# 3-D MODELLING OF QUATERNARY SEDIMENTS, DUNDAS VALLEY USING ROCKWORKS 2002

# 3-D MODELLING OF QUATERNARY SEDIMENTS DUNDAS VALLEY, HAMILTON, ONTARIO USING ROCKWORKS 2002

By

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# Abstract

The Dundas Valley is a deep bedrock valley underlying the Hamilton-Wentworth region of southern Ontario that has been infilled with up to 180m of Quaternary sediment. These sediments contain a valuable record of past environmental change, as well as control groundwater and contaminant migration pathways throughout the region. Unfortunately, the nature, origin and spatial distribution of sedimentary units comprising the infill are poorly understood. This thesis demonstrates the use of 3-D modeling of subsurface geological data obtained from water well and borehole records, engineering and construction reports to delineate the form and geometry of the sedimentary infill of the Dundas Valley. ROCKWORKS 2002 is used to analyze and model over 2000 data points and create a variety of 3-D images used as an aid to the interpretation of the late Quaternary geological history of the study area.

Sediments identified within the valley include fine-grained diamicts, clays, silty clays, sands, gravels and silty sands. These sediment types are grouped into five stratigraphic units that record changing environmental conditions during the late Quaternary. Unit 1 represents the eroded Paleozoic bedrock surface and is overlain by a patchy veneer of sandy gravel (Unit 2), probably deposited under fluvial or shallow lacustrine conditions. Fine-grained deposits of Unit 3 record glacially-influenced lacustrine deposition in the Dundas Valley, possibly during a subsequent episode of ice advance. Unit 4 consists of coarse-grained nearshore deposits associated with the development of post-glacial Lake Iroquois and uppermost silts and sands of Unit 5 record the development of protected lagoonal conditions at the western end of the Ontario basin.

The 3-D images of the Dundas Valley infill are also used to identify and delineate the geometry of aquifers and aquitards and to help predict potential directions of groundwater flow and potential contaminant movement.

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First of all I would like to thank my thesis supervisor, Dr. Carolyn Eyles for all of her support and encouragement over the past few years. She has been truly inspirational and has been a very positive influence on my life. I have learned so much in these past years and I will forever appreciate the friendship and guidance I have received. She has always made her students a top priority, be it reviewing our work, taking us to conferences, or making sure we were well fed during busy times. I cannot thank her enough for going above and beyond her responsibilities as a supervisor.

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# Chapter 1: Introduction

Canada is one of the most urbanized countries in the world with almost 80% of its population residing in urban areas (Environment Canada, 2005). Most of these urban areas are located in regions that were extensively covered by glacial ice at the peak of the last glaciation and are underlain by varying thicknesses of Quaternary-age glacial, fluvial and lacustrine sediments. In many of these urban centres there is growing concern over environmental issues such as clean water supply, groundwater contamination, waste disposal and geologic hazards, all of which are affected by the nature and distribution of subsurface deposits.

Unfortunately, little is understood about the nature, origin or spatial distribution of sediment types underlying many of the major urban centers of Canada, despite a relative abundance of available borehole data from these regions. Natural Resources Canada (NRCan) recently recognized this problem and major efforts are currently underway to improve the compilation and communication of geospatial information for Canadian communities. This thesis presents initial results of an ongoing study that aims to identify, characterize and interpret, the origin of Quaternary-age sediments infilling the Dundas Valley of southern Ontario, a deep bedrock valley that underlies the heavily urbanized region of Hamilton-Wentworth. The study focuses on the compilation and analysis of subsurface geologic data using three-dimensional (3-D) computer modelling techniques and will significantly contribute toward the Canadian geospatial database.

## 1.1 The Dundas Valley of Southern Ontario

Southern Ontario is underlain by an eroded Paleozoic bedrock surface dissected by numerous bedrock valleys (Eyles, 2002). The Dundas Valley, located at the western end of Lake Ontario, lies within one of the bedrock valleys forming a small break in the Niagara Escarpment (Fig. 1.1). The valley was carved into Paleozoic rocks of Silurian to Ordovician age during an extended period of time prior to the late Quaternary (Spencer, 1890; Grabau, 1901; Karrow, 1987; Eyles et al., 1997; Eyles, 2002) and was subsequently infilled with Quaternary-age sediments. The depth of the bedrock valley and nature of its sedimentary infill have been the cause of considerable speculation and controversy as there are very few natural exposures and none of the boreholes drilled within the valley to date have penetrated the entire valley infill (Karrow, 1987).

The Dundas Valley contains Quaternary-age sediments estimated to be between 180 m and 210 m thick (Greenhouse and Monier-Williams, 1986; Karrow, 1987; Edgecombe, 1999; Singer et al., 2003). During the Quaternary, southern Ontario was repeatedly overridden by the southern margin of the Laurentide Ice Sheet allowing deposition of a variety of glacial, fluvial and lacustrine sediments. Areas lying close to the Ontario and Erie lake basins were also subject to repeated inundation and exposure as lake levels rose and fell in response to isostatic crustal movements and ice damming and opening of lake basin outlets (Karrow, 1974). The thick succession of Quaternary sediment within the Dundas Valley thus potentially contains a valuable record of former ice marginal positions and lake level changes that may be used to increase the accuracy of late Quaternary paleoenvironmental and paleoclimatic reconstructions for southern

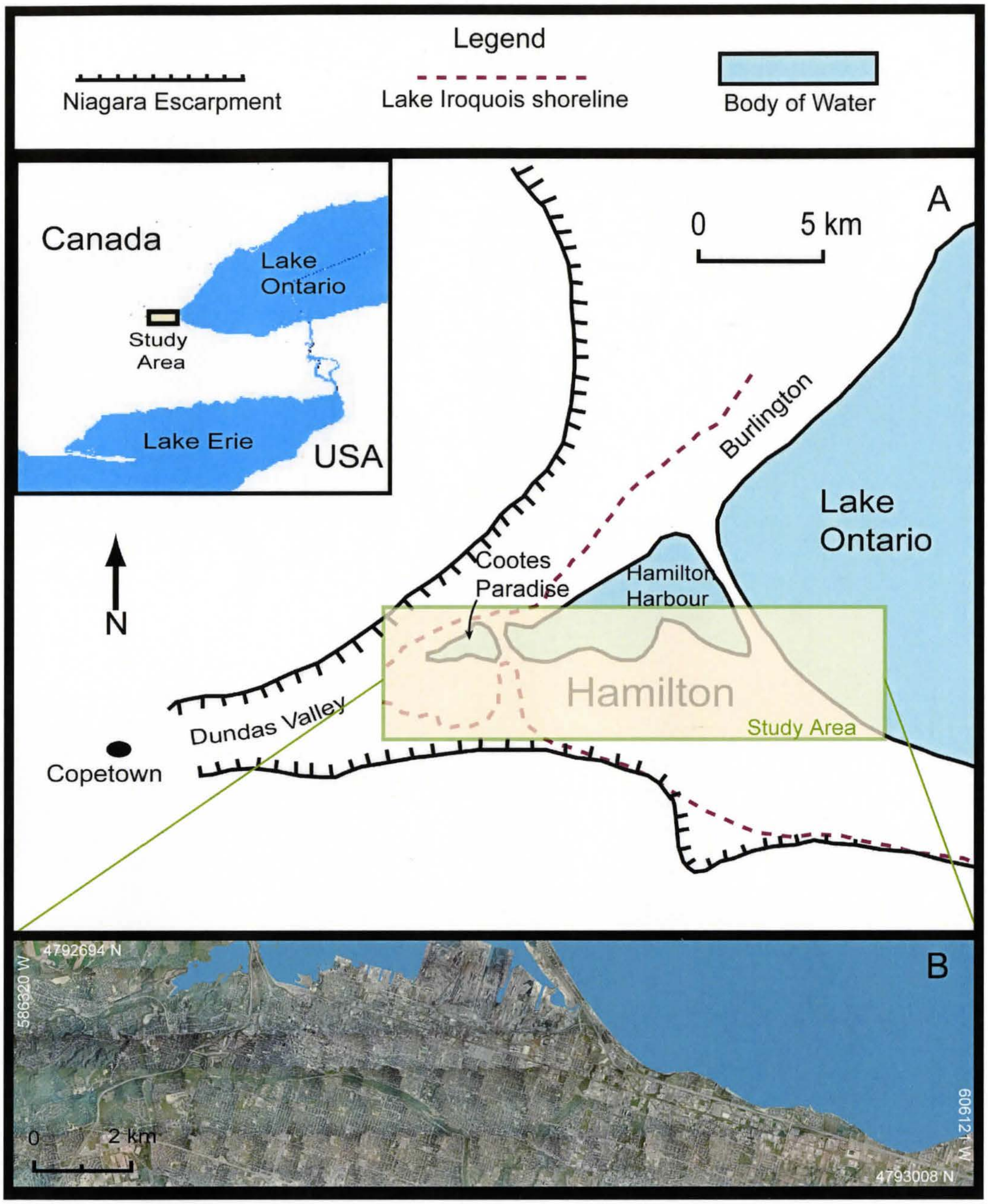



**Figure 1.1** – Location map of study area (yellow box) within the Dundas Valley of southern Ontario and identification of major geological features. B) Air photo of study area (courtesy of City of Hamilton, GIS Services).

Ontario. These reconstructions can also be used to validate the output of mathematical models describing the behaviour of the southern margin of the Laurentide Ice Sheet during the Quaternary (e.g. Mickelson et al., 1983; Alley, 1991; Clark, 1992; Clark and Walder, 1994; Breemer et al., 2002; Eyles et al., 2005).

Unfortunately, little is currently known about the nature and depositional origin of Quaternary sediments infilling the Dundas Valley. This is primarily due to the lack of natural exposures through valley infill deposits, but also due to a paucity of deep borehole or seismic data (Edgecombe, 1999). In order to increase the resolution and accuracy of current reconstructions of Quaternary paleoenvironmental change in southern Ontario, it is necessary to understand the nature and distribution of sediment types infilling the deep bedrock valley.

## 1.2 Hydrogeological Considerations

In addition to containing a thick sedimentary infill, the Dundas Valley also hosts the densely populated (over 710,000 people in 2004; Statistics Canada, 2005) and heavily urbanized region of Hamilton-Wentworth. This region has a long history of heavy industrial activity including metal and chemical manufacturing and processing and there are now serious concerns regarding contamination of ground and surface water bodies from past chemical spills and leakage from former industrial and waste disposal sites (e.g. Birks and Eyles, 1996). Groundwater from aquifers in the Dundas Valley supplies water to Cootes Paradise, Hamilton Harbour and ultimately Lake Ontario (Fig. 1.1); Hamilton Harbour is severely contaminated and has been identified as one of 43 Areas of Concern (AOC's) in the Great Lakes region (International Joint Commission, 1985). Much of the groundwater replenishing surface water bodies is transmitted via relatively shallow aquifers within the Quaternary sedimentary infill of the Dundas Valley (Groundwater Technology Canada Limited, 1994). In order to effectively protect both groundwater and surface water resources in the region, and to identify potential contaminant migration pathways, it is important to establish the subsurface characteristics of the valley infill sediments and their control on aquifer and aquitard geometries.

The initial results of 3-D subsurface geologic modelling presented here allow clear visualization of the stratigraphy and geometry of sedimentary units infilling parts of the valley and can be used to better inform hydrostratigraphic models.

## 1.3 Three-dimensional Modelling of Geological Data

There have been significant advances in 3-D subsurface geologic modelling in recent years including a variety of modelling techniques to be developed (Van Driel, 1989; Houlding, 1994, Berg et al., 2000). These techniques provide the ability to model relatively large data sets in regions underlain by complex geology but the accuracy and reliability of model outputs are still constrained by the quality of input data and the spatial analytical techniques used to visualize and analyze these data. The software package ROCKWORKS 2002 (RockWare, 2002) was used in this study to analyze and visualize subsurface geological data obtained from a variety of government and industry sources.

The creation of 3-D models is generally more complex in geology than in other fields of study, because when modelling the subsurface, the user often does not have a large or comprehensive database. Therefore, a large portion of the model is composed of information that has been interpolated between and extrapolated beyond available data points (Houlding, 1994; Thorleifson and Berg, 2002). Users of 3-D geological models need be fully aware of the limitations of both the database used for modelling purposes and the spatial analytical techniques applied to interpolate between data points.

An advantage of 3-D models is their ability to inform individuals with varying degrees of geologic knowledge. Contrary to 2-dimensional maps which require the viewer to interpret the image and create their own visualization, 3-D models provide the viewer with images portraying the extent and geometries of the subsurface geologic units. Three-dimensional models are not only used as a static output, but can also be used to help process and interpret the available data. Three-dimensional (3-D) geologic modelling has proven to be particularly useful in areas of North America and Europe that are underlain by successions of Quaternary sediment but where there is limited knowledge of the subsurface unit distributions (e.g. Matile et al., 2001; Tipping et al., 2001; Kopczynski et al., 2002; Ross et al., 2002; Hansel et al., 2004; Russell et al., 2004; Bajc et al., 2004; van Haften et al., 2004; Sarapera and Artimo, 2004). In these areas 3-D geological models have helped resolve questions regarding sediment genesis and history, groundwater resource evaluation, land-use management, aggregate resource inventory, and aquifer delineation.

## 1.4 Organization of Thesis

The objective of this study is to better identify, characterize and interpret the origin of Quaternary-age sediments infilling parts of the Dundas Valley of southern Ontario using 3-D computer modelling techniques. Three-dimensional model outputs are used to better understand the stratigraphy of the valley infill, the geologic history, and hydrostratigraphic characteristics of the region. Chapter 2 of this thesis establishes the geological context in which the sedimentary infill of the Dundas Valley formed, and includes discussion of the Paleozoic geology of southern Ontario, the characteristics and formation of the bedrock valley, and the late Quaternary depositional history of the region. Three-dimensional modelling techniques and their limitations are examined in Chapter 3. Chapter 4 discusses the 3-D model outputs and subsurface stratigraphy of parts of the study area. Hydrogeological applications are discussed in Chapter 5. Chapter 6 presents a final summary and conclusions. A journal article based on this research and published in a journal of the Geological Society of America, Geosphere, is attached as Appendix A.

# Chapter 2: Geological Background

## 2.1 Introduction

The Dundas Valley is located at the western end of Lake Ontario and forms a small break in the Niagara Escarpment. The valley is carved into Paleozoic rocks of Silurian to Ordovician age that overlie deeply buried igneous and metamorphic rocks of the North American craton and forms one of many valleys eroded into the Paleozoic bedrock surface during an extended period of time prior to the late Quaternary (Spencer, 1890; Grabau, 1901; Karrow, 1987; Eyles et al., 1997; Eyles, 2002). The depth of the bedrock valley and nature of its sedimentary infill have been the cause of considerable speculation and controversy as there are few natural exposures, few deep boreholes have been drilled in the valley (none of which have penetrated the entire valley infill; Karrow, 1987) and only limited geophysical data are available.

The buried bedrock valley in the Dundas area is estimated to be infilled with Quaternary-age sediments between 180 m and 210 m thick (Greenhouse and Monier-Williams, 1986; Karrow, 1987; Edgecombe, 1999; Singer et al., 2003). Although only deposits from the late Wisconsin have been identified in near surface exposures in the Dundas Valley to date (Karrow, 1987), it is possible that deposits from the early, or even pre-Wisconsin time period may be found in deeper parts of the valley. This thick succession of Quaternary sediment infilling the Dundas Valley contains valuable information regarding the extent of the Laurentide Ice Sheet over Southern Ontario and changing water depths in the Ontario basin, particularly during the final stages of the

Wisconsin glaciation and early postglacial. Information obtained from these deposits may be used to increase the accuracy of paleoenvironmental and paleoclimatic reconstructions for the southern Ontario region and to validate the output of models describing the behaviour of the southern margin of the Laurentide Ice Sheet (e.g. Mickelson et al., 1983; Alley, 1991; Clark, 1992; Clark and Walder, 1994; Breemer et al., 2002; Eyles et al., 2005).

In order to establish the geological context in which the sedimentary infill of the Dundas Valley should be considered, this chapter will examine the Paleozoic geology of southern Ontario, the characteristics and formation of the bedrock valley, and the late Quaternary depositional history of the region.

## 2.2 Paleozoic Geology of Southern Ontario

Paleozoic strata in southern Ontario range in age from upper Ordovician to middle Silurian and directly overlie the metamorphic and igneous Precambrian basement rocks (Karrow, 1963; Fig. 2.1). Accumulation of Paleozoic sediment in southern Ontario began approximately 450 million years ago during the Paleozoic, just prior to the collision of Baltica and Laurentia during the construction of Pangea (Eyles, 2002). During the early and middle Ordovician, southern Ontario was covered by clear and shallow ocean waters of the Iapetus Ocean in which carbonate reefs developed and limestones, sandstones, and siltstones of the lower Simcoe Group accumulated (Fig. 2.1, 2.2 A; Eyles, 2002). By the end of the Ordovician, ancestral North America (which formed the

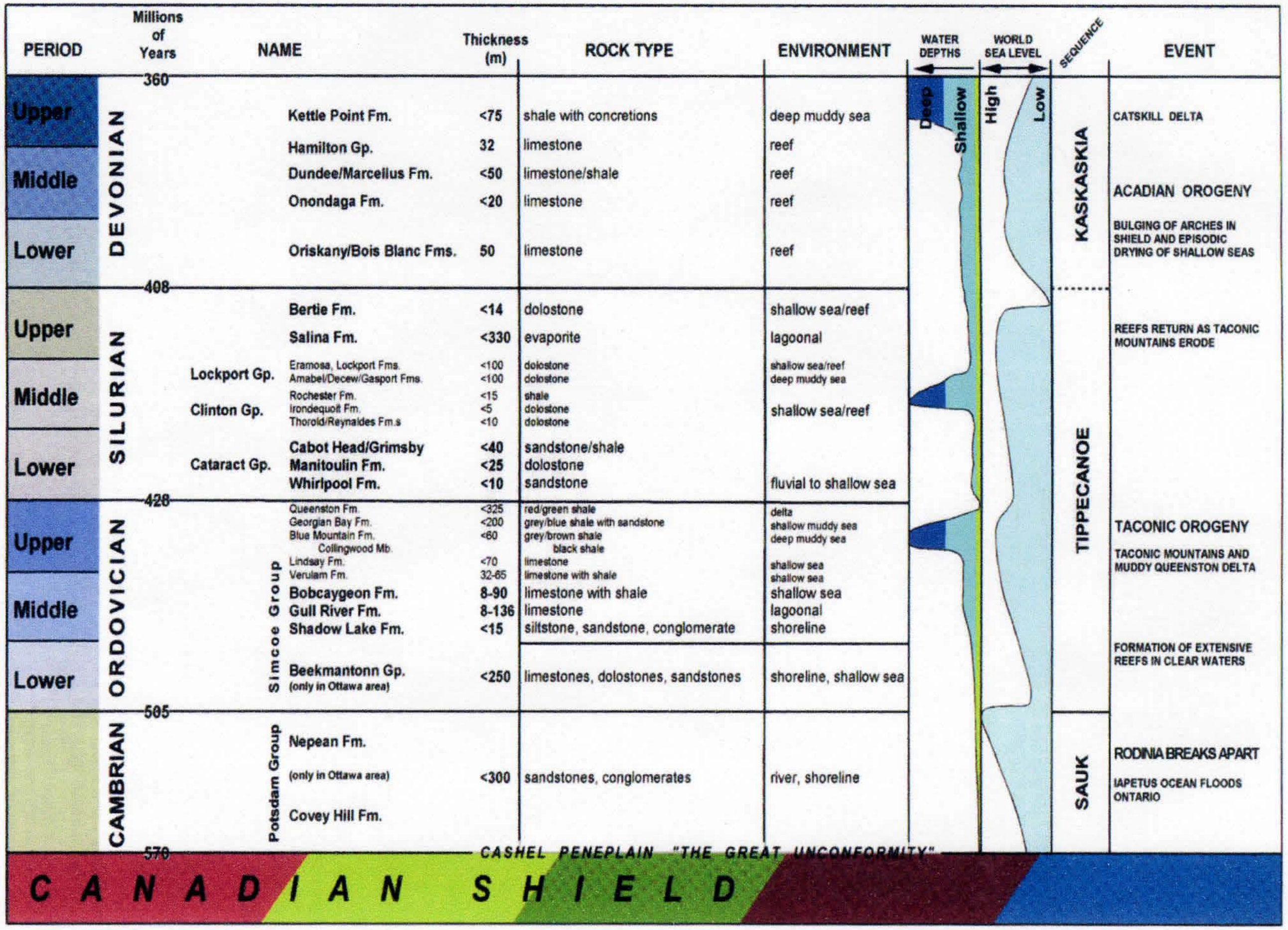



**Figure 2.1**– Paleozoic strata of southern Ontario and their proposed depositional environments. Note the relationship between changing water depths and sediment type. (from Eyles, 2002)

continent of Laurentia) began to drift toward Baltica (ancestral Northern Europe) and the Iapetus Ocean slowly closed. The ensuing collision between the two continents formed the Taconic Mountains during the Taconic Orogeny (Fig. 2.2 B).

The Taconic Orogeny was a time of land subsidence in southern Ontario as a result of loading of the eastern margin of the North American craton by the thickened crust in the orogenic belt (Johnson et al, 1992; Eyles, 2002). Land subsidence, cratonic uplift and warping related to orogenic activity on the eastern margin of Laurentia allowed the development of two large intracratonic sedimentary basins, the Michigan and Appalachian basins, separated by the Findlay-Algonquin arch. Shallow inland seas developed within the slowly subsiding Appalachian basin, allowing thick accumulations of sediment (up to 12 km in some areas) to develop (Eyles et al., 1997). The majority of the sediment entering the Appalachian Basin originated from erosion of the Taconic Mountains and created the Queenston Delta (Fig. 2.2 B). Deposition of extensive mud units at this time produced thick shales that now form the Whitby, Georgian Bay and Queenston formations that underlie much of southern Ontario (Fig. 2.1; Eyles, 2002).

The oldest of the late Ordovician shale formations thought to extend under the Dundas Valley in the Hamilton region is the Georgian Bay Formation (Fig. 2.3) which consists of dark grey shale with arenaceous bands (Karrow, 1987). The Georgian Bay Formation is overlain by younger shales of the Queenston Formation characterized by red mudstone interbedded with green siltstone bands (Fig. 2.3; Karrow, 1963). Both the Georgian Bay and the Queenston formations have low westerly dips and do not appear to be tectonically disturbed (Karrow, 1987). Outcrops of the Queenston Formation can be

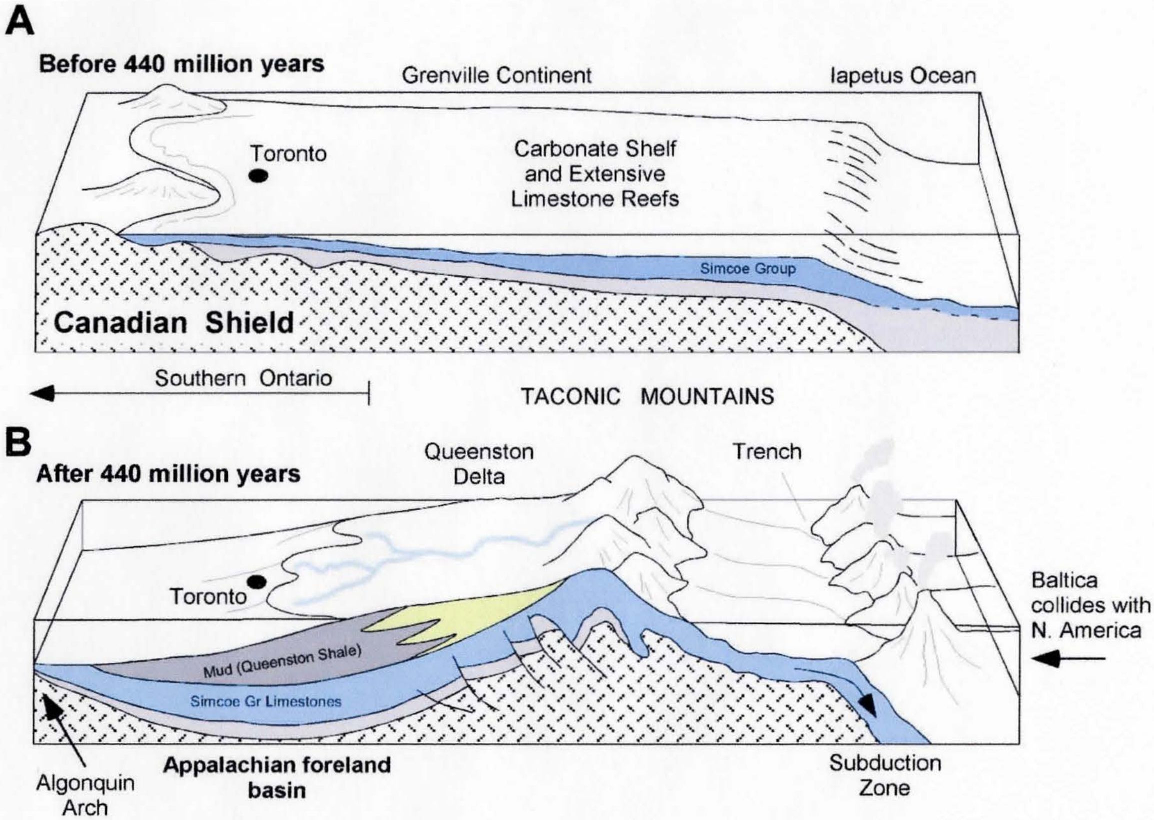



**Figure 2.2 – A)** Location of Toronto on the carbonate shelf of the Iapetus Ocean which allowed for deposition of the limestones of the Simcoe Group. This figure represents the period of time prior to the collision of Laurentia and Baltica which closed up the Iapetus Ocean. **B)** Location of the Taconic Mountains and the Queenston Delta in relation to Toronto, which lies in close proximity (approximately 70 km) to the Dundas Valley. (from Eyles, 2002).

seen along the base of the Niagara Escarpment and shales of this unit are therefore assumed to form the floor of the Dundas Valley (Fig. 2.3).

The Queenston shale is overlain by interbedded dolomite, sandstone, and shale of Silurian age (Fig. 2.3; Karrow, 1987; Johnson et al., 1992; Eyles, 2002). The lower and middle Silurian deposits in the Dundas Valley region include the Whirlpool Sandstone, Manitoulin Dolomite, Cabot Head Shale, Grimsby Sandstone, Thorold Sandstone, Reynales Dolomite, Irondequoit Dolomite, Rochester Shale, and Lockport Dolomite (Fig. 2.3).

The Whirlpool Sandstone, the Manitoulin Formation, and the Cabot Head/Grimsby formations are grouped together to make up the early Silurian Cataract Group (Fig. 2.1). The Whirlpool Sandstone formed as the Queenston Delta prograded into shallow seas covering the Appalachian Basin and marks the beginning of a transition from fluvial to shallow marine environments (Eyles, 2002). Coarse-grained, cross bedded sandstones of the Whirlpool Sandstone were probably deposited by a river flowing across the Queenston Delta (Fig. 2.3; Johnson et al., 1992; Eyles, 2001). Overlying dolostone deposits of the Manitoulin Formation formed on a storm-dominated shallow marine shelf (Johnson et al., 1992) and pass upwards into deeper water shales of the Cabot Head/Grimsby formations (Fig. 2.3; Johnson et al., 1992).

