and/or agricultural runoff (Howard and Haynes, 1993).

2.7.4 Implications for Groundwater Flow Modeling

Groundwater flow modeling, or determining the flow pathways for a region, can take place on a variety of scales. Firstly, computer modeling is used to model large scale areas by manipulating field data values such as water table levels, surface water discharge values, and recharge estimates in various areas using a simplified stratigraphic model. These values are then inputted into a computer program, along with unknown values which are then adjusted to achieve the most probable fit. A second method of determining hydraulic conductivities of layered systems assigns hydraulic conductivity values to textural units of boreholes, using their thicknesses the total hydraulic conductivity can be determined. This method is extremely small scale as the hydraulic conductivity value determined is representative of only the area immediately surrounding the borehole.

Modeling the flow of groundwater through the subsurface is useful for predicting the location and productivity of aquifer systems. In the Halton Region, groundwater flow modeling requires a firm understanding of the stratigraphy within buried bedrock valleys as they contain thick assemblages of coarse-grained fluvial sediments (e.g. SU I, III, and V) relative to surrounding areas, and act as significant groundwater conduits. Buried bedrock valleys allow transport of water from recharge areas north and west of the Niagara Escarpment through coarse-grained aquifers in the valley infill sediments to Lake Ontario (Holysh, 1997).

Hydraulic conductivity, also known as the permeability coefficient, refers to the rate of flow of water through a medium under a hydraulic gradient (Dominico and Schwartz, 1998). In order to realistically model groundwater flow within the buried bedrock valley system, estimates of hydraulic conductivity within the aquifers and aquitards need to be established. Comparison of values calculated in this study with those determined by Holysh (1997) will help evaluate the accuracy of groundwater flow modeling in procedures currently used.

Holysh (1997) created a 3-layer groundwater flow model to identify groundwater recharge areas, local water budgets, and assessment of the effects of groundwater pumping on surface waters in the Halton Region. Local studies of surface and groundwater flow conducted by numerous consulting companies (Holysh, 1997 and references therein) provided the basis for parameters inputted into the MODFLOW computer program, designed to model ground and surface water flow. Layer 1 of the model, described as 'overburden soil' corresponds to the Halton Till Complex (SU VI; Holysh, 1997). Layer 2 is described as 'permeable sand and gravel units', that infill the bedrock valleys below the Halton Till (Holysh, 1997) and includes the fine-grained clays of SU II, the sands of SU III, the sand-rich Northern/ Newmarket Till (SU IV), and the Mackinaw Interstadial gravels (SU V) of this study. Layer 3 represents the upper weathered zone of the Queenston Shale bedrock (Holysh, 1997) and corresponds to the gravels and clast-rich diamicts of SU I described herein.

Holysh (1997) estimated a hydraulic conductivity through Layer 1 (the Halton Till Complex) by manipulating hydraulic conductivities within the Halton Till Complex within the MODFLOW program, until the values satisfied the 'real world' surficial water and groundwater flux data. The final MODFLOW hydraulic conductivity estimate for the Halton Till Complex was 5.0×10^{-6}m/s or 0.432m/day (Holysh, 1997).

Detailed borehole logging carried out in this study shows considerable textural variability in sediment type within the Halton Till Complex both spatially and vertically. This implies that it is impractical to estimate a single hydraulic conductivity for the complex without taking into consideration this extreme textural variability. Hence, an average hydraulic conductivity value for the Halton Till Complex is estimated here by estimating representative hydraulic conductivities for each of the different sediment layers (i.e. textural subunits) identified within the complex by borehole logging. This assumes that each textural subunit is homogeneous and isotropic.

The approach used here calculates average vertical hydraulic conductivity, K_z, for the Halton Till Complex (SU VI) using total thicknesses of each textural subunit (e.g. sand, clay, silt, mud-rich diamict) within each borehole (m_i) and their respective hydraulic conductivities (K_i; Table 2.3)

$K_z = \Sigma m_i / \Sigma (m_i / K_i)$ (Equation 2.1; Dominico and Schwartz, 1998)

No direct or indirect measurements of hydraulic conductivity (e.g. pump tests, slug tests, etc) were available for any of the studied boreholes, so a range of values of K_i were obtained from texts (Table 2.3) to solve for K_z (Equation 2.1).

Table 2.3: Estimates of hydraulic conductivity for units contained within the Halton Till Complex (from Dominico and Schwartz, 1998).

Material	Hydraulic Conductivity Range (m/s)
Sand	$9 \times 10^{-7} - 6 \times 10^{-3}$
Silt	$1 \times 10^{-9} - 2 \times 10^{-5}$
Clay	$1 \times 10^{-11} - 5 \times 10^{-9}$
Mud-rich diamict	$1 \times 10^{-12} - 2 \times 10^{-6}$

Table 2.3 shows the large variability in estimated hydraulic conductivities for different sediment types; hence, both high- and low-end values of hydraulic conductivity for each textural subunit were used to compute average hydraulic conductivity of the Halton Till Complex (Table 2.4).

Table 2.4 outlines the range of potential vertical hydraulic conductivity values calculated for SU VI in each borehole. The wide range of values calculated between boreholes was anticipated as the textural characteristics of subunits within the Halton Till Complex vary greatly over short spatial distances.

Table 2.4: Calculated average hydraulic conductivity (low-end and high-end ranges) for SU VI (the Halton Till Complex) in individual boreholes.

Borehole	**Avg. Kz (m/s) High-end range**	**Avg. Kz (m/s) Low-end range**
Georgetown 1 (G1)	2.019×10^{-08}	3.174×10^{-11}
Georgetown 2 (G2)	1.607×10^{-08}	2.012×10^{-11}
Milton 1 (M1)	1.133×10^{-08}	1.358×10^{-11}
Trafalgar 1 (T1)	1.773×10^{-08}	2.358×10^{-11}
Trafalgar 3 (T3)	9.820×10^{-09}	1.290×10^{-11}
Fifth Line 1 (FL1)	3.211×10^{-08}	6.418×10^{-11}
Sixth Line 1 (SL1)	1.089×10^{-08}	1.298×10^{-11}
Sixth Line 2 (SL2)	1.964×10^{-08}	1.961×10^{-11}
Sixth Line 3 (SL3)	1.724×10^{-08}	1.898×10^{-11}
Total Average Kz:	1.720×10^{-08}	2.420×10^{-11}

The high-end values of hydraulic conductivities for the Halton Till Complex for individual boreholes range from 9.82×10^{-09} to 3.21×10^{-08} m/s and low-end values range from 1.29×10^{-11} to 6.42×10^{-11} m/s, values much lower than the 'real world' MODFLOW K_z value calculated by Holysh (1997; 5×10^{-6} m/s). The high-end total average K_z value for SU VI, calculated as an average of the results from all boreholes, 1.72×10^{-8} m/s is very different to the final K_z value of 5.0×10^{-6} m/s, determined by Holysh (1997) using

MODFLOW, which more closely represent 'real world' conditions. Gerber and Howard, (1999) identified hydraulic conductivity values of $3x10^{-6}$ m/s to $4x10^{-7}$ m/s in the Halton Till Complex of the Duffin's Creek area, north of Toronto, values very similar to those used in Holysh's (1997) MODFLOW model. The extreme discrepancy between hydraulic conductivity calculated using textural characteristics of units in this study and the 'real world' values determined by Holysh (1997), may be explained by vertical fractures within the mud-rich diamict, which would dramatically increase the vertical hydraulic conductivity of the Halton Till Complex.

Although estimations of average K values for a complexly layered system, such as the Halton Till Complex, can be made by summing K values of individual textural subunits, this method does not greatly improve on estimates made by other researchers using pump test data (Holysh, 1997; Gerber and Howard, 1999). All methods used to estimate average hydraulic conductivities of such a complex system produce values many times lower than those that exist in the real world. This suggests that current understanding of the hydrogeological behaviour of the Halton Till Complex is inadequate.

2.8 Conclusions

Identification of the bedrock/ sediment contact in the eleven cored boreholes examined in this study provides new data regarding the form of bedrock valleys in southern Ontario; these valleys appear to be characterized by a narrow, steeply incised channel, possibly formed by fluvial processes, lying within a broader, glacially-scoured valley form. The position and orientation of these bedrock valleys may have been influenced by pre-existing bedrock jointing patterns.

The Georgetown and Milton bedrock valleys are infilled with a thick succession of interbedded glacial, fluvial and lacustrine sediments that record repeated ice advance and retreat of the Laurentide Ice Sheet over southern Ontario during the Late Quaternary. Six distinct stratigraphic units (SU I to SU VI) are identified within the valley infill deposits, and provide a valuable record of past depositional events. SU I is coarse-grained and records fluvial and subaerial debris flow deposition on the bedrock surface in the deepest parts of the valleys; overlying fine-grained deposits of SU II formed during subsequent lacustrine flooding of the valley floors. Sand-rich sediments of SU III are interpreted as fluvial deposits formed as sandy braided rivers, fed by advancing glaciers to the north, infilled the valley topography. Subsequent glacial overriding by Nissouri stadial ice deposited the subglacial till that forms SU IV and is equivalent to the Northern/ Newmarket Tills seen in outcrop. Ice retreat from the area during the Mackinaw Interstadial allowed deposition of coarse sands and gravels of SU V; readvance of Ontario lobe ice during the Port Huron stadial deposited a variety of glacial, fluvial and lacustrine sediments that comprise the uppermost SU VI and are equivalent to the Halton Till Complex.

Each of the stratigraphic units identified within the Georgetown and Milton valley infills can be considered to represent potential aquifer or aquitard units as their identification is based on textural characteristics. SU I and SU III overlie impermeable shale bedrock and form relatively thick and extensive units in the deepest parts of the bedrock valleys; this lowermost coarse-grained unit is likely to form the most productive aquifer within the buried bedrock valley.

Detailed logging of sediments infilling buried bedrock valleys may help in groundwater flow modeling by providing a more realistic view of the subsurface stratigraphy and its extreme textural variability. Current estimates of hydraulic conductivities for the uppermost Halton Till Complex grossly underestimate real world conditions and illustrate the need for better hydrogeological understanding of these complex valley infills.

CHAPTER 3: SHALLOW SEISMIC REFLECTION SURVEYING

3.1 INTRODUCTION

The Regional Municipality of Halton began searching for sustainable groundwater aquifers to supply drinking water to the growing communities of Georgetown and Milton in the fall of 2000. Their investigations focussed on locating aquifers in buried bedrock valleys and involved geophysical surveying to determine the position and orientation of bedrock valleys and later drilling of 11 continuously-cored boreholes within the valleys. Sedimentological analysis of the borehole cores provides data on the position of the bedrock/sediment interface and excellent vertical resolution of the stratigraphy within the buried bedrock valleys (see Chapter 2). However, in order to assess the detailed form of the bedrock surface and characteristics of potential aquifers, the lateral continuity and variability of individual stratigraphic units within the valley infills must be determined. Lateral correlation of stratigraphic units between individual boreholes provides some data regarding unit geometries but geophysical methods, involving laterally continuous imaging of stratigraphic boundaries can provide the most detailed information. Shallow seismic reflection surveys are particularly useful in this regard as they identify boundaries between lithologic units with different acoustic impedance properties and can locate the bedrock/ sediment interface and contacts between subsurface stratigraphic units (Pritchett, 1990; Boyce and Koseoglu, 1997).

The aim of the shallow seismic reflection surveys conducted in this study was to delineate the shape and internal topography of the buried bedrock valley, and resolve the internal geometry of stratigraphic units within the sediment infill of the valley in as much detail as possible. Borehole data show extreme variability within the stratigraphy of the valley infill even over short distances (Fig. 2.8). Mapping these small-scale changes in sediment characteristics requires high spatial resolution readily attainable with shallow seismic reflection surveying (Buker et al., 1998b). Determination of the subsurface geometry and distribution of glacial sediments using shallow seismic reflection surveys has proven successful in several areas of southern Ontario (Barlow and Lockhard, 1989; Greenhouse and Karrow, 1994; Boyce et al., 1995; Mohajer et al., 1995; Schneider et al., 1997), and elsewhere (Widerhold et al., 1998; Buker et al., 1998a).

3.2 STUDY AREA

Four seismic reflection survey transects were conducted in an agricultural setting, a few kilometers south of the town of Georgetown (Fig. 3.1). Pre-existing surveys run by GAPS (Geophysical Applications and Processing Services; Guelph, ON) in the Halton Region were run outside the town of Milton and also in areas north of Georgetown. The seismic survey transects of this study were conducted along paved and unpaved rural roads roughly perpendicular to the strike of the Georgetown buried bedrock valley (Fig. 1.7). A seismic reflection survey conducted by International Water Supply (IWS) in

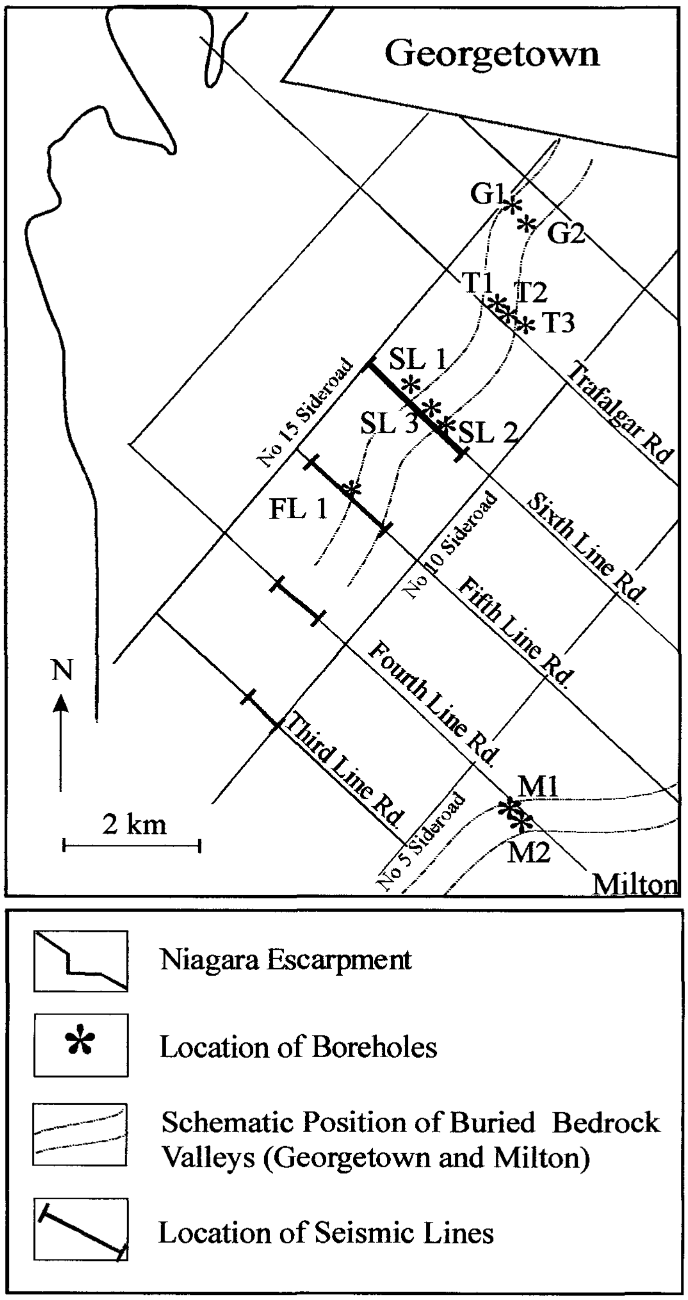

Figure 3.1- Location map of study area showing position of seismic transects run in this study. Refer to figure 2.1 for regional location.

1989 delineated the broad form and position of the Georgetown valley (Fig. 2.12). This study resurveyed the IWS transects (on Sixth Line and Fifth Line Roads; Fig. 3.2, 3.3), and extended these transects lengthwise to verify that the IWS results had correctly located the buried bedrock valley. Transects were also run on the Sixth and Fifth Line Roads as boreholes drilled (FL1, SL1-3; Fig. 2.11, 2.12) at these locations provide ground-truthing and specific depth to bedrock information. Two additional seismic reflection survey transects were run south of the IWS transects along the Fourth and Third Line Roads to determine the southern extent of the buried bedrock valley (Fig. 3.4, 3.5). All four transects lie roughly perpendicular to the strike of the Georgetown bedrock valley outlined on the OMOEE database (Fig.1.8). All transects were run along paved roads with gravel shoulders with the exception of the Third Line Road transect which was run along a hard packed dirt road.

3.3 SEISMIC REFLECTION SURVEYING TECHNIQUES

The oil and gas industry has relied on deep seismic reflection techniques for exploration for decades (Hunter et al., 1987). The rising price of petroleum products since the 1950s led to the rapid advancement of seismic acquisition equipment and computer processing packages. Only in the past 20 years has the technology advanced to provide seismic surveys with the sensitivity to detect high frequency reflections from shallow horizons to help solve complex groundwater and engineering problems (Evans, 1997; Hunter et al., 1987).