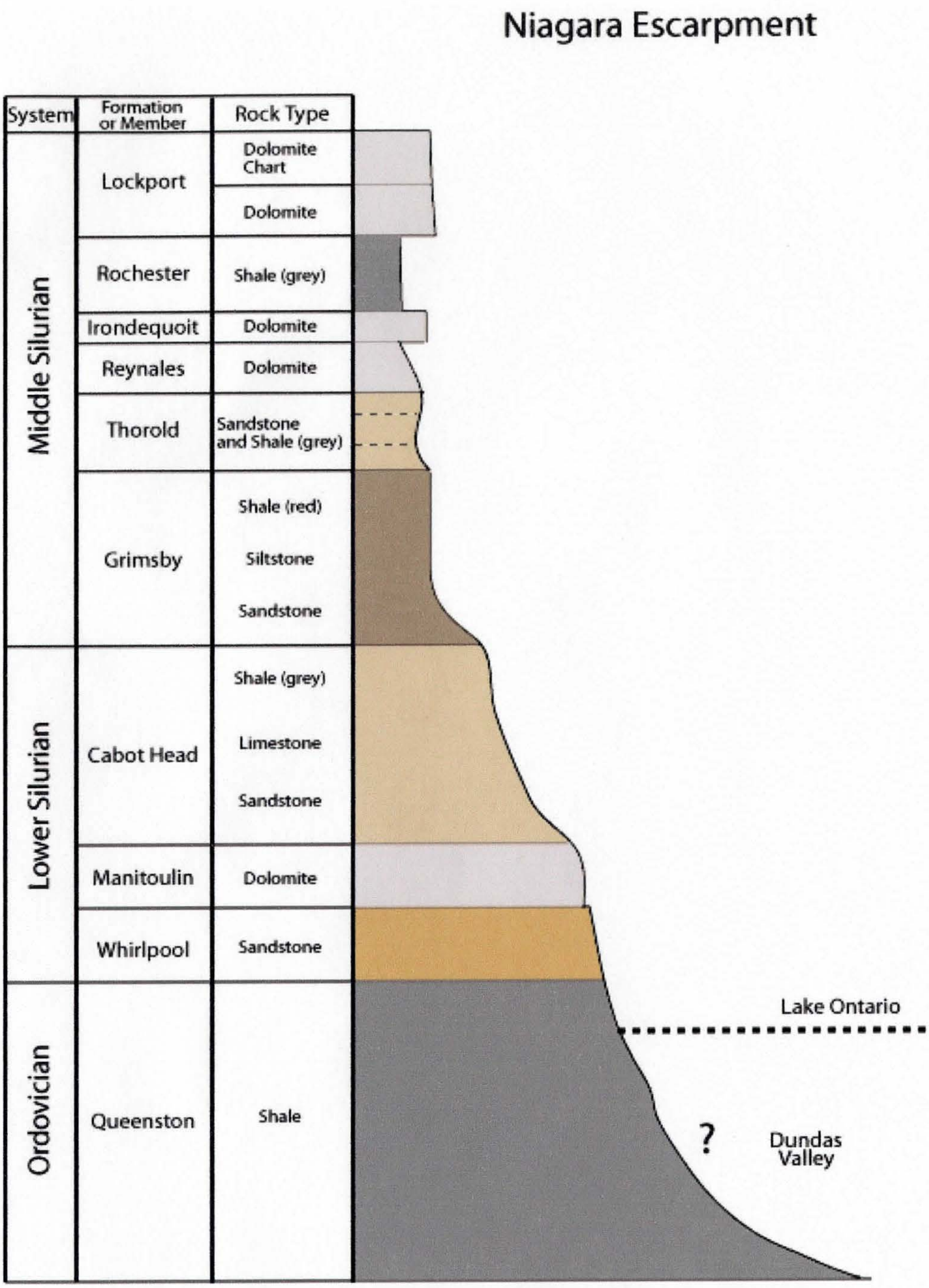



**Figure 2.3** – Stratigraphic cross section of the Paleozoic geology that is typically found in the Hamilton area (modified from McCann, 1987). Not to scale.

The 30 meter-thick middle Silurian Clinton Group deposits, which lie above the Cataract Group, contain the Thorold, Reynales, Irondequoit, and Rochester formations (Fig. 2.3). The Thorold Formation, composed of sandstone with shale intraclasts, was deposited under shallow, possibly intertidal, conditions (Johnson et al., 1992). The overlying dolomitic Reynales Formation indicates deposition in a subtidal to basinal environment as water depths increased over southern Ontario (Johnson et al., 1992). Massive dolostones of the distinctive one to three meter-thick Irondequoit Formation, formed as water depths became slightly shallower and higher energy environments developed. The Rochester Formation is the youngest, and the thickest deposit (approximately 24 meters) of the Clinton Group. This unit was deposited as the sea covering southern Ontario deepened and allowed deposition of fine-grained shale under low energy conditions (Fig 2.3).

The uppermost Paleozoic sedimentary unit observed in the Dundas Valley is the Lockport Formation, a resistant dolostones unit with cherty dolostone horizons (Fig. 2.3). This formation records deposition in a shallowing sea which developed as sediment input from the Taconic Mountains was decreasing and carbonate reefs began to form in relatively clear waters (Eyles, 2002).

The Silurian deposits described above show similar structural characteristics to the Ordovician deposits exposed in the Hamilton area in that they also have a gentle westward dip and show no evidence of substantial tectonic disturbance (Karrow, 1987; Eyles et al., 1997). However, in the Dundas Valley there are several small vertical strike-slip faults in the Ordovician deposits that have either a southeasterly or northeasterly strike with a southwesterly dip (Karrow, 1987; Eyles et al., 1997). Karrow (1987) suggests these faults are most likely the result of pressure-release during the excavation of the Dundas Valley.

### 2.2.1 The 'Big Gap'

There is a large unconformity between Paleozoic bedrock and overlying Quaternary deposits in southern Ontario. This unconformity has been referred to as the "Big Gap", and represents a time span of over 200 million years in which the Paleozoic sediments were exposed and eroded (Eyles et al., 1997; Eyles, 2002). Hence, there is no sedimentary record spanning the Devonian to the Pleistocene in southern Ontario. It has been estimated that approximately 7 kilometers of rock may have been stripped from southern Ontario during the Tertiary (Eyles, 2002) and it is during this time period that erosion of the Dundas Valley by fluvial processes is thought to have begun (Karrow, 1987; Eyles et al, 1997; Edgecombe, 1999).

## 2.3 Formation of the Dundas Valley

Erosion of the Paleozoic bedrock surface across southern Ontario created a series of bedrock valleys that record the positions of former fluvial drainage networks (Fig. 2.4). Many of these valleys may have been further modified by glacial processes during times of ice coverage. The form of the bedrock valleys can be used to determine the processes responsible for their formation and may be used to differentiate between glacial and fluvial erosion processes and identify tectonic influences on valley development. In many cases, the bedrock valleys have been infilled with varying thicknesses of Quaternary sediment and the form of the bedrock surface is no longer evident.

### 2.3.1 Form of The Buried Bedrock Valley

The Dundas Valley extends eastward from Copetown towards Hamilton Harbor and runs parallel to the long axis of Lake Ontario (Fig. 1.1). The Niagara Escarpment forms the northern and southern boundaries of the valley which is approximately 3.5 km wide at its western terminus and is 12.8 km wide at its easternmost end within Hamilton Harbor (Fig. 1.1; Karrow 1987; Edgecombe, 1999). Valley length is approximately 12 km and topographic profiles show that the elevation of the valley floor drops from 190 m.a.s.l. in the west to 90 m.a.s.l. in the east where it enters Lake Ontario (Fig. 2.5A Greenhouse and Monier-Williams, 1986; Karrow, 1987; Edgecombe, 1999; Singer et al., 2003).

Monier-Williams and Greenhouse (1986) investigated the form of the bedrock valley using shallow seismic methods and propose an elevation drop in the valley floor of approximately 180 m between Copetown and the Burlington Bar. They also suggest that the western termination of the valley is formed by an abrupt 100 m increase in bedrock elevation just east of Copetown (Figs. 1.1, 2.5B; Monier-Williams and Greenhouse, 1986); to the west of this point the local relief of the valley is dramatically reduced and the abrupt change in bedrock elevation may record the former position of a waterfall at the head of the valley ('Copetown Falls'; Fig. 2.5B).

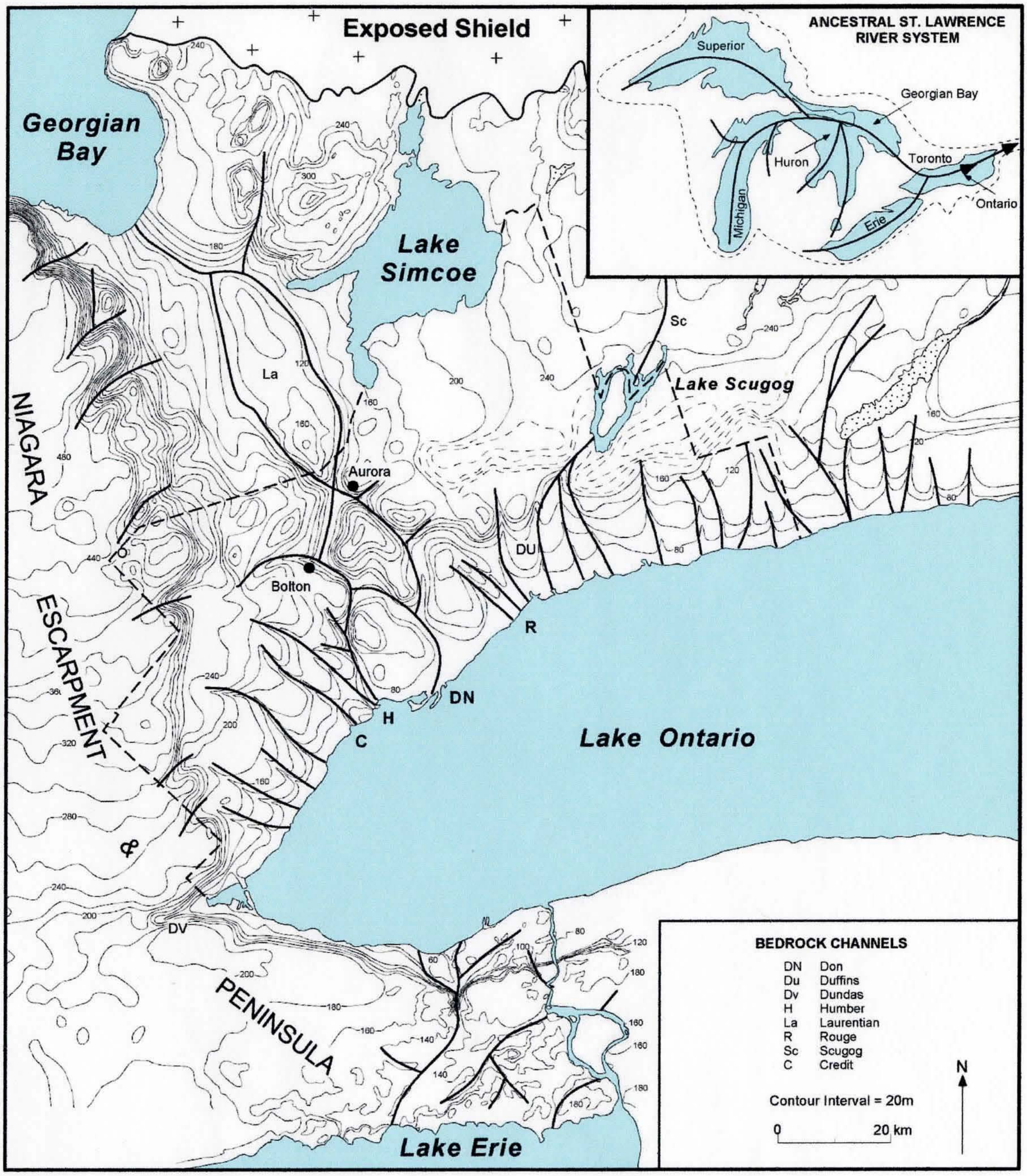



**Figure 2.4 -** Bedrock valleys of southern Ontario. Many of these valleys, such as the Laurentian channel, were cut by ancient fluvial systems that flowed toward the Atlantic (see inset map). The majority of these valleys have since been illed with Quaternary glacial sediments. (from Eyles, 2002).

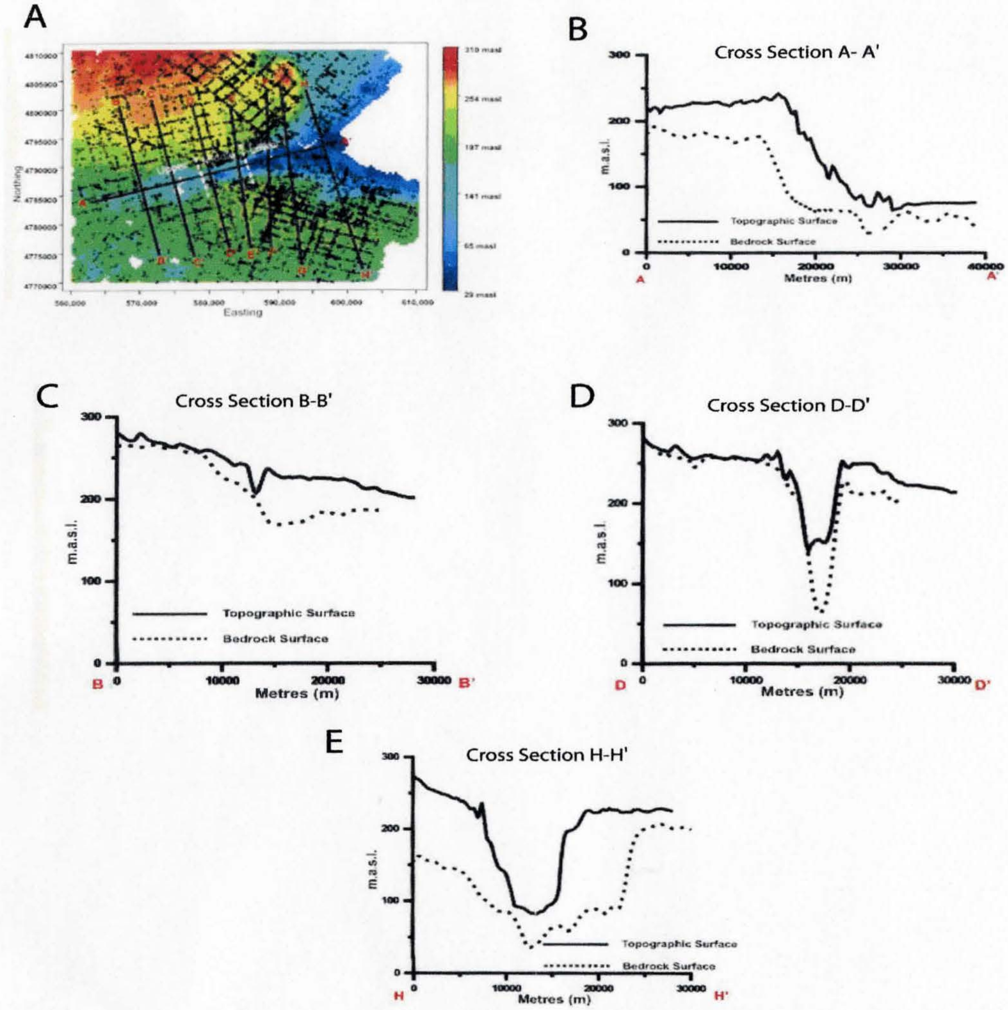



**Figure 2.5 - A)** Digital elevation map of the bedrock surface in the Dundas Valley compiled from HWUGD data. Upper, middle and lower sub-divisions of the valley identified by Edgecombe (1999) are also indicated. The black lines represent cross sectional profiles constructed by Edgecombe (1999). **B)** Down valley profile through the Dundas Valley which indicates the relative drop (in m.a.s.l.) on both the topographic surface as well as the bedrock surface from the upper to the lower part of the valley. **C)** A cross- sectional profile through the upper section of the Dundas Valley. **D)** A cross-sectional profile through the middle section of the valley. **E)** A cross- sectional profile through the lower section of the valley. See Fig. 2.5A for cross-section locations. All figures from Edgecombe, 1999.

The maximum depth of the bedrock valley is also difficult to establish, as bedrock has not yet been reached by drilling in the deepest parts. Based on the deepest borehole drilled to date (137 m in the vicinity of the Burlington Bar) it has been suggested that the depth to bedrock is most likely 180 meters (Greenhouse and Monier-Williams, 1986; Karrow, 1987; Singer et al., 2003). Edgecombe (1999) compiled information from water well data contained in the Hamilton-Wentworth Urban Geological Database (HWUGD) and the Ontario Ministry of the Environment (OMOE) database, as well as from seismic profiles collected in the valley, and estimated that the bedrock surface lies at a maximum depth of 210 meters below the current ground surface.

Karrow (1987) proposed that the form of the buried Dundas Valley is very straight, narrow, and deep. Edgecombe (1999) created digital elevation maps of the ground and bedrock surface from OMOE water well data, and sub-divided the Dundas Valley into three sections (upper, middle, and lower), each with distinct morphological characteristics (Fig. 2.5A). The **upper section** begins at the western most end of the valley (near Copetown), and extends eastward towards 'Copetown Falls' (Fig. 2.5A). This section of the valley is approximately 5 to 7 kilometers wide and is characterized by a gently undulating bedrock surface that is elevated in the north relative to the south (Fig. 2.5C; Edgecombe, 1999). The upper section of the valley also contains a possible pre-existing tributary or southwest extension of the Dundas Valley (Greenhouse and Monier-Williams, 1986). Karrow (1987), and Greenhouse and Monier-Williams (1986), suggested that the bedrock valley in this upper section was 40 to 50 meters deep. Edgecombe (1999), however, used data from the Hamilton-Wentworth Urban Geological

Database (HWUGD) to determine that the valley floor is more likely 80 to 90 meters below the ground surface. The HWUG database was also used to identify a large, steep scarp in the floor of the valley ('Copetown Falls'; Fig. 2.5B) which identifies the end of the upper section, and beginning of the middle section.

The **middle section** of the Dundas Valley differs from the upper section by having straighter and narrower bedrock walls that clearly define the location of a bedrock channel (Fig. 2.5D). In this section, the topographic surface of the valley has a relief of approximately 125 meters, and a width of 3.5 to 5 kilometers.

The **lower section** is characterized by a widening of the bedrock valley as the escarpment diverges to the north and south close to the Lake Ontario shoreline (Fig. 2.5A and E). However, the elevation of the bedrock surface is probably overestimated in this section as there are no deep boreholes that reach bedrock. Hence, bedrock relief in both the middle and lower sections of the valley may be underestimated due to the lack of data. Additional information regarding the form of the bedrock surface in the middle section of the valley was obtained from gravity data analyzed by Edgecombe (1999). These data showed the broad valley floor to be incised by a narrow sinuous channel.

### 2.3.2 Early Stages of Valley Development

It is generally accepted that the Dundas Valley was initially created by fluvial erosion during the Tertiary when water drained eastward into the Lake Ontario basin (Spencer, 1890; Straw, 1968; Karrow; 1987; Eyles et al., 1997). During the Quaternary the valley was subjected to repeated erosion and infilling by both glacial and fluvial processes (Straw, 1968; Karrow 1987; Barnett, 1992; Eyles, 2002).

An extensive fluvial system is thought to have existed across the Great Lakes basins during the Tertiary that drained eastward into the Atlantic Ocean. Spencer (1890) called this network of rivers the Laurentian River System. Many of the large bedrock valleys that exist in southern Ontario are thought to have formed as part of this system (Flint and Lolcama, 1985; Barnett, 1992; Eyles, 1997). There are many theories on how the Dundas Valley contributed to the Tertiary drainage systems of southern Ontario but it is generally thought to be a pre-glacial drainage link between the Erie and Ontario basins. Spencer (1890), Grabau (1901), Karrow (1973), and Eyles (1997) all mapped the regional bedrock topography in southern Ontario in order to reconstruct pre-glacial drainage systems (Fig. 2.6 A, B, C, and D). Spencer (1890) originally proposed the idea that drainage was to the east into a Great Laurentian River which then discharged into the Atlantic Ocean (Fig. 2.6A). Others, such as Grabau (1901), suggested that the Dundas Valley was formed by the "Ancient Dundas River", part of a tributary drainage system that drained to the southwest towards the Mississippi River (Fig. 2.6B). However, the presence of a bedrock scarp at the head of the Dundas Valley (Fig. 2.5B), and the shape of the valley, which widens to the east, indicate that the water probably flowed eastward and not towards the southwest.

Eyles et al. (1997) created a bedrock surface map from water well data (Fig. 2.6D) that showed the Dundas Valley formed the principal drainage outlet for southwestern Ontario, and that water flowed in an easterly direction (in support of

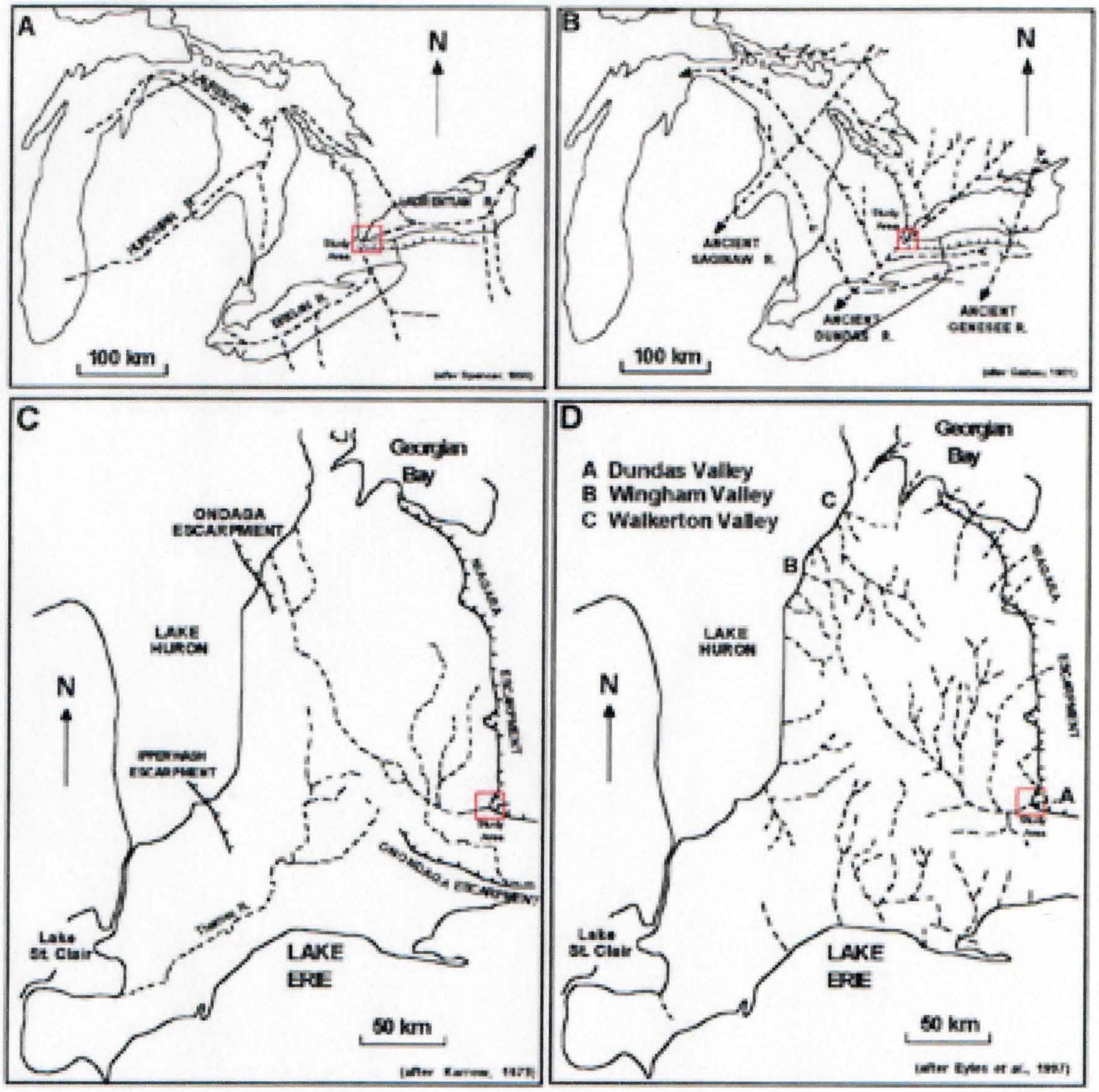



**Figure 2.6 –** Postulated preglacial (possibly Tertiary) drainage patterns for southern Ontario. (A) after Spencer (1890), (B) after Grabau (1901), (C) after Karrow (1973), and (D) after Eyles et al. (1997). (from Eyles et al., 1997)

Spencer's (1890) theory). Previous work by Karrow (1987), and Greenhouse and Monier-Williams (1986) also indicated eastward flow of water through the Dundas Valley from the tributary valley that enters the upstream end of the valley from the south-southwest.

## 2.4 Controls on Valley Development

The most significant controls on development of the Paleozoic bedrock surface topography in southern Ontario, including the Niagara Escarpment, are the arching of the underlying Proterozoic basement, structural weaknesses and differential erosion of the overlying carbonate and shale strata by glacial and fluvial processes (Eyles et al., 1997). Bedrock escarpments appear to follow the strike of the resistant Paleozoic strata such as dolostone units of the Lockport and Cataract groups (Eyles et al., 1997). In contrast, the location and orientation of bedrock valleys is controlled largely by weaknesses in the bedrock caused by easily eroded lithologies (such as shale) or structural weaknesses such as faults or joints (Eyles and Scheidegger, 1995).

### 2.4.1 Structural Weaknesses

In southern Ontario the bedrock surface is, for the most part, covered by glacial sediments, some of which also show signs of jointing. It appears as though repeated glacio-isostatic depression and rebound during the Quaternary promoted bedrock jointing and caused these joints to propagate upwards into overlying Quaternary sediments. The joints also appear to have significantly influenced the trend of modern drainage networks as they form areas of weakness easily exploited by running water. Eyles and Scheidegger (1995) determined a statistical relationship between the orientation of bedrock channels, regional joint sets, and modern river channels. It is therefore possible that the location and orientation of the Dundas Valley is related to structural weaknesses in the underlying Paleozoic bedrock (Eyles et al., 1997).

Although no major faults have been identified in the Dundas Valley, there is evidence that linear features (lineations) identified on the bedrock surface may be fault related. The lineations in the Dundas area appear on aeromagnetic anomaly and bedrock topography maps produced from water well databases as a series of narrow linear depressions on the bedrock surface (Fig. 2.7; Edgecombe, 1999). They have approximately 25 meters of vertical relief, range from 200 to 500 meters in width, and are approximately 25 kilometers in length. There are 4 major and several minor lineations visible in the Dundas area (Fig. 2.7). These lineations show a preferred southwest to northeast orientation and trend parallel to known structural elements such as faults and joints (Gross and Engelder, 1991).

Additional evidence to suggest that the location and orientation of the Dundas Valley is fault-controlled comes from the differential elevation of bedrock on either side of the valley (Eyles et al., 1997). The bedrock surface is 25 to 50 meters higher on the north side of the valley than on the south side (Fig. 2.5D; Edgecombe, 1999). This difference in elevation does not appear to be caused by lithological changes as the upper bedrock units on both sides of the valley are Lockport Dolomite. It also cannot be

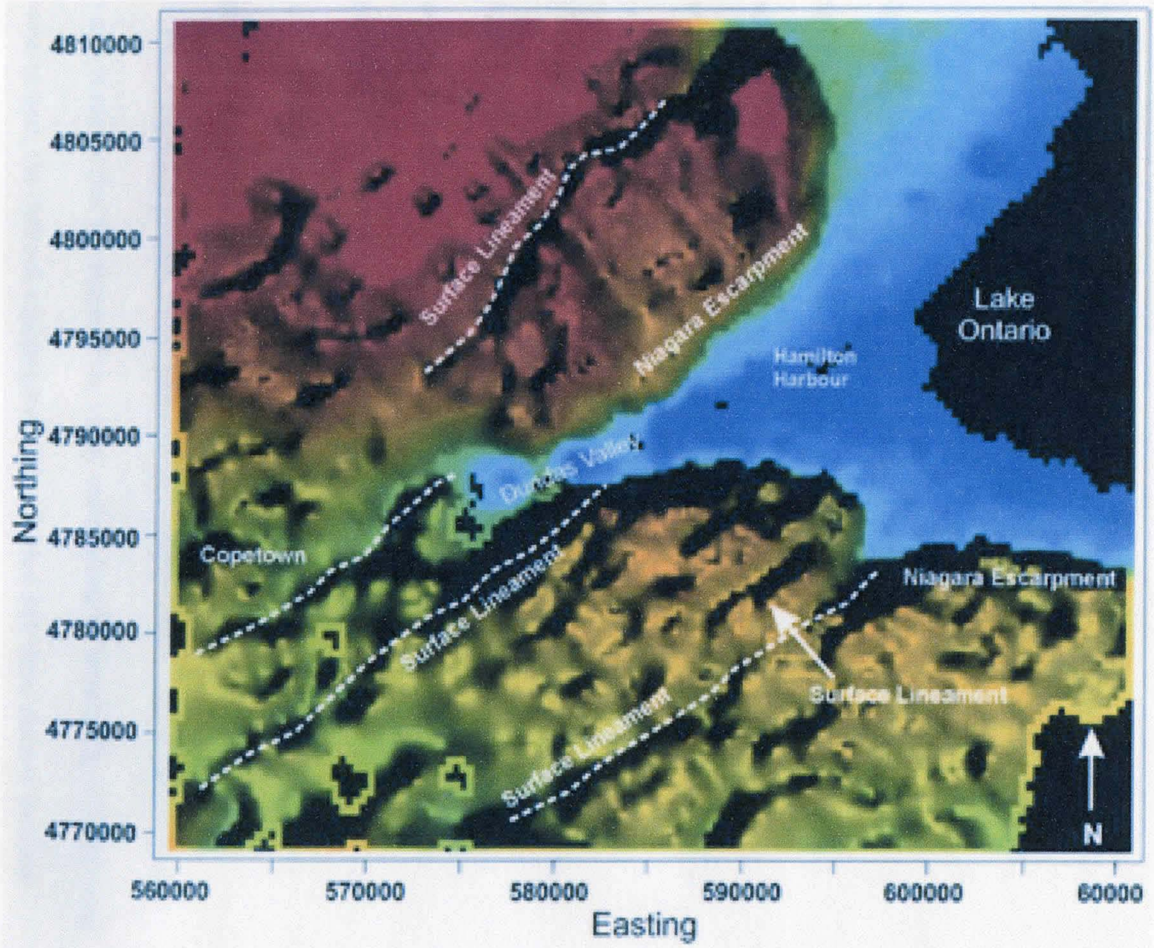



**Figure 2.7** – Location of major surface lineaments in the area surrounding the Dundas Valley. Bedrock surface was created with data from the HWUG database (from Edgecombe, 1999)

attributed to the regional dip of the bedrock surface as the slope is to the southwest (Edgecombe, 1999).

### 2.4.2 Erosion Processes

It is generally accepted that the Dundas Valley is the result of both fluvial and glacial erosion processes (Karrow, 1987; Barnett, 1992; Eyles et al., 1997). The deep, steep walls of the bedrock valley suggest glacial erosion, while the sinuous channel cut into the valley floor (identified by Edgecombe, 1999) is most likely the result of more recent fluvial incision. Initial development of the Dundas Valley was probably caused by fluvial erosion by the waters of the Laurentian River system during the Tertiary and was followed by valley widening and deepening as a result of both glacial and fluvial processes during the Quaternary. However, the form and topography of the bedrock valley floor is not well understood and requires further analysis before detailed interpretations of valley development can be made.

## 2.5 Late Quaternary Geological Record of Southern Ontario

During the Quaternary period, southern Ontario was subjected to repeated glacial activity (Barnett, 1992; Eyles, 2002). During times of ice advance, tills were deposited in subglacial positions and glaciolacustrine diamicts formed in ice-marginal lakes that developed as glacial ice blocked drainage pathways and caused water levels to rise (Eyles and Eyles, 1983). Exposure of the land surface and lowered lake levels during episodes of ice withdrawal allowed for the deposition of fluvial and deltaic sands and gravels. These repeated advances and retreats of glacial ice resulted in the deposition of Quaternary sediments up to 200 meters thick in some areas of southern Ontario (Eyles, 2002).

Deep bedrock valleys are likely to contain the longest record of Quaternary deposition as they provide protection for sediments from subsequent erosion. The Dundas Valley is one such deep bedrock valley and probably contains an extensive late Quaternary depositional record. In order to understand the potential record contained within the Dundas Valley, the late Quaternary geological history of southern Ontario will be examined.

### 2.5.1 Pre-Wisconsin Deposits

The longest and best documented late Quaternary sedimentary record in southern Ontario is found in the Toronto area at the Don Valley Brickyard and Scarborough Bluffs (Fig. 2.8). At the Don Valley Brickyard, the oldest Quaternary-age glacial till exposed in the region, the York Till, directly overlies Paleozoic bedrock, and is interpreted to have been deposited during the Illinoian glaciation over 135,000 years ago (Eyles and Clark, 1987; Barnett, 1992; Eyles, 2002). The York Till is a dark grey diamict that contains clasts derived from the underlying Ordovician shales and is interpreted as a subglacial till (Karrow, 1967). It is overlain by deltaic deposits of the Don Formation which formed during the Sangamon Interglacial between 125 and 80,000 years ago (Berger and Eyles, 1994; Eyles, 2002). Alternating beds of sand and mud in the Don Formation indicate that the deltaic environment was subject to storm events (Eyles and Clark, 1987); fossils, seeds, and pollen contained within the muds indicate deposition under warm climatic conditions (Eyles and Clark, 1987; Eyles, 2002).

### 2.5.2 Early Wisconsin Deposits

Approximately 60,000 years ago the global climate cooled significantly and initiated the Wisconsin glaciation (Berger and Eyles, 1994). The Wisconsin glaciation is divided into early, middle and late periods. The early Wisconsin period is characterized by climate cooling when the Laurentide Ice Sheet began to advance into Ontario from the north and east. During this time, the Scarborough Formation, an extensive deltaic deposit passing upwards from prodelta muds at the base into delta front and delta top sands (Scarborough Sands) developed along the northern shore of the Ontario basin in the Scarborough area (Karrow, 1967; Eyles, 2002). The uppermost Scarborough Sands contain large channels, a variety of cross-bedding types, and accumulations of peat, all of which indicate deposition in fluvial or delta top environments (Eyles and Eyles, 1983; Kelly and Martini, 1986). A large channel at Bluffer's Park (40 meters deep and 1500 meters wide) is eroded into the upper part of the Scarborough Sands and is filled with younger sediments of the Sunnybrook drift (Eyles, 2002). The Sunnybrook drift is thought to have been deposited approximately 45,000 years ago (Berger and Eyles, 1994), and consists of a grey colored fine-grained diamict (Eyles and Eyles, 1983; Hicock and Dreimanis, 1989; Eyles et al, 2005). Eyles (2002) suggests that the

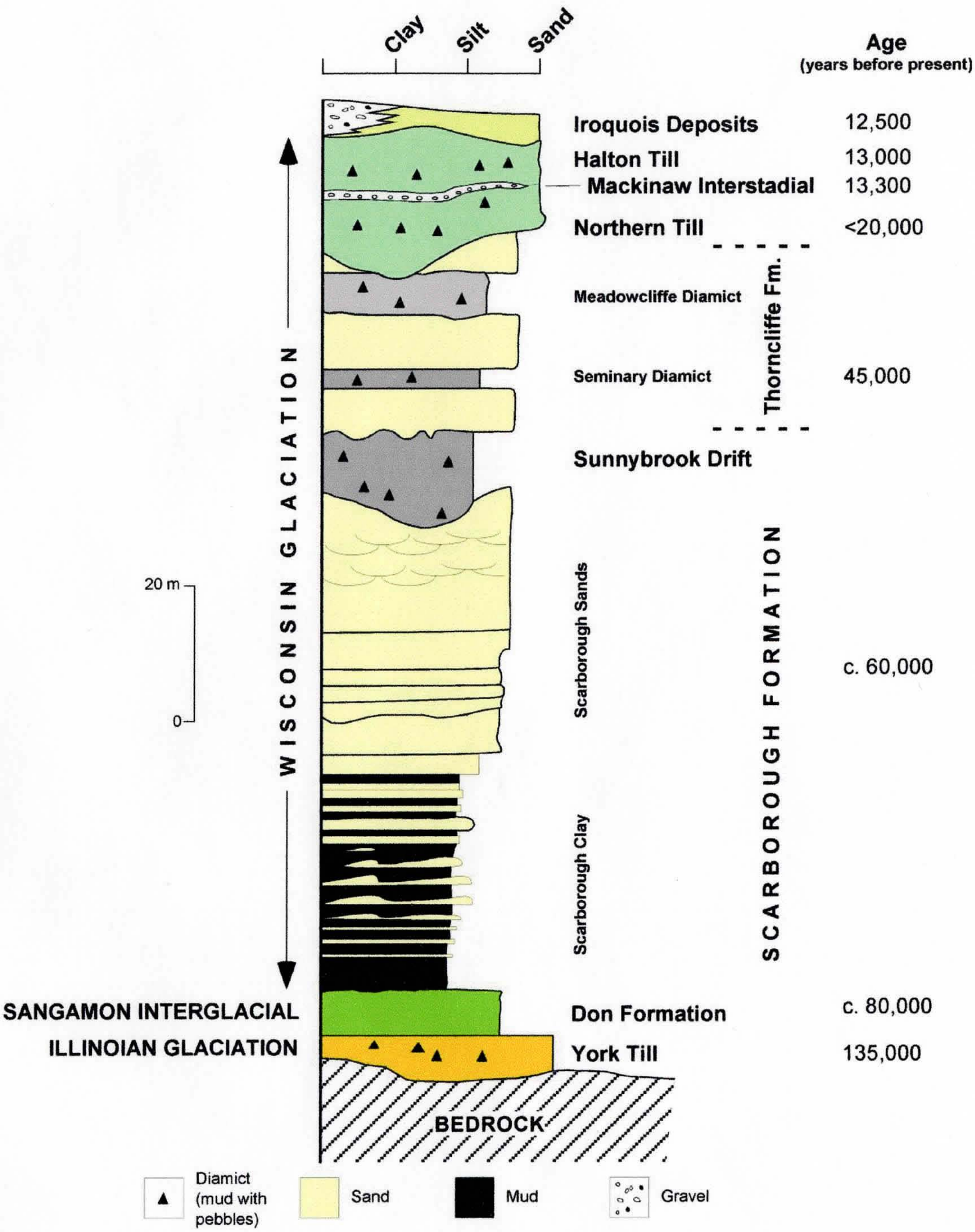



**Figure 2.8** – Schematic log summarizing the Quaternary sedimentary record exposed in the Toronto area along the Scarborough Bluffs and the Don Valley Brickyard. (from Eyles, 2002).

Sunnybrook was deposited in a glacial lake that was dammed in front of the Laurentide Ice Sheet by the processes of 'rain-out' of suspended sediment and ice-rafted debris and slumping on the lake floor.

### 2.5.3 Middle Wisconsin Deposits

During the middle Wisconsin period climate is thought to have warmed slightly allowing ice margins to retreat from the western end of Ontario basin and deltaic deposits to form (Karrow, 1967). The upper part of the Sunnybrook drift contains a thick succession of laminated silts and clays that pass upwards into deltaic sands of the Thorncliffe Formation (Fig. 2.8). This records shallowing of the deep, cold lake in which the Sunnybrook drift was deposited, possibly in response to partial unblocking of the lake outlets by ice margin retreat (Eyles and Eyles, 1983). The Thorncliffe sands were deposited during the time when the lake was shallow and subject to storm wave activity (Eyles and Clarke, 1987; Barnett, 1992). Due to fluctuations in lake level, two other diamict units (Seminary and Meadowcliffe) are found interbedded with the sands of the Thorncliffe Formation (Fig. 2.8; Eyles and Eyles, 1983).

### 2.5.4 Late Wisconsin Deposits

During the late Wisconsin the Laurentide Ice Sheet reached its maximum extent (Fig. 2.9A) and completely covered southern Ontario (Karrow, 1987; Barnett, 1992; Boyce and Eyles, 2000; Eyles et al., 2005). The late Wisconsin period includes three stadial events when ice margin advances occurred (Nissouri, Port Bruce, and Port Huron stadials), as well as two interstadial events when the ice margin retreated slightly (Erie and Mackinaw interstadials; Barnett, 1992).

The Laurentide Ice Sheet was not thick or extensive enough to fully cover southern Ontario and reach the United States until approximately 20,000 years ago during the late Wisconsin (Eyles and Westgate, 1987; Barnett, 1992; Eyles, 2002; Eyles et al., 2005). Eyles (2002) estimated that southern Ontario was covered by approximately 1 kilometer of ice at this time (Fig. 2.9A), which caused isostatic depression of the earth's crust by approximately 400 meters. Extensive sheets of subglacial till were deposited across southern Ontario as the Huron-Simcoe and the Ontario-Erie lobes of the Laurentide Ice Sheet advanced during the Nissouri stadial (Boyce and Eyles, 2000; Eyles, 2002).

Approximately 13,300 years ago, the Laurentide Ice Sheet retreated from the Toronto area and an extensive layer of coarse-grained sand and gravel outwash was deposited by fluvioglacial systems during a time period referred to as the Mackinaw Interstadial (Eyles, 2002). This was a relatively short interstadial period, as ice once again covered southern Ontario around 13,000 years ago during the Port Huron stadial. During this ice advance the Ontario-Erie lobe of the Laurentide Ice Sheet moved rapidly over fine-grained lacustrine deposits previously deposited around the margins of Lake Ontario (Fig. 2.9B; Karrow, 1987; Hicock and Dreimanis, 1989; Boyce and Eyles, 2000; Eyles, 2002) and overrode the edge of the Niagara Escarpment depositing the mud-rich

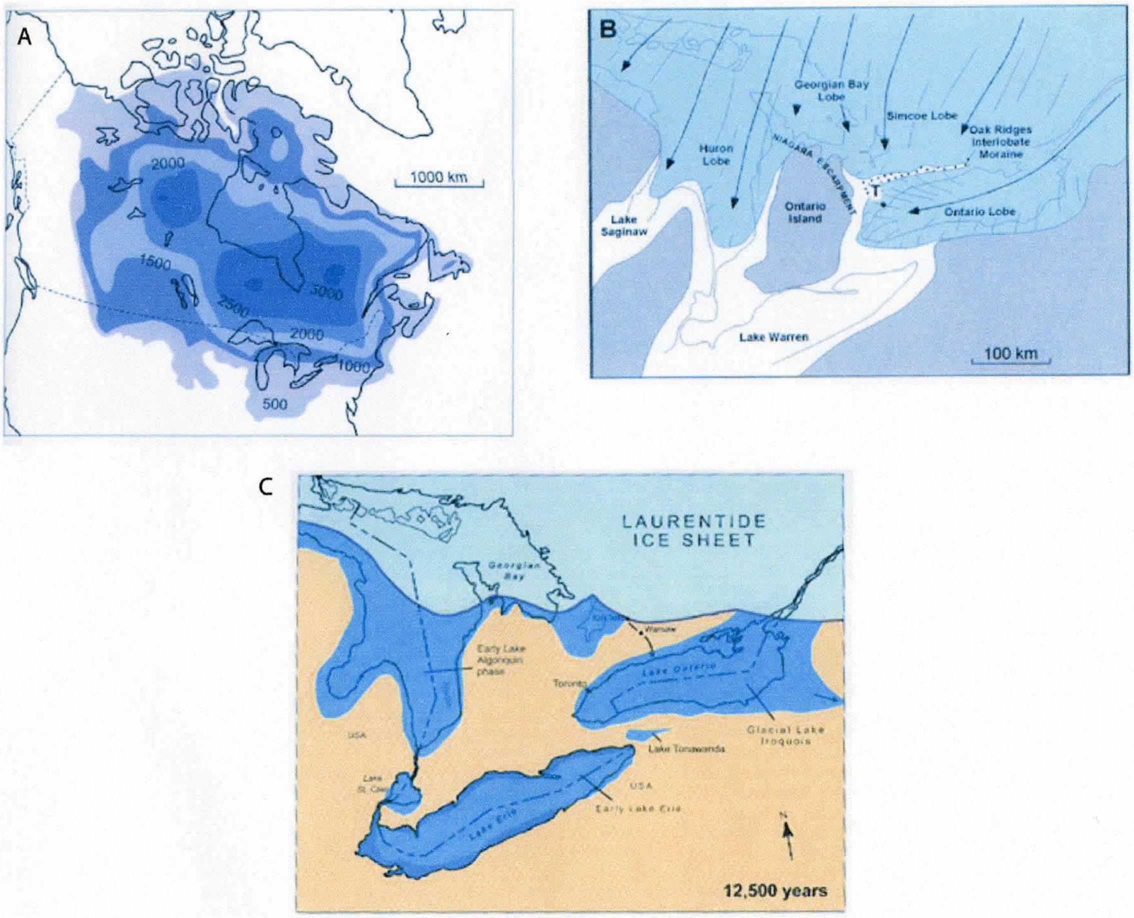



**Figure 2.9 – A)** The maximum extent of the Laurentide Ice Sheet covering North America around 20,000 years ago. The numbers on the map indicate the depth of the ice in meters. **B)** The extent of the Laurentide Ice Sheet during its final surge over Southern Ontario (13,000 years ago). **C)** Post-glacial Lake Iroquois dammed between the Laurentide Ice Sheet and the Niagara Escarpment (not shown in this figure) around 12,500 years ago (from Eyles, 2002).

sub-glacial tills and interbedded sands of the Halton and Wentworth Tills (Karrow, 1963; Karrow, 1987; Eyles, 2002; Singer et al., 2003). The till found to the east of the Niagara Escarpment is referred to as the Halton Till, while the till found to the west of the escarpment is referred to as the Wentworth Till (Karrow, 1987; Singer et al., 2003).

One thousand years after the final advance of the Laurentide Ice Sheet margin, it began to retreat leaving behind post-glacial Lake Iroquois in the Ontario basin (Fig. 2.9C; Eyles, 2002). Lake Iroquois deposits mark the beginning of what is referred to as the post-glacial time period.

### 2.5.5 Post-glacial Lake Iroquois

Lake Iroquois was a deep (approximately 45 meters above present Lake Ontario levels) and extensive lake that covered large areas of the Dundas Valley (Fig. 2.10 A) and northern shoreline of the Ontario basin. The City of Hamilton is located on the former Lake Iroquois lake plain, referred to as the 'Westdale Plain' (Karrow 1987). The Westdale Plain slopes gently northward and has an elevation of approximately 107 meters above sea level near the southern margin of the valley dropping to 75 meters above sea level near Cootes Paradise (Fig. 2.10 B; Groundwater Technology Canada Limited, 1994). The Lake Iroquois shoreline surrounds Lake Ontario with an approximate 3 km swath and is underlain by silty sand and clays, with fine silts and lagoonal deposits on top (Karrow, 1987). Sediments underlying the Westdale Plain include sands and gravels formed under high energy shoreline conditions and silty-sands

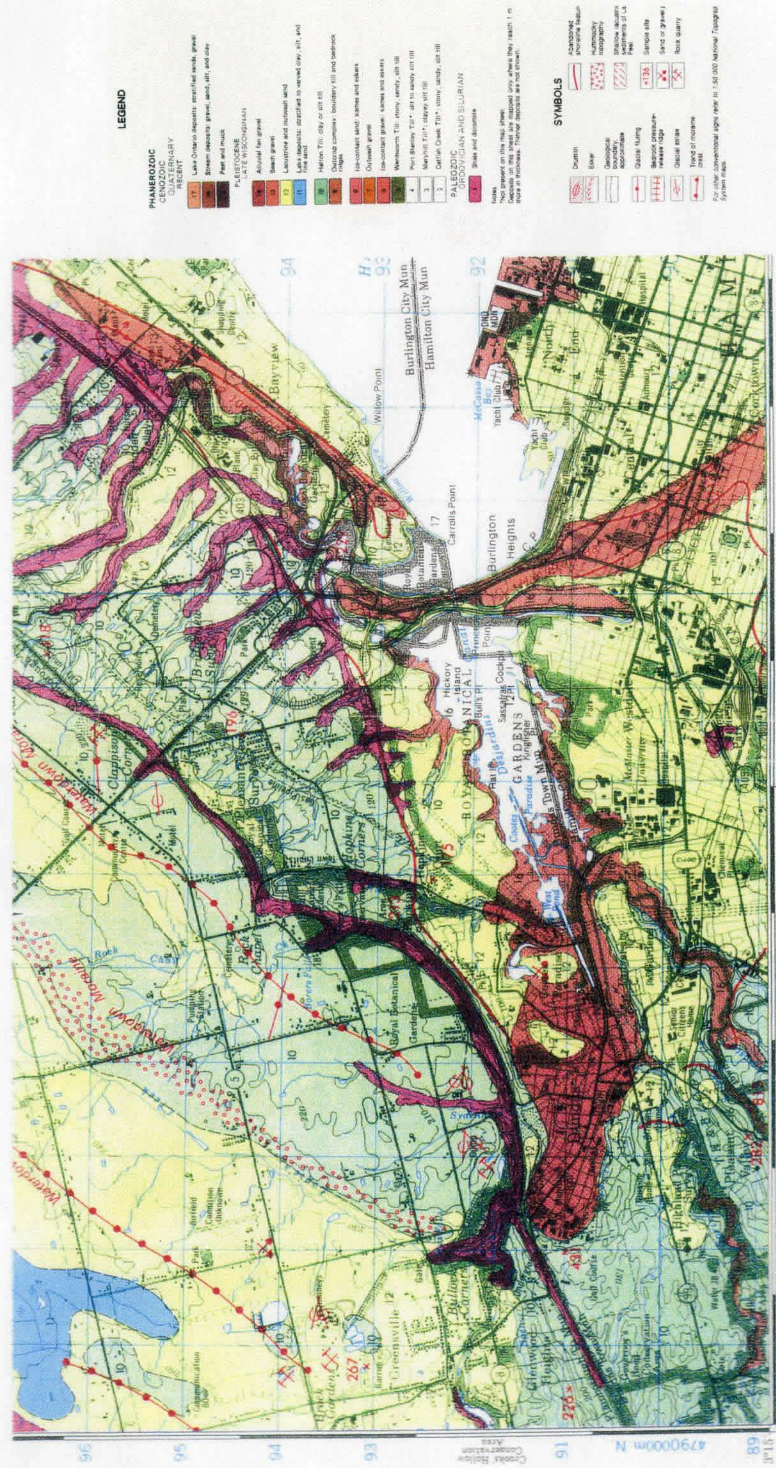


Figure 2.10 A – Quaternary surficial geology of the Hamilton-Wentworth region. Scale 1:50,000 (from Karrow, 1987).

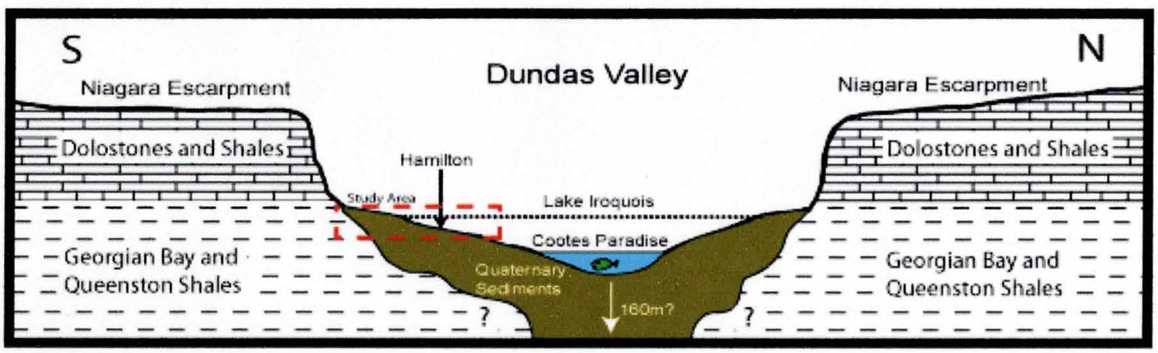



**Figure 2.10 B** – Schematic cross-section of the Dundas Valley showing bedrock, Quaternary sediment infill, the former level of post-glacial Lake Iroquois (dotted line) and modern level of Cootes Paradise.

deposited under relatively low energy. Lagoonal depositional conditions developed when beach bars formed at the western end of Lake Iroquois and isolated Cootes Paradise and areas to the west from the open lake (Fig. 1.1; Coleman, 1937; Karrow, 1987).

Small streams also supplied limited amounts of sediment to the valley from early Holocene to recent times (Karrow, 1987). An example of such a fluvial deposit is the Dundas alluvial fan which is a smooth fan of gravel that spreads southeast from the northern edge of the escarpment towards Cootes Paradise. The change in elevation from the head of the fan to the foot is approximately 46 meters and the fan crosses over the former Lake Iroquois shoreline; Karrow (1963 and 1987) thus determined that the Dundas alluvial fan is younger than Lake Iroquois. The alluvial fan and associated streams most likely developed as the water level of Lake Iroquois lowered following deterioration of the ice dams along the St. Lawrence (Karrow, 1987).

## 2.6 Bedrock Valley Infills in Southern Ontario

The bedrock valleys in southern Ontario, including the Dundas Valley, potentially contain a lengthy record of the late Quaternary events described above. Valley infills have been described from the Milton-Georgetown, Elora and Rockwood areas (Karrow et al., 1961; Karrow, 1963; Karrow, 1987; Greenhouse and Karrow, 1994), each of these valley infills will be briefly examined below.

### 2.6.1 Milton-Georgetown Valley Infill

Meyer (2001) examined the sedimentary infill of buried bedrock valleys in the Milton-Georgetown area and identified six distinctive sedimentary units. The lowermost unit was composed of coarse grained fluvial and colluvial sediments, most likely deposited by rivers flowing along the valley and by mass flow processes reworking sediment on the steep sided valley walls. This was overlain by fine grained silts and clays formed as a result of ponding of water in the bedrock valleys and rippled, laminated and massive sands deposited in fluvial environments. Meyer (2001) determined that these sedimentary units were deposited prior to ice advance during the Nissouri stadial of the mid-Wisconsin and may be equivalent to the lacustrine and glaciolacustrine deposits of the Thorncliffe Formation exposed along the Scarborough Bluffs.

A subglacial till unit overlying the fluvial sands was interpreted as equivalent to the Northern / Newmarket tills, believed to have been deposited during the Nissouri stadial. The uppermost sedimentary units consist of a blanket of fluvial outwash gravel thought to have been deposited during the Mackinaw interstadial and a thick unit of interbedded diamicts, sands and silts interpreted as the Halton Till complex (Meyer, 2001). The Halton Till complex was deposited during the Port Huron stadial as the Ontario-Erie sub-lobe of the Laurentide Ice Sheet rapidly advanced across previously deposited lacustrine deposits (Meyer, 2001). No post-glacial Lake Iroquois deposits were identified in the Milton-Georgetown channels.

### 2.6.2 Elora and Rockwood Valley Infill

Cores taken from the sedimentary infills of the Elora and Rockwood bedrock valleys were examined by Greenhouse and Karrow (1994). The Elora Valley was found to contain the Catfish Creek Till from the Nissouri stadial, overlain by the Maryhill Till and the Tavistock Till, both deposited during the Port Bruce stadial. The youngest till identified within the Elora Valley was the Port Stanley Till / Wentworth Till, deposited during the Port Huron stadial. At Rockwood, a similar succession of tills were identified with the exception of the Tavistock Till that was absent (Greenhouse and Karrow, 1994). In both the Rockwood and Elora valleys, multiple tills (4 within the Elora valley, and 2 within the Rockwood valley) were also found to underlie the Catfish Creek Till and may date back to the last interglacial (Greenhouse and Karrow, 1994).

# Chapter 3: Methodology

## 3.0 Introduction

There are many ways to create subsurface geology models and the process followed will have considerable affect upon the type and reliability of the model output. This chapter describes in detail the process used to create a 3-D subsurface geological model for a part of the Dundas Valley in Hamilton (Fig. 3.1), beginning with the selection of appropriate software and concluding with a discussion of some of the limitations of the models produced.