Sixth Line Road

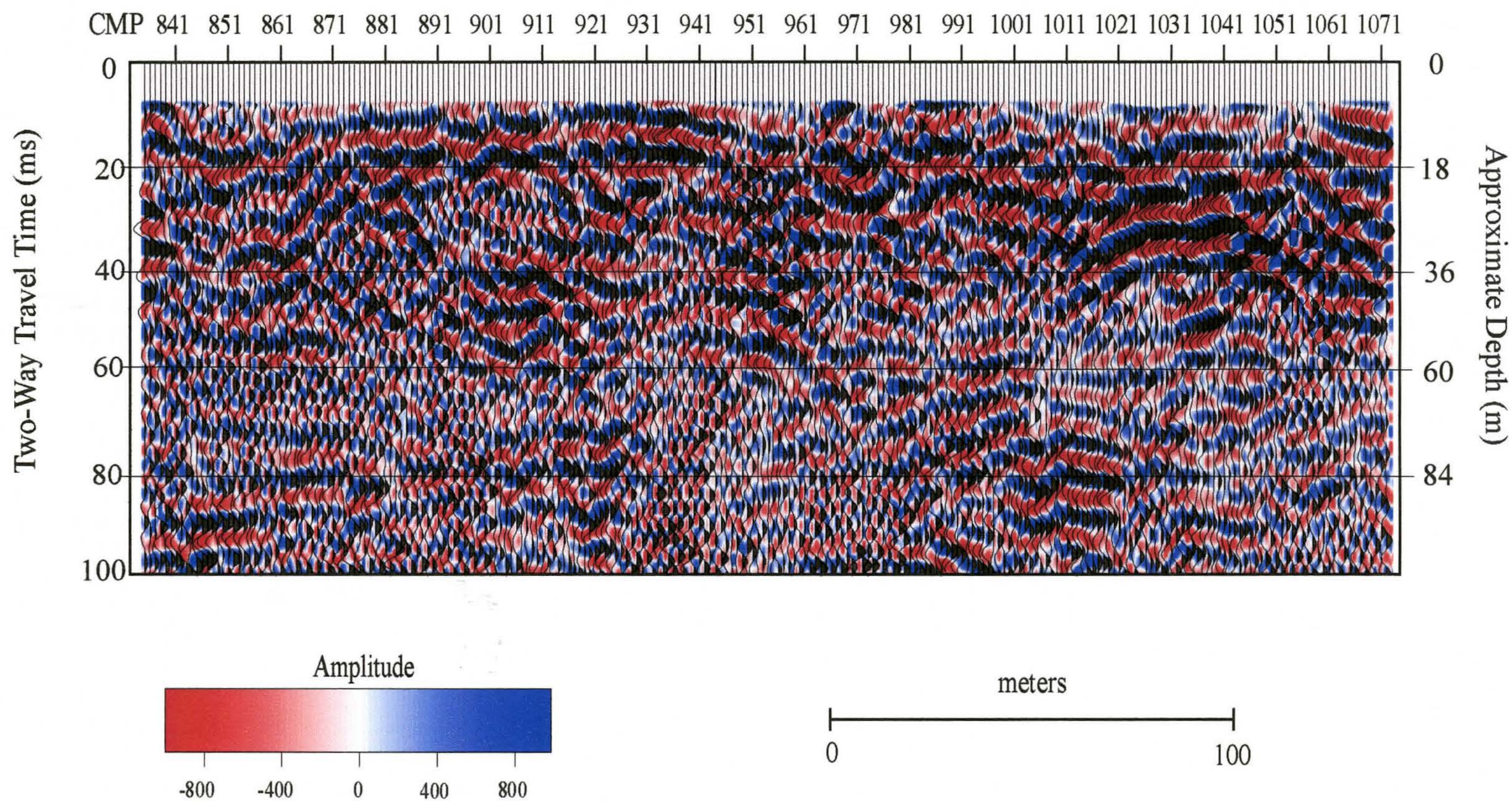

Figure 3.2- 360m long portion of Sixth Line Road shallow seismic reflection survey. Refer to Figure 3.1 for location.

Fifth Line Road

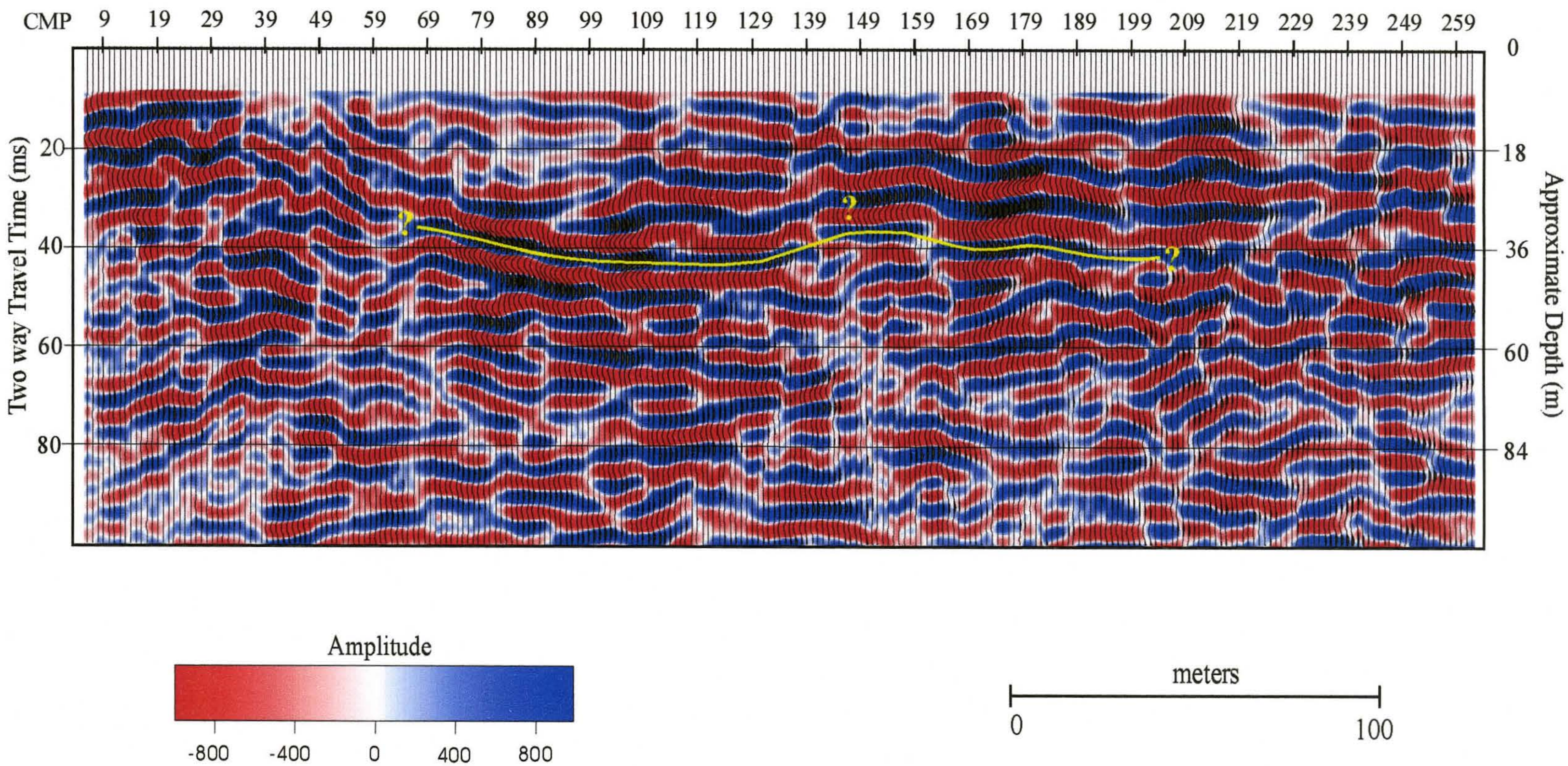

Figure 3.3- 380m long portion of Fifth Line Road shallow seismic reflection survey. Refer to Figure 3.1 for location. Interpreted bedrock reflector highlighted with a yellow line.

Fourth Line Road

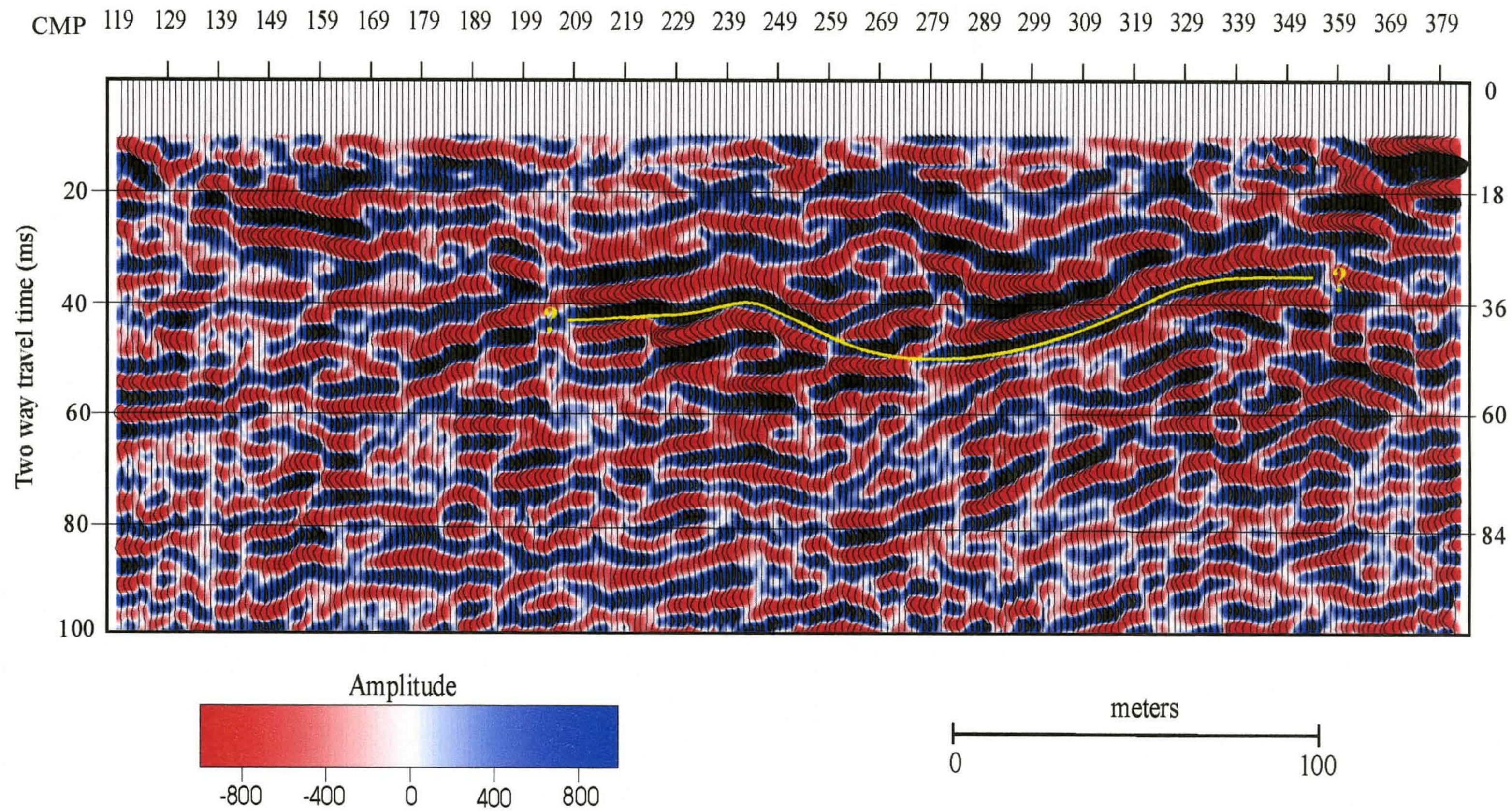

Figure 3.4- 400m long portion of Fourth Line Road shallow seismic reflection survey. Refer to Figure 3.1 for location. Interpreted bedrock reflector highlighted with a yellow line.

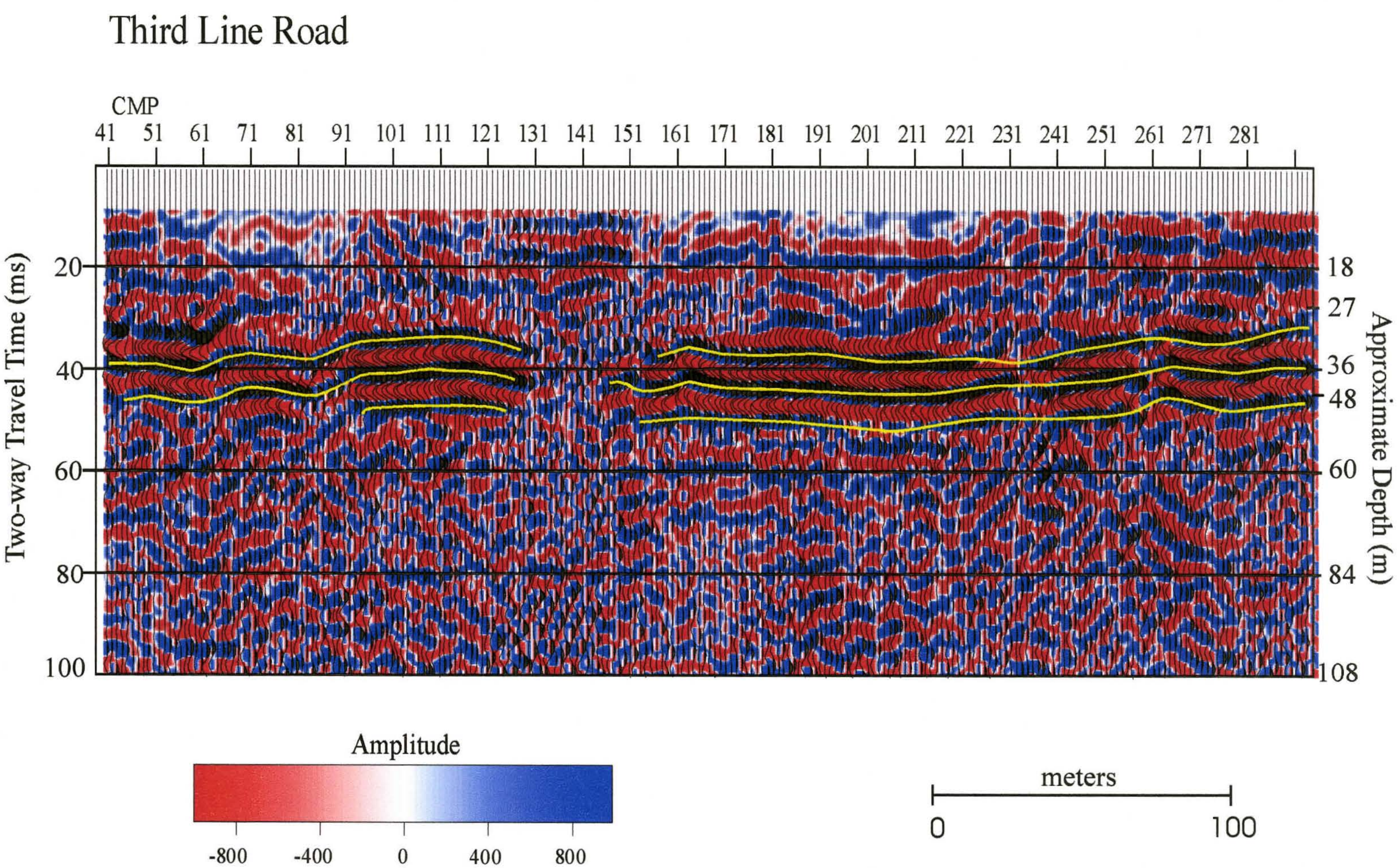

Figure 3.5-380m long portion of Third Line Road shallow seismic reflection survey. Refer to Figure 3.1 for location. Interpreted bedrock reflector highlighted by the uppermost yellow line. Two yellow lines below are interpreted to represent weathered surfaces within the Queenston shale bedrock.

Data acquisition using seismic reflection methodology begins with an artificial energy source (e.g. sledgehammer, explosives) which induces an elastic wave (compressional or 'p-wave') similar to a sound wave, into the subsurface. Reflections occur as the p-waves pass through geologic boundaries of differing densities and/or seismic velocities (Fig. 3.6). The intensity of the reflection is a function of the bulk density and velocity of sound through the medium, referred to as the 'acoustic impedance' (Pritchett, 1990). Reflection events are recorded on the surface by a linear array of motion-sensitive transducers (geophones), which convert ground motion to an electrical signal whose amplitude is proportional to the vertical velocity of the ground motion (Sharma, 1997). Signals recorded by each geophone (receiver) are amplified, converted to digital form and recorded on a seismograph. The ground motion recorded by each geophone is displayed as an individual trace on a seismic field record, which is a plot of time versus signal amplitude. These data are then manipulated and processed to produce a seismic reflection section which resembles a geological cross-section (Boyce and Koseoglu, 1997).