## 3.1 Software Selection

It is important to select an appropriate software package prior to creating a database for modelling subsurface geological data, as most modelling software requires that the database conforms to a certain format in order for information to be imported correctly. Both the desired model output as well as the available input data should also be considered when selecting a modelling program. In this study, ROCKWORKS 2002 was chosen to model the data because it is capable of analyzing and visualizing lithologic, geophysical, geochemical, stratigraphic, hydrogeologic and borehole data. Multiple algorithms are also available within this program with which to analyze complex data sets (see section 3.5.1). In addition, ROCKWORKS 2002 is able to produce several types of images of the modelled subsurface geology, including 3-D block

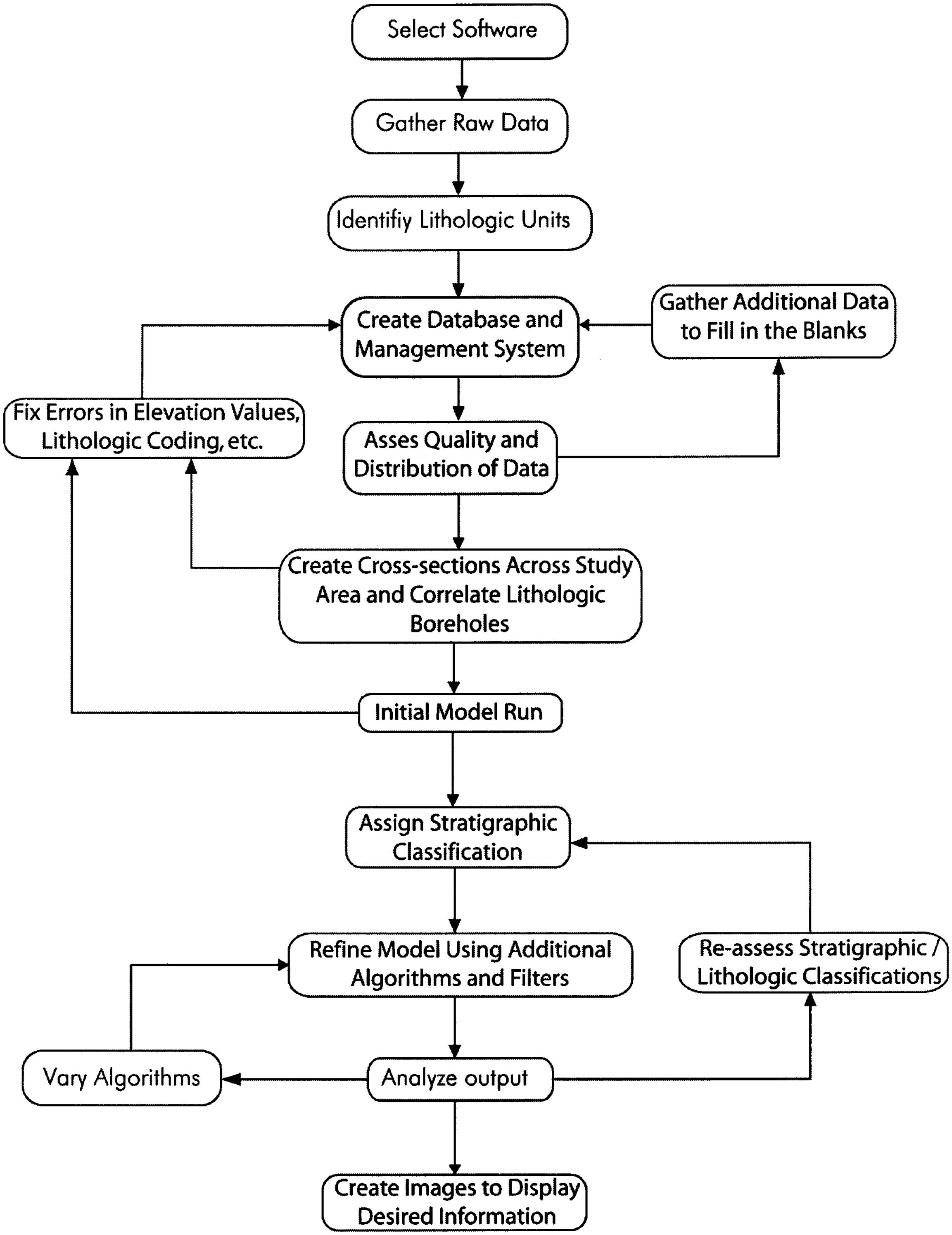



**Figure 3.1** - Flow Chart outlining the steps involved with creating 3-dimensional models of the subsurface stratigraphic units.

diagrams, tube diagrams, fence diagrams, and cross-sections (see section 3.6). Excel was used to create and manage the subsurface geology database as it has the capacity to handle large quantities of data and interfaces easily with ROCKWORKS 2002.

## 3.2 Data Collection

In order to create a model analyzing and displaying subsurface unit geometries within the study area, it was necessary to gather as much subsurface geological data as possible (Fig. 3.1). For this study, data were gathered from seven different sources including the Ontario Ministry of Transportation, the Ministry of the Environment, the Hamilton Conservation Area, McMaster University construction records, the Hamilton Urban Geological Database, the Henkel Canada Limited site investigation and various engineering geotechnical reports (Fig. 3.2). Over 2000 records were used to create a subsurface database covering an area of over 230 $km^2$ (Fig. 3.2).

The data used to create the database were available in a variety of formats. For example, water well borehole data from the Ministry of the Environment (OMOE) were available as a large digital database that could be queried and directly imported into the project database (Fig. 3.3A). Each of the borehole records contained within the OMOE database includes the borehole location and elevation, the nature of lithologic units identified within the borehole and the depth of contacts between each of the lithologic units. Hydrogeological information such as water table depth is also included in the OMOE database but was not used to create the 3-D subsurface models in this study.

Data were also obtained from paper copies of well logs (e.g. construction and geotechnical reports) that were entered into the database by hand (Fig. 3.3B). Although importing large quantities of digital data into the database is much easier than entering individual well log data by hand, the advantage to the latter is the ability to refer back to the original source if any discrepancies arise within the model. The paper copies of well logs also contain more descriptive information about the characteristics of geologic units, which helps in the creation of more accurate facies descriptions and determination of stratigraphic units through amalgamation of individual lithologic units (see section 4.1). Essentially, the large digital databases are good for populating the project database quickly, but the paper copies provide a good distribution of highly detailed borehole logs, and should be incorporated into the dataset whenever possible.

As data were inputed into the project database they were carefully screened and any questionable data points were eliminated. Each data entry was visually scanned to check that the elevation, location, and lithology descriptions seemed reasonable in the context of known geological constraints. For example, data points that created anomalous 'spikes' relative to neighboring points were eliminated from the database. Alternative computer-based methods of quality control can also be performed using the distance-to-point and trend surface polynomial residual gridding algorithms available in ROCKWORKS 2002 (see section 3.5.1), although these methods were not used in this study. These algorithms do not specify which individual boreholes are erroneous, but identify suspect areas that should be examined more closely.

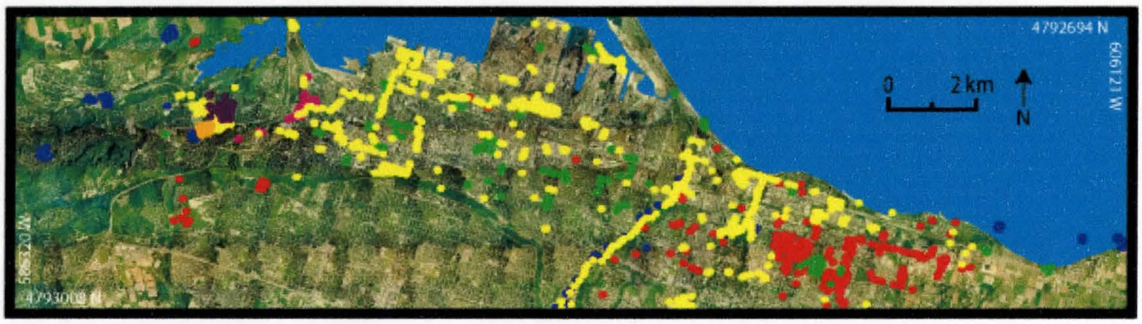



**Figure 3.2** - Georeferenced air photograph showing borehole locations (photo courtesy of Hamilton GIS Services). Over 2000 borehole records were used in this study.

Hamilton Urban Geology Database (yellow dots)

Ministry of Transportation Database (pink dots)

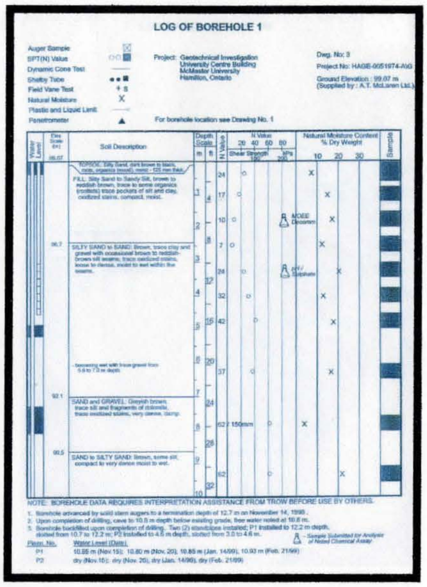
Hamilton Conservation Authority (blue dots)

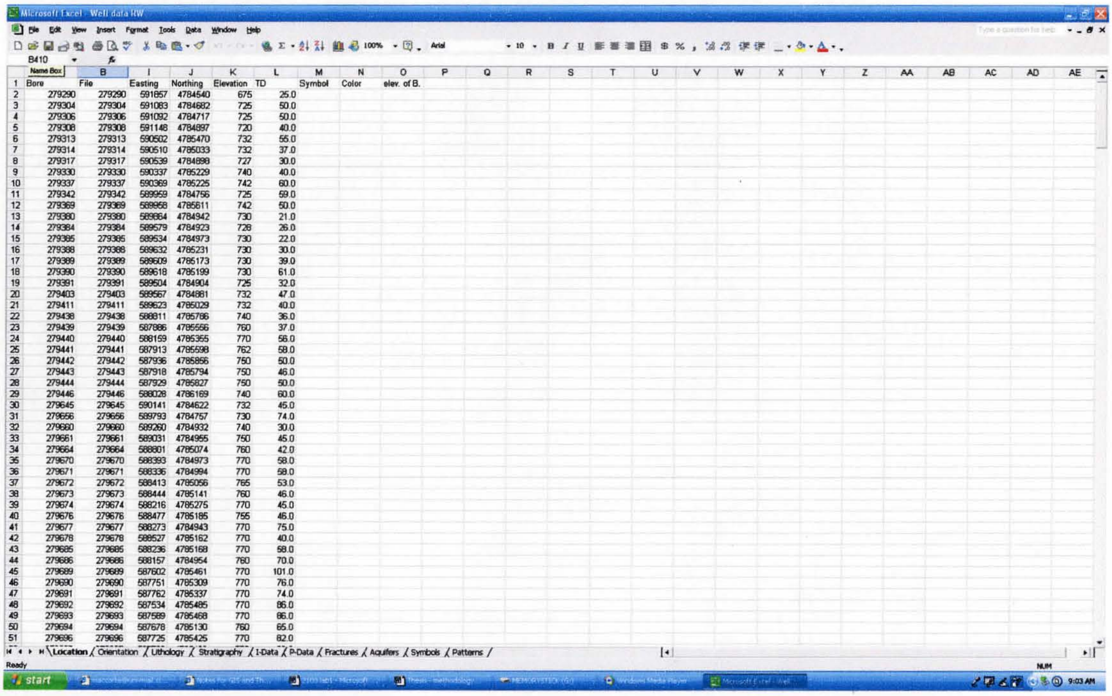
Henkel Canada Limited site investigation (orange dots)

OMOE Water Well Database (red dots)

Hamilton geotechnical reports (green dots)

McMaster University construction reports (purple dots)



| | Bore | File | Easting | Northing | Elevation | TD | Symbol | Color | elev. of B. |
|---|---|---|---|---|---|---|---|---|---|
| 2 | 279290 | 279290 | 591857 | 4784540 | 675 | 25.0 | | | |
| 3 | 279304 | 279304 | 591083 | 4784682 | 725 | 50.0 | | | |
| 4 | 279306 | 279306 | 591092 | 4784717 | 725 | 50.0 | | | |
| 5 | 279308 | 279308 | 591146 | 4784897 | 720 | 40.0 | | | |
| 6 | 279313 | 279313 | 590502 | 4785470 | 732 | 55.0 | | | |
| 7 | 279314 | 279314 | 590510 | 4785033 | 732 | 37.0 | | | |
| 8 | 279317 | 279317 | 590539 | 4784898 | 727 | 30.0 | | | |
| 9 | 279330 | 279330 | 590337 | 4785229 | 740 | 40.0 | | | |
| 10 | 279337 | 279337 | 590369 | 4785225 | 742 | 60.0 | | | |
| 11 | 279342 | 279342 | 589959 | 4784756 | 725 | 59.0 | | | |
| 12 | 279369 | 279369 | 589958 | 4785611 | 742 | 50.0 | | | |
| 13 | 279380 | 279380 | 589864 | 4784942 | 730 | 21.0 | | | |
| 14 | 279384 | 279384 | 589579 | 4784923 | 728 | 26.0 | | | |
| 15 | 279385 | 279385 | 589534 | 4784973 | 730 | 22.0 | | | |
| 16 | 279388 | 279388 | 589632 | 4785231 | 730 | 30.0 | | | |
| 17 | 279389 | 279389 | 589609 | 4785173 | 730 | 39.0 | | | |
| 18 | 279390 | 279390 | 589618 | 4785199 | 730 | 61.0 | | | |
| 19 | 279391 | 279391 | 589504 | 4784904 | 725 | 32.0 | | | |
| 20 | 279403 | 279403 | 589567 | 4784881 | 732 | 47.0 | | | |
| 21 | 279411 | 279411 | 589623 | 4785029 | 732 | 40.0 | | | |
| 22 | 279438 | 279438 | 588811 | 4785786 | 740 | 36.0 | | | |
| 23 | 279439 | 279439 | 587886 | 4785556 | 760 | 37.0 | | | |
| 24 | 279440 | 279440 | 588159 | 4785355 | 770 | 56.0 | | | |
| 25 | 279441 | 279441 | 587913 | 4785598 | 762 | 58.0 | | | |
| 26 | 279442 | 279442 | 587936 | 4785856 | 750 | 50.0 | | | |
| 27 | 279443 | 279443 | 587918 | 4785794 | 750 | 46.0 | | | |
| 28 | 279444 | 279444 | 587929 | 4785827 | 750 | 50.0 | | | |
| 29 | 279446 | 279446 | 588028 | 4786169 | 740 | 60.0 | | | |
| 30 | 279645 | 279645 | 590141 | 4784622 | 732 | 45.0 | | | |
| 31 | 279656 | 279656 | 589793 | 4784757 | 730 | 74.0 | | | |
| 32 | 279660 | 279660 | 589260 | 4784932 | 740 | 30.0 | | | |
| 33 | 279661 | 279661 | 589031 | 4784955 | 750 | 45.0 | | | |
| 34 | 279664 | 279664 | 588801 | 4785074 | 760 | 42.0 | | | |
| 35 | 279670 | 279670 | 588393 | 4784973 | 770 | 58.0 | | | |
| 36 | 279671 | 279671 | 588336 | 4784994 | 770 | 58.0 | | | |
| 37 | 279672 | 279672 | 588413 | 4785056 | 765 | 53.0 | | | |
| 38 | 279673 | 279673 | 588444 | 4785141 | 760 | 46.0 | | | |
| 39 | 279674 | 279674 | 588216 | 4785275 | 770 | 45.0 | | | |
| 40 | 279676 | 279676 | 588477 | 4785185 | 755 | 46.0 | | | |
| 41 | 279677 | 279677 | 588273 | 4784943 | 770 | 75.0 | | | |
| 42 | 279678 | 279678 | 588527 | 4785162 | 770 | 40.0 | | | |
| 43 | 279685 | 279685 | 588236 | 4785168 | 770 | 58.0 | | | |
| 44 | 279686 | 279686 | 588157 | 4784954 | 760 | 70.0 | | | |
| 45 | 279689 | 279689 | 587602 | 4785461 | 770 | 101.0 | | | |
| 46 | 279690 | 279690 | 587751 | 4785309 | 770 | 76.0 | | | |
| 47 | 279691 | 279691 | 587762 | 4786337 | 770 | 74.0 | | | |
| 48 | 279692 | 279692 | 587534 | 4785485 | 770 | 86.0 | | | |
| 49 | 279693 | 279693 | 587589 | 4785468 | 770 | 86.0 | | | |
| 50 | 279694 | 279694 | 587678 | 4785130 | 760 | 65.0 | | | |
| 51 | 279696 | 279696 | 587725 | 4785425 | 770 | 82.0 | | | |

**Figure 3.3 - A)** section of the queried MOE water well database. **B)** Typical borehole log from a construction report.

## 3.3 Data Management

Once the data have been collected, one of the next steps is to create a database management system that can be used to organize and identify individual borehole data sets within the project database (Fig. 3.1). This study required a coding system to identify individual boreholes, their locations, and the subsurface elevation of lithologic units they contained.

Borehole locations were all identified using Universal Transverse Mercator (UTM) coordinates. It was necessary for the coordinate system used in the project to be consistently applied throughout the database to ensure that ROCKWORKS 2002 was able to identify the location of any borehole in the study area as well as its position relative to the surrounding boreholes.

The data imported from the larger digital databases had their own borehole identification (ID) numbers, which were incorporated into the project database. Data obtained from paper records, were given a unique borehole ID that was written on the hardcopy and included in the Excel spreadsheet to provide a quick means of referencing the original borehole logs. When certain model images of the borehole data are created, the borehole ID appears above the corresponding well log. This allows quick referencing back to original data sources if there appear to be discrepancies with a specific borehole record. The most efficient method of coding the paper records was to make the first 2 or 3 letters of the borehole code represent the project title or folder, followed by the project number, and then finally the borehole number. For example, a borehole log obtained from one of the engineering consultancy firms was given the ID HF-4-17-3. In this case the HF indicates that the data can be found in the Hamilton Files consulting report folder, 4 represents the folder number, 17 indicates that the log can be found in the 17th project within the folder, and 3 is the borehole number for that project.

Once a system for coding individual borehole data was established, the layout for the rest of the database was considered. The database layout needs to comply with the format requirements of the chosen modelling software. ROCKWORKS 2002 requires that the data be entered into a specific table structure, and the Excel database was created in the same format to facilitate data import.

## 3.4 Lithologic Coding

In order to ensure that the lithologic data from the various sources were entered into the database in a consistent manner, descriptions of sediment characteristics obtained from digital databases, borehole records, and lithology codes from the water well database, were generalized into six distinct textural categories (i.e. clay, silt, sand, gravel, fine-grained diamict, and bedrock; Fig. 3.1). These textural categories are used in this study to identify and delineate subsurface lithologic units. A lithologic unit is defined here as a geologic unit with specific textural characteristics that can be identified from driller's logs or borehole records and may mapped between boreholes in the subsurface. Using a simple textural coding system as a basis for the identification of lithologic units helped to minimize discrepancies produced by differences in sediment descriptions created by different well drillers. For example, sediments categorized as 'sand' include deposits described as sand, silty-sand, fine sand, coarse sand and pebbly sand on borehole logs. Unfortunately, some lithologic detail is lost in this process but it allows classification of textural data of variable quality provided on driller's logs and in the digital databases.

Most borehole records identify the depths at which significant changes in sediment characteristics were encountered during drilling. However, slight changes in sediment characteristics are not always noted and it was often necessary to manually check sediment descriptions on driller's logs (if available) to ensure correct identification of lithologic units.

Identification of lithologic units also took into consideration the nature and likely genesis of the sediment as textural descriptions often varied considerably between individual boreholes. For example, the lithologic unit identified as 'fine-grained diamict' includes sediments described on driller's logs and in borehole records as fine-grained tills, pebbly silty clays or clayey silts with gravel. These poorly sorted sediment types are difficult to distinguish from one another and are most likely the same sediment type, recorded differently by different well drillers.

It was also necessary to create a numeric suffix to add to the descriptive coding system for the lithological units. Most boreholes contained more than one unit of each textural type and in order to ensure correct stratigraphic correlation of lithologic units, each textural type was labeled from the top down with a numeric suffix. For example, if two separate gravel units were recorded in a borehole, the uppermost gravel unit was referred to as 'gravel' and the lower gravel unit was labeled 'gravel2'. This method of coding allows for additional lithologic units to be added to the stratigraphy in the future without altering the current codes. Subsequent units of similar lithology found deeper in the sedimentary succession would be coded as 'gravel3', 'gravel4' and so on.

For each borehole record, the elevation of the upper and lower contacts of each lithologic unit was entered into the Excel spreadsheet. When all the data were entered into the project database, a manual scan of the data was performed to check for errors. The most common errors discovered were in the recorded elevations of the borehole top and of lithologic unit boundaries. These errors were often found in data that originated from the large digital databases. In some instances, the depth of unit boundaries were recorded in Imperial rather than metric units and could be rectified with a simply unit conversion. Unfortunately, some unit elevations were recorded incorrectly and, unless a hardcopy of the data was available with the correct information, these records were deleted from the database to eliminate introducing errors into the model.

### 3.4.1 Creating Cross-Sections

Once the elevations of lithologic unit contacts for every borehole were included in the dataset, the project database was imported into ROCKWORKS 2002 and preliminary models of the subsurface stratigraphy were run (Fig. 3.1). Initially, a series of cross-sections were constructed across the study area. The objective of the cross-sections was to identify laterally continuous lithologic units that may be used to develop a subsurface stratigraphy. Lithologic units were identified through careful correlation of textural characteristics between adjacent boreholes along numerous transects across the study area

(Fig. 3.4). This allowed cross sections to be created that connected textural units at specific stratigraphic positions with one another. In order to check the consistency of the correlations made, many 'closed' sections were constructed (starting and ending at the same well) which allowed an individual lithologic unit to be traced back to its original stratigraphic position. This ensured that the units did not cross each other along a single transect. In some instances initial lithologic codings made from the well logs were found to be wrong and had to be corrected (Fig. 3.5 A and B). Once the lithologic units were correctly identified on the cross-sections, a table was created in the project database labeled "stratigraphy" which included stratigraphic data (the elevations of upper and lower contacts of each lithologic unit) for each borehole. These data were then entered into ROCKWORKS 2002 and preliminary models were run.

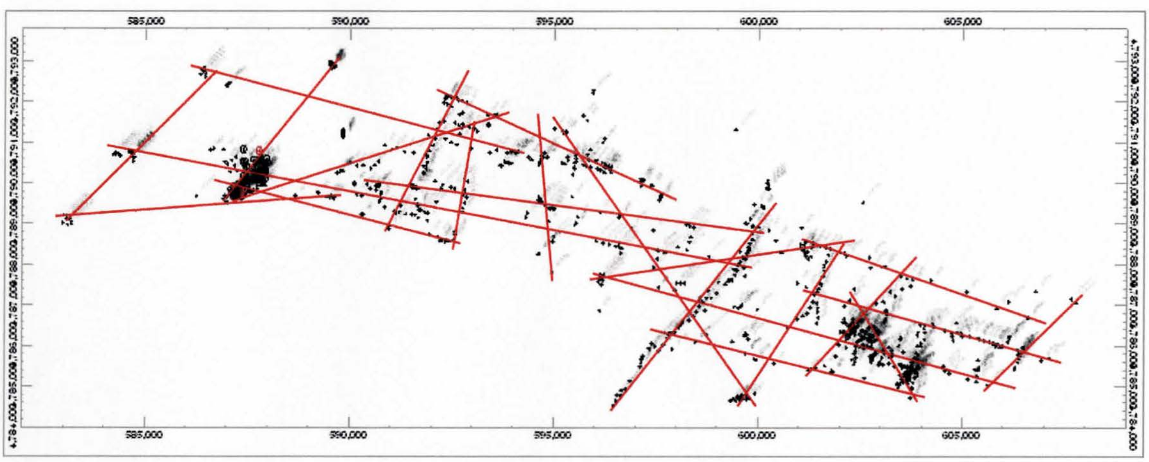



**Figure 3.4** - Borehole location map showing a few of the transects (red lines) that were used to create cross-sections through the study area.

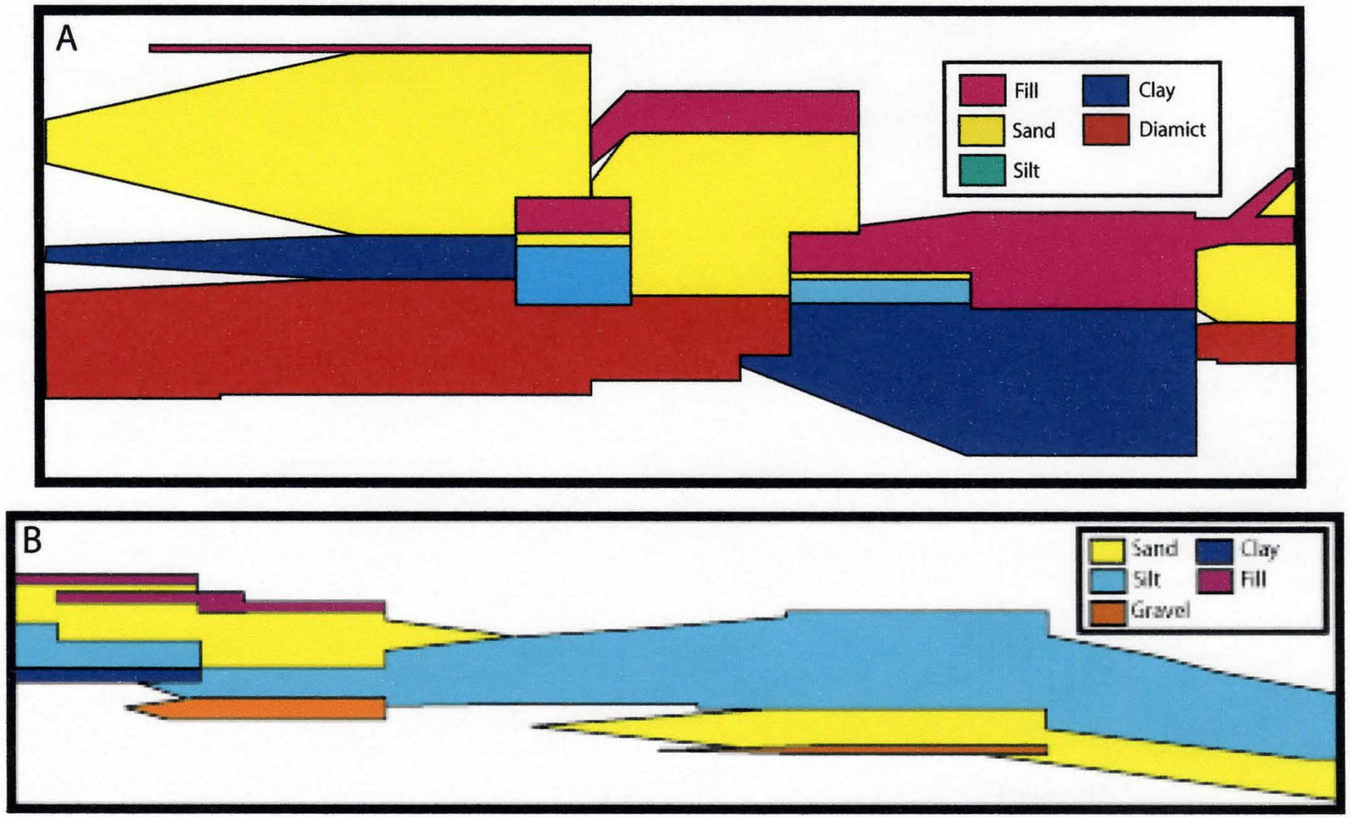



Figure 3.5 - A) Borehole correlation diagram showing initial correlations made between INCORRECTLY labeled lithologic units below a section of the study area. Original logs and lithologic classifications were rechecked and units relabled correctly prior to re-running the correlation program. Image is shown at 20X vertical exaggeration. B)Corrected borehole correlation diagram showing lateral continuity and cross-sectional geometry of individual lithologic units indentified below a section of the study area. Image is shown at 40X vertical exaggeration.

## 3.5 Producing a 3-D Model

Once all the subsurface lithologic units were correctly assigned a numeric code, a box model of the study area was created using ROCKWORKS 2002 software (Fig. 3.6 A and B). The geological data used to create the model can be analyzed and interpreted in a variety of ways through the use of different algorithms and settings available in the software (Fig. 3.1).

An algorithm is defined by the National Aeronautics and Space Administration (NASA, 2005) as a mathematical relationship between an observed quantity and a variable used in a mathematical process to calculate a quantity. In the case of creating 3-D geological models, borehole information is stored in the project database as a series of data points which are used in the selected mathematical process (the algorithm) to calculate node values that will create the unit grids of the model. A node is a point of data created by calculating what should be there based on the proximal point data. Calculated nodal values are used by the software to create grids of the units within the model in order to display the images. Each algorithm calculates the nodal values in a different way (Table 3.1).