3.4 METHODOLOGY

Seismic reflection surveying was chosen as the most suitable geophysical method for the acquisition of data pertaining to the nature and form of the Georgetown buried bedrock valley and its infill stratigraphy. A high-resolution shallow seismic reflection survey was used in this study as depth to bedrock, even in the deepest parts of the valleys, is shallow (ie. <100m). By definition, high-resolution surveys have a depth of penetration ranging from tens to hundreds of meters, and focus on reflection events with dominant frequencies above 100Hz. In contrast, conventional seismic reflection techniques use frequencies ranging from 10 to 90Hz with depths of penetration in the thousands of meters (Hunter et al, 1987). Surveys completed in this study aim to resolve small-scale variations in stratigraphy and lithofacies within the buried bedrock valley infill, as well as the nature of the bedrock surface hosting the Quaternary sediments.

The Common Depth Point (CDP) technique is one of the most commonly used techniques in shallow reflection profiling and was employed in this study (Boyce and Koseoglu, 1994; Sharma, 1997). The CDP method involves continuous profiling where subsurface reflection points are repeatedly sampled over a range of source-receiver separations (Boyce and Koseoglu, 1994). Repeatedly sampling the same subsurface points permits attenuation of random noise, and therefore increases the signal to noise ratio (Evans, 1997). The CDP technique involves "roll along" shooting where the shot point and geophones advance along the survey transect at increments equal to the geophone spacing or some multiple of this distance (Boyce and Koseoglu, 1994; Fig. 3.6, 3.7). In this study, 48 geophones in the spread were connected to a 24-channel seismograph, and roll-along box. The first shot is recorded by geophones 1 to 24, the second shot by geophones 2-25, the third shot by geophones 3-26, continuing down the spread. The resulting overlap between spreads leads to a redundancy of data collected for each reflection mid-point in the subsurface (Fig. 3.6; Boyce and Koseoglu, 1994). This redundancy is referred to as 'fold' and in this study data collected were 12-fold as there were 24 active channels and shots were performed at every geophone location.

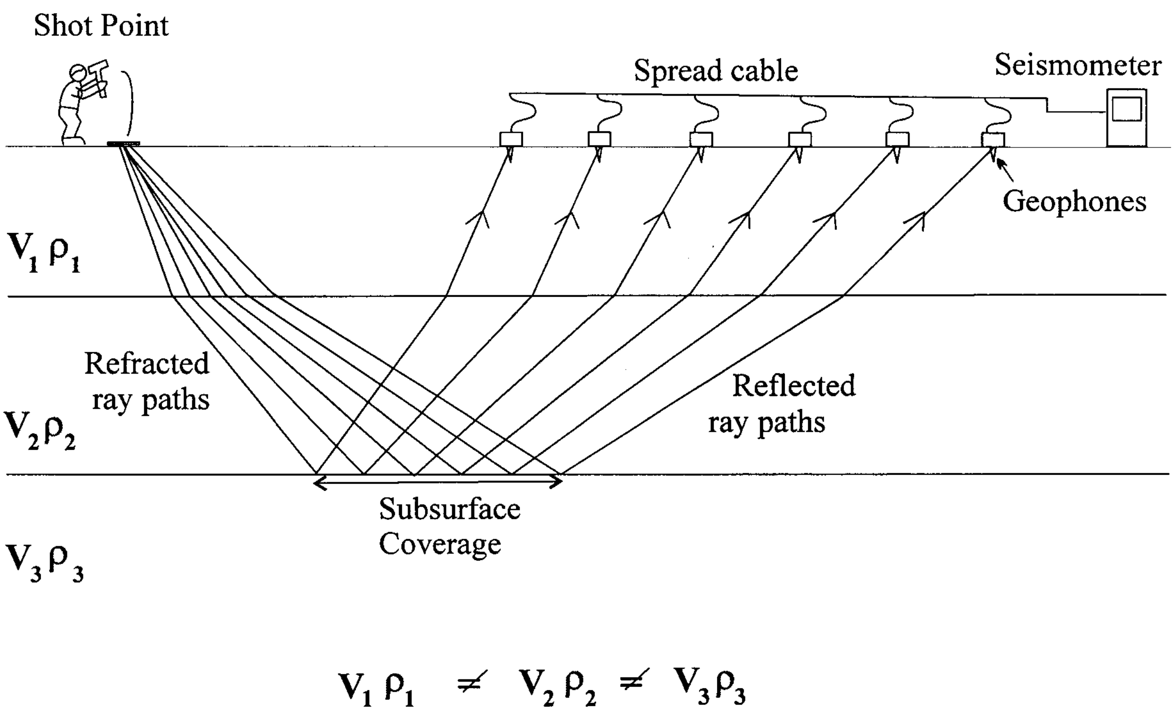

Figure 3.6; Schematic diagram illustrating the principles of seismic reflection profiling using an 'end on' layout of CDP survey technique. The product of velocity and density (acoustic impedance) of each underlying layer are different to those above. Arrival times and amplitudes of reflected waves are detected by geophones on the ground surface, and recorded by a seismograph. The shot point is positioned at a set distance from the closest receiver, and both shot and active receiver are moved along the spread incrementally (modified from Boyce and Koseoglu, 1997).

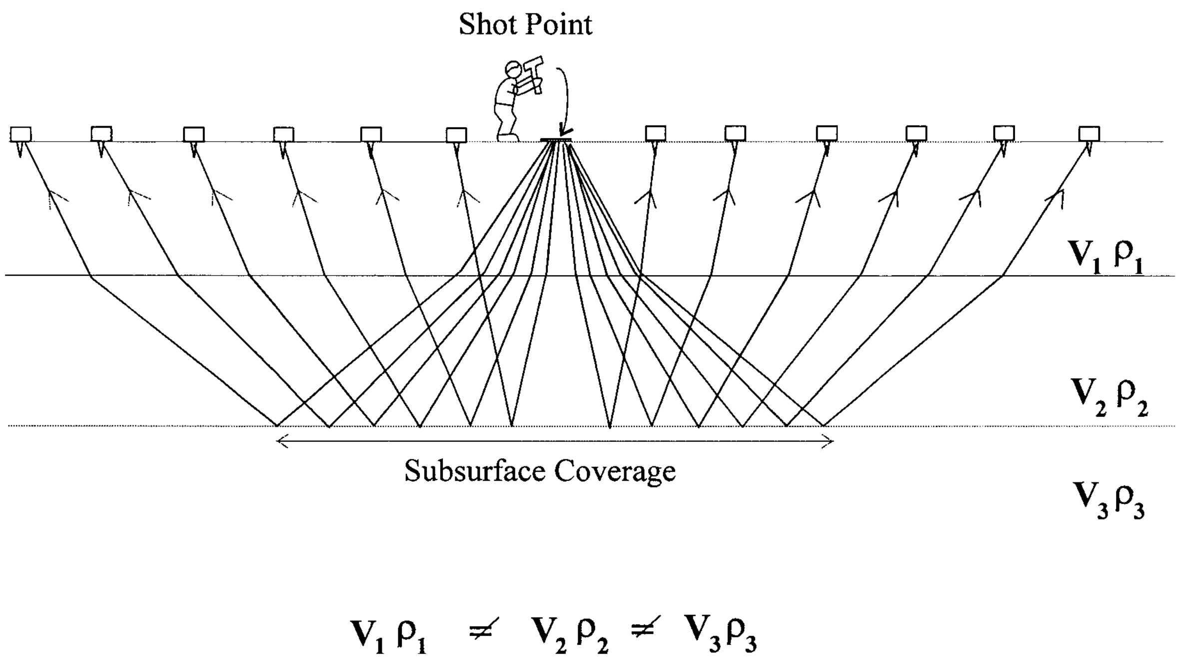

Figure 3.7- Schematic diagram to illustrate Common Depth Point reflection surveying using a split-spread layout. The shot point is positioned in the center of the spread as opposed to the end of the spread as in the 'end on' layout (Fig. 3.6; modified from Boyce and Koseoglu, 1997).

In general, increasing the number of stacked traces improves the signal-to-noise ratio because signal, defined as desirable data, (ie. seismic reflection) is additive while random noise, undesirable data, is not (Knapp and Steeples, 1986a; Evans, 1997). The fold of a CDP stack is an important parameter, however, in many situations increasing fold above a certain point may make no noticeable improvement in data quality (Evans, 1997). In the case of high resolution shallow reflection surveys, there is commonly a large amount of random noise making the CDP method particularly effective at increasing the signal-to-noise ratio and producing an accurate subsurface image.

3.4.1 Data Acquisition

A four-man field crew performed the shallow seismic reflection surveys over a four week period, from May 9th to May 30th, 2000. Data for the shallow reflection surveys were acquired using and end-on layout (Fig. 3.6) as opposed to a split spread layout (Fig. 3.7). The end-on layout was chosen as it provides a wider range of source-receiver offsets, and allows more traces to record with minimal interference from ground roll energy as compared to the split-spread design (Boyce and Koseoglu, 1997).

Initial field tests showed that a 5lb sledgehammer striking an aluminum plate was an adequate energy source to produce a seismic signal that could penetrate the subsurface to a depth of 100-150m and still yield acceptable data. Data from nearby boreholes suggested depth to bedrock was roughly 75m and a conservative 'target depth for the bedrock surface was set at 100-150m below surface. The sledgehammer struck the aluminum plate five to eight times, with each hammer blow stacked on top of one another to produce one shot record. Increasing the number of hammer blows increases the signal-to-noise ratio as signal is additive whereas random noise is not (Evans, 1997). The sledgehammer was chosen as the energy source as it is an inexpensive, easily repeatable, rapid and non-destructive method of data acquisition. Vertical resolution of beds was also critical to the survey design, and it was believed that a 5lb sledgehammer would produce frequencies necessary to adequately resolve the subsurface layers of the valley infill stratigraphy.

Three-meter spacing was used for both the source and receivers, giving a common mid-point (CMP) spacing of 1.5m. The survey was shot with a constant maximum source to receiver offset of 18m maintained throughout the surveys to resolve the bedrock contact and sedimentary infill stratigraphy, estimated to lie within 150m of the surface. These survey parameters were determined prior to data acquisition using "walk away noise tests" in which several offsets were tested and the optimum shot record results were used to set the standard for the survey.

Consistent recording parameters were maintained during all data acquisition. Data were acquired using single 100 Hz OYO Geospace geophones wired in series and attached via water-resistant connectors and cables to a roll-along box and a 24-channel StrataView seismograph. Geophones were planted in the hard packed road shoulder gravel by twisting and applying downward pressure so as not to loosen hard packed gravel. Loose gravel and debris were removed prior to planting the geophones to improve the geophone-ground coupling. When a paved driveway, bridge, or railroad tracks were encountered, geophones were left out and dead traces later deleted during processing. A 250ms sample interval, and a record length of 256ms were employed throughout the surveys as they were found to be optimum for the survey being conducted with a maximum depth to bedrock of 150m. A 100 Hz low cut filter was also applied throughout the surveys to minimize the effects of distant traffic and ground roll.

3.4.2 Data Processing

Processing of seismic data involves transforming digital information obtained in the field into a visual cross-sectional format. Data processing improves the usefulness and quality of the data through a series of processes, some simplistic and others more specialized and sophisticated (Coffeen, 1978). Corrections are made for surface topographic variations, and the upper weathered layer of the subsurface. Filtering is applied to retain only the best frequencies in the data set, and reflections are more sharply defined using deconvolution (Coffeen, 1978). Following these steps, records are stacked together for interpretation.

Since seismic data may be recorded and processed by different companies, a standard field format SEG was developed by the Society of Exploration Geophysicists (Evans, 1997). The seismograph in this study recorded data in a SEG 2 digital format, which was not compatible with the SEGY processing package used at GAPS. Therefore, data processing began with conversion from SEG2 to SEGY format. Following the conversion, survey information and field notes regarding instrument settings such as shot and cable locations, roll-along box settings, and spread characteristics were combined to produce a geometry database for each transect. This allowed the field data to be run through an interactive program designed to analyze the geometries and edit spoiled traces.

A deconvolution operator was subsequently applied to aid in the interpretation of distinct reflection events by preventing reflections from interfering with one another. Deconvolution is a mathematical process which involves compressing the amplitude of a stretched wavelet into a shorter wavelet (Coffeen, 1978). The trace is processed with an operator, another trace, that combined with the first reduces repetition in the trace (Coffeen, 1978).

Static corrections were applied to the data set to correct for surface elevation and the upper weathered layer. Static corrections smooth reflections to the extent that hills and valleys are no longer discernible on the reflections (Coffeen, 1978). Static corrections involve shifting traces up and down to compensate for the increase or decrease in travel time due to elevation differences of individual geophones. Attempting to perform extensive static corrections was futile for this study as the elevation values used to perform static corrections were scarce and unreliable. Therefore, lining up reflection events became a "best guess" method, and was soon disregarded as a step in data processing. Elimination of this critical step may have aided in the poor quality of the final sections.

Data were gathered into common depth point (CDP) bins by assigning each trace to a gather corresponding to the midpoint between shot and receiver locations. This step transfers the data to a format that allow random noise elimination by drawing velocity and semblance plots to determine the degree of coherence (ie. similarity) of the gathered traces. This can be achieved by stacking the gathered traces. In digital processing, the amplitudes of the traces are expressed as numbers; thus, stacking traces simply involves adding the values together (Coffeen, 1978). Two peaks on two traces will combine to produce a larger amplitude peak and these traces are said to be similar or coherent (Coffeen, 1978; Telford et al, 1990). However if a peak and a trough are added, they will cancel one another out or produce a small amplitude peak and are said to be dissimilar or incoherent (Telford et al, 1990). Therefore, the ratio of energy of the stack compared to the sum of the energies of the individual traces would be a measure of the degree of coherence (Telford et al, 1990). Semblance plots can then be used to determine other processing parameters, such as normal moveout (NMO) corrections, by calculating semblance for various combinations of time shifts between channels. NMO corrections account for the delay in arrival time of a reflection with increasing offset distance between the source and the receiver due to the increase in path length of the wavelength (Pritchett, 1990).

Following NMO corrections, filters were applied to reduce noise. Seismic sources induce sound of many frequencies including those we can hear (the hammer hitting the plate) and those that travel through the earth. The latter travels only within a narrow range of frequencies from approximately 10-100Hz (Coffeen, 1978). Therefore, all other frequencies that do not carry seismic information (ie. blades of grass hitting a geophone, etc) can be disregarded by eliminating all frequencies that do not penetrate into the earth (Coffeen, 1978). This is the process of filtering or band pass filtering, as it allows a narrow band of frequencies to pass, but rejects others.

The next step in the processing series involved muting first arrival waves. When looking at shallow beds, refraction data tend to obscure reflection data at distances far away from the source. Therefore, traces recorded by geophones located far from the source are muted, or cut-off down to a depth (or time) where the reflections are free of refractions (Coffeen, 1978). Unfortunately, reflection events (signal) existing in these upper areas was often lost when muting traces at great distances.

The data were then stacked and a few other band pass filters and deconvolution operators were applied to give the cleanest cross-section possible. The final section was then displayed, plotted and saved to disk for post-processing cosmetic clean-up.

3.4.3 Survey Resolution

The earth acts as a low pass filter allowing low frequencies to readily pass through the earth, while attenuating high frequencies (Sharma, 1997). Attenuation of amplitude and is due to geometrical spreading of the induced wave with time, as well as frictional dissipation of elastic energy into heat as the wave passes through the subsurface (Sharma, 1997). The source frequency determines the vertical resolution, as well as the depth of penetration according to the equation; $\lambda = v / f$, where λ is wavelength, v is velocity and f is frequency. High frequencies, such as guns or explosives attenuate more rapidly than lower frequency waves as a function of time (Sharma, 1997), therefore they give little information at depth, but resolve near surface beds very well. Sledgehammers induce lower frequencies and therefore propagate into the ground to greater depths, at the cost of near surface resolution. The vertical resolution of this study can be estimated using the velocities obtained during data processing. For example, a velocity of 1816 m/s was estimated for a section of overburden lying above bedrock. Using the equation, $\lambda = v / f$ with a frequency of roughly 100Hz emitted from the sledgehammer (estimated from power spectra derived at GAPS), the wavelength would be roughly 18m. Assuming beds can be resolved at one-quarter of the wavelength, we can estimate a vertical resolution of 4.5m. This means that a bed greater than 4.5m can be resolved with the parameters used in this study.