Grid nodes are simply calculated data points assigned on grid line intersections (Fig. 3.7). Most software programs allow users to select different grid sizes for their model. If a smaller grid is chosen to cover the study area, there will be a greater number of grid intersections, which will result in the creation of a greater number of grid nodes. A smaller grid is beneficial in locations with laterally variable sedimentary units, as unit

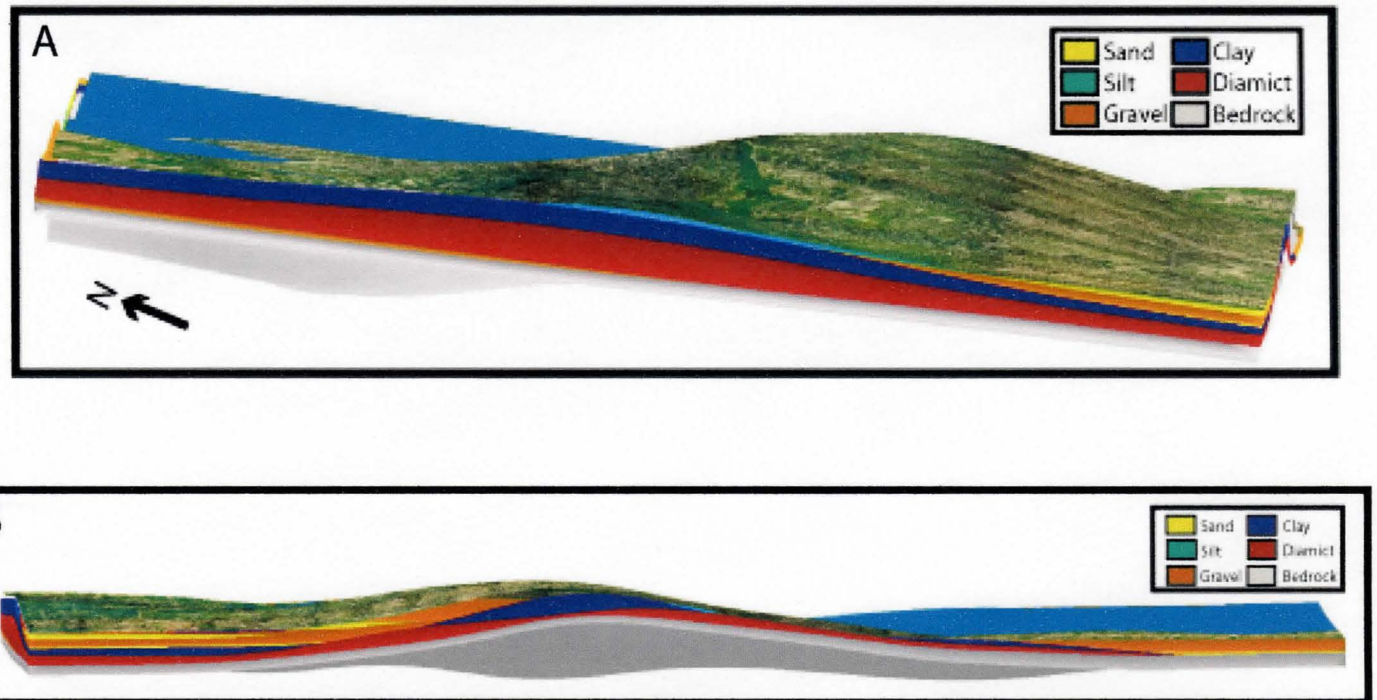



**Figure 3.6** - A) 3-D box model (looking toward the east) showing lithologic units underlying the study area. Note the lateral continuity of diamict and clay units within the valley infill. B) 3-D box model looking Norh. The bedrock 'high' in central area connects southward with the base of the Niagara Escarpment. Images are shown at 20X vertical exaggeration.

**Table 3.1:** Algorithms available with ROCKWORKS 2002 for analyzing and interpreting spatial data.

| **Algorithm** | **Description** |
|---|---|
| Closest point | Each node is assigned the value of the closest point |
| Inverse Distance | Weighted averages are used to calculate the node values |
| Directional Weighting | Allows the user to specify a direction bias within an inverse distance grid |
| Kriging | Identifies patterns and directional trends throughout the model |
| Multiple Linear Regression | Simple distance weighting is applied to regression analysis |
| Trend Polynomial | Finds regional trends within the data |
| Triangulation (grid based) | Creates networks of triangles in order to assign grid values |
| Hybrid | Interpolates data using two or more gridding methods with the ability to weight their respective influences on the data |

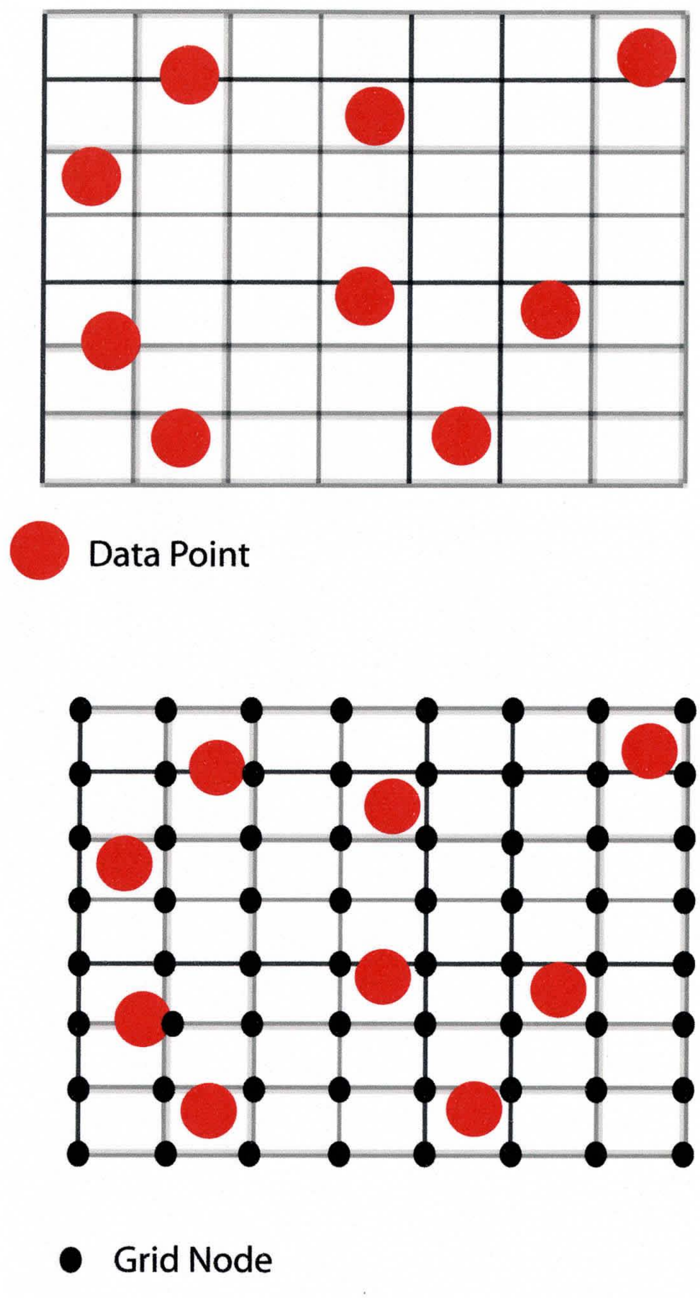



**Figure 3.7** - the creation grid nodes which are calculated based on the values of the available data points.

thickness changes can be modelled more accurately. However, increasing the number of grid nodes created by the model requires additional computational time as well as additional computer memory to store the grid surfaces.

### 3.5.1 Available Algorithms

There are 10 algorithms available in ROCKWORKS 2002 that may be used to create node values and analyze the dataset in different ways (Table 3.1). Of the 10 algorithms, 2 are used to evaluate the quality of the data rather than for interpretation of the data itself (i.e. distance to point and trend residual polynomial; Table 3.2).

**Data quality** can be evaluated by applying a *trend residual polynomial* algorithm that shows locations in the study area with anomalies or possible 'bad data' by identifying local deviations from regional trends in the dataset (Table 3.2). Locations with 'bad data' appear as spikes on the model output. A trend surface polynomial was applied to the large water well databases in this study in order to identify locations where data may be suspect and should be examined more carefully. The trend residual polynomial algorithm provides a reliable check of data quality in areas underlain by planar tabular ('layer cake') unit geometries, but is not as effective when geologic units have highly irregular geometries.

The distance to point algorithm creates an image of the modelled area showing the distance of each node to the closest data point (Table 3.2). This is useful for indicating areas within the study area with poor data coverage where model results may

**Table 3.2**: Algorithms available with ROCKWORKS 2002 for analyzing data quality

| Algorithm | Description |
|---|---|
| Distance to Point | Produces a model of the study area mapping the values of the distances from the data points. This model is used to indicate areas of good and bad data coverage. |
| Trend Residual Polynomial | Produces spikes on the map of the study area in locations where data deviates from the regional trend for each unit. |

have reduced reliability. The distance to point algorithm was used to identify areas of poor data coverage in Lake Ontario and on the four corners of the study area where very few data points exist (Fig. 3.2 and 3.8).

**Spatial analysis and interpretation** of the model database may be performed using a variety of different algorithms (Table 3.1; Fig. 3.1). Each algorithm calculates the node values differently and thus controls how the data is processed in the creation of the model. The same database can produce very different model outputs depending on the algorithms used (Fig. 3.9). In this study, data were modelled using all available analytical algorithms (Table 3.1) in order to identify and select the most representative model of the study area. The decision as to which algorithm to use and which model was most representative was based on repeated manual checking of the model output with individual input data points.

In this case, the model that best represented the subsurface geology of the study area was created using the *inverse distance* algorithm which assigns values to the grid nodes that are weighted averages of either nearby data points or a selection of directionally distributed neighbors. The advantage of the inverse distance algorithm is that it produces a smooth and continuous grid that does not exaggerate its extrapolations beyond the given data points; however, this algorithm also runs the risk of producing a "bulls-eye" effect in some data sets.

The inverse distance algorithm provides the option of determining the exponent weight, which determines how "local" or "global" the gridding process will be. An exponent weight of "1" was selected to use only local (proximal) borehole information in

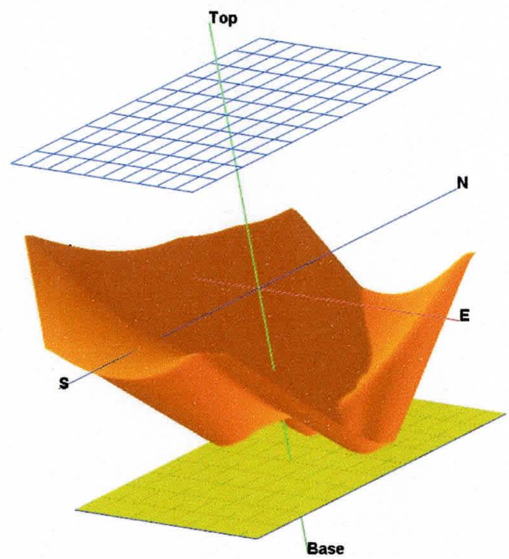
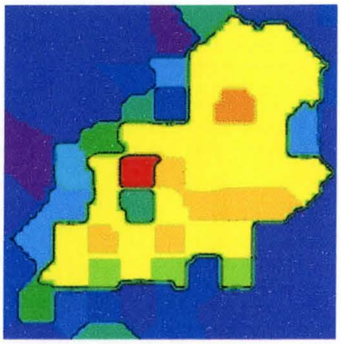
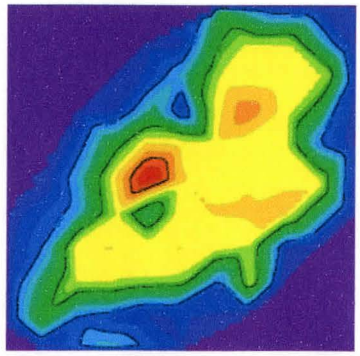


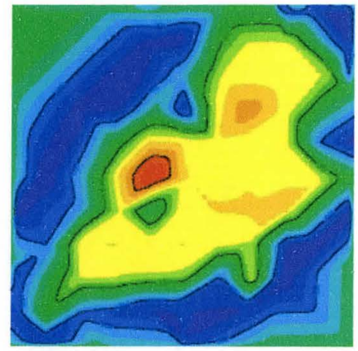

**Figure 3.8** – Model of the study area using the distance to point algorithm. The high points indicate areas where the data coverage is poor (see fig. 3.2 for location of data points).



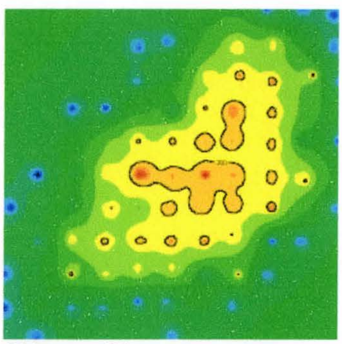
A) Closest Point



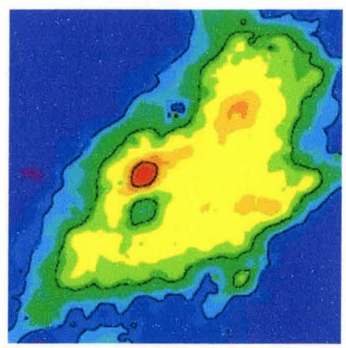
B) Triangulation without edge interpolation



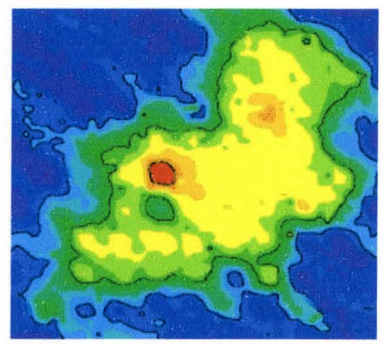
C) Triangulation with edge interpolation



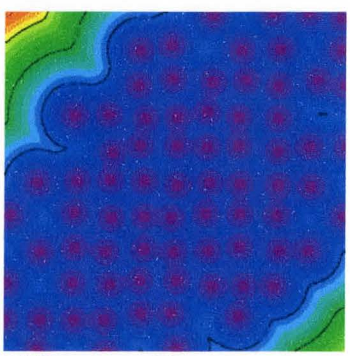
D) Inverse Distance



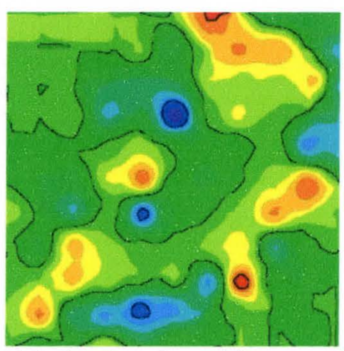
E) Directional Weighting = 1.0 (45 degrees)



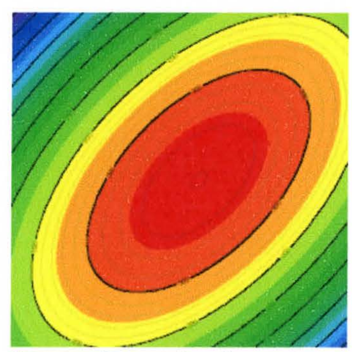
F) Directional Weighting = 2.0 (135 degrees)



G) Distance to Point



H) 2nd-order polynomial residuals



I) 2nd-order trend-surface polynomial

**Figure 3.9** - Variations in model output using different algorithms (A to I). (from ROCKWORKS 2002).

the calculation of the grid node; in this way, the values of distant data points exert less influence than nearby points (ROCKWORKS, 2002). This allows the model to recognize local variability in unit values, an important factor when modelling subsurface geological conditions.

A second option available with the inverse distance algorithm is the ability to perform a quadrant search. This option tells the program that instead of simply finding the nearest neighbors to incorporate into the calculated node value, it should look for a point in each 90-degree sector around the projected node location. This kind of directional search can improve the interpolation of grid values that lie between data point clusters. However, when the quadrant search was applied to this dataset, the lithological units were stretched unrealistically in the north-south direction over topography (Fig. 3.10). This is most likely the result of clustering of data points in a North-South direction within the study area; given this constraint on the distribution of available data, quadrant searching was not reasonable to use on this dataset.

### 3.5.2 Refining the Model

Once an algorithm has been selected to compute the model, minor adjustments can be made to the data in order to refine the model. In this study, a smoothing filter was administered to reduce spurious "noise" within the grid model and emphasize regional trends. The smoothing filter provides options to adjust the size of the filter. Filter size refers to the number of adjacent nodes used to create a new set of averaged (smoother)

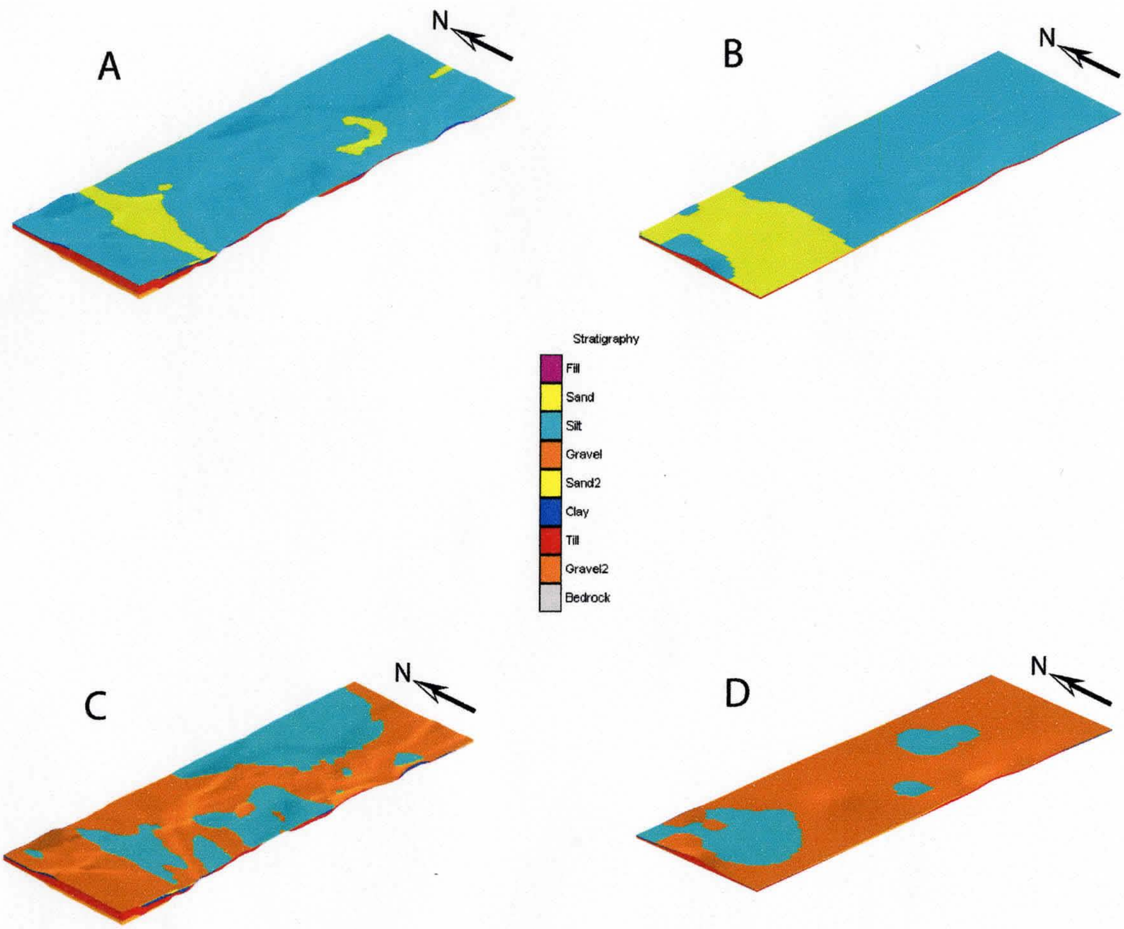



**Figure 3.10** - Examples of the variation in model output using the quadrant search option of the inverse distance algorithm (A and C), compared with model output using the inverse distance algorithm without quadrant search (B and D). A and B are models of Sand, and C and D are models of Silt. Manual checking of the database shows that images A and C incorrectly portray the distribution of the units in question.

grid nodes. A filter size of "1" results in each node being assigned the average of itself and the 8 nodes immediately surrounding it, 1 layer deep. A filter size of "2", computes nodes with values calculated from the average of the node value and that of the 24 immediately surrounding nodes, 2 layers deep. Using a large filter size is appropriate for study areas with a high density of node values, but in areas with sparse data coverage, a lower filter size should be used to avoid weighting the node average on distant points that may have little similarity with the node in question.

ROCKWORKS 2002 also allows the number of iterations to be set from 1 to 4, which refers to the number of times that the smoothing filter will pass over the study area. The higher the number of iterations, the smoother the model will become because the node values will be continuously averaged based on the previously computed averages. If the filter size and iterations are set too high for the corresponding project node density, then the program will begin to assimilate the node values and create units that are more extensive than they are in reality. Smoothing filters are beneficial to run in areas underlain by geological units with planar tabular, or gently undulating geometries, or areas with highly variable borehole coverage in order to smooth out the modelled surfaces (Fig. 3.11).

Further refinements of the model can be made by changing the order in which subsurface layers are constructed. In ROCKWORKS 2002, 'Onlap' can be activated which instructs the program to construct the model from the bottom upwards, giving priority to the underlying units. This means that the lowermost unit (bedrock) is

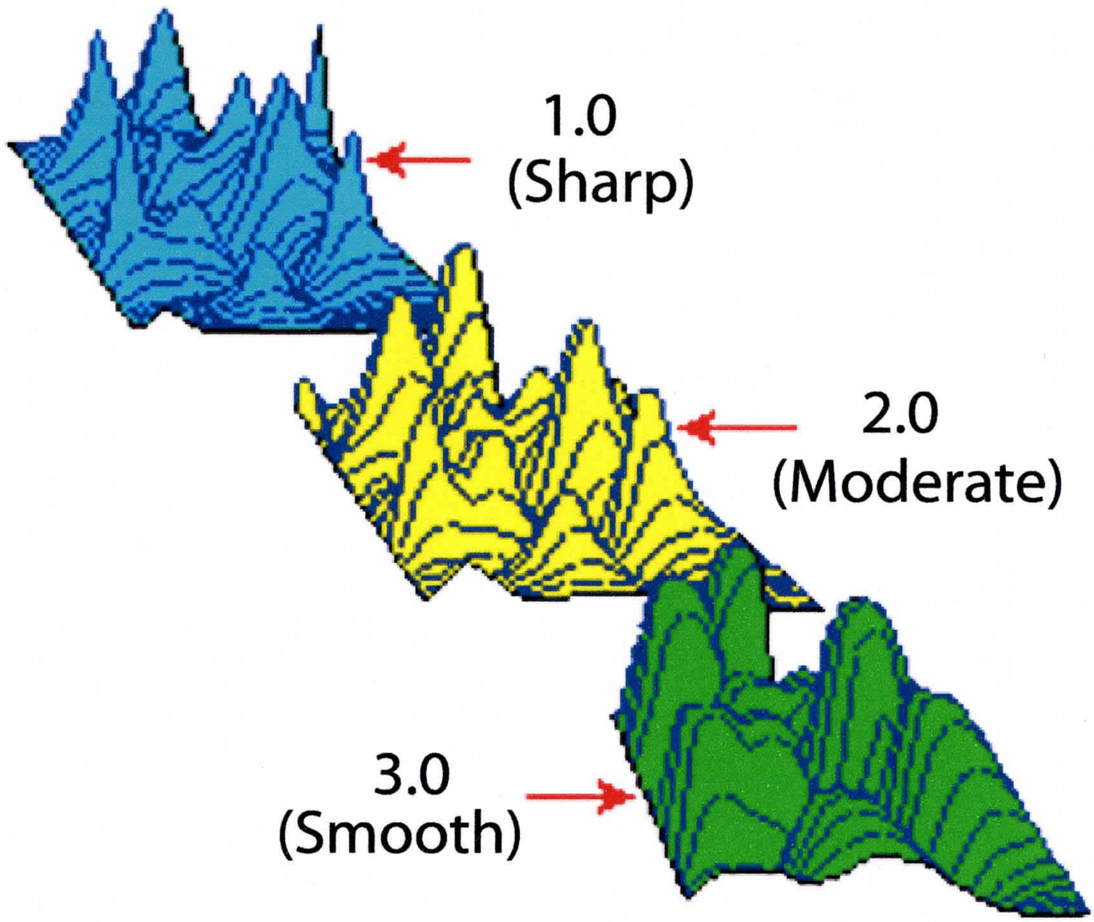



**Figure 3.11 -** Effects of the smoothing filter. The value of the filter determines the amount of smoothing of peaks in the model output. (from ROCKWORKS 2002).

modelled first and when the bottom of the overlying unit is modelled, it will not be permitted to intersect the upper surface of the bedrock. This allows for undulation along contacts between units and prevents the program from intertwining the surfaces of overlying and underlying units (Fig. 3.12).

In this study, the inverse distance algorithm was used in conjunction with Onlap and a smoothing filter size of 1 that ran twice, to create a model that appears to most accurately represent the study area based on prior knowledge of regional subsurface geology and history (Fig. 3.6 A and B).

### 3.5.3 Modelling Major Physiological Features

There are three major physical features of the landscape that need to be considered when modelling the subsurface geology of the Dundas Valley - the Niagara Escarpment, Lake Ontario and the shape of the valley itself (Fig. 1.1; 2.5D). These features create unique and complex unit geometries and data distributions that pose problems for the modelling software.

The Niagara Escarpment forms a distinct and abrupt boundary along the northern and southern sides of the valley. In the past, this geological 'boundary' controlled the extent of lacustrine inundation and glacial ice cover and is a major influence on surface sediment distribution in the region. The differences in sedimentary types and successions found above and below the Niagara Escarpment require that subsurface geological units in each of these areas be kept separate so that the modelling program does not attempt to

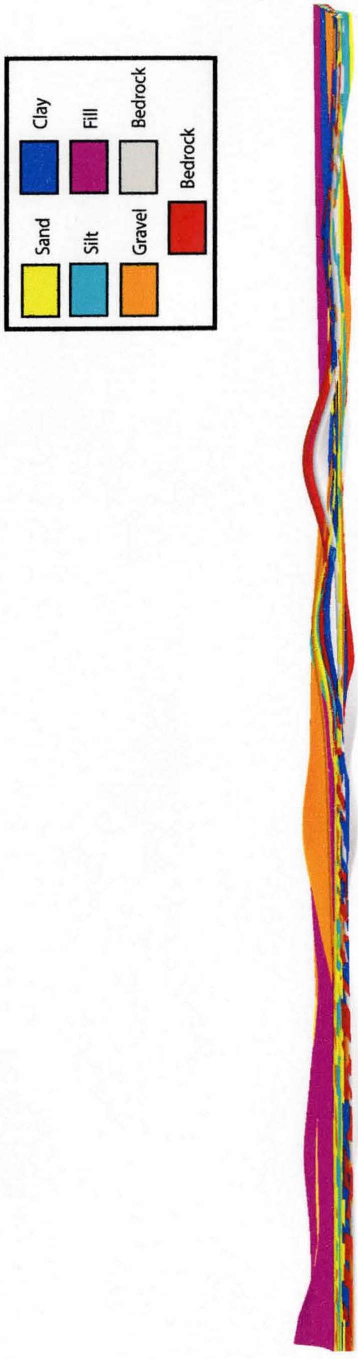



**Figure 3.12** - A box model of the study area with Onlap turned off. Note the unrealistic intermixing of subsurface units.

correlate their lithologies. This study did not include data from areas above the escarpment but was restricted to the valley infill; future modelling studies of the broader region will have to address the problem of dealing with the geological boundary created by the escarpment. Filtering algorithms such as the polygon filter, distance filter, and grid filter may be appropriate for this purpose.

The shape of the valley infill itself must also be considered when analyzing the model output. Sedimentary units within valleys tend to thicken towards the center, and thin towards the margins. ROCKWORKS 2002 tries to create and maintain planar unit geometries with flat surfaces and therefore tends to raise the surface elevation of a unit near the center of the valley and lower the elevation along the valley wall. This problem should be acknowledged when interpreting the model output.

Lake Ontario forms a prominent boundary at the eastern terminus of the Dundas Valley (Fig. 1.1) as it forms a region in the study area with very little to no data coverage (Fig. 3.2). This is a problem for the modelling process (see section 3.7) as ROCKWORKS 2002 extrapolates the sedimentary units identified along the lake shoreline into the lake (Fig. 3.13). Future 3-D modelling of the area will apply additional filtering algorithms such as the polygon or the distance filters to avoid this problem.