3.5 RESULTS

Despite processing and post-processing clean up of the data, the four shallow seismic reflection transects run south of the Georgetown area remained very noisy. It was difficult to pinpoint the position of the bedrock valley and its incised channel throughout the sections, however some information exists on depth to bedrock outside the valley, where the Quaternary sediments appear to be layered fairly uniformly. The final plots are not shown in their entirety, as they are extremely large; only portions of the best data sets are included in this chapter.

Figure 3.2 illustrates the profile taken from a 360m portion of the 2km long reflection survey run along the Sixth Line Road (Fig. 3.1). This profile is extremely noisy, and contains no major or minor reflection events. There are a few low amplitude reflection events in the upper 40ms, but they are discontinuous across the profile due to noise, and static problems. Overall, the Sixth Line Road profile did not provide much information on the subsurface sediment layers or the bedrock topography. This was expected as this survey was run in the wettest and windiest time of the month and it was clear during data acquisition that the data being collected would not be high quality.

The Fifth Line Road reflection survey transect (Fig. 3.1) totaled 1.5km in length, and Figure 3.3 shows a 380m long portion that represents the most coherent data collected. The vast majority of the profile shows very noisy, low amplitude, discontinuous reflection events that give little coherent information on the bedrock topography, or the location of the buried bedrock valley. One planar tabular, low amplitude and fairly continuous reflector interpreted as flat-lying bedrock, lies at roughly 42ms between CMPs 69 and 209 (Fig. 3.3). Nearby boreholes (located at CMP 6 and 210) support interpretation of this reflector as the bedrock surface as they record depth to bedrock at 42 and 47m below ground surface, corresponding to a two-way travel time of 47-50ms (Fig. 3.3). This flat-lying reflector is interpreted to represent as glacially scoured bedrock within the broader bedrock valley outside the narrow fluvially-incised channel. Above the bedrock reflector, reflection events are very low amplitude and discontinuous, most likely due to static problems left unresolved during data processing. Therefore, the geometry of the valley infill deposits underlying the Fifth Line Road remains poorly understood.

Figure 3.4 shows a 400m long portion of the total 1.2km seismic transect run over the Fourth Line Road. This segment also contains discontinuous, low amplitude reflectors that offer little information on the valley infill stratigraphy or bedrock topography, with the exception of one area; a fairly continuous, and gently undulating reflector lying between CMPs 239 and 339 at roughly 35 to 50ms (Fig.3.4). This is interpreted to represent an undulating portion of the bedrock surface within the broad glacially-scoured part of the buried bedrock valley; however, there is no borehole information available from this road to validate this interpretation.

The last survey transect was run along the Third Line Road, which is a hard-packed dirt road and contrasts with the gravel-based paved road of the other 3 survey transects. The final cross-section presented (Fig. 3.5) contains three parallel, planar-tabular, high-amplitude, continuous reflection events occurring at roughly 30-40ms. The uppermost reflector is interpreted to represent the bedrock surface with the underlying reflection events corresponding to density changes in the underlying weathered Queenston shale bedrock. The breaks in lateral continuity (e.g. between CMP 131-151; Fig. 3.5) are interpreted as changes in ground surface topography that were not accounted for in the static corrections, or may be caused by an increase in the amount of coarse-grained sediment at the surface that dissipated the induced energy. There are a few undulating reflection events in the Quaternary sediments overlying bedrock (e.g. 10-30ms; Fig. 3.5), however they are very low amplitude, and discontinuous. Below 50ms there are no coherent reflection events at all.

3.6 FACTORS AFFECTING RESOLUTION

Successful production of a shallow seismic reflection profile depends on the detection of high frequency energy reflected from a target horizon such as a specific overburden layer or the overburden-bedrock interface (Hunter et al., 1984). Several factors may lead to poor or 'noisy' results including coarse-grained surficial sediments, unfavorable weather conditions, and/or faulty instrumentation.

3.6.1 Weather Conditions

Geophones are motion-sensitive transducers that convert ground motion to an electrical signal whose amplitude is proportional to the velocity of the motion. Hammering a metal plate induces a wave into the ground resulting in minimal ground movement; detection of this movement by geophones illustrates their highly sensitive nature. Raindrops hitting geophones produce large spikes on individual geophone traces. Therefore, seismic surveying even in the lightest rain was avoided whenever possible. Unfortunately, the seismic surveys reported here were conducted during the month of May 2000 when the weather was predominantly wet and windy. This contributed a considerable amount of noise to the data set.

Surveying over damp roadbed conditions or humid weather commonly led to noisy traces, which were subsequently deleted on processing. Although their impact then was minimal on the data set, their deletion decreased survey fold and therefore resolution. Wind also disrupted the seismic signal as it frequently moved nearby trees and grasses affecting ground movement and adding further noise to the data set.

3.6.2 Background 'Noise'

In addition to the weather, traffic (automobile and train), farm equipment, lawn mowers, cyclists, low flying aircraft, and crew movements also added noise to the data set. Whenever possible, recording was halted until the noise had subsided and the seismometer ceased to record a disturbance, but surveying was occasionally completed with a lawn mower and/or tractor noise in the distance. Waiting for farmers to finish plowing, or irrigating in distant fields was not feasible given the time frame available to conduct the survey.

3.6.3 Energy Source

The use of a 5lb sledgehammer as the energy source affected the resolution of the data set. Energy output of the hammer was limited, and a larger sledgehammer, a 12-gauge Buffalo gun or explosives may have been more appropriate for the production of higher resolution data. Another problem was the ringing of the hammer on the aluminum plate, which produces a ground-coupled airwave, another major source of signal interference on shallow reflection records. Processing removed the interference but in eliminating the interference near surface reflection events were lost.

3.6.4 Roadbed Conditions

Roadbed conditions along the survey transects led to further data quality problems. The best results were obtained from the transect along the Third Line Road which is a hard packed dirt road and contrasts with the other 3 roads which are paved country roads. Local residents note that the Fourth Line Road is underlain by a thick gravel base; it is possible that these coarse-grained unsaturated roadbed sediments dampened the high frequency energy at the surface leading to particularly weak reflections at depth (Fig. 3.4).

3.6.6 Elevation Data

It is usual to survey elevation data at the beginning and the end of each spread, however in this study, elevation data were not recorded in the field, making static analysis virtually impossible. Static analysis involves the removal of time delays associated with individual traces. These slight delays may be due to elevation differences (for both shot and receivers), near surface velocity layer changes and/or source-energy coupling, such as poor coupling, bad trigger mechanisms, or inaccurate offsets. Ontario Base Maps of the area (1:10,000) gave a very rough estimate of the elevations at the beginning and end of each spread, and were used as an alternative to primary elevation data. However this is a very inaccurate method and caused several problems during data processing and as such static corrections were not completed.

3.7 RECOMMENDATIONS FOR FUTURE SURVEYS

The ground coupled airwave records the sound energy of the hammer hitting the plate carried through the air and detected by the geophones. Burying geophones or placing them in drilled holes would reduce this ground-air coupling. Although loose surficial gravel and sand were removed prior to emplacement of the geophones, placing them below the surface would result in better signal reception. Drilling holes would also provide information on the nature of the near surface sediment conditions (ie. coarse- or fine-grained unsaturated sediments). If it was known that the transects were underlain by a thick bed of loosely consolidated gravel, the survey could have been moved further away from the roadbed to a more appropriate location.

Modifying the survey parameters such as geophone spacing and common offset spacing would also produce better quality data. The original target depth of 150m below surface is far too deep for this site. It is known that bedrock lies at roughly 30-50m outside the bedrock valley, and a maximum depth of 75m within the valley, therefore a maximum target depth around 75-80m have been more appropriate. Decreasing the common offset of geophones from 18m to 12m (for example) would also target the near surface reflection events. The only drawback would be the increased time necessary to run the survey.

Acquiring elevation data at the beginning and the end of each spread would facilitate more accurate static corrections and aid in lining up the skewed reflection events. Clearly statics were a problem in this survey, although the area was not overly hilly. Running a refraction survey would also aid in picking velocities for subsurface units and thus further aid in data processing and perhaps yield a more accurate picture of the subsurface.

3.8 CONCLUSIONS

This study aimed to bring together detailed sedimentological data from 11 cored boreholes and subsurface data from four shallow seismic reflection surveys in an attempt to resolve details of bedrock surface topography and identify the geometry of sedimentary units within the Georgetown buried bedrock valley. Shallow seismic reflection surveys were thought to potentially yield the most informative picture of subsurface characteristics. A common depth point (CDP) survey with an end-on layout was chosen to be the most likely method to produce an informative and accurate final product.

Unfortunately, shallow seismic reflection surveying did not identify the buried bedrock valley or the stratigraphy of infilling sediments due to several reasons, including undesirable roadbed conditions and the presence of coarse-grained surficial sediments, lack of elevation data, and static corrections. Wet and windy weather conditions may also have affected the results.

CHAPTER 4: CONCLUSIONS

This study provides the first detailed sedimentological analysis of continuously cored sediment from buried bedrock valleys infills in southern Ontario. A total of 500m of core taken from eleven boreholes drilled in the Georgetown and Milton bedrock valleys, were logged and interpreted in this study. In addition to the sedimentological analysis, micropaleontological work and grain size analysis of the sediments aided in the subdivision of stratigraphic units identified within the valley infill.

New data regarding the bedrock surface topography in the Georgetown and Milton valleys were compiled from borehole information, pre-existing shallow seismic reflection surveys and MOEE waterwell data. These helped identify the dimensions and form of the bedrock valleys, which are up to 1km wide, and 70m deep. The bedrock valleys appear to have two components of topographic relief on the bedrock surface, with a deep and narrow channel incised into a broader, relatively flat-floored valley. The incised channel is interpreted as a fluvially-eroded channel that was later modified by glacial scouring to form the broader valley.

Sediments infilling the bedrock valleys consist of interbedded gravels, sands, fine-grained muds and sand-rich, clast-rich and mud-rich diamicts. These sediments are grouped into six distinct Stratigraphic Units according to their textural characteristics and stratigraphic position; however, not all of the stratigraphic units are present in all boreholes. The deepest, incised parts of the bedrock valleys contain more stratigraphic units than those areas overlying broader parts of the valley.

Stratigraphic Units are interpreted to have been deposited in fluvial, lacustrine and glacial environments. Those at the base of the succession (SU I, II, and III) are thickest in the deepest parts of the incised bedrock valleys and thin over the adjacent bedrock highs. They are interpreted to have formed by a combination of fluvial and slope processes (SU I, III) and by lacustrine flooding of the valley floor (SU II).

Comparison of the nature and geometry of the Stratigraphic Units identified in core with sediments exposed in nearby outcrops suggests that SU I and II record Early to Mid-Wisconsin deposition in the incised bedrock valleys. Overlying fluvial sands of SU III were probably deposited by sandy braided rivers flowing along the length of the valley and may be equivalent to the Mid-Wisconsin Thorncliffe Formation exposed at the Scarborough Bluffs. The sand-rich diamict of SU IV, interpreted to represent the Northern/ Newmarket Till, was deposited during the Nissouri Stadial of the Late Wisconsin. This till infills the remaining topography of the buried bedrock valleys and forms a blanket over the whole area. Glacial erosion and 'broadening' of the bedrock valleys probably during advance of the Nissouri Stadial ice. Overlying coarse-grained deposits of SU V have been mapped in outcrop as the Mackinaw Interstadial gravels, and uppermost deposits of SU VI represents the Halton Till Complex, formed during the Port Huron Stade of the Late Wisconsin.

Stratigraphic Units were identified in core on the basis of textural characteristics and relative stratigraphic position and can therefore be considered to broadly represent subsurface aquifer or aquitard units. Relatively coarse-grained sediments of SU I, SU III, and SU V have the potential to form productive aquifers. The gravels and clast-rich diamicts of SU I that overlie shale bedrock at the base of the bedrock valleys form a productive aquifer unit; however SU I deposits found on the relative bedrock highs and interpreted as weathered bedrock, are too localized and discontinuous to effectively transmit groundwater. Overlying sands of SU III are thickest and most extensive along the deepest parts of the incised bedrock channel and are most likely to form productive aquifers within the valley infill particularly when they directly overlie coarse-grained deposits of SU I. Although SU V, the regionally extensive Mackinaw Interstadial gravels, form a thick, coarse-grained subsurface unit, these gravels lie at shallow depths making them highly susceptible to surface contamination. The overlying stratigraphic unit, SU VI, is equivalent to the Halton Till Complex and because of its fine-grained nature is considered as a surficial aquitard; however hydrogeological studies indicate that fractures and sandy interbeds within the mud-rich diamict greatly increase the hydraulic conductivity of the unit and it cannot be assumed to offer effective protection to underlying aquifers.

The sedimentological work reported here has significance both for improving understanding of Late Quaternary depositional histories in southern Ontario and for developing sedimentological models that can be used to predict aquifer location and geometry in bedrock valley infills. Identifying the characteristics of subsurface aquifers not only helps in the search for future drinking water supplies but also permits delineation of potential contaminant migration pathways in industrialised urban areas such as Toronto and Hamilton. This study also has applications to understanding the nature of Quaternary infills of other buried bedrock valleys in areas such as the north-central USA where an older, but similar record of depositional events is preserved (Gray, 1991; Goldthwait, 1991).

REFERENCE LIST

Barlow, R.B., and Lockhard, M.A., 1989. Overburden sounding research – Groundwater Studies: Ont. Geol. Survey, Current Research.

Barnett, P.J., 1992. Quaternary Geology of Ontario; *in* Geology of Ontario, Ont. Geol. Surv., Special Vol. 4, Pt. 2, 1011-1088.

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F., and Pugin, A., 1998. On the Origin of the Oak Ridges Moraine: **35**, 1152-1167.

Berger, G. and Eyles, N., 1994. Thermoluminescence chronology of Toronto-area Quaternary sediments and implications for the extent of the mid-continent ice sheet(s): Geology, **22**, 31-34.

Bleuer, N.K., 1991. The Lafayette Bedrock Valley System of Indiana: Concept, Form, and fill stratigraphy, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays-Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258.

Bleuer, N.K., Melhorn, W.N., Steen, W.J., and Bruns, T.M., 1991. Aquifer systems of the buried Marion-Mahomet trunk valley (Lafayette Bedrock Valley System) of Indiana, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays-Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258.

Boggs, S., 1987. Principles of Sedimentology and Stratigraphy: Merrill Pub., Columbus.

Boulton, G. and Hindmarsh, C., 1987. Sediment deformation beneath glaciers: Rheology and geological consequences: Journal of Geophysical Research, **92**, 9059-9082.

Boyce, J.I. and Eyles, N., 1991. Drumlins carved by deforming till streams below the Laurentide Ice Sheet: Geology, **19**, 787-790.

Boyce, J.I. and Eyles, N., 2000. Architectural element analysis applied to glacial deposits: Internal geometry of a late Pleistocene till sheet, Ontario, Canada: GSA Bulletin, **112**, 98-118.

Boyce, J.I, Eyles, N. and Pugin, A., 1995. Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto, Ontario: Can. J. Earth Sci, **32**, 1331-1349.

Boyce, J.I and Koseoglu, B.B., 1997. Shallow seismic reflection profiling of waste disposal sites: *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF

Brookfield, M.E., Gwyn, Q.H.J., and Martini, I.P., 1982. Quaternary sequences along the north shore of Lake Ontario, Oshawa-Port Hope. Can. J. of Earth Sci., **19**: 1836-1850.

Buker, F., Green, A.G., and Horstmeyer, H.,1998. Shallow seismic reflection study of a glaciated valley: Geophysics, **63**, 1395-1407.

Chapman, L.J. and Putnam, D.F., 1984. The Physiography of Southern Ontario; Ontario Geological Survey, Special Volume 2, 270p. Accompanied by Map P.2715 (coloured), scale 1:600 000.

Coffeen, J.A., 1978. Seismic Exploration Fundamentals; The use of seismic techniques in finding oil: Petroleum Publishing Co., Tulsa, OK.

__________, 1984. Interpreting Seismic Data: PennWell, Tulsa, OK.

Collinson, J.D., and Thompson, D.B., 1982. Sedimentary Structures: George Allen and Unwin, London.

Costello, W.R., and Walker, R.G., 1972. Pleistocene Sedimentology, Credit River, southern Ontario: A new component of the braided river model: Journal of Sedimentary Petrology, **42**, 389-400.

Dominico, P.A. and Schwartz, F.W., 1998. Physical and Chemical Hydrogeology, Second Ed.: Wiley and Sons Inc, New York.

Dreimanis, A. and Goldthwait, R.P., 1973. Wisconsin Glaciation in the Huron, Erie and Ontario Lobes: Geological Society of America, Memoir 136.

Edgecombe, R.B., 1999. Bedrock Topography and Sediment Infill of the Dundas Valley, Hamilton, Ontario. (M.Sc. thesis): Hamilton, Ont., 103 p.

Evans, B.A., 1997. A Handbook for Seismic Data Acquisition in Exploration. Society of Exploration Geophysicists, Tulsa, OK.