## 3.6 Data Visualization

There are numerous methods of visualizing the model output including simple borehole correlations (Fig. 3.5 B), tube diagrams (Fig. 3.14A), fence diagrams (Fig. 3.14B), and 3-D box models of the total subsurface geology (Fig. 3.14C) or individual stratigraphic units (Fig. 3.14D). Once the model is run it is displayed on screen in the 3-D plotter, a true 3-D visualization tool that allows rotation of the model around both vertical and horizontal axes.

Due to the large number of data points and the geographic extent of the study area, ROCKWORKS 2002 had difficulty creating fence and tube diagrams from the whole project database. A smaller subset of high-quality data from the McMaster campus area was therefore modelled in order to illustrate the image producing capabilities of ROCKWORKS 2002. The area encompassing the McMaster Campus and a nearby residential area was chosen because of the large number of good quality borehole records available from a relatively small geographic area (58 records for an area of 0.13 $km^2$; Fig. 3.15). Numerous two- and three-dimensional images were created from this smaller database to help identify the subsurface geometry and distribution of individual sediment units (see Figs. 3.5 B, 3.14 A through D). One of the more useful images is the box model (Fig. 3.14 C) that shows a solid 3-D representation of the underlying geology but only displays 3 sides of the 'box' at any one time. In order to visualize the full geometry of each of the modelled units, an 'explosion diagram' (Fig. 3.14 D), can be created in which the units within the box model (Fig. 3.14 C) are vertically separated from one another.

The images created by ROCKWORKS 2002 were used to establish the geometry and lateral continuity of subsurface units in the study area and to better understand the depositional origin and history of the sedimentary infill of the Dundas Valley (see Chapter 4). The images were also used to locate and characterize aquifer and aquitard units and to identify possible groundwater and contaminant migration pathways (see Chapter 5).

## 3.7 Limitations of the 3-D models

It is important to note that the 3-D subsurface models of the Dundas Valley presented in this thesis do not give an entirely accurate representation of subsurface geological conditions in all parts of the study area. These inaccuracies are due to sparse data coverage in certain areas and the geological complexity of the region. The study area contains three major physiographic features that strongly influence subsurface unit geometries and data distributions - the Niagara Escarpment, Lake Ontario and the shape of the valley itself (Fig. 1.1; 2.5D). These features pose particular problems for the ROCKWORKS 2002 modelling software.

One such challenge is the lack of data in certain sections of the study area (Fig. 3.8). ROCKWORKS 2002 requires a rectangular study area and creates maps extrapolating the subsurface lithologic units identified to all extremities of this area based on available data points, regardless of the distance to the model edges. The study area in

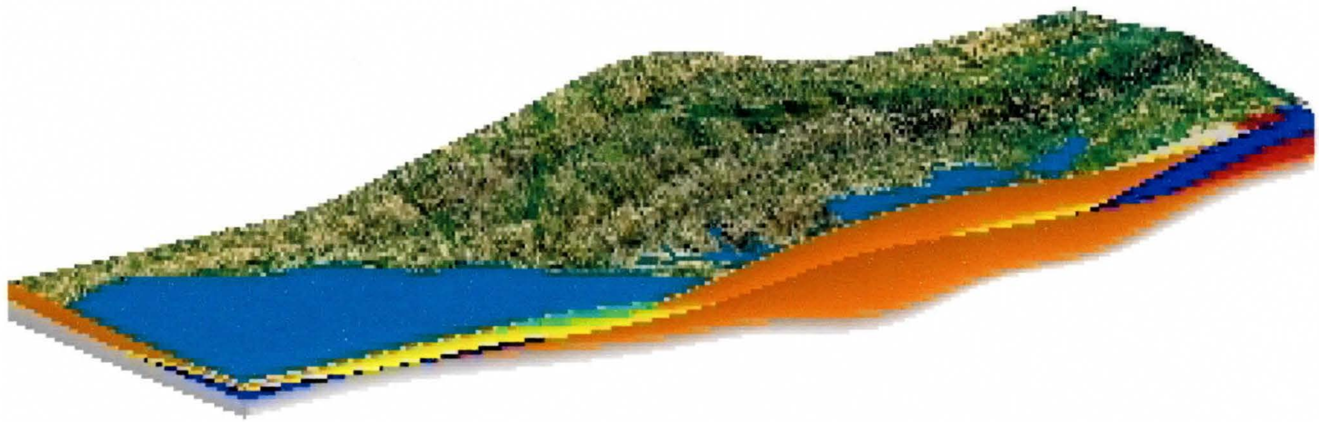


**Figure 3.13** - Box model of the study area showing extrapolation of the sandy-gravels (orange) of unit 2 identified along the lake shoreline into areas of the lake in which there is no data coverage. This problem will be eliminated in future model runs by the application of a filtering algorithm that will remove areas of poor data coverage from consideration by the model. Image is shown at 20 times vertical exaggeration.

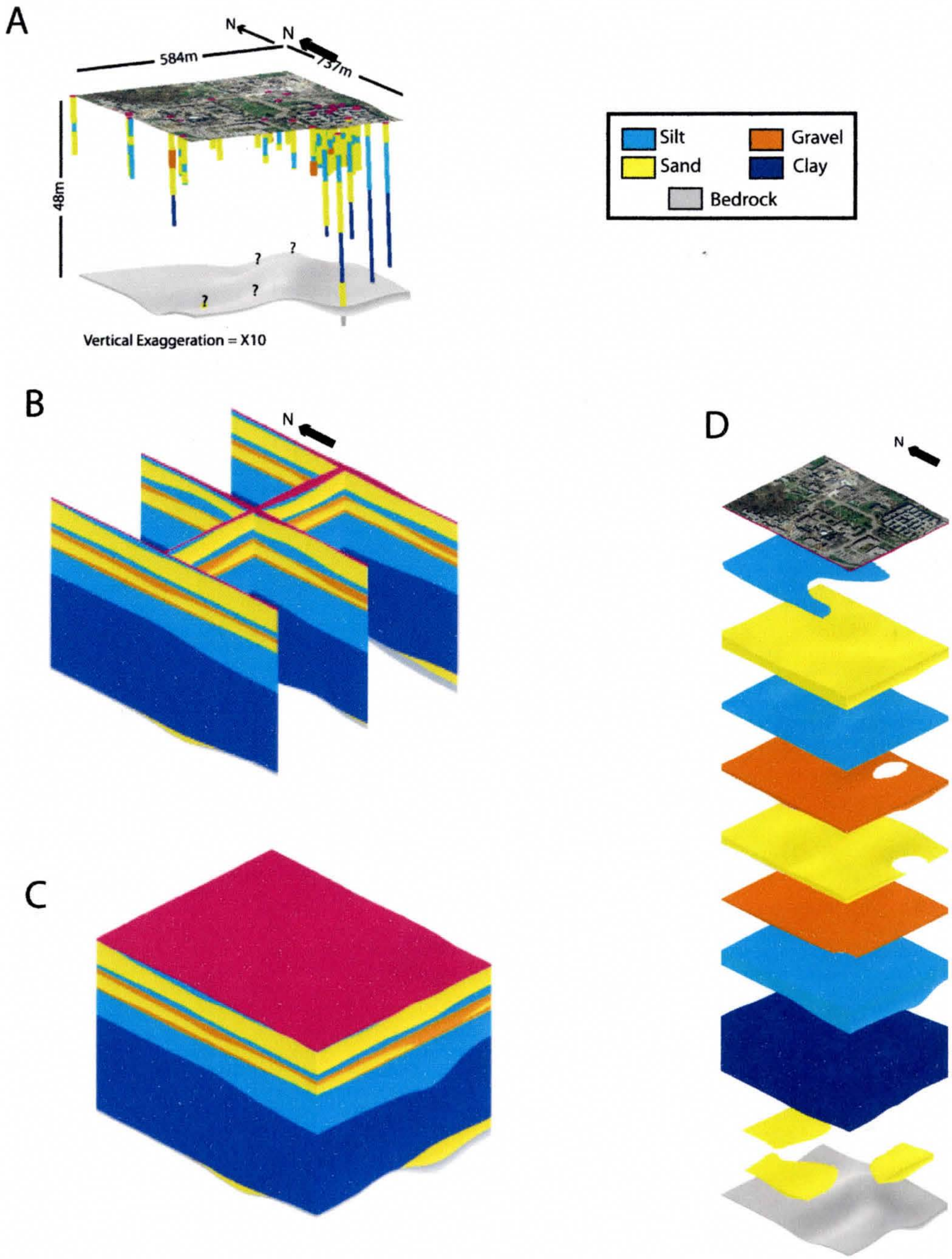



**Figure 3.14** - Images of the subsurface geology beneath the McMaster University campus (a subset of the study area) A) a tube diagram showing modelled bedrock surface. Air photo is overlain to show borehole locations, B) a fence diagram, C) a box diagram, and D) an 'exploded' box model in which the individual lithological units have been vertically separated in order to show unit geometries more clearly. Air photo is overlain to provide geographic context.

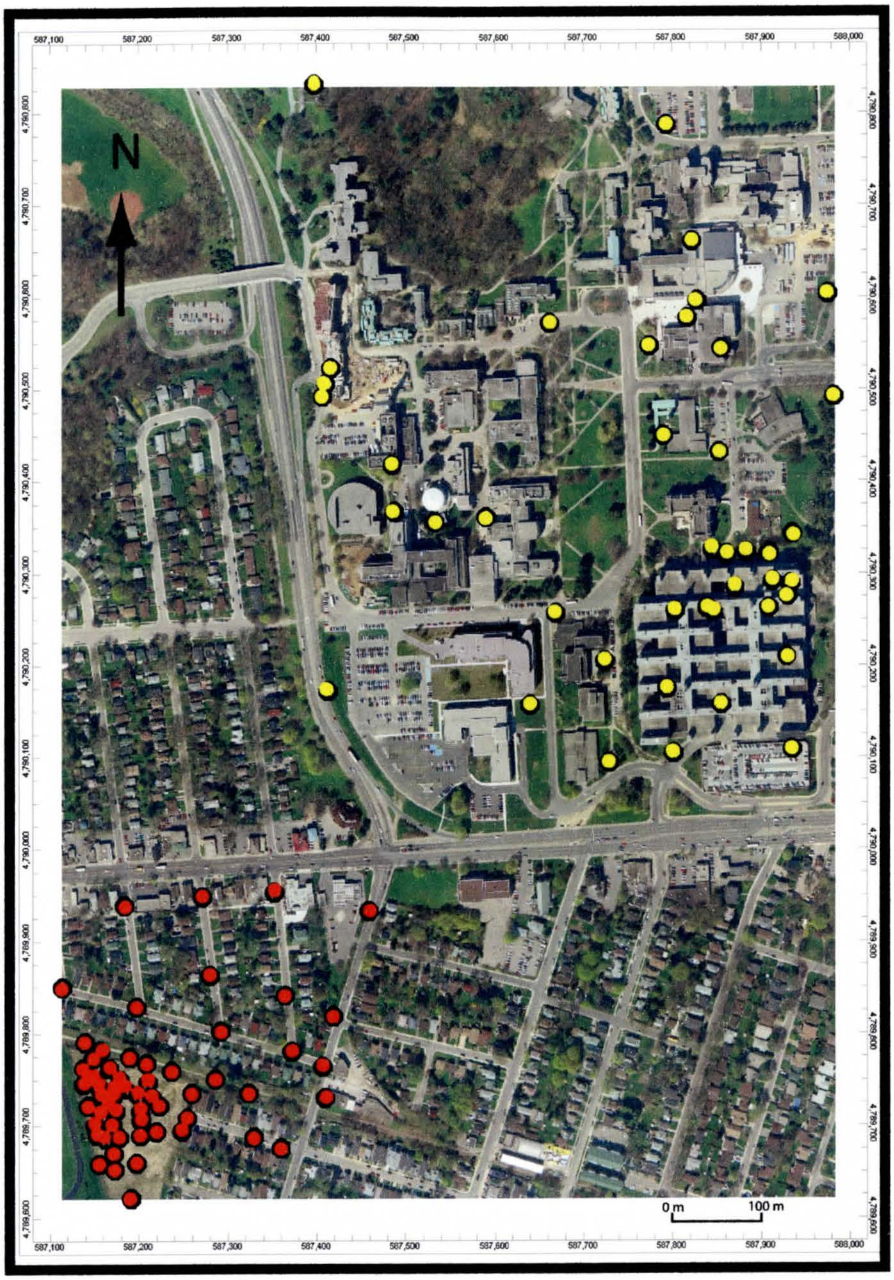



**Figure 3.15** - Georeferenced air-photograph showing location of boreholes on the McMaster campus (yellow dots) and Henkel site (red dots).

this case encompasses water bodies such as Lake Ontario, Hamilton Harbour and Cootes Paradise (Fig. 1.1). However, there are no data points available from these areas, and the form of modelled subsurface units beneath these water bodies should be considered unreliable (Fig. 3.8).

The Niagara Escarpment forms a distinct and abrupt boundary along the northern and southern sides of the Dundas Valley. In the past, this geological 'boundary' controlled the extent of lacustrine inundation and glacial ice cover and is a major influence on surface sediment distribution in the region. The differences in sedimentary types and successions found above and below the Niagara Escarpment require that subsurface geological units in each of these areas be kept separate so that the modelling program does not attempt to correlate their lithologies. This study did not include data from areas above the escarpment but was restricted to the valley infill; future modelling studies of the broader region will have to address the problem of dealing with such a geological boundary.

Despite these limitations, the modelled 3-D subsurface stratigraphy below most of the study area is consistent with known geological conditions and can be applied with confidence.

# Chapter 4: Subsurface Stratigraphy: interpretation of model output

Nine separate subsurface lithologic units were identified in the study area on the basis of their textural characteristics and stratigraphic position. These are recorded from bottom to top as; bedrock, gravel2, diamict, clay, sand2, gravel, silt, sand, and fill; their subsurface distribution is shown in the 'exploded' 3-D box model (Fig. 4.1). In order to facilitate paleoenvironmental and hydrostratigraphic interpretation of this complex succession, vertically and/or horizontally juxtaposed lithologic units with similar textural characteristics have been grouped together to form five 'stratigraphic units' (Units 1 through 5; Fig. 4.1).

## 4.1 Identification of Stratigraphic Units

Stratigraphic units are defined here as geologic units with distinct characteristics that can be mapped in the subsurface and may be used to identify hydrostratigraphic units including aquifers/aquitards and/or to help reconstruct depositional histories. In this study, stratigraphic units consist of one or more lithologic units that are closely associated in vertical succession, have similar textural characteristics and were probably deposited under similar environmental conditions (Fig. 4.1). For example, sand2 and gravel are commonly associated in both vertical and lateral succession which suggests they formed in similar or laterally adjacent depositional environments ('Walther's Law'; Middleton, 2004). The two lithologic units have thus been grouped together to form a single

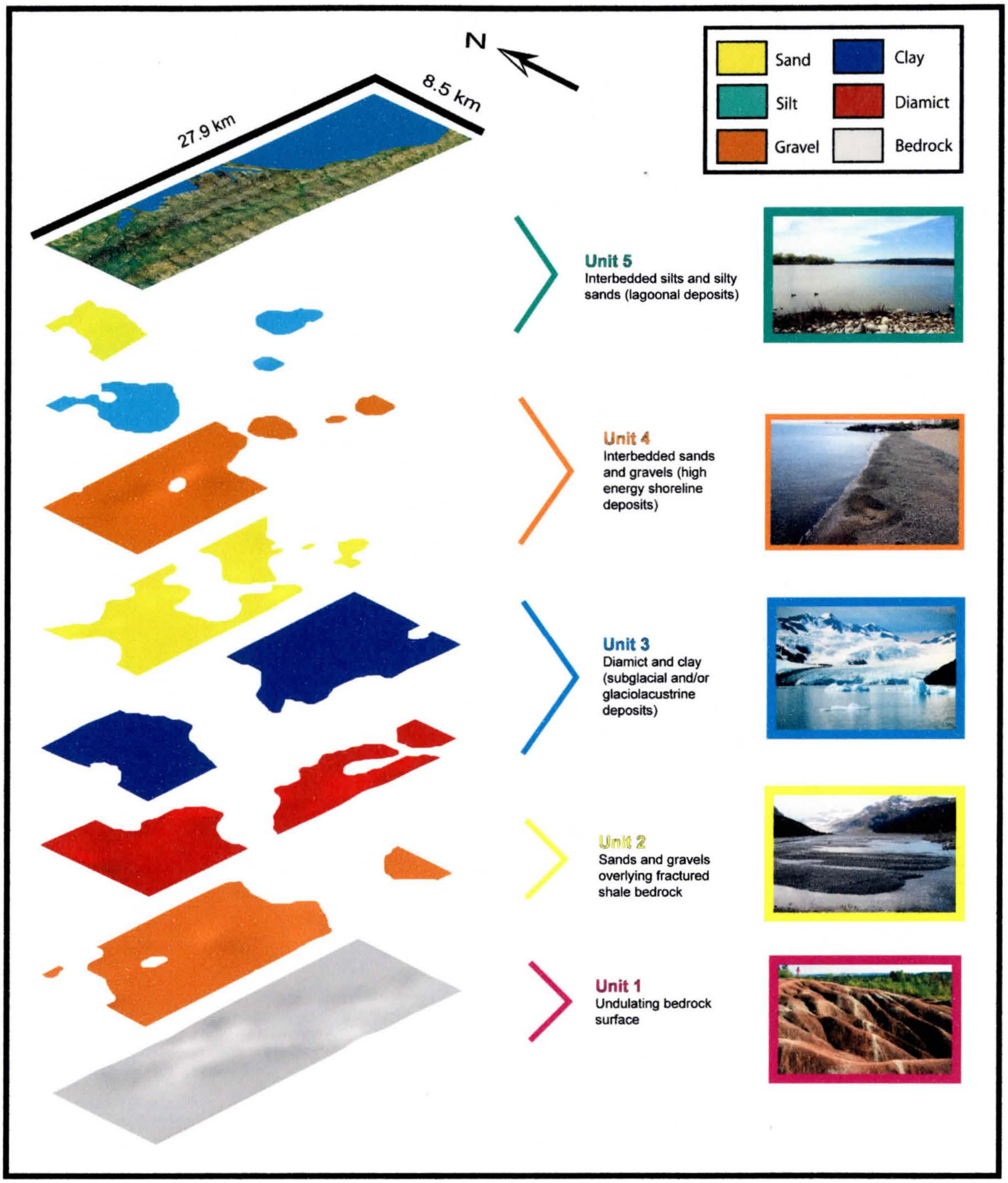



**Figure 4.1** - 3-D 'exploded' model of lithologic units beneath the study area showing each unit as a vertically separated layer. Texturally similar lithologic units are grouped to identify stratigraphic units (Units 1 through 5) which record deposition under specific environmental conditions (modern analogies shown by photographs at right).

stratigraphic unit (Unit 4, Fig. 4.1). A detailed description and interpretation of the five stratigraphic units is presented below.

## 4.2 Description and interpretation of stratigraphic units

### 4.2.1 Unit 1: Bedrock

Bedrock (Unit 1) lies at depths of between 1 and 50m below ground surface in the study area, and is thought to lie at over 180m in the deepest parts of the Dundas Valley (Karrow et al., 1961; Karrow, 1987; Edgecombe, 1999). Bedrock consists of red and grey shales of the Georgian Bay and Queenston formations in the deeper parts of the valley, and interbedded shales and dolostones along the valley walls (Fig. 2.10 B, 4.1; Straw, 1968; Karrow, 1987). The study area, which does not include the steep valley walls, or the deep, central portion of the Dundas Valley, is characterized by an undulating bedrock surface with a relief of 130m. A prominent bedrock high can be identified from the subsurface data that trends east-west along the southern edge of the study area (Fig. 4.2).

Unfortunately, bedrock topography is not well constrained in this study due to a lack of borehole data from the deeper sections of the Dundas Valley; this problem has also been recognized by other researchers working in the area (e.g., Monier-Williams and Greenhouse, 1986; Karrow, 1987; Edgecombe, 1999). Karrow (1987) suggested that bedrock elevation recorded in some borehole records may be inaccurate as sections of highly compacted clays have been misinterpreted as bedrock, giving an artificially high

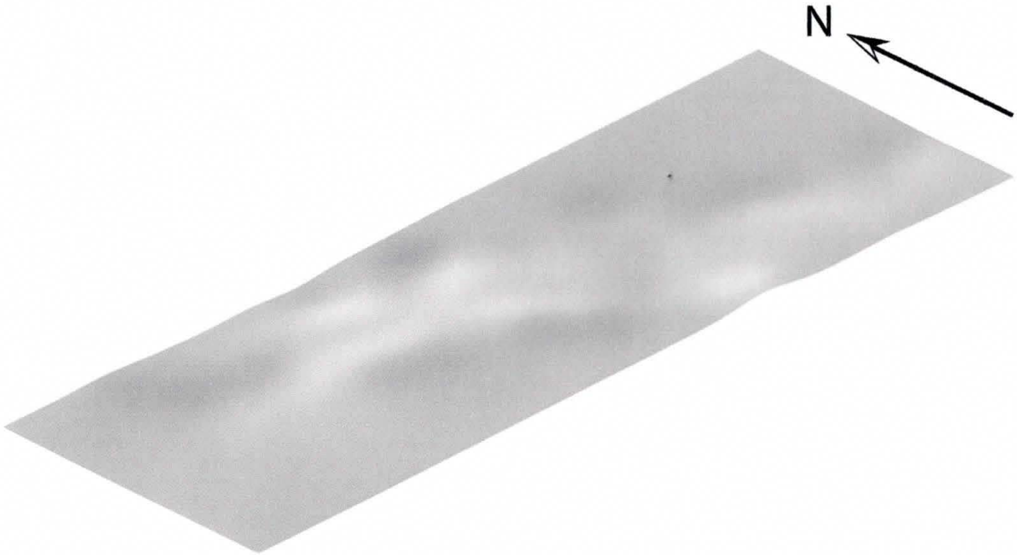



**Figure 4.2** - Undulating bedrock topography showing a centralized bedrock high trending east -west along the southern edge of the study area. Image is shown at 10 x vertical exaggeration.

bedrock elevation in certain areas. Edgecombe (1999) suspected that misinterpretation of the elevation of the bedrock surface may be a serious issue within the central portions of the Dundas Valley, as the digital elevation model of bedrock topography created from OMOE water well data indicates a significant bedrock high running along the center of the valley; such a bedrock high is unlikely to exist in reality. Given these data limitations it is unwise to speculate on the origin of topographic features identified on the bedrock surface in this study. Better understanding of the bedrock topography awaits improved seismic profiling or the drilling of several lengthy boreholes to reach bedrock in the valley.

### 4.2.2 Unit 2: Discontinuous Sandy Gravels

Quaternary sediments immediately overlying bedrock include discontinuous sandy-gravels (Unit 2), which infill lows in the irregular topography of the bedrock surface (Fig. 4.1). Some model images produced by ROCKWORKS 2002, show Unit 2 to be thicker and more laterally extensive than would be expected from manual examination of the database (Fig. 3.13; western end of the model in 4.1). One possible explanation for this enhancement of the unit thickness and continuity is that the model was built using 'Onlap', which constructs the stratigraphic units of the model from the lowermost unit (bedrock) to the uppermost unit (fill). By giving priority to the underlying units in the modelling process, these units can appear thicker and more extensive than would be expected, as appears to be the case with the gravel of Unit 2.

The coarse-grained texture and patchy distribution of Unit 2 deposits suggests they formed under relatively high energy conditions, such as those in fluvial or shoreline environments and that there were spatial restrictions on their deposition. The stratigraphic position of Unit 2 overlying bedrock also indicates that these may represent lag deposits formed by reworking of sediment in fluvial or shallow lacustrine environments. Unit 2 sediments most likely record deposition during a time when fluvial or lacustrine systems existed in the Dundas Valley (e.g. Fig. 2.4; Flint and Lolcama, 1985; Barnett, 1992; Eyles, 1997) following a period of bedrock erosion. The most recent episode of extensive bedrock erosion was during the maximum of the late Wisconsin glaciation (Nissouri stadial; Fig. 2.9A) when ice completely overrode the region. Unit 2 deposits therefore probably post-date this event.

The permeable sandy-gravels of Unit 2, in combination with the fractured bedrock surface, form a discontinuous confined aquifer beneath the study area.

### 4.2.3 Unit 3: Fine-grained Diamicts, Clays and Silty Clays

Unit 3 is composed of a variety of fine-grained sediments ranging from clays to silty clays and fine-grained diamicts (Fig. 4.1). These sediment types have been grouped together to form a single stratigraphic unit due to their close vertical and lateral association.

The texture, blanket-like geometry and depositional context of Unit 3 suggest that it formed predominantly under low energy lacustrine conditions in which fine-grained sediment settled out of suspension (Fig. 4.1; Karrow et al., 1968). The stratigraphic position of Unit 3 also suggests that this lacustrine environment most likely formed as late Wisconsin ice retreated from the western end of the Ontario basin and early Lake Iroquois began to form in the isostatically depressed area between the retreating ice front and the Niagara Escarpment (Fig. 2.9 C; Karrow et al., 1961). Scattered clasts within the fine-grained diamicts may have originated as debris rafted into the lake by icebergs (Eyles and Eyles, 1983; Barnett, 1992; Eyles, 2002; Karrow, 1987). This fine-grained unit has been considered to be equivalent to the Halton Till where identified in surface outcrops and shallow cores (Karrow, 1974, 1987; Groundwater Technology Canada Limited, February 1994) in parts of the Dundas valley; these diamicts may thus record re-advance of ice in the Ontario basin during the Port Huron stadial (see section 2.5.4). In the absence of any data regarding clast fabric, sedimentary structures or deformation features, it is impossible to differentiate between either a subglacial or glaciolacustrine origin for these poorly-sorted fine-grained deposits. Further analysis of the spatial relationship between silty clays and diamicts within the valley infill is required to better constrain the extent of glacial and/or lacustrine influence in the valley.

The fine-grained sediments of Unit 4 have low hydraulic conductivities and do not allow fluids to readily flow through and therefore this unit serves as an extensive lower aquitard throughout the region (Karrow, 1987; Edgecombe, 1999).

### 4.2.4 Unit 4: Coarse-grained Sands and Gravels

Unit 4 is an extensive unit of coarse-grained sands and gravels that overlies the fine-grained diamicts and silty clays of Unit 3 (Fig. 4.1). Coarse-grained deposits at this stratigraphic horizon have been recognized by other researchers (Karrow, 1974; Edgecombe, 1999) and noted to vary in thickness across the Dundas Valley from 3 to 50 meters. Unit 4 deposits are restricted to areas lying below the elevation of the former Lake Iroquois shoreline (Fig. 1.1 and 4.3).

The coarse-grained nature of Unit 4 and its erosional basal contact suggest it formed under high energy conditions, in either fluvial or nearshore environments. The regional extent and geometry of this unit, which thickens towards the central portions of the valley, and its stratigraphic position above fine-grained lacustrine deposits, suggest that it probably formed in shoreline environments associated with postglacial Lake Iroquois (Fig. 4.1, and 4.3; Karrow, 1987; Eyles, 2002; City of Hamilton, 2004). The coarse-grained nearshore deposits of Unit 4 have similar characteristics to those forming along the modern Lake Ontario shoreline (Fig. 4.1). Differentiation of sands and gravels formed along the former Lake Iroquois shoreline from those subsequently deposited on the Dundas alluvial fan is difficult as the fan crosses through the area once occupied by Lake Iroquois (Karrow, 1963; Karrow, 1987).

Unit 4 was studied in greater detail within a sub-section of the study area, comprising the McMaster campus and the Henkel site (see section 5.2.3). The coarse-grained nature and lateral extent of this unit across the western part of the study area allow it to function as a significant regional aquifer and a major conduit for the migration of pollutants from contaminated sites towards surface water bodies such as Cootes Paradise and Hamilton Harbour(Groundwater Technology Canada Limited, 1994; Conestoga-Rovers & Associates, 1996).