Evans, J.M., 2000. Sustainable Growth in America's Heartland; 3-D Geologic Maps as the Foundation. Central Great Lakes Mapping Coalition; USGS Circular 1190.

Eyles, C.H. and Eyles, N., 1983. Sedimentation in a large lake: A reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada: Geology, **11**, 146-152.

Eyles, C.H. and Eyles, N., 1984. Reply to Comments on "Sedimentation in a large lake: reinterpretation of the Late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada": Geology, **12**, 188-190.

Eyles, N. 1997. Environmental geology of a Supercity: The Greater Toronto Area: *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF.

Eyles, N., Arnaud, E., Scheidegger, A.E. and Eyles, C.H., 1997. Bedrock jointing and geomorphology in southern Ontario, Canada; an example of tectonic predesign: Geomorphology, **19**, 17-34.

Eyles, N., and Boyce, J.I., 1997. Geologic constraints on municipal waste management in southern Ontario, Canada; *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF.

Eyles, N., Boyce, J.I, and Hibbert, J.W., 1992. The geology of garbage in southern Ontario: Geoscience Canada, **19**, 50-62.

Eyles, N., Boyce, J.I., and Mohajer, A.A., 1993. The bedrock surface of the western Lake Ontario Region; Evidence of reactivated basement structures?: Geographie physique et Quaternaire, **47**, 269-283.

Eyles, N. and Clark, B., 1988. Last interglacial sediments of the Don Valley Brickyard, Toronto, Canada, and their paleoenvironmental significance: Can. J.Earth Sci., **25**, 1108-1122.

Eyles, N., Clark, B.M., Kaye, B.G., Howard, K.W.F. and Eyles, C.H., 1985. The Application of Basin Analysis Techniques to Glaciated Terrains: An Example from the Lake Ontario Basin, Canada, Geoscience Canada, **12,** 22-32.

Eyles, N. and Clinton, L., 1998. Toronto Rocks; the geological legacy of the Toronto Region., University of Toronto Press, Toronto.

Eyles, N. and Eyles, C.H., 1992. Glacial depositional systems; *in* Facies Models, Response to Sea Level Change, Walker, R.G and N.P James eds., Geol. Assoc. of Canada, St. Johns, NF.

Eyles, N, and Scheidegger, A.E., 1995. Environmental significance of bedrock jointing in Southern Ontario: Environmental Geology, **26**, 269-277.

Eyles, N. and Schwarcz, H.P., 1991. Stable isotope record of the last glacial cycle from lacustrine ostracods: Geology, **19**, 257-260.

Eyles, N. and Westgate, J.A. 1987. Restricted regional extent of the Laurentide ice sheet in the Great Lakes basins during early Wisconsinan glaciation: Geology, **15**, 537-540.

Eyles, N. and Williams, N.E. 1992. The sedimentary and biological record of the last interglacial- glacial transition at Toronto, Canada, *in* Clark, P.U., and Lea, P.D., eds, The Last Interglacial-Glacial Transition in North America: Boulder, Colorado, Geological Society of America Special Paper 270.

Flint, R.F., 1967. Glacial and Pleistocene Geology. Wiley and Sons, New York.

Flint, J.J., and Locama, J., 1985. Buried ancestral drainage between Lakes Erie and Ontario: Geol. Soc. of Am. Bulletin, **97**, 75-84.

Folk, R.L, 1974. Petrology of Sedimentary rocks, Hemphill, Austin, TX.

Gerber, R.E. and Howard, K.W.F., 1996. Evidence for recent groundwater flow through Late Wisconsinan till near Toronto, Ontario: Can. Geotechnical Journal, **33**, 538-555.

Gerber, R.E. and Howard, K.W.F., 1999. Recharge through a regional till aquitard: Three-dimensional flow model water balance approach: Groundwater, **38**, 410-422.

Goldthwait, R.P., 1991. The Teays Valley problem; A historical perspective, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays-Mahomet Bedrock Valley System: Boulder, Colorado, GSA Special Paper 258.

Grabau, A.W., 1901. Guide to the geology and paleontology of Niagara Falls and vicinity. N.Y. State Mus. Bull., **45**, 1-284.

Gray, H.H., 1991. Origin and history of the Teays drainage system: The view from midstream, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays- Mahomet Bedrock Valley System: Boulder, Colorado, GSA Special Paper 258.

Greenhouse, J.P. and Karrow, P.F., 1994. Geological and geophysical studies of buried valleys and their fills near Elora and Rockwood, Ontario: Can. J. Earth Sci., **31**, 1838-1848.

Gross, M.R., and Engelder, T., 1991. A case for Neotectonic joints along the Niagara Escarpment: Tectonics, **10**, 631-641.

Hicock, S.R. and Dreimanis, A., 1989. Sunnybrook drift indicates a grounded early Wisconsin glacier in the Lake Ontario basin: Geology, **17**, 169-172.

Hobson, G.D., and Terasmae, J., 1969. Pleistocene geology of the buried St. Davids Gorge, Niagara Falls, ON; Geophysical and palynological studies: Geological Survey of Canada Paper 68-67, 7p.

Holysh, S., 1997. Halton Aquifer Management Plan, Phase 2 Report: Municipal Wellhead Protection Program – Technical Study. Unpublished report.

Howard, K.W.F., 1997. Impacts of Urban Development on Ground Water: *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF

Howard, K.W.F., and Beck, P., 1986. Hydrochemical interpretation of groundwater flow systems in Quaternary sediments of southern Ontario: Can. J. of Earth Sciences, **23**, 938-947.

Howard, K.W.F., Eyles, N., Smart, P.J., Boyce, J.I., Gerber, R.E., Savlatori, S.L., and Doughty, M., 1997. The Oak Ridges Moraine of southern Ontario: A Ground-water resource at risk: *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF

Howard, K.W.F., and Haynes, J., 1993. Groundwater contamination due to road de-icing chemicals – salt balance implications: Geoscience Canada, **20**, 1-8.

Hunter, J.A., Pullan, S.E., Burns, R.A., Gagne, R.M., and Good, R.L., 1984. Shallow seismic reflection mapping of the overburden-bedrock interface with the engineering seismograph – some simple techniques: Geophysics, **49**, 1381-1385.

Hunter, J.A., Pullan, S.E., Burns, R.A., Gagne, R.M., and Good, R.L., 1987. Applications of a shallow seismic reflection method to groundwater and engineering studies: in *Ontario Geological Survey Special Volume 3, Proceedings 1987*, p. 704-715.

International Water Supply, 1989. Regional Municipality of Halton, Town of Halton Hills – Georgetown, Groundwater Investigation Program Geophysical Survey, unpublished report.

Jefferson, R.D., Steeples, D.W., Black, R.A. and Carr, T., 1998. Effects of soil-moisture content on shallow-seismic data: Geophysics, **63**, 1357-1362.

Johnson, M.D., Armstrong, D.K., Sanford, B.V., Telford, P.G., and Rutka, M.A., 1992. Paleozoic and Mesozoic Geology of Ontario: *in* Geology of Ontario, Ont. Geol. Surv., Special Vol. 4, Pt. 2, p. 907- 1010.

Karrow, P.F., 1959. Pleistocene geology of the Hamilton Map Area: Ontario Department of Mines, Geological Circular no. 8.

__________, 1963. Pleistocene geology of the Hamilton-Galt area: Ontario Department of Mines Geological Report 16, 68p. Accompanied by Maps 2029, 2030, 2033 and 2034, scale 1 inch to 1 mile.

__________, 1967. Pleistocene geology of the Scarborough area: Ontario Department of Mines Geological Report 46, 108p.

__________, 1973. Bedrock topography in southwestern Ontario; A Progress Report: the Geological Association of Canada, Proceedings, **25**, 67-77.

__________, 1984a. Sedimentation in a large lake: a reinterpretation of a late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada: Comment. Geology, **12**, 185.

__________, 1984b. Lithofacies types and vertical profile models: an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences: Discussion. Sedimentology, **31**, 883-884.

__________, 1987. Quaternary Geology of the Hamilton-Cambridge Area, Southern Ontario: Ontario Geological Survey Report 255, 94p. Accompanied by Maps 2508 and 2509, scale 1:50000 and 4 charts.

__________, 1989. Last interglacial sediments of the Don Valley Brickyard, Toronto, Canada, and their paleoenvironmental significance: Discussion: Canadian Journal of Earth Sciences, **26**, 1078-1082.

Karrow, P.F., Clark, J.R., and Terasmae, J., 1961. The Age of Lake Iroquois and Lake Ontario: Journal of Geology, **69**, 659-667.

Kelly, R.I. and Martini, I.P., 1986. Pleistocene glaciolacustrine deltaic deposits of the Scarborough Formation, Ontario, Canada. Sedimentary Geology, **47**, 27-52.

Kempton, J.P, Johnson, W.H., Heigold, P.C. and Cartwright, K., 1991. Mahomet Bedrock Valley in east-central Illinois; Topography, glacial drift stratigraphy, and hydrogeology, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays- Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258.

Knapp, R.W. and Steeples, D.W., 1986. High-resolution common-depth-point reflection profiling: Field acquisition parameter design: Geophysics, **51,** 283-294.

Lawson, D.E., 1982. Mobilisation, movement and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska: Journal of Geology, **90,** 279-300.

Leeder, M.R., 1985. Sedimentology, Process and Product; George Allen and Unwin, London.

Lewis, D.W. and McConchie, D., 1994. Practical Sedimentology, Second Edition: Chapman and Hall, New York.

Miall, A.D., 1997. The Geology of Stratigraphic Sequences: Springer, Berlin.

Mohajer, A.A., Boyce, J.I., and Eyles, N., 1995. Shallow seismic reflection investigation of bedrock and Quaternary strata in the Rouge River Valley, Toronto. Atomic Energy Control Board Project No. 2.263.3.

Muller, E.H. and Prest, V.K., 1985. Glacial Lakes in the Ontario Basin, *in* Quaternary Evolution of the Great Lakes ed. P.F. Karrow and P.E. Calkin, GAC Special Paper 30.

Nelson, J.W., 1998. Bedrock geology of the Paducah 1x2 CUSMAP Quadangle, Illinois, Indiana, Kentucky, and Missouri, USGS Bulletin 2150-B.

Norton, L.D., Hall, G.F., and Goldthwait, R.P., 1983. Pedologic evidence of two major Pre-Illinoian glaciations near Cleves, Ohio: Ohio Journal of Science, **83**, 168-176.

Plint, G., Eyles, N., Eyles, C.H., and Walker, R.G., 1992. Control of Sea Level Change; *in* Facies Models, Response to Sea Level Change, Walker, R.G and N.P James eds., Geol. Assoc. of Canada, St. Johns, NF

Pritchett, W.C., 1990. Acquiring Better Sesimic Data. Chapman and Hall, New York.

Pugin, A., Pullan, S.E., and Sharpe, D.R., 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario: Can. J. of Earth Sci, **36**, 409-432.

Rutka, M.A., and Eyles, N., 1989. Ostracod faunas in a large late Pleistocene ice-dammed lake, southern Ontario, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, **73**, 61-76.

Scaife, J.E., 1997. Geophysical Techniques in Urban Areas: *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF

Scheidegger, A.E., 1980. The orientation of valley trends in Ontario. Zeitschrift fur Geomorphologie: **24**, 19-30.

Schneider, G.W., Nobes, D.C., Lockhard, M.A., and Greenhouse, J.P., 1997. Urban Geophysics in the Kitchener-Waterloo Region, Ontario: *in* Environmental Geology of Urban Areas, ed. N. Eyles. Geological Assoc. of Canada, St. John's, NF.

Sharma, P.V., 1997. Environmental and Engineering Geophysics. Cambridge University Press, Cambridge.

Sharpe, D.R., and Russell, H.A.J., 1999. The Aurora-Maple Channel Aquifer system in the Oak Ridges Moraine Area, southern Ontario. Geological Survey of Canada, vignette on ORM website: http://sts.gsc.nrcan.gc.ca/page1/envir/orm/orm.htm.

Sharpe, D.R., Hinton, M.J., and Russell, H.A.J., 1999. Groundwater Resources in the Oak Ridges Moraine, Greater Toronto Area. Geological Survey of Canada vignette on ORM website: http://sts.gsc.nrcan.gc.ca/environ/orm/orm.ca

Spencer, J.W., 1890. Origin of the Great Lakes of America: Quart. Journ. Geol. Soc. London, **46**, 523-531.

Straw, A., 1968. Late Pleistocene glacial erosion along the Niagara Escarpment of Southern Ontario: Geol. Soc. of America Bulletin, **79**, 889-910.

Telford, W.M, Geldart, L.P., and Sheriff, R.E., 1990. Applied Geophysics, Second Edition. Cambridge University Press, Cambridge.

Teller, J.T., 1973. Preglacial (Teays) and early glacial drainage in the Cincinnati area, Ohio, Kentucky, and Indiana: GSA Bulletin, **84**, 3677-3788.

Teller, J.T. and Goldthwait, R.P., 1991. The Old Kentucky River; A major tributary to the Teays River, *in* Melhorn, W.N., and Kempton, J.P., eds., Geology and hydrogeology of the Teays-Mahomet Bedrock Valley System: Boulder, Colorado, Geological Society of America Special Paper 258.

Walker, R.G., 1992. Turbidites and submarine fans; *in* Facies Models, Response to Sea Level Change, Walker, R.G and N.P James eds., Geol. Assoc. of Canada, St. Johns, NF

Westgate, J.A., 1979. Quaternary geology of the Markham area. Ontario Geological Survey, unpublished map with marginal notes.

Weiderhold, H., Buness, H.A., and Bram, K., 1998. Glacial structures in northern Germany revealed by a high-resolution reflection seismic survey: Geophysics, **63**, 1265-1272.

White, O.L., 1975. Quaternary geology of the Bolton Area, Southern Ontario; Ontario Div of Mines, GR 117, 119p. Accompanied by Maps 2275 and 2276, scale 1 inch to 1 mile.

APPENDIX 1: SEDIMENT LOGS

Georgetown Borehole #1 (G1)

Depth Below Surface (ft)	Sediment Description
0-9.8'	Upper 10'- soil with sparse boulders of dolomite, shale and limestone. Med brown, friable at 4.5'-5.5'. Clasts- well rounded, sparse, 1.5cm avg, few pebbles
10-10.5'	Brown/red pure CLAY. Dense and cohesive with abundant pebble sized clasts of dolomite, shale, and limestone, range-8-10mm.
10.5-16'	Pebbly SANDY-SILT DIAMICT- brown/red, several sm (avg 10mm) pebbles w few quartz granite clasts. Few larger clasts (fairly well sorted.)
18.8-20.2'	Pebbly CLAYEY-SILTY SAND DIAMICT- reddish/brown with v abundant clasts of dolomite, shale, and granite/felds. Matrix- more clay than above, silt lenses- light brown w/in diamict- approx 5-6 wide.
20.2-20.5'	Light brown SAND (diamict??) Sand is vfg- same as lenses above. Sparse clasts- well rounded, 1-2 cm wide.
22.4-26'	Brown SILTY-CLAY w v. few clasts of well round shale and dolomite. 3.5" band of lan deformed sands with no clasts- possible ripples. Sand fg-mg. Remaining unit- silty w clay rich lenses, brown, massive, grades into and out of clayey silt and silty clay- no sand.
27.2-31'	Med brown SAND, massive, no clasts, reddish in areas INTERBEDDED w dense CLAY, brown, massive. Roughly 70% of unit is sand, 30% clay.
32.2-36.2'	Med-dark brown/red SAND, med grained, no clasts. Small 6" zone of bioturbated (?)sands- light-med brown
37.5-39.5'	Med brown (not red) SAND, med grained, no clasts, massive, abrupt lower contact with silt below.
39.5-40.1'	Med brown SILT, dense, massive, no clasts, no clay/sand, sharp contacts.
40.1-40.9'	Med-coarse grained SAND, med-light brown, massive, sharp contact above.
43'-45.7'	Coarse grained SAND- bands of alternating mg red sand and brown cg sand. Bands approx. 2" wide (in upper 1.5' only). Lower 0.5'- thin (2cm) bands of orange/brown sand with sparse/few dolomite and limestone clasts <4cm.
45.7-46.1'	SILTY CLAY DIAMICT- abrupt contact with above. Abundant clasts of dolomite, shale, well rounded to subangular, small (avg 8mm).
48.2-50.1'	SANDY DIAMICT- well consolidated/lithified, v lg boulders- >10cm, abundant small clasts (avg 1.5cm) of shale, dolomite, feldspar, arenite etc. Matrix is fg-mg sand, light gray/brown, silty in some areas.
50.1-51'	Dark gray/brown CLAY DIAMICT- clay rich with abundant pebble sized clasts ranging from 6mm to 3cm, avg -7mm.
51-53'	Dark gray dense CLAY- very few sparse shale clasts, massive, abrupt basal contact.
53-54.2'	Interbedded CLAY and SANDY SILT beds (each approx 3cm). Both units are steel gray colour with bedding perpendicular to coring.
54.2-56'	Very dense steel gray CLAY. Massive, no clasts.
57.5-58.5'	Dense gray CLAY. One area (2" wide) with few clasts of shale, dolomite- well rounded, approx 1cm, slightly pink in areas.
58.5-60.5'	SAND with CLAY CLASTS- clay clasts approx 2.5 cm in diameter, no clasts or laminations. Sand is very fine grained and silty. Gradational down hole to fine grained SILTY CLAY. Majority is silt- also colour variation from steel gray to med brown with depth. No clay clasts in silty clay lower area.
61.3-62.2'	Fine grained brown SAND, fine laminations here and there.
62.2-63'	Very coarse grained SAND, no lam, dark brown, no clasts, abrupt basal contact –not horizontal!- runs approx 50 deg from horizontal.
63'-65.7'	Fine grained to very fine grained brown SAND, possibly rippled- thin laminae.
65.7-67.4'	Brown CLAYEY-SILT- dense, no clasts, massive.

67.4-71'	Dark brown, med grained SAND, finely laminated. Pink/gray- orange/brown laminations (perpend. to core), no clasts. Pale brown lam slightly more cg than others.
71'-74'	Brown (SILTY) SAND- fine grained dark brown, finely lam in upper 8"(remaining is massive). 2 large clasts (5cm) of well rounded dolomite, but no small clasts. Predominately sand, but minor silt present.
74'-74.7'	Gray SAND (SILTY)- slightly more silty than above unit, abrupt contact with brown sand above approx 15 degrees from horizontal.
74.7-75.8'	Gray CLAY- dense, sticky with sparse small shale clasts. Massive.
75.8-76'	Gray SAND (SILTY)- same as unit at 74-74.7'.
76-81'	Very dense, sticky gray (slightly brown) CLAY with sparse small (>.5cm) clasts of shale and dolomite. No large clasts, structure or variability along 5'.
81-83.5'	Dense brown CLAY, sticky, very few small clasts (.4-.8cm), massive, gradational contact with lower diamict below. No visible contact.
83.5-85'	SILTY-CLAY DIAMICT- with abundant pebble sized clasts of red shale, and dolomite, avg 1-2 cm.
85'-85.8'	Brown/gray SILT- no clasts, abrupt lower contact 55 deg from horizontal, unit is slightly sandy.
85.8-91.2'	CLAY DIAMICT- upper 0.3'- massive, dense, clay grades down into pebbly diamict- abundant clasts of dolomite, shale etc, ranging from 6mm-5cm with an avg of 1-2 cm. Few sandy partings approx 45 deg from horizontal.
91.2-93'	SILTY CLAY DIAMICT- gray with few small 4-12mm pebbles of shale and dolomite. Upper 1" gray, grading downhole to brown in lower 1".
93'-96'	SAND- coarse to med grained with several pebble sized clasts of dolomite and shale.
97-98.5'	SAND- very coarse grained with several clasts of shale, dolomite (75% shale). Dolomite is well rounded, shale- subrounded.
98.5-99'	SAND- med grained orange/brown, NO clasts, sharp contacts above and below.
99-101'	GRAVEL/COARSE SAND- possibly a diamict (clast supported) in vcg sand. Dark brown sand, clasts/gravel is poorly sorted 7mm-5cm with pebble horizon. Clasts of variable comp- dolomite, shale, granite, sandstone and qtzite.
102.2-105.5'	Upper 2.5'- GRAVEL, well rounded clasts of regional and foreign composition. Poorly sorted- 3cm-8cm, avg of 4-5 cm. Unit grades down into very COARSE SAND with pebbles.
105.5-111'	SAND AND SILTY SAND- Brown sand and silty sand grading downhole into 3-4" bands of dense silty sand. All of the bands/beds are massive with no internal structure and no clasts.
111'-116'	SAND grading down to SILTY SAND- Upper 3" is rusty laminations with a black band in the central area- remainder of unit is massive. Upper 2.5' is brown fine to med grained SAND grading down to SILTY gray SAND. No clasts.
116.5- 121'	Med to fine grained SAND. No clasts, no laminations, no variability in upper 3'. Lower 1.5' grading down into SILTY SAND to CLAYEY SILT. Still med brown/gray colour with no clasts.
121-126'	Grading rapidly from SILTY CLAY to dense gray sticky CLAY. Few shale clasts.
126-131.7'	Gray CLAY with few scattered angular to subangular shale clasts ranging from 3-5mm. Clay is very dense and sticky. Lower 6" disturbed dark and light brown laminations (possibly from the coring) and no clasts.
131.7-135.8'	Interbedded CLAY and SILTY SAND. Clay unit with a 10cm pebbly diamict horizon with abundant shale and minor dolomite clasts. Below this pockets of sand (large clasts- not beds). No straight contacts- all undulating.
135.8-136'	GRAVELLY SAND unit- clasts of dolomite, shale, and limestone. Sandy but unconsolidated. Clasts are well rounded and poorly sorted.
138-139'	BOULDERS- Variable composition – granite, shale, dolomite ranging in size form 5cm-10cm. All are well rounded, with no matrix present (washed away in drilling??).

139-141'	Fine grained brown SAND with well formed cross bedding and/or ripples. No clasts.
144-146'	Queenston SHALE BOULDERS- several boulders all greater than 6-8cm, well rounded, no matrix.
146.5-151.5'	SHALE BOULDERS grading down into CLAY diamict. Red clay with few shale clasts especially in upper area grading to no clasts in lower area at contact with shale bedrock. Shale clasts are subangular to well rounded.
151.5-153.5'	QUEENSTON SHALE- Red, very fine grained, one 1.5" band of gray/blue dolomitized shale between red shale layers.
153.5'	END OF HOLE.

Georgetown Borehole #2 (G2)

Depth Below Surface (ft)	Sediment Description
0-1'	Dark brown/black CLAYEY SILT SOIL- no clasts, high organic matter.
1-4.5'	CLAY DIAMICT- slightly silty, med brown with abundant well rounded clasts of dolomite and angular clasts of shale.
4.5-10'	CLAY DIAMICT-med brown clay rich and dense with abundant well rounded shale, dolomite and limestone clasts ranging from 0.5-4cm, avg 1-2cm. Few silty sandy partings. One 5cm band/bed of pale brown fine grained SAND with no clasts- faintly and finely laminated.
10-13.4'	CLAY DIAMICT- Med brown with abundant dark dolomite and shale clasts, approximately 0.5-3cm, avg 1cm.
17.8-20'	Fine SAND, med brown with few to several clasts in the upper 4" but grading down to no clasts. Central area contains laminated sand. Lower 4" contains few clasts of dolomite and shale. Pebble horizon in lower area in coarse sand.
21-25'	Coarse SAND in upper 2' grading to med to fine grained sand. Med –fine sand is somewhat bedded brown and black. Dark bands 2-4cm wide perpendicular to the core. No clasts.
25-25.5'	Massive medium grained brown SAND with no clasts.
25.5-26.2'	Cross bedded/rippled med grained SANDS. Each laminae 1-2cm. No clasts.
26.2-30'	Laminated brown very fine grained SANDS with laminae running perpendicular to the core. Upper 2"- massive silty sand bed.
30-32'	Very fine grained SANDS- gray/brown, finely laminated (lam<1mm). No clasts.
32-38.3'	Interbedded fine to medium SANDS and fine grained SILT. The beds are roughly 15 wide with the contacts between the beds being gradational. The sands are brown with gray laminae and in one area exhibit climbing ripples. The silts are dense, gray, and massive.
38.3-40'	CLAY DIAMICT- abundant red shaley clasts- small (<0.5cm), few large clasts, well rounded dolomite at contact with sands above. Clay is dense and bluish gray.
40-43'	SILT- slightly undulating laminae in some areas, massive in others. Laminae roughly 1-3mm wide.
43-45'	CLAY- gray with 3-4 silty partings. No clasts.
45-50'	CLAY- gray, massive, no clasts and no partings.
50-51.2'	SILT with beds/pods of gray clay (as above units) approx. 2.5cm wide. No clasts.
51.2-54'	Interbedded fine grained and very fine grained SILTY SANDS with CLAY. Sands are finely laminated, and clays are massive. Beds range in thickness from very thin to thick (2mm to 3cm). Laminae run planar tabular and perpendicular to the core, but some undulate slightly.
54-56'	Massive gray SILTY CLAY with no clasts.

56-60'	Interbedded SILTS (laminated) and CLAYS (massive). Silt laminae roughly 1-4cm wide, possibly silt/clay laminae- too thin to tell. Beds of clay in silts range in width from 2-10cm, avg of 5cm. Very few small shaley clasts in one clay bed in the middle of the unit.
60-65'	Fine grained SILT to very fine grained SAND with a few scattered CLAY beds (roughly 3-6cm each). Silt is faintly and finely laminated (0.1-0.3cm) in a few areas. Predominately massive though. No clasts, but one very thin band of pebbles in the central area.
65-66'	Massive brown SILTY SAND (sandy silt??) unit. No clasts. Finely laminated as above.
66-68'	Interbedded CLAY and SILT. Clay- few small clasts possibly a diamict. Shale clasts all <1cm. Silt- same as above units. Abrupt contacts between the beds (not gradational).
68-75'	CLAY DIAMICT- few small (<1cm) shale clasts in upper 1' grading down to more abundant clasts in the lower areas of the unit (also well rounded dolomite clasts). Few silty partings perpendicular to the core in the upper area. Lower 4'- abundant angular shale clasts (1-2cm). The colour of the shale clasts reflected in colour of matrix. Blue-gray shale in upper 2.5', red/brown in lower 2.5'. One large (>5cm) boulder in central area.
76-80'	CLAY DIAMICT- Clasts becoming much larger than those in the upper 7' unit. Brown clay matrix, somewhat silty. Very abundant well rounded dolomite and subangular shale (blue and red). Clasts range 0.5-5cm, avg2-3cm. A very pebbly diamict.
81-81.4'	Same as unit above.
81.4-82.2'	Fine grained med brown SAND. Faint thin laminations (<1-3mm). Abrupt contacts. No clasts.
82.2-83'	Pebbly till as above. Shale and dolomite clasts abundant and up to 3cm, well rounded to subangular.
83-85'	SILT- grayish brown silt unit with no clasts. Faint bedding/laminae (4mm wide) somewhat convoluted or undulating lam (secondary result of coring?).
85.5-86.2'	Same as above.
86.2-89.5'	SILTY DIAMICT- abundant med to large clasts of shale, dolomite and granite. Clast are predominately well rounded, avg 2-3cm, but range 0.5-6cm diameter. Matrix is somewhat sandy.
91.6-95'	BOULDERS in med SANDS- Large shale and dolomite boulders- well rounded varying in size from 1-8cm. Boulders lie in medium grained reddish brown SAND matrix. Massive unit.
96.4-98.5'	BOULDERS- Large 1-5cm, avg2cm, well rounded shale, dolomite, limestone, and sst in sandy matrix. Massive unit.
98.5-105'	CLAY DIAMICT- Abundant small clasts (<2cm; 1cm avg) of shale, dolomite, etc in gray clay. Range 0.5-3cm. Predominately well rounded with few subangular shale clasts.
107-110'	SANDY DIAMICT- Well rounded clasts of dolomite and shale. Large clasts- range 0.5-3-4cm; avg.2cm). Few large boulders in upper area. Matrix contains a few clay rich areas.
111.5-115'	SANDY-CLAYEY DIAMICT- Abundant boulders of shale and dolomite. Boulders are predominately well rounded ranging from 0.5-6cm. Matrix is sandy with clayey areas (hardened –difficult to tell matrix composition).
115'-	BEDROCK- Boulders of Queenston shale- red shale, fine grained, one blue-gray band of dolomitized shale.
115'	END OF HOLE.

Milton Borehole #1 (M1)

Depth Below Surface (ft)	Sediment Description
0-8.2'	SOIL- fine grained sandy silt, light- med brown, high organic matter, few pebbles and boulders.
8.2-10'	SOIL- Unconsolidated soil- few boulders in brown clay soil- boulders of dolo and shale with high pin point porosity are angular to subang. Clay is massive, dense and sticky.
10-13'	CLAY DIAMICT- abundant clasts of subangular to well rounded shale and dolo clasts ranging from 0.3-3cm, avg of 0.5cm. Colour of shale varies- dark brown to red/brown to light brown.
13-13.5'	Gray SILT with very few gray shale clasts (<.5cm), massive unit. Abrupt upper contact.
14.5-17'	CLAYEY SILT- very few gray shale clasts, massive, clasts- 0.5-1cm. Abrupt lower contact.
17-17.5'	Fine grained SILTY SAND interbedded with CLAY. Finely laminated/ bedded up to 1.5cm (avg-1cm), no clasts. Medium to dark brown colour.
17.5-18.5'	CLAY (silty?) DIAMICT with abundant subangular shale and dolo clasts. Range in size from 0.4-3cm, avg. 0.8cm. Reddish brown colour.
21-23.4'	SILTY CLAY DIAMICT with fine grained brown sand partings. Clasts are abundant- shale, dolo etc and well rounded, ranging from 0.5-7cm, avg. 4cm
24-28.5'	SILTY CLAY to CLAY DIAMICT- One small 10cm horizon of fine to medium grained brown sandy clay with shale clasts. Clasts are abundant (as above) but abundance decreases downhole to few clasts at bottom of unit.
29-30'	Fine grained brown/red SAND, no clasts, slightly silty. Abrupt lower contact with silty sand.
30-32'	Gray/brown SILTY SAND- more fine grained than above unit. No clasts, massive, grades down into a medium grained sand. Abrupt lower contact.
32-32.4'	SILT- gray brown bed of silt.
32.4-33'	Interbedded SILTS and SANDS- silt as above, sand- fine grained, brown, no clasts, thinly laminated.
33-33.2'	SILTY SAND DIAMICT- shaley (blue) clasts only. Few angular-subangular clasts.
34.5-35'	Same as above.
35-38.4'	CLAY DIAMICT- Abundant clasts of shale, dolo and lmst. Well rounded to subangular ranging from 0.5-8cm, avg. 0.8cm. Shale clasts are blue-gray and red. Clay is massive, no partings or beds.
39.5-53.6'	CLAY DIAMICT- Same as above unit. Matrix is reddish brown in colour. Slight lamination in one area (46') with bands of reddish brown and dark brown interbeds (7cm each). Clasts are well rounded to subrounded.
53.6-54.2'	SANDY CLAY DIAMICT- Abundant clasts. Same as diamict above, but with a sandy matrix.
54.2-57'	Interbedded gray and CLAY DIAMICT with fine grained SANDY DIAMICT. Abundant clasts of shale and dolo throughout all units. Well rounded to subrounded. Possibly flaser bedding or pods of sand in mud.
57-58.4'	CLAY DIAMICT- Few shaley clasts- much fewer than the diamict above. Very sticky clay with a little silt. Gradational upper contact.
63-63.2'	SANDY SILTY DIAMICT- fine grained sand with abundant shaley clasts (0.3-2cm; avg. 0.4cm). Well rounded to subangular.
63.2-63.4'	CLAY DIAMICT- abundant clasts (0.5-5cm; avg.0.8cm). Well rounded to subangular.
63.4-68.5'	Gray SILTY CLAY DIAMICT- several to few shaley clasts. Few well rounded dolo clasts, small (<1.5cm; avg 0.5cm). Massive unit, no variability, no partings, but very cohesive and dense unit.