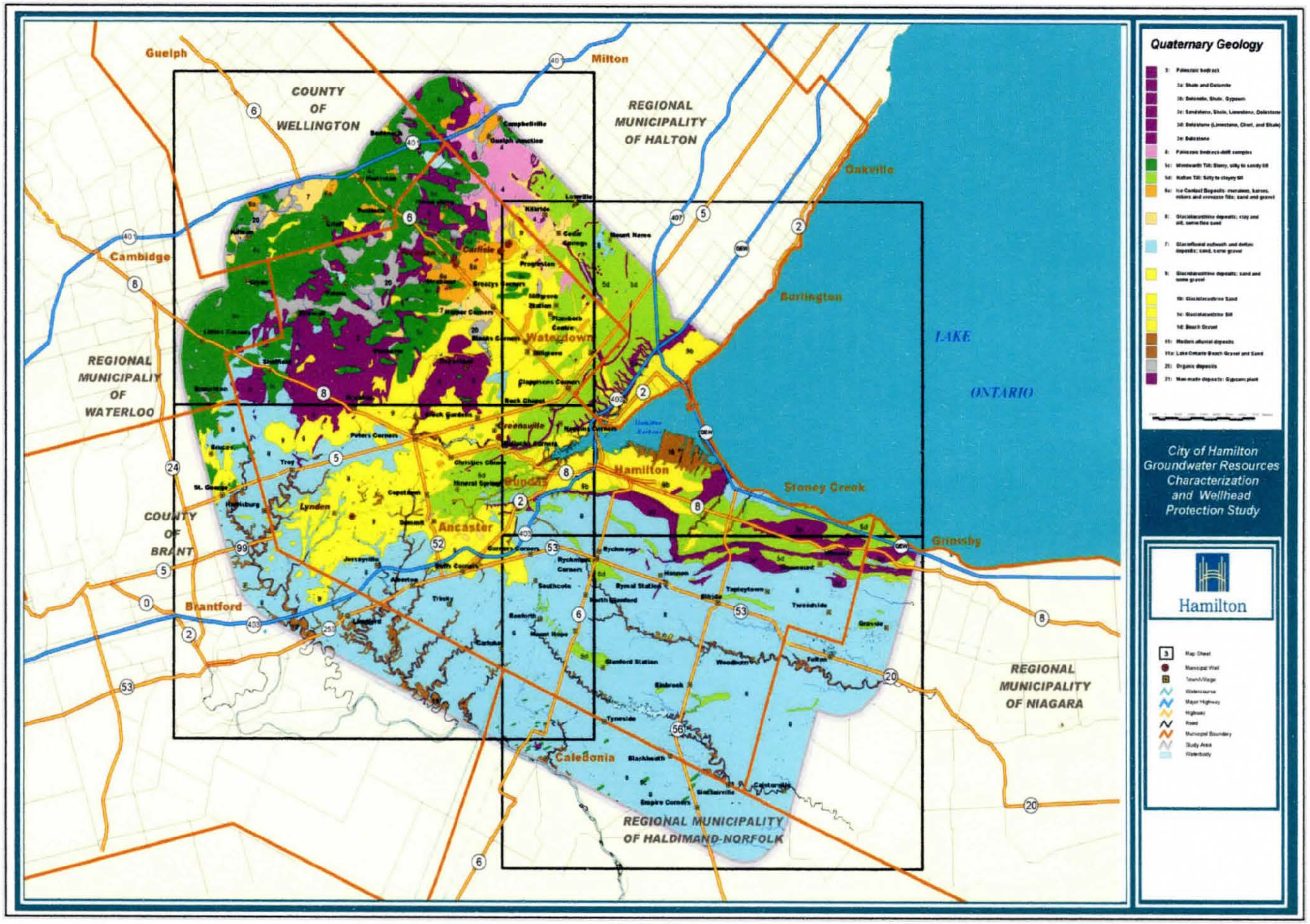



Figure 4.3 – Map of the Hamilton region showing the distribution of Quaternary sediments. Note the distribution of the Lake Iroquois sediments (yellow '9b') surrounding the modern Lake Ontario and the Halton Till deposits (light green '5d') that terminate half way up the Dundas Valley. (Map courtesy of The City of Hamilton's Groundwater Resources Characterization and Wellhead Protection Study, 2005).

### 4.2.5 Unit 5: Silts and Silty Sands

The uppermost sedimentary unit in the study area (Unit 5) consists of silts and silty sands with trace of gravel and clay (Fig. 4.1). These deposits are restricted to the western portion of the study area and show considerable spatial variability in textural characteristics. In general, the sediments of Unit 5 show a gradual fining towards the north, with the more sandy horizons being restricted to the southern part of the study area (Fig. 4.1). Interbedding of various textural types suggests that these sediments were deposited in an environment subject to temporal and spatial changes in sediment supply and depositional energy; these types of conditions are typical of shallow lacustrine/lagoonal environments (Eyles and Eyles, 1983) affected by changing wave and current energies and fluvial inputs. These types of environment existed at the western end of Lake Iroquois as the lake shallowed and beach bars developed allowing closed lagoons, similar to the modern Cootes Paradise (Fig. 1.1 and 4.1) to form. These lagoonal environments, protected from wave activity in the Ontario basin by extensive shoreline spits and bars, are thought to have formed around 11,000 y.b.p. (Coleman, 1937; Karrow et al., 1961; Karrow, 1987). There were two main beach bars that developed; the Aldershot bar extended from the north shore of Burlington in a southwesterly direction, and the other one extended from Hamilton in a northward direction (Colman, 1937; Karrow, 1963). The gradual fining of the sediments in Unit 5 to the north reflects deposition of silts and fine-grained sands in progressively deeper portions of the lagoon towards the centre of the valley. These deposits eventually formed the Westdale plain as lake levels lowered (Fig. 1.1, 4.1).

The sediments of Unit 5 are relatively permeable, particularly in the southern part of the study area (Fig. 4.1). However, this unit does not form a significant aquifer as it lies predominantly above the water table but it does facilitate the infiltration of water (and contaminants) into the more extensive aquifers of Unit 4 beneath.

## 4.3 Summary

The 3-D model outputs show that the subsurface stratigraphic units beneath the study area consist of an irregular bedrock surface (Unit 1), which is overlain by a patchy veneer of sandy gravel (Unit 2), most likely the result of deposition under fluvial or shallow lacustrine conditions. Overlying fine-grained diamicts and silty clays (Unit 3) record flooding of the valley and deposition under glaciolacustrine or possibly subglacial conditions. The widespread extent of these fine-grained deposits (Fig. 4.1) suggest that the valley was flooded as a result of either local ponding of water trapped in the valley between the Niagara Escarpment to the west and an ice margin advancing from the east, or by ice blocking outlets to Lake Ontario along the St. Lawrence seaway (Fig. 2.9 C).

Unit 3 is erosionally truncated by coarse-grained sediments of Unit 4, interpreted as shoreface deposits formed around the margins of post-glacial Lake Iroquois during recession of ice from the Ontario basin. Unit 4 sediments are restricted to areas lying below the level of the Lake Iroquois shoreline and form an important and relatively continuous aquifer in areas close to Cootes Paradise, Hamilton Harbour and Lake Ontario (Fig. 4.1; 1.1).

The uppermost sediments within the study area comprise Unit 5 and are restricted to the western portion of the study area. These deposits formed under lagoonal conditions as extensive bars developed at the western end of Lake Iroquois. Unit 5 lies predominantly above the water table in the unsaturated zone and facilitates infiltration of contaminants into more extensive aquifers of Unit 4 below.

The depositional history of the Dundas Valley recorded by the five stratigraphic units identified in this study is consistent with that proposed by Karrow (1963, 1987) on the basis of outcrop studies in the Hamilton-Wentworth region. However, the 'exploded' box model of the subsurface presented here (Fig. 4.1) allows new insight into the depositional origin of individual stratigraphic units through visualization of their spatial distribution and geometric form. For example, Figure 4.1 shows that fine-grained diamict and clays of Unit 3 infill all of the low areas of the stratigraphy and are limited in thickness only over bedrock highs. This supports a predominantly glaciolacustrine origin for these deposits. Coarse-grained deposits of Unit 4 are widely distributed across the study area but become more patchy in their distribution toward the east (Fig. 4.1). The spatial variability of textural characteristics within Unit 5 is consistent with deposition under lagoonal conditions that deepened toward the north. These attributes of the subsurface sediment units were not realized previous to this study and are critically important to the accurate reconstruction of past environmental conditions.

# Chapter 5: Hydrogeological Applications

## 5.0 Introduction

3-D modelling of geological data has important applications in the field of hydrogeology, which is the science of water occurrence, movement and transport beneath the Earth's surface (EPA, 2005) and includes study of the interactions of water processes with geological materials, particularly for the development and management of water resources (Fetter, 2001). The use of 3-D models in hydrogeological applications has increased dramatically in recent years (e.g. Artimo et al., 2004; Kassenaar, 2004; Meriano, 2004; Micheal, 2004; Stone, 2004). Shallow aquifers within Quaternary sediments often have complex geometries and a high degree of hydraulic variability (Howard and Beck, 1986). Modelling of the subsurface geology and lithologic unit geometries was used to identify the distribution and form of aquifers in a selected part of the study area in which groundwater contamination had occurred. The aim of this part of the study was to identify potential directions of groundwater and contaminant movement based on the physical characteristics of subsurface sediment units identified on the 3-D subsurface geology models. The area around the McMaster campus and the Henkel industrial site was selected for study because of the availability of closely spaced, high quality geological and hydrochemical data.

The regional hydrology of the Dundas Valley is influenced by bedrock topography, in particular, the presence of the Niagara Escarpment (Fig. 4.1 and 4.2). The overall study area lies on the lakeward side of the escarpment where regional groundwater flow paths are predominantly either towards Cootes Paradise and Hamilton Harbour or directly towards Lake Ontario (Fig. 5.1, City of Hamilton, 2004). In the area of the McMaster campus and the Henkel site the general direction of groundwater flow is toward the north and northeast, but little is known about specific groundwater flow pathways (Groundwater Technology Canada Limited, February 1994; Groundwater Technology Canada Limited, March 1994; Global Tox, 1994; Fig. 5.1).

## 5.1 The McMaster Campus / Henkel Site Study Area

The Henkel site is a 3.5 acre industrial property located at the western end of Ward Avenue and Royal Avenue in West Hamilton, approximately 500m to the southwest of the McMaster campus, and lies on an area of relatively flat topography in the Dundas Valley, referred to as the Westdale Plain (Fig. 5.2; Karrow, 1987). The site was originally used for agricultural purposes until 1945 when it was developed for industrial uses and a chemical manufacturing plant was built. In 1987 the site was bought by Henkel Canada Limited and was subsequently closed in 1988 upon the discovery of significant water and soil contamination. In 1989 Henkel decommissioned the site, removed all of the existing buildings, and began an extensive environmental site investigation and remediation plan (Conestoga-Rovers & Associates, 1996).

In order to assess and monitor contaminant migration, it is necessary to understand groundwater characteristics and movement, which are strongly affected by subsurface geological conditions. The water table in the area of the Henkel site lies approximately 3 meters below the ground surface and appears to follow the surface topography. Groundwater flow is generally to the north and northeast towards Cootes Paradise (Groundwater Technology Canada Limited, February 1994; Groundwater Technology Canada Limited, March 1994; Global Tox, 1994; Fig. 5.1).

Ninety-seven borehole records were used to construct 2-dimensional cross-sections through the McMaster campus/Henkel site study area (e.g. Fig. 5.3) and to create 3-D models of the area (Fig. 3.14D). The model outputs show a subsurface sediment stratigraphy that is very similar to that described elsewhere in the Dundas Valley (Fig. 4.2). However, few boreholes penetrate to bedrock in this area and the full thickness of Quaternary sediment overlying bedrock is not known. Only the upper three stratigraphic units identified in the broader study area (Units 3, 4 and 5; Fig. 3.14D) can be modelled with confidence, although limited data are available for Unit 2 deposits overlying bedrock beneath the McMaster campus (Fig. 5.3).

## 5.2 Identification of aquifers and aquitards

Given that the objective of the McMaster campus/Henkel site study was to determine aquifer characteristics and potential contaminant migration pathways from the subsurface geological models, the stratigraphic units identified in the broader study area were classified according to their hydrostratigraphic characteristics as either aquifers or aquitards.

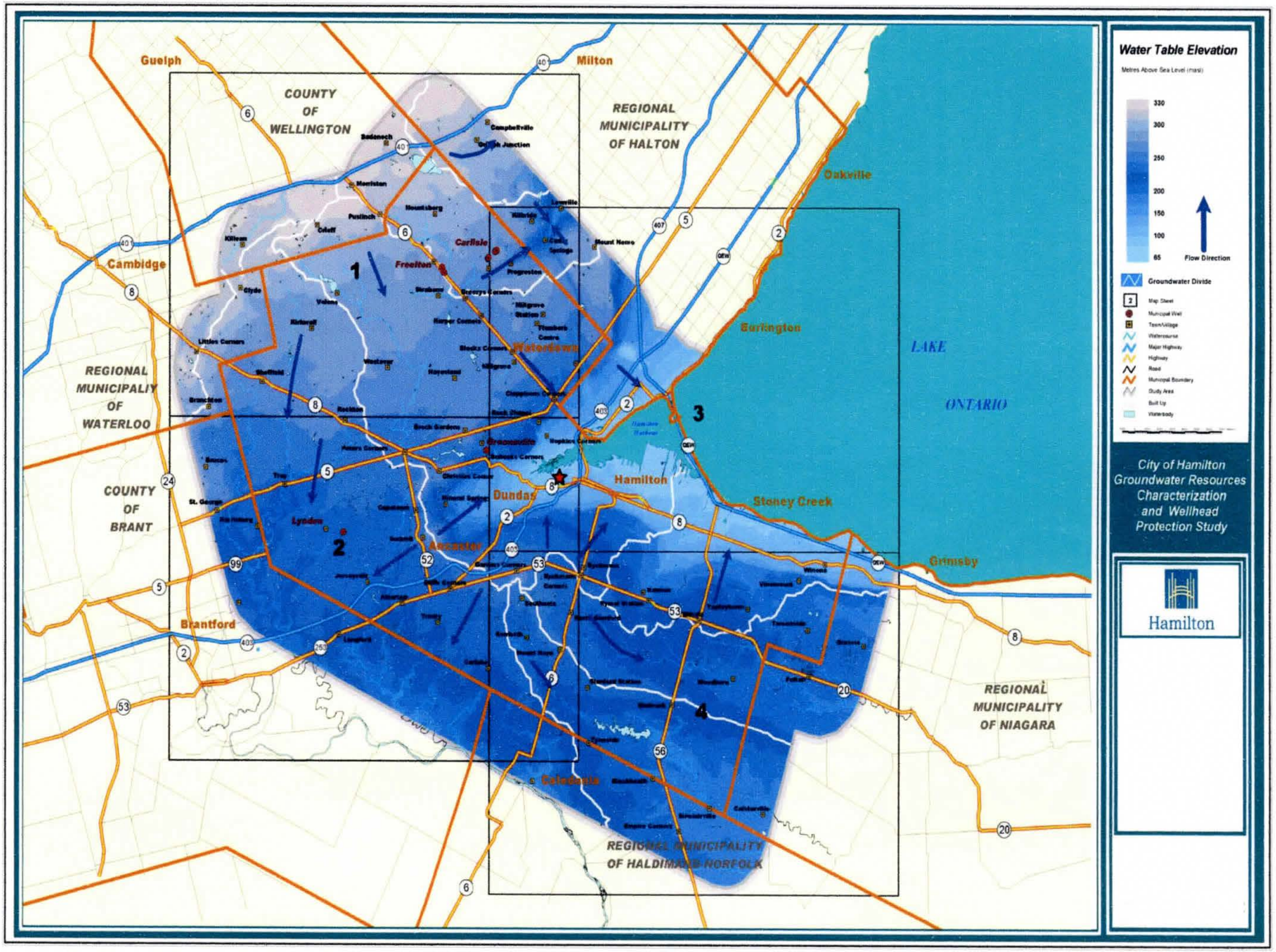



**Figure 5.1** - Map showing water table elevations and groundwater flow directions in the Hamilton region. The red star indicates the location of the McMaster University campus and the Henkel site. (Map courtesy of The City of Hamilton's Groundwater Resources Characterization and Wellhead Protection Study, 2005).


**Figure 5.2 -** An air photo showing the location of the property previously owned by Henkel Canada Limited (Henkel site), the McMaster University campus, and Cootes Paradise. (Air photo courtesy of the City of Hamilton's GIS Services department).

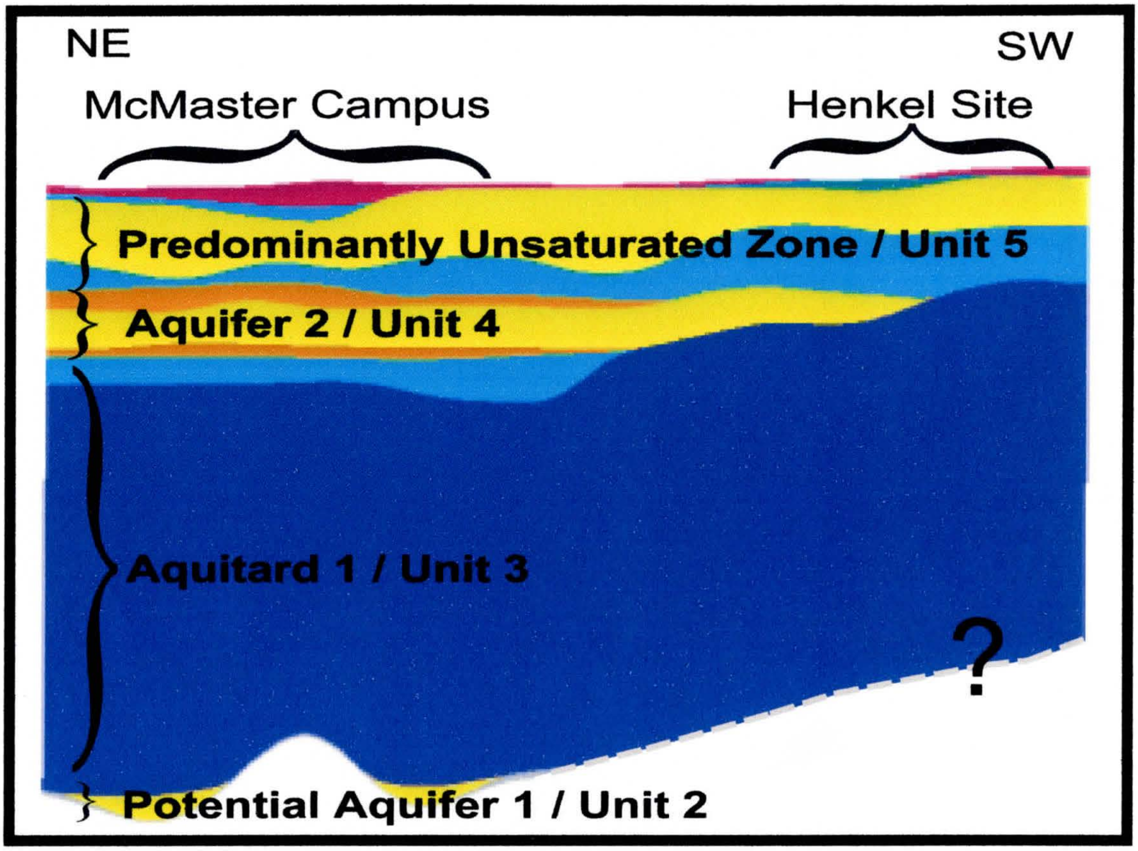



**Figure 5.3** - North-east to south-west cross-section through the sedimentary units beneath the McMaster and Henkel locations indicating the positions of the aquifers and aquitards, and their correlation to the stratigraphic units. "?" indicates the predicted position of the base of Unit 3/top of the bedrock surface in the absence of deep borehole data below the Henkel site.

An aquifer is defined as a geologic deposit that is able to store and transmit economically sufficient quantities of water to wells and springs in order to be considered a productive source (Bates and Jackson, 1984; Fetter, 2001; Singer et al., 2003). Aquifers can form in bedrock or overlying sediments and can range in size from a few hectares to hundreds of square kilometers (Singer et al., 2003). Permeable or highly fractured bedrock and relatively coarse-grained sediments such as gravels and sands form the most productive aquifers in southern Ontario (Singer et al., 2003). In contrast, an aquitard is a deposit of low permeability that retards the flow of water and therefore does not supply enough water to be considered a productive source (Bates and Jackson, 1984; Fetter, 2001; Singer et al., 2003). Aquitards are formed by impermeable and unfractured bedrock such as shale, or fine-grained sediments such as silts, clays and fine-grained diamicts.

In the McMaster campus/Henkel site study area, models of the subsurface geology allowed identification of 2 major aquifers separated by a regional aquitard. The lowermost aquifer identified is formed by stratigraphic Unit 2 (discontinuous sandy-gravels overlying bedrock; herein labeled as Aquifer 1 (Figs. 5.3 and 5.4). This aquifer is overlain by a regionally extensive aquitard (Aquitard 1: Fig. 5.3) formed by the fine-grained deposits of stratigraphic Unit 3, (Fig. 5.3), and a shallow unconfined aquifer (Aquifer 2) formed by the interbedded gravels and sands of stratigraphic Unit 4 (Fig. 5.3). The uppermost sediments in the study area (stratigraphic Unit 5; Fig. 5.3) are predominantly unsaturated as they generally lie above the water table. The characteristics of each of these hydrostratigraphic units will be described below.

### 5.2.1 Potential Aquifer 1 (stratigraphic Unit 2)

Boreholes drilled during the Henkel site investigation (Groundwater Technology Canada Limited, March 1994) all terminated in stratigraphic Unit 3 (Aquitard 1) and did not reach the lower aquifer (aquifer 1; Fig. 5.3). However, three boreholes drilled on the McMaster University campus reached bedrock and penetrated this coarse-grained unit (Figs. 5.3 and 5.4). Aquifer 1 directly overlies bedrock and modelling of the very limited McMaster University campus data, together with what is known of the characteristics of this unit in the broader study area, suggest that it consists of small, localized pockets of coarse sediment lying within low areas on the eroded bedrock surface (Fig. 5.4).

During initial environmental investigation of the Henkel site, the Ministry of the Environment (OMOE) reported that sands and gravels overlying bedrock in the area of the Henkel site are sufficiently conductive to be utilized as a source of groundwater, and therefore constitute an effective aquifer for small scale operations (Groundwater Technology Canada Limited, February 1994). The McMaster University Life Sciences building also used water from this aquifer for cooling purposes, and pump tests conducted on their well produced a flow rate of approximately 1.15 liters per second (Groundwater Technology Canada Limited, March 1994; Groundwater Technology

Canada Limited, February 1994). Conestoga-Rovers & Associates, (1994) have estimated that the hydraulic conductivity for Aquifer 1 is $3.0 \times 10^{-2}$ cm/s.

### 5.2.2 Aquitard 1 (stratigraphic Unit 3)

The fine-grained silts, clays and diamicts comprising stratigraphic Unit 3 form an almost continuous blanket within the sedimentary infill of the Dundas Valley and an effective regional aquitard. In the McMaster campus/Henkel site study area, Aquitard 1 appears to thicken to the north and northeast towards Cootes Paradise (Fig. 5.3). Unfortunately, none of the boreholes drilled during the Henkel site investigation penetrated the full thickness of this unit, therefore the nature and topography of the base of this unit on the underlying aquifer formed by Unit 2 is difficult to establish. However, Unit 3 deposits do reach thicknesses of between 11 and 23 meters beneath the McMaster campus, indicating that it is a relatively thick layer (Fig. 5.4).

### 5.2.3 Aquifer 2 (stratigraphic Unit 4)

The interbedded sands and gravels of Unit 4 form a continuous aquifer (Aquifer 2) that underlies both the McMaster campus and Henkel site (Fig. 5.3). Horizontal hydraulic gradients for this aquifer range from 0.006 m/m on the site to 0.004 m/m off the site and hydraulic conductivities were found to range from $2.3 \times 10^{-6}$ cm/s to $6.4 \times 10^{-3}$ cm/s (Conestoga-Rovers & Associates, 1995). The average porosity of this unit was determined to be 39 % and groundwater flow velocity was calculated to be approximately

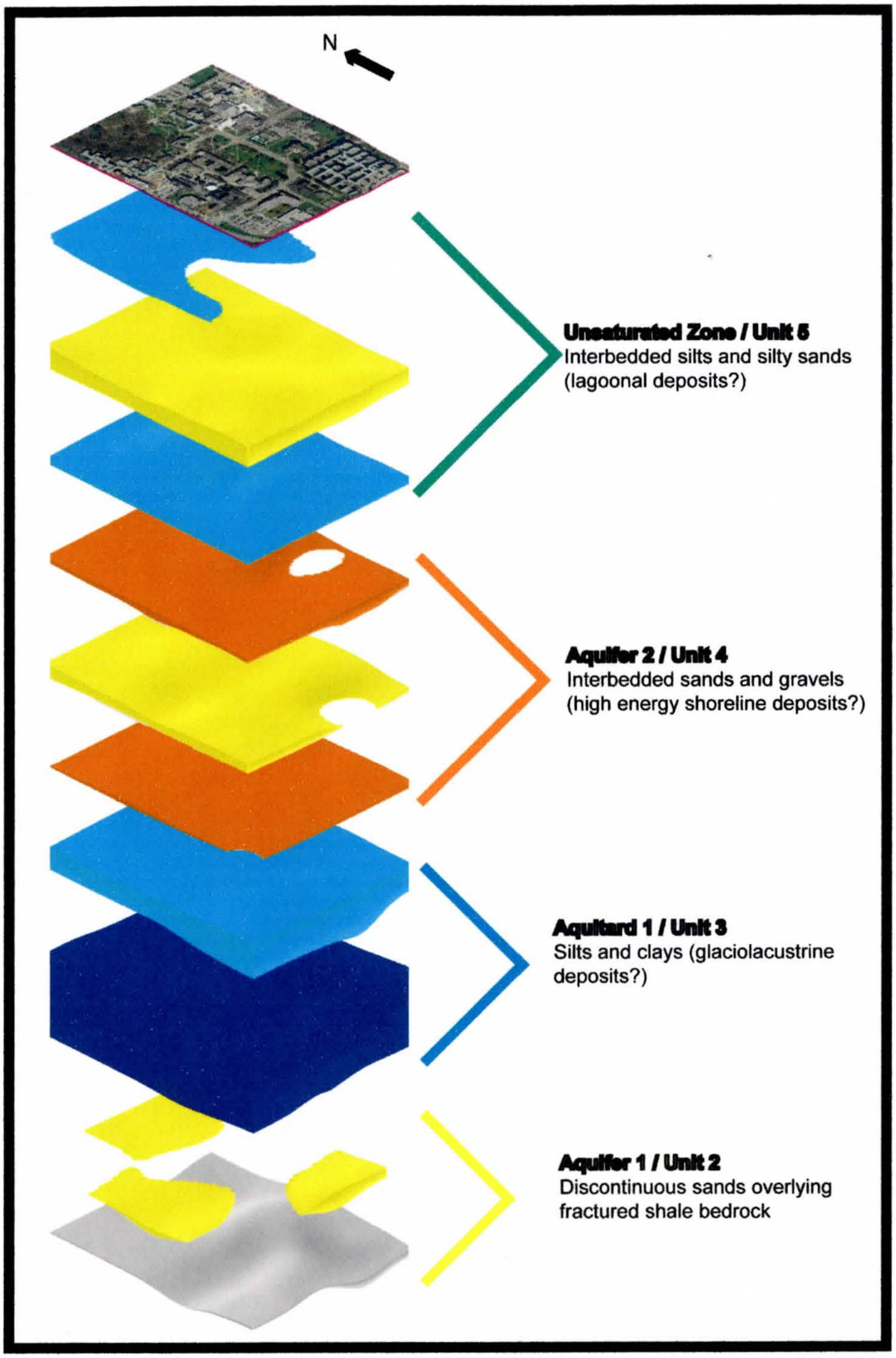



**Figure 5.4** - Three-dimensional box model of the sediments beneath the McMaster University campus showing the patchy and uneven distribution of Aquifer 1 (Unit 2).

2.7 meters per year on the site and 1.8 meters per year off the site (Conestoga-Rovers & Associates, 1995). Unit 4 varies in thickness from 2 to 4 meters across the Henkel site and from 1 to 3 meters below the McMaster campus (Fig. 5.3).