68.5-71'	Gray CLAY with very few small (<1cm) angular shale clasts. Massive unit, with a gradational lower contact.
71-73.5'	Interbedded red CLAY and gray CLAY. Red clay contains clasts of shale but gray clay contains no clasts. Each bed approx. 2cm wide consistently. Clays in red shale are small (<0.8cm), but run along a uniform horizon across the core. Lower 15cm massive red clay with clasts.
75.6-76.3'	Interbedded red and white/brown SILT. Thin and continuous laminae (2-3mm) laminae continuous through the core. Few clasts of angular blue-gray shale- small (<1cm) avg. 0.5cm
76.3-78.4'	SANDY GRAVEL- Sand is coarse grained; pebbly/bouldery horizon. Variable clasts of quartzite, shale, dolo, lmst, etc. Abundant well ronded boulders ranging from 0.5-6cm, avg. 2cm.
83-83.5'	Granite boulder and GRAVEL-. Loose boulders of granite, and dolo. No matrix just approx. 12 boulders.
85-87'	Large BOULDERS (no matrix) of shale and dolo. Boulders are well rounded, ranging from 4cm to larger than the core. Average 4-6cm.
87-89'	Loosely consolidated GRAVEL- Reddish brown coarse grained sand forms the matrix. Abundant small clasts (<1cm) with larger clasts approx. 5cm wide. All angular to subangular fragments of shale and dolo.
89-91.3'	Fine grained SAND- finely laminated and very contorted. Thin coarse grained pebbly sand horizons- discontinuous bands/lenses of coarse grained sand. Abundant small clasts (<1cm) of dolo (well rounded) and shale.
91.3-93.4'	Medium grained loosely consolidated SAND with pebbles. Abundant pebbles/gravel. Abundant well rounded dolo and shale clasts, 0.5-5cm avg; 2cm.
93.4-98.5'	Fine grained SILTY SAND with medium grained sand partings here and there. Few small shale clasts (<1cm) and subangular. Medium brown colour. Lowermost 15cm, medium grained SAND, less consolidated.
98.5-100'	CLAYEY SILT- very few small clasts (<1cm) of shale. Massive unit, 3 fractures/ partings roughly 45 deg to the horizontal. Medium brown colour.
100-103.4'	Gray brown SILTY SAND- fine grained with few angular red shale clasts ranging from 0.5-1cm. Very cohesive unit- possibly some silt or clay in the matrix; largest grains are fine grained sand.
104-107.2'	Same as above SILTY SAND unit with a thin (6cm) bed of brown fine grained sand with no clasts at roughly 105'.
107.2- 108'	SAND- finely laminated (0.5cm) and well consolidated. No clasts and sharp contacts above and below.
108- 109.7'	Gray-brown SAND with abundant well rounded clasts of dolo and shale ranging from 0.5cm-3cm; avg.1cm.
109.7-110.5'	CLAYEY SILT- red unit with shale and dolo clasts up to 2cm, avg.1cm. Gradational lower contact.
110.5-113.5'	SAND- 2 pebbly/gravel horizons- 1 contains very coarse sand (3cm wide). Sands are laminated (0.5cm) dark and light bands and are convoluted, not horizontal. Few coarse grained sand stringers. Unit is light- med grey/blue.
114.3-117.8'	Fine grained SAND- with bands/beds of medium grained sand. Finely bedded in a few areas (1cm) but predominately massive. Few silty beds. No clasts. Sharp basal contact.
117.8-118.3'	Red CLAY unit with boulders of Queenston shale. No clasts, just red clay.
118.3-118.5'	Fine grained SAND- with bands/beds of medium grained sand. Finely bedded in a few areas (1cm) but predominately massive. Few silty beds. No clasts. Sharp basal contact.
119.2-123.3'	Fine grained gray/brown SAND (red/brown in lower 15cm). Several red shale and black dolo clasts, well rounded ranging from 0.5-3cm, avg.1cm. Most abundant in upper half of unit. Few silty/clayey sand beds here and there approximately 3-6cm wide each.

123.4- 126'	Fine grained red/brown SAND with abundant shale clasts. Clasts are small (<3.5cm) avg. 0.8 cm. Massive unit with a gradational lower contact.
126- 128.2'	Red/brown SANDY CLAY with abundant shale clasts. Clasts of shale and dolo are the same as above unit. Massive unit.
128.2- 128.5'	BEDROCK- fine grained red and gray/blue shale boulders.
128.5	END OF HOLE.

Milton Borehole #2 (M2)

Depth Below Surface (ft)	**Sediment Description**
0-69'	No core recovered.
69-74'	CLAY DIAMICT- gray (dark) with few to abundant clasts of shale ranging from 0.5-2cm. Pebbly unit in some areas. Lower area thick (2-3cm) wide bands of clast barren clay- very dense gray clay. Massive unit.
74-79'	CLAY DIAMICT grading into LAMINATED CLAYS- red and gray bands of clays. Gray bands- very dense clay with no clasts- very soft; Red bands- increasing thickness from few mm at top of unit to 3cm in lower area. Red layers contain small red shale clasts. Bedding perpendicular to core direction. Clasts are small (<1cm) and mostly shale. Sharp basal contact.
79-80.5'	Convoluted bedding (photos 10,11) in very fine grained SANDS- beneath a coarse grained sand horizon (4cm wide). No clasts, clean white sand- sharp basal contact.
80.5-83'	GRAVELS in a medium grained SAND matrix- similar to above but larger stones. Gravel ranges from 2-7cm; (avg.4cm) with composition ranging from granite to shale to dolo. Well rounded to subrounded clasts. Matrix is reddish/brown.
89- 90'	Large BOULDERS- no matrix remaining. Boulders of shale, dolo, dolomitized shale, gneiss (micaceous ultramafic rock) are well rounded.
94- 95'	BOULDERS- No matrix remaining. Boulders of shale, dolo, dolomitized shale and gneiss. Size ranges from 2-6cm, well to subrounded.
99- 100.3'	SANDY GRAVELS- Boulders/clasts ranging from 1-4cm; avg.2cm. Stony unit. Only one foot recovered. Sand is fine and brown and somewhat silty. Several clasts of shale, dolo and dolomitized shale.
104-109'	SANDY SILTY DIAMICT with large BOULDERS. Matrix of red fine sand/ silt with abundant clasts of shale, dolo, lmst, etc. Clasts are subrounded and range from 0.5-5cm; avg.1-2cm. Massive unit with matrix becoming coarser with depth.
109-113.5'	SANDY DIAMICT- Few areas with CLAYEY SANDY DIAMICT. Abundant clasts of predominately shale with dolo, and dolom. shale. Clasts are angular to subangular 1-5cm; avg1.5cm. Larger shale boulders are platey and weathered. Massive unit.
114-117.7'	SANDY SILTY DIAMICT- Stony with clasts of shale, dolo, dolomitized shale, etc. Range from 0.5-3cm; avg.2cm. Clasts are very abundant. Few silty/clayey cohesive diamict areas, predominately sandy matrix. Red/brown colour.
119-122.7'	SANDY SILTY DIAMICT- Stony, but fewer and smaller stones than above, range 0.5-2cm; avg.1.5cm. Same composition.
124-128'	SANDY SILTY DIAMICT- Large shaley clasts, few dolo clasts. Abundance of clasts varies from few to abundant- fewer than above units. Red brown colour. Gradational down into a light brown SILTY SAND unit- very fine grained sand with a few (to sparse) small (<1cm) well rounded dolo and shale clasts. Little clay- cohesive unit.

129-130'	CLAYEY SILTY SAND- small clasts of shale and dolo ranging from 0.5-2cm; avg.<1cm. Same as above units. Gradational lower contact.
130-131.5'	Light brown SILT- finely laminated- disturbed bedding (drilling??).
134-138'	Very fine grained SAND- slightly silty. Clasts are abundant, but very small (<1cm) of black shale and gray dolo and well rounded. Few large 1-2cm clay clasts in central area- clay is dark gray (possibly clayey silt).
139-143.5'	Very fine grained SAND- Abundant very small shale clasts (<1cm) of shale, dolo ranging from 0.3-3cm). Few large red shale cobbles/boulders. Upper 10cm finely laminated fine grained sand. Unit is light to med brown,
144- 146.3'	Very fine grained SAND- slightly silty with abundant small (<1cm) shale clasts- same as above.
146.3-147'	Brown SILT layer, no clasts, slightly convoluted thin laminae.
147-148.2'	Very fine grained SAND. Dense gray clay clasts at contact with upper silt layer. Sand is brown, clean and contains no clasts.
149- 152'	SAND- fine grained sand becoming more silty with depth. Clean, light brown and faintly laminated perpendicular to the core. Few areas with a wavy structure- possibly ripples. No clasts.
152-153'	SILT with clay clasts/ clay covering sand clasts (roughly 3cm each). Few pebbles of shale on the clay. Sandy clay with pebbles in lower 2-4cm- dense much more cohesive than other units.
154-155.5'	SILTY SAND DIAMICT- Gravels in silty sand matrix- clasts/cobbles of shale, dolo, dolomitized shale, etc, ranging from 1-5cm; avg1.5cm. Lenses of coarse grained red sand too in lower area.
159-162'	SILTY DIAMICT with SANDY areas- abundant clasts 1-2cm of well rounded dolo and shale. Massive med-dark brown/ gray unit.
164-165.5'	SILT with CLAY interbeds- faint laminations in silt with thin (<0.5cm) clay (dense, dark gray) laminae. Little core recovered.
169-170'	SILTY SAND- medium grained brown sand. Abundant clasts/cobbles of dolomitized shale, shale, and dolo ranging from 0.5-3cm. Sandy unit, but silt makes it fairly cohesive.
174-174.4'	Very fine grained SILT with very few cobbles approx. 2cm. Sharp basal contact. Light brown colour and massive.
174.4-178.4'	Fine SAND grading down to medium grained SAND. Well sorted dark to medium brown colour with localized reddish areas of more coarse sand. Possibly faintly laminated (<1cm).
179-179.5'	Fine grained brown SAND, no clasts, massive structure. Sharp basal contact.
179.5-181.8'	SILTY SAND- very fine grained sand/silt- brown with sparse small (0.5cm) shale clasts here and there. Massive structure.
184-185.2'	Brown SILTY SAND with very few clasts of shale ranging from 1-2.5cm. Sharp basal contact. Massive unit.
185.2- 186'	SHALE ROCK FRAGMENT- Red shale (Queenston??)- diamict-like. Abundant shale (black) clasts. Very dense and consolidated.
186-187'	Fine grained SAND and SILT interbeds approximately 2cm wide each. Silt is white, dense, hard and massive while sand is light brown, and finely laminated (0.5cm wide laminae).
187-187.7'	SHALE ROCK FRAGMENT- Red well consolidated shale fragments with no clasts. Likely Queenston shale fragment.
187.7-188.5'	Very dense white/gray SILT- no sand or clay. Massive unit with no clasts. Sharp upper contact with shale.
189-194'	Gray SILTY CLAY- finely laminated in areas, massive in others. Laminated upper 0.5' and lower 1.5'. Laminae roughly 0.5-1.5cm wide. Few red shale clasts found in lower 25cm are small (<1cm).
194-198.3'	Dense gray/white SILT- fine/thin laminae approx. perpendicular to core, slightly undulating. Abundant small (<0.75cm) red shale clasts in lower 2 feet only locally staining the silt red. Laminated in lower area with numerous microfaults cross cutting the laminae.

198.3- 199'	CLAYEY SILT- dense medium gray with abundant small red shale clasts (<0.8cm).
199-203'	SANDY SILTY DIAMICT- grading from brown at top to bed at basal contact. Abundant clasts throughout of shale, dolo etc, ranging from 3-5cm; avg1cm. In lower 10cm inclined clay bed (?) or clay fragments. Clay is dense with a few black shale clasts.
203- 204'	Laminated CLAYS- dense clay beds roughly 0.5-1.5cm each changing in colour from one clay bed to the next.
204.5- 209'	Interbedded SANDY DIAMICTS and CLAY DIAMICTS- sharp contacts between each. Sandy diamict is reddish/brown in colour with a few subangular shale and dolo clasts. Clasts here are poorly sorted, small 0.5-4cm; avg.1cm. Matrix is sandy (slightly silty). Clay diamict is gray with abundant small clasts of shale (<0.5cm) and better sorted than the sandy diamict. Clasts range in size from 0.2-1cm.
209- 214'	SANDY DIAMICT- Red fine to medium grained SAND with abundant poorly sorted clasts of black dolo and red shale ranging in size from 0.5-3cm; avg<1cm. Clasts are well rounded.
215-218.5'	SANDY DIAMICT- Same as above.
219-224'	SANDY DIAMICT- Same as above, but gravel/ cobbles/ clasts are larger and unit here is less dense than above. Also a 6cm SAND (no clasts) horizon at 222'. Unit is less red than above (medium brown colour).
225-229'	SANDY/ GRAVELLY DIAMICT- Very stony diamict! Stones range in size form <1to >15cm. Matrix is red and clasts are prodominately dolomitized shale (blue/gray). Clasts are poorly sorted. Large dolom. shale fragment (>15cm) marks the end of the run.
229-232.5'	GRAVEL- Unconsolidated cobbles, gravels and boulders ranging in size from 0.5-6cm; avg2cm. Poorly sorted shale, dolom shale and dolo are well rounded to subangular. No matrix.
232.5- 234'	GRAVEL- Same as above, but consolidated with a medium grained SAND for the most part. Lower area is unconsolidated rocks and boulders.
234'	BEDROCK- Queenston shale- red fine grained shale with bands of gray/ blue dolomitized shale approximately 10cm wide here and there.
234'	END OF HOLE.

Sixth Line Borehole #1 (SL1)

Depth (ft) below surface	**Sediment Description**
0 – 4'	CLAY rich yellow/brown SOIL w/ a few clasts of granite and dolo. Clasts <3cm, well rounded. Org matter common throughout. Upper ½' – very dark brown soil (A horizon?)
4 – 9'	CLAY till – yellow/brown CLAY till – becoming much more cohesive in lower 2' – more deep brown. Upper 3' – very well fractured horizontally. Abundant wr clasts of shale, dolo, granite and granodiorite, ranging from 0.5-3cm, avg 1-2cm
9 – 10'	Same as above
10 – 12'	CLAY till – brown, abundant shale, dolo, clasts, small<2cm, shale most common, well r., little silt
14 – 15'	Same as above, darker brown, w/ more clasts of shale and dolo
15 – 16'	Mg-cg SAND w/ large pebbles of regional and shield material – wr to angular, sharp contacts above and below
16 – 17'	CLAY till – brown – abundant small angular and wr clast of dolo and shale <1cm, clay rich, minor sand
17 – 18.5'	CLAY till w/ minor amounts of sand, brown w/ larger stones of local composition, sharp contact to grey clay w/ small <1cm

18.5 – 20.75’	Grey CLAY till – small clasts of local comp, 1 large shale clast ~4cm, sharp contact w/ brown clay below
20.75 – 21.5’	Brown CLAY (sandy?) with small stones of shale, dolo and sandstone, <1cm avg, wr-sa
23.5 – 27’	Large boulder of gneiss @ upper contact, ~5-6cm wide (can’t tell rounding, cut by drill) CLAY DIAMICT – brown, abundant clasts of local material, small 1-2cm
32 – 35.5’	Fg brown SAND, poss ripples amp ~2cm – asymmetrical?, v. faint, no clasts,
37 – 40’	Mg and fg SANDS – brown, poss ripples/laminations (v. faint) in lower section. 2’ of lost core. No clasts. One small horizon w/ few wr clasts of dolo, shale, etc, ~2cm ea. Sharp contacts b/w mg and fg sand
42 – 47’	CLAY (diamict) – grey/brown colour, few to sparse clasts of shale, dolo – more abundant in upper 6” than remainder. Clasts are small (<2-3cm in upper 6”) and small downwards to <1cm, wr. Massive? Not lam or rippled, but has lenticular beds of sand – small <1cm and different colours of clay.
47 – 52’	CLAY – few small (<1cm) clasts. Grey/brown colour, middle area slightly laminated (undulating laminations) laminae <1cm wide. Colour variations – pinkish grey/brown
52 –57’	CLAY – grey/brown – massive, no clasts, dense and sticky. One thin bed of silty clay in the middle ~6cm wide
59.5 – 61’	Same CLAY as above – grey/brown, no clasts, abrupt lower contact
61 – 62’	Fg SAND w/ CLAY – rolls into worms like clay, but is sandy. No clasts. Same brown colour
65.5 – 67’	Fg SAND w/ boulders of granite and local material., wr 2-5cm and 1 large boulder >6cm. Some is brown (slight red) and somewhat clayey
68 – 71.5’	Fg SAND w/ gravel. Gravel – wr to angular, local and shield material, 1cm-6cm, poorly sorted. Brown sand v. cohesive, some silt?/clay?
72 – 77’	Red SANDY DIAMICT – clasts – local and shield material – abundant, angular-wr, poorly sorted 1-4cm, 2cm avg. Minor clay/silt makes it so cohesive. Massive contact.
77 – 82’	Red CLAY – poss weathered bedrock? V. deep red colour w/ dolo and shale clasts – same as bedrock. Well consolidated – not shaley overall – in a few places. Massive. Except beds of blue dolo, shale in lower area
82’	Bedrock – Red Queenston Shale.