The coarse-grained deposits of Unit 4 appear to have an irregular, erosional contact with underlying fine-grained sediments of Unit 3. An isopach map of Unit 4 was constructed to illustrate more clearly the thickness variations of this coarser-grained unit across the study area (Fig. 5.5) and shows that the thickest areas of stratigraphic Unit 4 (Aquifer 2) lie beneath the Henkel site and extend toward the McMaster campus in a northeasterly direction. Examination of the 3-D model images also suggests that the upper surface of Unit 3 (Aquitard 1) which underlies Aquifer 2, slopes downward towards the northeast (Fig. 5.6 and 5.3). It appears that the thickest areas of Aquifer 2 have formed within the lows on the surface of Unit 3. The elongate areas of thicker coarse-grained sediment comprising Aquifer 2 (Unit 4) may represent linear beach ridges or berms formed as a result of storm activity along the high energy shoreface of Lake Iroquois.

Given that Unit 4 deposits form an important near-surface aquifer (aquifer2) beneath the McMaster campus/Henkel site study area, and regional groundwater flow is in a northerly direction toward Cootes Paradise, it is likely that local groundwater flow is focused in the thickest areas of the aquifer and is moving toward the north-northeast. This would allow both water, and the contaminants it contains, to migrate from the Henkel site toward the southern edge of the McMaster campus (Figs. 5.5, 5.7 and 5.8).

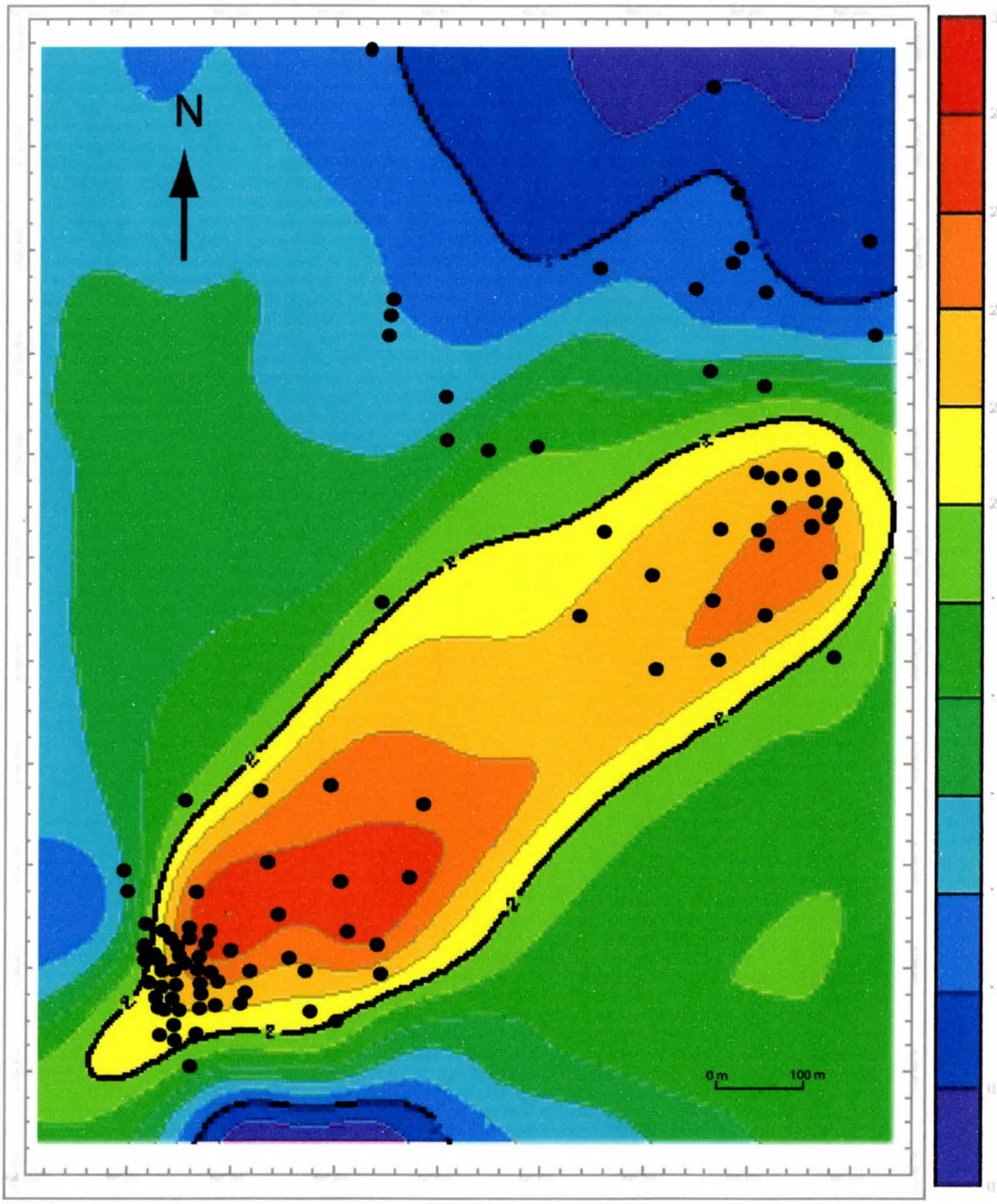



**Figure 5.5** - Isopach of Unit 4 (Aquifer 2) beneath the McMaster University campus and Henkel sites. The red indicates areas where the gravel is thickest, and purple represents areas where the gravel is the thinnest (scale in meters). The black dots represent the borehole locations (see Fig. 3.15 for location map). Note that the thickest areas of gravel have a northeast-southwest trend which may influence the flow of groundwater.

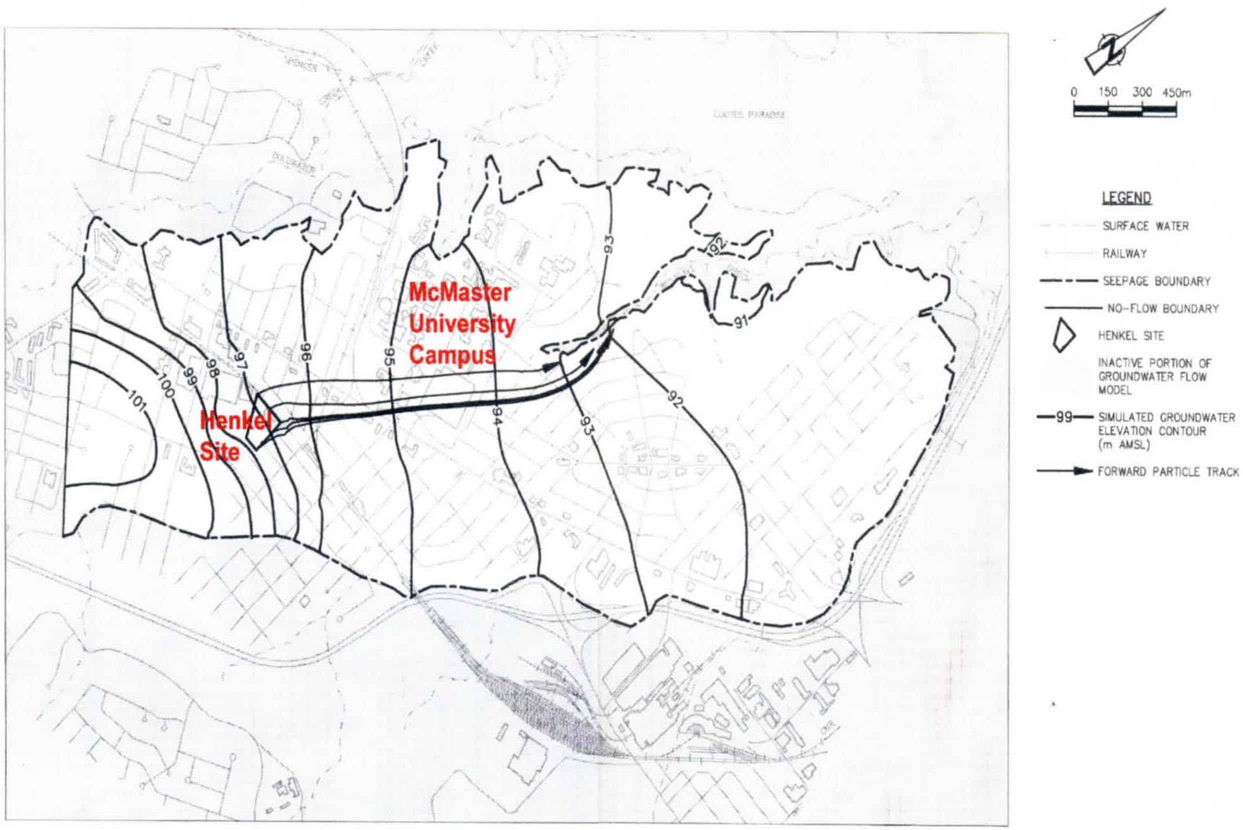



**Figure 5.6** - Simulation of the regional groundwater flow from the Henkel Canada Limited site to Cootes Paradise. The arrowhead lines represent the predicted flow path of contaminants across the simulated groundwater elevation contours. (From Conestoga-Rovers & Associates, 1996).

Groundwater flow modelling conducted by Conestoga-Rovers & Associates (1995) predicts similar directions of subsurface water movement from the Henkel Site toward Cootes Paradise in a north-northeasterly direction (Fig. 5.7; Conestoga-Rovers & Associates, 1996). Groundwater chemistry data also obtained by Conestoga-Rovers & Associates from monitoring wells along Main Street (Fig. 5.7 and 5.8; Conestoga-Rovers & Associates, 1995) identified a subsurface contaminant plume of cresol migrating from the Henkel site in a similar direction. The position of the cresol plume corresponds closely with the thickest areas of Unit 4 identified on the 3-D models (Figs. 5.5, 5.7).

Figure 5.8 shows the distribution of cresol at concentrations in excess of 10ug/L identified in monitoring wells in the area between the Henkel site and the McMaster campus during August 1995 (Conestoga-Rovers & Associates, 1995). The blue lines are concentration contours of cresol within Aquifer 2 (Fig. 5.4), and the red lines are concentration contours of cresol measured at shallow depths (within the upper 5 meters of the predominantly unsaturated zone of Unit 5). The cresol appears to have migrated a considerable distance from the Henkel site within the permeable sediments of Aquifer 2 within the direction of predicted groundwater flow toward the north-northeast (Fig. 5.8).

The preferred migration route of contaminants closely corresponds with the thickest parts of Unit 4 identified in this study from 3-D modeling of subsurface geological data. This correspondence between the well defined 3-D geometry of a relatively coarse-grained sediment unit and a contaminant plume clearly demonstrates the importance of 3-D modeling of the physical characteristics of subsurface sediments as a means to help

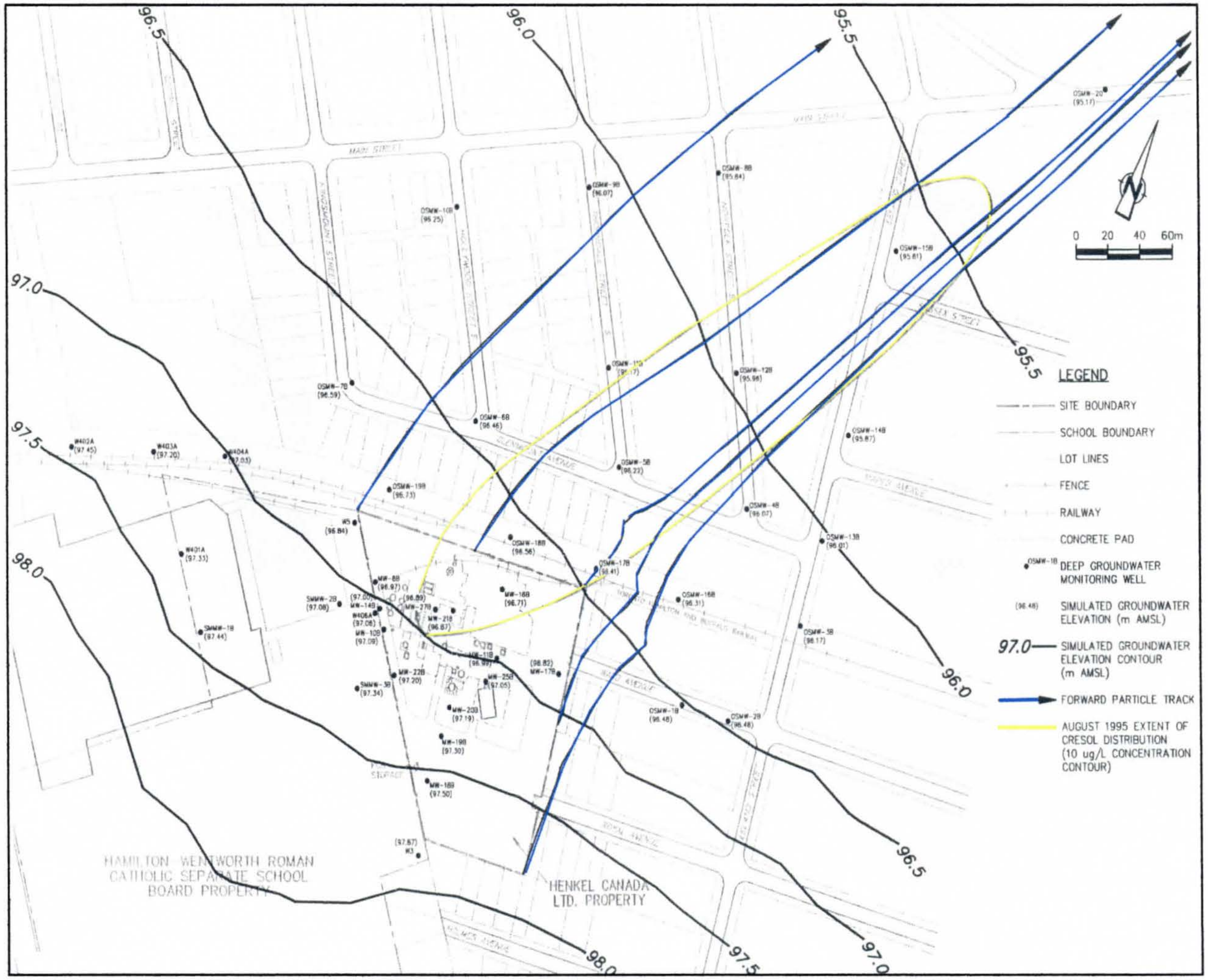



**Figure 5.7** - Simulated groundwater elevations on the Henkel site. The groundwater elevations are decreasing to the northeast, causing the groundwater flow (blue lines) to travel in the same direction. Note the cresol distribution (yellow line) that has been added to the image which flows in the same direction as the flow lines. (From Conestoga-Rovers & Associates, 1996)

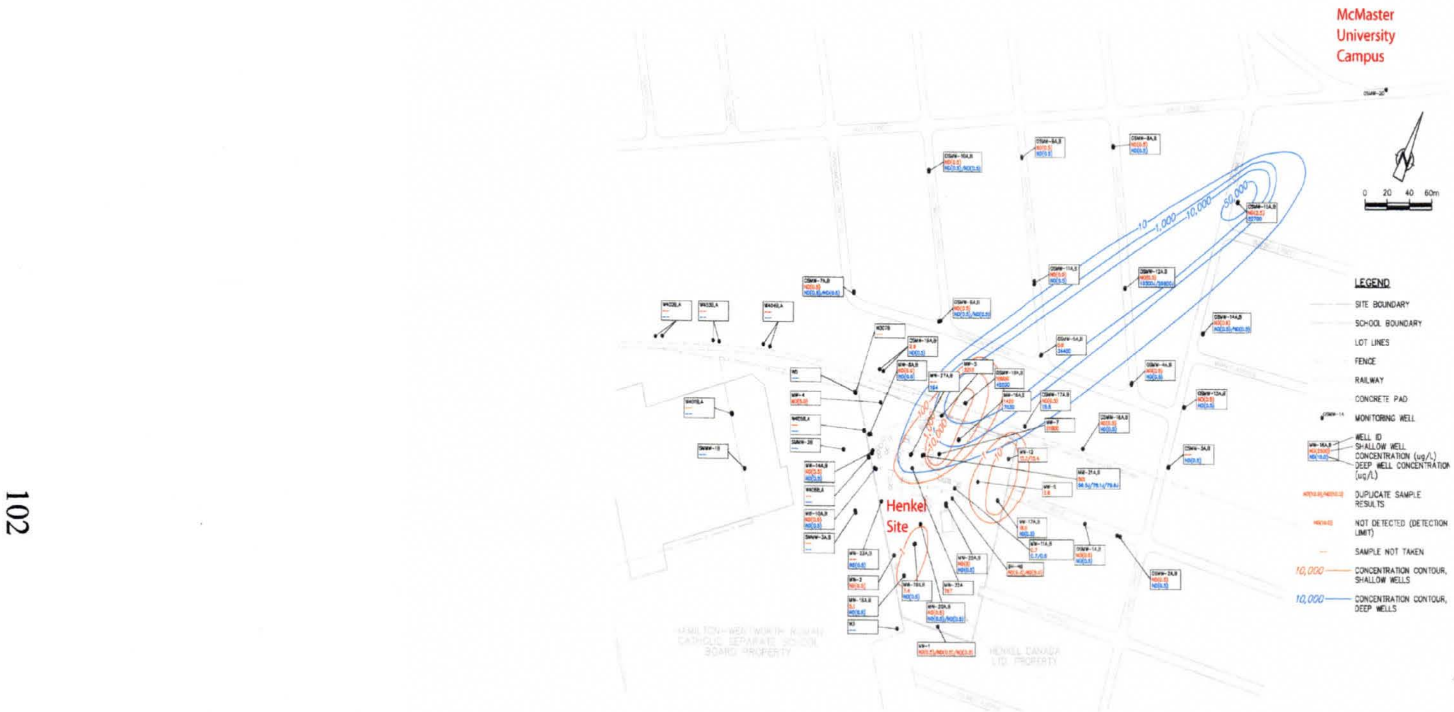



**Figure 5.8** - Map showing the distribution of cresol beneath the Henkel site. The blue concentration contours show that the cresol has traveled further toward the northeast within the deeper sediments (Aquifer 2).

identify potential contaminant migration pathways. Such 3-D modeling of subsurface material properties may provide a rapid and effective means of better constraining the geographic extent of contaminant monitoring or remediation programs in the future.

### 5.2.4 Upper Predominantly Unsaturated Zone (stratigraphic Unit 5)

The uppermost hydrostratigraphic zone identified on the Henkel site is equivalent to stratigraphic Unit 5 (Fig. 5.3) and consists of relatively fine-grained sands and silts deposited during the progressive shallowing of Lake Iroquois and the development of lagoons protected by shoreline bars (Fig. 1.1). These sediments become finer-grained toward the north suggesting deposition in deeper and lower energy environments in the more central parts of the Dundas Valley (Fig. 4.2).

The water table lies approximately 3 meters beneath the ground surface in the McMaster campus/Henkel site study area and a large portion of Unit 5 thus lies in the upper unsaturated zone (Fig 5.3; Groundwater Technology Canada Limited, 1994; Groundwater Technology Canada Limited, 1994; Global Tox, 1994; Conestoga-Rovers & Associates, 1996). Unit 5 shows considerable lateral and vertical variability in textural characteristics. Some areas of Unit 5 contain thick layers of silt that may act as a confining layer, impeding the movement of fluids into underlying coarse-grained deposits of Unit 4. In other areas, where the silt layer is thin or absent, fluids may readily migrate downwards and enter Aquifer 2 (Fig. 5.3). Groundwater chemistry data obtained by Conestoga-Rovers & Associates (1995) shows that lateral migration of contaminants from Henkel site has been much less significant in Unit 5 than in underlying coarse-grained sediments of Aquifer 2 (Unit 4; Fig 5.8) Recharge of the aquifers is more likely to occur within the southern portion of the study area which is primarily overlain by sands with lesser amounts of silt (Fig. 5.3).

## 5.3 Advantage of 3-D Subsurface Geology Models in Hydrostratigraphic Applications

Review of the investigative reports produced by Groundwater Technology Canada Limited (1994; 1995), Global Tox International Consultants Incorporated (1994), and Conestoga-Rovers & Associates (1995; 1996), showed that the majority of information regarding aquifer and aquitard characteristics below the Henkel site came from monitoring the path of contaminants migrating from the site, rather than from understanding the underlying geological framework. In contrast, this study has used borehole records as a source of information on subsurface sediment characteristics for the Henkel site and McMaster University campus, and has focused in particular on the identification and delineation of coarse-grained units that form subsurface aquifers. The cross sections, 3-D models and isopach maps produced in this study allow the characteristics of individual stratigraphic units, particularly aquifer units, and their regional geometries to be analyzed and visualized. This is important as it allows rapid and accurate delineation of subsurface units with material properties that influence the location of potential groundwater flow paths.

The ability to visualize the subsurface geometries of aquifers and aquitards in the area around the Henkel site at an early stage in the environmental investigation process would have allowed remediation strategies to be focused in the best locations to intercept the major contaminant plumes. In the event of a large contamination spill or leak, valuable time is lost as investigators try to determine the best locations to position extraction systems or barriers. Having detailed 3-D models of the subsurface geology of an area available prior to any contaminant leak would greatly facilitate the creation of effective remedial plans (Houlding, 1994). In particular, the precursory creation of 3-D geological models for locations proximal to known environmentally hazardous areas (e.g. sites that contain or manufacture highly toxic substances) would allow for rapid and effective responses to any contaminant spills.

# Chapter 6: Summary and Conclusions

## 6.1 Summary

Having a thorough understanding of the subsurface geology of an area is imperative if we are to achieve a better understanding of its geologic history, the location and form of aquifers and aquitards and potential contaminant migration pathways. The images created by ROCKWORKS 2002 were used in this study to establish the geometry and lateral continuity of subsurface units and to better understand the depositional origin and history of the sedimentary infill of the Dundas Valley.

Nine separate subsurface lithologic units were identified in the study area on the basis of their textural characteristics and stratigraphic position. These are (from base to top); bedrock, gravel2, diamict, clay, sand2, gravel, silt, sand, and fill. Texturally similar lithologic units in close vertical and lateral proximity were also grouped together to form five 'stratigraphic units', ranging from bedrock (Unit 1) to silts and silty sands (Unit 5; Fig. 4.2) as an aid to paleoenvironmental and hydrostratigraphic interpretation.

Each of the individual lithologic units and their regional geometries were analyzed and visualized in a variety of ways using ROCKWORKS 2002 (see Fig. 3.9). The resulting images were used to help interpret the depositional origin of stratigraphic units and the late Quaternary geological history of the study area (Fig. 4.1). Unit 1 represents the eroded Paleozoic bedrock surface and is overlain by a patchy veneer of sandy gravel (Unit 2), probably deposited under fluvial or shallow lacustrine conditions. Overlying fine-grained deposits of Unit 3 record glacially-influenced lacustrine deposition as the valley was flooded during ice advance, possibly during the Port Huron stadial. Coarse-grained sediments of Unit 4 represent nearshore deposits associated with the development of post-glacial Lake Iroquois with overlying silts and sands of Unit 5 recording the development of lagoonal conditions in the valley as shoreline bars developed.

The 3-D subsurface models produced in this study significantly improve our knowledge of the infill stratigraphy of the Dundas Valley. Previous studies of the Quaternary stratigraphy and depositional history of the valley were based on outcrop data and sparse borehole information (Karrow, 1963, 1987). This study is based on a widely distributed network of borehole data that allows analysis of deeper and more regionally extensive stratigraphic units. Interpretation of the overall depositional history recorded by the stratigraphic units identified in this study is however, remarkably consistent with that made previously by Karrow (1963, 1987). The advantage of the 3-D modeling approach used here is in the creation of models that allow analysis of the geometry and spatial variability of textural characteristics of individual stratigraphic units that can be used to better interpret past environmental conditions. This is well illustrated by the isopach map of stratigraphic Unit 4 (Fig. 5.5) that shows a linear zone of thick sands and gravels that may represent an individual beach ridge within the shoreface deposits of Lake Iroquois.

The 3-D images are also used here to help identify and delineate the geometry of permeable and impermeable units that function as aquifers and aquitards in the valley infill (Fig. 5.4). The form and geometry of permeable sediment units may also be used to help predict potential directions of groundwater and contaminant flow (Fig. 5.7).

## 6.2 Distinctive characteristics of the modelling process used in this study

This study identifies the methods and tools that can be used to effectively visualize and analyze the subsurface characteristics and 3-D distribution of Quaternary sediments in a buried bedrock valley using ROCKWORKS 2002. Although the study area is restricted at present to the south side of the Dundas Valley, it provides preliminary data on which to base initial development of a 3-D stratigraphic model to describe the infill of the broader valley. This type of 3-D imaging and analysis of subsurface sediments may be applied to other regions where relatively thick Quaternary sediments overlie bedrock (e.g. Matile et al., 2001; Tipping et al., 2001; Kopczynski et al., 2002; Ross et al., 2002; Hansel et al., 2004; Russell et al., 2004; Bajc et al., 2004; van Haften et al., 2004; Sarapera and Artimo, 2004).

The nature of the 3-D subsurface modelling process used in this study differs from that undertaken by other groups of researchers in a number of ways. First, the input data used in the creation of the model database have been thoroughly screened and edited to identify and eliminate any poor quality data points. This is particularly important when using large digital databases created by government or other agencies.

Additional high quality data from construction reports were also manually added to the database used in this study. Many other 3-D modelling studies rely primarily on digital water well databases for data input (e.g. Hansel, 2002, Russell et al., 2004; Kassenaar et al., 2004; Logan et al., 2004).

Secondly, the models created initially for this study used a small subset of high quality data points from the McMaster campus and Henkel site area (Fig. 3.15). Careful analysis of the model outputs created from this relatively small database allowed the main components of the subsurface stratigraphy to be established. Additional data were then added to the database and the 3-D models were expanded to cover the entire study area. This allowed the larger model outputs to be carefully screened to ensure the most accurate representation of the subsurface geology and to identify areas in which the model output may be unreliable. There are many advantages to this process but it is time-consuming and is not feasible for many studies.

Thirdly, this study used a variety of different algorithms available in ROCKWORKS 2002 to analyze and visualize the database. The model outputs created from the different algorithms were manually checked by reference to individual data points and the most appropriate algorithms were selected for use. This process ensured that the most representative images of the subsurface geology were created.

Finally, this study also used a genetic approach to the identification and classification of subsurface units by taking into consideration the likely genesis of the sediment as well as its textural characteristics. This allowed the most appropriate 'grouping' of textural types into stratigraphic units that could be used to reconstruct depositional histories. Consideration of the genesis of each of the stratigraphic units also served as a guide to establish subsurface unit geometries and distributions. Few other studies have used such a 'genetic' approach to the classification of subsurface sediment units and tend to rely only on basic textural classifications used for input data from sources such as waterwell databases. In many instances, these databases contain such a wide variety of sediment classifications that the model output is unrealistically complex and the dominant sedimentation patterns cannot be easily identified (e.g. Hansel, 2004). Application of a genetic approach to the creation of 3-D models in this study has allowed reconstruction of a geologic history for the Dundas Valley that conforms closely to known geologic constraints.

## 6.3 Future Directions

The next step for 3-D geologic modelling in the Dundas Valley is to deal effectively with the physiological boundary presented by the Niagara Escarpment, and the lack of data in certain sectors of the study area such as Cootes Paradise, Hamilton Harbour and Lake Ontario. Filtering algorithms such as the polygon filter, distance filter, and grid filter available in ROCKWORKS 2004 may be appropriate for this purpose. These filters effectively modify the area that is being modelled and allow the user to identify sectors or data points that should not be included in the extrapolation process. Application and testing of these filtering algorithms on the existing Dundas

Valley database will be conducted before the study area is expanded to include additional areas of the valley.

Another future application for the 3-D modelling study will be to integrate groundwater flow information into the subsurface stratigraphic models (e.g. Thorleifson and Berg, 2002). This type of project will require collaboration between scientists with a variety of background expertise and will have many different applications. Currently 3-D models of subsurface geology are being created by the Ontario Geological Survey for three areas of Southern Ontario; including the Waterloo, Barrie-Oro, and Hamilton-Wentworth regions (Cam Baker, pers. comm., 2005). The purpose of these models is to aid in the location and delineation of aquifers in order to better evaluate water resource potential and develop groundwater protection strategies.

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# Appendix A - Geosphere Manuscript

MacCormack, K.E., J.C. Maclachlan, and C.H. Eyles. "Viewing the Subsurface in Three Dimensions: Initial Results of Modeling the Quaternary Sedimentary Infill of the Dundas Valley, Hamilton, Ontario." *Geosphere* 1.1 (2005): 23.

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