Sixth Line Borehole #2 (SL2)

Depth Below Surface (ft)	**Sediment Description**
0 – 3’	Dense light brown CLAY rich soil w/ few shale clasts, angular, small <1cm
3 – 7’	Light brown CLAY diamict – sandy. Small (<1cm) clasts of shale – few, massive.
7 – 10’	Brown (yellow) CLAY diamict, slightly sandy. some clasts of local comp. wr, <1cm, abundant, clay – stick, dense, massive
10 – 11’	Same as above – longer more poorly sorted clasts
11 – 14.5’	Same as above – fewer clasts, light brown/yellow, abrupt contact w/ grey CLAY below
14.5 – 16’	Same as below – more SAND than above CLAY
16 – 21’	Dense grey CLAY diamict w/ abundant small shale + dolo clasts avg 1-2cm. Clasts wr to subangular, local comp, CLAY – massive.
23 – 24’	(SILTY?) CLAY diamict w/ boulders. 1 lg >5cm shale boulder, till – few 1-2cm shale clasts. clay – grey, massive
26 – 28’	Grey CLAY – dense, few small angular shale clasts, <1cm, black, subangular

28 – 31'	Massive light brown SAND – vfg – slightly silty sand, no clasts
31 – 34.5'	Faintly rippled/lam light brown SAND – vfg grading to fg (possibly mg at base), No clasts
39 – 40'	Vfg light brown SILTY SAND, no clasts, massive – somewhat CLAYEY possibly?
41 – 42'	Vfg SAND – brown (med), possible ripples or crossbeds?, abrupt lower contact, no clasts
42 – 46'	Lam SILTY SAND (SAND) – light brown/yellow, no clasts, lam range <1cm to 2cm, some areas more silty than others. Seasonal? GRADED beds. Horizontal not undulating – planar tabular
46 – 51'	Massive. Light brown/yellow SILT – poss SILTY (SAND) – massive, no clasts, boring…
51.75 – 55.5'	SILTY (SAND) – light brown/yellow – massive – poss. Beds of slightly more SANDY SILT. No clasts, boring
55.5 – 56'	Blue/grey CLAY till as below – SANDY, dense
56 – 57'	Grey CLAY, SANDY – till – dense, v. abundant small clasts of local origin, wr
57 – 59.7'	Lam SILTY SAND (lam of silt) – grey/brown colour, poss gradual bedding again, no clasts, Lam ~1cm wide. SILT beds – paler brown – slightly CLAYEY too
59.7 – 61'	Vcg SAND with clasts/stones – wr, local comp
61 – 62'	Boulders – no matrix, local and shield material, wr, 1->5cm
66 – 67'	Boulders, w.r, local, 1->5cm, no matrix
73 – 76'	Boulders – in vvcg SAND – wr to sa, local comp, range 1-5cm, SAND – massive – middle horizon of smaller boulders
79.5 – 81'	Gravel, local and shield material – well rounded, poorly sorted, 1-5cm, bottom – CLAYEY SILT with gravel, light brown
82 – 83'	SILTY SAND – grey/brown, massive, no clasts, dense, abrupt lower ct.
83 – 84.5'	Boulders – lager, local and shield comp, 0.5 - >5cm, wr.
84.5 – 85.3'	SAND – mg, brown w/ clasts, massive, local and shield comp, wr
85.3 – 91'	Brown SANDY DIAMICT – v. abundant pebbly clasts, large, poorly sorted, wr, range 2cm - >6cm, local – few shield, massive.
91 – 91.5'	Vcg SAND with very large shale boulder at basal contact
91.5 – 94'	Red SANDY DIAMICT w/ abundant clasts of local, poorly sorted, lower diamict (below clay bed) has larger more abundant clasts (1-2cm)
94 – 94.3'	Grey, massive, dense CLAY bed – no clasts, no SAND, massive
94.3 – 96'	Red SANDY DIAMICT – larger clasts than above – 2->5cm, wr to sa, local and shield material, abrupt contact with clay
96 – 101'	Red SANDY DIAMICT, poorly sorted, CLAY rich, dense, massive, bottom 6" – boulders of predom local origin ranging 1-4cm, wr. Unit – v abundant clasts – pebbly, 1->5cm – p sorted, massive.
101 – 104'	Pebbly red SANDY DIAMICT – same as above
104 – 106'	Dense and dry red CLAY – same as Queenston shale colour – bands of bluish clay – possible bedrock?? No clasts. Grad? Contact with diamict above

Sixth Line Borehole #3 (SL3)

Depth Below Surface (ft)	Sediment Description
0 – 3’	Light yellow/brown soil – CLAY clasts of shale – small
3 – 8’	Same as above – CLAY till – brown/yellow, abundant small clasts, sa-sr, small <1cm-2cm w/ few large 3cm clasts, local comp
8 – 10’	CLAY till – light brown, few –abundant clasts of local material, clasts – wr, 1-3cm
10 – 12’	CLAY till – brown, few ang – sa clasts, CLAY rich, dense
12 – 14.5’	Massive yellow-brown CLAY, no clasts, grad contact with SILT below – lam
14.5 – 15’	Lam SILT – yellow/brown colour, no clasts, faintly lam, abrupt lower contact
15 – 17’	Mg red SAND, poss faintly lam?, no clasts
17 – 22’	Mg red faintly lam SANDS, no clasts
22 – 24’	Mg SAND – rippled, brown, no clasts, ripples – faint, abrupt lower contact, few clay clast within sand
24 – 27’	CLAY diamict – upper – light brown, lower – grey/brown, abundant small clasts (<1cm-1cm) of local comp, ang – sr, dense, somewhat sandy
27 – 32’	Grey CLAY diamict – abundant small (<1cm) shale, dolo clasts, well sorted clasts, massive.
32 – 34’	Same as above – grey/brown colour
34 – 37’	More brown than grey now – medium brown
37 – 42’	Grey/brown CLAY diamict – abundant small clasts <1cm, local comp, ang-sa, grey/brown colour
42 – 43’	Dense, massive gray CLAY, no clasts, abrupt basal contact
43 – 47’	Fg grey/brown SAND, rippled and interbedded with massive bed of silt (sand). Beds ~3-5cm, (few), no clasts
47 – 50’	Same as above and below – brown SILTY SAND interbedded with clayey (silt) (grey) beds. no clasts. silty clay interbeds are massive, grey
50 – 57’	Rippled/ crossbedded SANDS w/ no clasts – brown (med) interbeds of massive clay (silty) – grey, ~4cm wide, no clasts
57 – 62’	Vfg brown SAND – cross bedded with distinct foresets, no clasts, amplitude of beds ~3cm, interbedded with beds (1-4cm) of clay and silty clay (grey, massive, no clasts), cross beds above and below interbeds, abrupt contact between each bed
62 – 67’	Same as above – rippled/ cross bedded SANDS, no clasts, in/b w/ 1-3cm beds of clayey silt – grey, massive, SAND – brown (med), no clasts
67 – 71’	Mg SAND – brown, no clasts, poss laminations, well sorted
72 – 74’	Mg rippled SANDS, brown, no clasts, clearly defined foresets, one 4cm bed of massive grey clay between sands – abrupt contact
74 – 77’	Boulders, little vcg SAND matrix – brown, clasts – ang-wr, poorly sorted, 0.5->4cm, shield and local
77 – 80’	Boulders – large-small – poorly sorted, subangular to sr, in clayey sand matrix (mostly washed away), 2->6cm, shield and local mat
80 – 81’	Pebbley gravel – gravel ~1cm – well sorted here in sandy matrix
81 – 82’	Diamict as below – large clasts, 2-5cm
82 – 87’	Brown CLAY-RICH SANDY DIAMICT– pebbly, massive, clasts – local, wr-ang, poorly sorted, ang to wr
87 – 92’	Red SANDY DIAMICT, abundant clasts, local comp, 0.5-5cm, ang-sr, poorly sorted, clayey, massive
92 – 97’	Same as above, CLAYEY red SAND diamict, massive

97 – 102'	Grey CLAY DIAMICT, abundant clasts, small – 1-3cm, local comp, dense clay, massive, clasts – ang to wr
102 – 105'	Dense grey CLAY – laminated at base – lam ~0.5-1.5cm, upper – massive, no clasts, sharp basal contact with clay diamict below
105 – 106'	CLAY DIAMICT – grey, abundant-few cm clasts, local origin, wr-sa
106 – 106.2'	Large boulder - >7cm long, shield material?? Few small clasts above
108 – 111'	Poorly sorted, abundant clasts, SILTY SAND DIAMICT, (red)/brown w/ abundant wr local clasts, 1-4cm, abrupt lower contact
111- 112'	Grey SILT –slightly sandy – faintly laminated, undulating, no clasts.
112 – 117'	Same as below – contacts between beds – loading structures, (CLAYEY) SILT beds loading into SILT below. Few laminations SANDY beds ~6cm wide
117 – 122'	Grey SILTY SAND – vvfg, faintly laminated/bedded, each bed <1cm (~0.5cm), no clasts, dense and cohesive
122 – 127'	Cross bedded SILT (SANDY?) – vvfg SANDY SILT – grey, no clasts, cohesive, few small. Interbeds of dense clay (~4cm) and coarser fg sand, both - thin 2.5cm
127 – 132'	Cross bedded/low angle ripples or laminations (undulating), no clasts., vfg, no interbeds of CLAY as above
132 – 134'	Cross bedded grey SILTS – no clasts, beds ~2-3cm, (slightly SANDY?)
134 – 135'	SILTY SAND, cross bedded, no clasts, well defined foresets, abrupt lower contact, grey brown.
135 – 136'	Red/brown fg-mg SAND w/ few pebbles, sa-sr, 2-4cm, abrupt lower ct.
141 – 142	Boulders – angular-sa, large >5cm, local + shield mat.
142 – 147	Mg-cg SAND – no clasts, brown (med), massive except middle layer – climbing ripples?? Some structure – below this few small 2cm wr clasts of local comp
147 – 149'	Mg SAND – brown (med), massive, no clasts
149 – 150'	Gravel – small, 1-3cm, local and shield material, wr, no matrix – just boulders/gravel
157.5 – 162'	Mg-cg brown SAND – one clast/gravelly layer in middle of section, massive, no clasts aside from one layer, more cg in lower area, gravel – wr local, 1-4cm
162 – 167'	Vcg-cg SAND – dark brown, few clasts – wr, local clasts – v. few scattered – small, 1-2cm, massive.
167 – 172'	Fg SAND grading down to cg SAND with abundant pebbles and clasts of local and shield mat, pebbles more abundant at base of tube/section, massive, brown (light/med), not gravel – vcg SAND with pebbles
172 – 174'	Pebbly cg SAND – dark brown, clasts – local and shield, wr to sa, 1-5cm, poorly sorted
174 – 175.5'	Mg SAND – laminated – clasts form laminae, stratified, local and shield, v small <1cm, wr
175.5 – 176'	Grey, massive SILTY CLAY – abrupt contact, no clasts
176 – 177.5'	Laminated, fg SANDS, brown, poss ripples?, no clasts
177.5 – 177.7'	Thin grey SILTY CLAY – as above bed ~3cm – abrupt contacts
177.7 – 178.2'	Large boulders in SILTY SAND diamict?
178.2 – 182'	SILTY SAND (diamict?) – few clasts, wr shield and local origin, wr 1-3cm, massive
182 – 185'	SAND – fg, slightly SILTY with few pebbles of local origin, lower area – cg SAND – pebbly, med brown colour
185 – 186'	Faintly laminated area – no clasts, ~8cm wide, SILTY SAND
186 – 187'	Pebbly – med-dark brown, poorly sorted
187 – 190'	Pebbly SAND with mud – diamict?? Not as dense as usual, Pebbles/clasts – wr, poorly sorted – 1-4cm, massive
190'+	Bedrock – Queenston Shale

Fifth Line Borehole #1 (FL1)

Depth Below Surface (ft)	Sediment Description
0 – 1'	Black soil
1 – 1.5'	Fg SAND, brown, no clasts, massive
4 – 7'	Cg, vcg and fg SAND – vcg @ top, fg (SILTY) middle, cg bottom. All massive, dirty, few wr local clasts in upper vcg layer
8.5 – 9'	Cg SAND, brown, no clasts, faintly stratified, poorly sorted
9 – 14'	Interbedded red CLAY and brown SANDY SILTY layers. Beds avg 2-3cm, range 1-7cm. 1 large bed (vcg yellow sand) in middle. Abrupt contacts b/w each
14 – 15.75'	Brown/grey massive CLAY, sticky, dense, no clasts. Slightly more brown at lower contact.
18 – 18.25'	Brown/red mg SAND, no clasts, massive, sharp contact w/ SILTY SAND below
18.25 – 18.5'	Light brown SILTY SAND, faint stratification – poss ripples? Thin bed ~8cm
18.5 – 19.2'	Brown/red mg SAND, no clasts, massive
21.5 – 22.2'	Upper contact – red SAND, mg, sharp lower contact, few small local clasts, wr
22.2 – 26'	Brown rippled sands, same as below – laminated?/ bedded, v. faint foresets but definitely stratified – fg not mg as above
26.5 – 30.2'	Brown fg rippled SANDS, no clasts, med brown, ripples – very faint, ~2-4cm beds? Too faint to tell – darker foresets clear but difficult to see bedding
32 – 37.75'	Fg med brown rippled (lower), massive SANDS. Lowermost 6" more SILTY, no clasts, lower SILTY area – light brown
37.75 – 40.5'	Fg SANDS, brown with cross beds? No clasts. Beds ~1-3cm, foresets <1cm size – poss ripples
40.5 – 41.2'	Red SANDY CLAY as below w/ few clasts. Abrupt upper contact.
43.5 – 46.2'	Gradational into SILTY, SANDY CLAY at upper contact. Rolls into worms, but is somewhat SANDY. Few small pebbles (<1cm). Colour brown (light brown as in CLAY clasts below). Red fg SAND at base, same as below, few pebbles as below
48 – 51.2'	Red (quartzite shale colour) fg SAND. Few wr clasts ~2-3cm in central area. One large ~4-5cm CLAY clast – light brown (same as CLAY clasts seem below), light brown, massive, abrupt contacts – pod not a bed
53.5 – 56.2'	Vcg SAND w/ pebbles, red/brown colour, pebbles – 1-3cm, wr to sa, granite + local mat., massive
59.5 – 61.25'	Boulders (sa-sr), local, 2-6cm; Into vcg sand w/ pebbles + clasts of local shield mat, 1-3cm, poorly sorted, brown.
68 – 72'	Mg (fg) brown SAND. Few med size (2-3cm) pebbles here/there – wr, dolomite and shale, massive, unconsolidated
73 – 76'	Pebbly brown fg SAND, pebbles – small <2cm, local, wr, abundant – SAND – massive, not cohesive, unconsolidated, number of pebbles decreases downwards to none at lower contact, no clasts as below
76.5 – 81.2'	Brown fg SAND w/ pebbles (few, wr, local, 1-2cm), massive – few beds of slightly more cohesive (SILTY?) SAND in lower area, few clay clasts as below
82 – 86.5'	Brown fg SAND, no clasts, massive, (dirty)
86.5 – 91.5'	Red SAND w/ a few scattered pebbles (`2-3cm, w.r., local) +small (1-2cm) light brown clay clasts, here/there – more in lower area than upper (flattened balls?). SAND is massive, dark brown/red colour, dirty – more CLAY/SILT
92 – 94.2'	SANDY CLAY w/ pebbles/clasts. Not cohesive like most diamicts – dirty, clay rich, red v. thin (<1cm) CLAY clasts flattened, light brown – stick out from dark red SAND, clasts pebbles of local composition, wr
94.2 – 95'	Vcg SAND w/ boulders – local comp, abundant, wr, 2-4cm, sharp upper contact, brown

95 – 96’	Boulders – s.ang to s. rounded, 2-4cm, 2cm avg., no matrix, local comp.
99 – 101.2’	Brown, vcg SAND w/ minor CLAY/SILT, pebbly w/ boulders – poorly sorted, local material – poss diamict – enough CLAY?? SAND – poorly sorted, massive, pebbles, wr, 1-5cm, 2cm avg.
105.5 – 106.5’	Boulders – 1cm to >5cm, well rounded, few subang, local + few shield material. V. little matrix in 1 area – CLAYEY (not washed away like SAND??)
114.2 – 116.5’	Vcg. SAND w/ pebbles of local comp, subang to subrounded larger pebbles. Smaller abundant wr pebbles. SAND – dirty, contains CLAY, but not very cohesive
118 – 120.5’	Cg SAND w/ pebbles, brown, cg to vcg, pebbles – local composition, range 0.5-2cm, several at lower contact w/ CLAY – very pebbly, less SAND than pebbles, all well rounded, SAND is dirty – some CLAY, poss diamict – not cohesive thought
120.5 – 121.5’	Grey CLAY, massive, no clasts, abrupt upper contact w/ gravelly SANDS
125.2 – 126.5’	Large boulders – granite + local material >6-7cm, well rounded + few small pebbles in a CLAYEY matrix
128 – 131.5’	Upper portion – large boulders, granite and local composition, wr, large >4cm, abrupt contact w/ large boulders. Middle portion – many small pebbles of various lithologies (shield, local, small 1-2cm) Lower portion – 1 lg granite boulder >6cm, wr. Base – CLAY w/ small pebbles <1cm, regional, shield material directly beneath large boulder, large boulders same as top of tube – wr >4cm, local +shield
133 – 135’	Large wr boulders of local and regional comp., Large – 2cm-6cm
136 – 137’	Boulders – wr to subang, shield + local comp, poorly sorted ,<1cm to >4cm, no matrix
137 – 139.5’	Same as above
Bedrock	Red and blue/grey Queenston shale bedrock and loosely consolidated red shale/clay.