Viewing the subsurface in three dimensions: Initial results of modeling the Quaternary sedimentary infill of the Dundas Valley, Hamilton, Ontario

K.E. MacCormack
J.C. Maclachlan
C.H. Eyles
School of Geography and Earth Sciences, McMaster University, 1280 Main St. W., Hamilton, Ontario L8S 4K1, Canada

ABSTRACT

The Dundas Valley is a bedrock valley infilled with up to 180 m of Quaternary sediment that underlies the Hamilton-Wentworth region of southern Ontario. Although the infill of the Dundas Valley contains a valuable record of past environmental change and controls groundwater and contaminant migration pathways in the region, the nature, origin, and spatial distribution of sedimentary units comprising the infill are poorly understood. This paper presents the initial results from the compilation and three-dimensional modeling of subsurface geological data obtained from water well and borehole records, and engineering and construction reports from the Hamilton region. RockWorks v.2002 was used to model and create images describing the bedrock topography and valley infill stratigraphy. Analysis of cross sections and three-dimensional box models created by RockWorks v.2002 allows five texturally distinct stratigraphic units to be identified within the valley infill. These units include bedrock (unit 1), draped by a discontinuous veneer of coarse sand and gravel (unit 2) interpreted as fluvial in origin, extensive silty clays and fine-grained diamicts (unit 3) that record either glaciolacustrine or subglacial conditions, coarse sands and gravels (unit 4) formed under high-energy shoreface conditions associated with postglacial Lake Iroquois, and silts and silty sands (unit 5) formed in lagoonal environments. The three-dimensional images showing subsurface sediment distributions and geometries for the Dundas Valley can be used not only to better constrain the late Quaternary depositional history of the region, but also to identify and delineate major aquifers and aquitards, essential for groundwater protection and remediation planning.

Keywords: subsurface modeling, Dundas Valley, Quaternary sediments, Hamilton, Ontario, three-dimensional modeling.

INTRODUCTION

Southern Ontario is underlain by a variable thickness of Quaternary-age sediments that blanket an eroded Paleozoic bedrock surface dissected by numerous bedrock valleys (Eyles, 2002). The area was repeatedly overridden by the southern margin of the Laurentide Ice Sheet during the late Quaternary and was also affected by changing lake levels in the Great Lakes basins (Barnett, 1992; Eyles, 2002). Bedrock valleys form important repositories of paleoenvironmental information as they are infilled with thick successions of Quaternary sediment that may be used to reconstruct former ice marginal positions and lake level changes. These data are critical for the creation of an accurate record of past environmental change in eastern North America during the late Quaternary.

The Dundas Valley of the Hamilton-Wentworth region forms a prominent west-east re-entrant in the Niagara Escarpment, extending from Copetown in the west to Lake Ontario in the east (Fig. 1A). The modern valley is underlain by a buried bedrock valley estimated to be infilled with up to 180 m of Quaternary sediment including stacked units of coarse- and fine-grained sediment of glacial, lacustrine, and fluvial origin (Greenhouse and Monier-Williams, 1986; Karrow, 1987; Edgecombe, 1999; Fig. 2). These deposits contain a valuable record of the relative importance of glacial, lacustrine, and fluvial processes as ice marginal positions and lake levels fluctuated over time at the western end of the Ontario basin. Unfortunately, there are few exposures through these valley infill deposits and their subsurface characteristics and distribution are poorly understood; no boreholes drilled to date penetrate the entire thickness of the valley infill deposits.

The Dundas Valley hosts a densely populated (over 650,000 people) and heavily urbanized region (Fig. 1B) and there are serious concerns regarding pollution of ground and surface water bodies by contaminants migrating from the numerous closed landfill sites, industrial sites, and buried chemical storage sites in the area (Birks and Eyles, 1996). Coarse-grained units within the valley infill form significant local and regional aquifers; groundwater from these aquifers supplies water to Cootes Paradise, Hamilton Harbour, and ultimately Lake Ontario (Fig. 1A). Hamilton Harbour is severely contaminated and has been identified as one of 43 areas of concern in the Great Lakes region (International Joint Commission, 1985). 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.

This paper describes initial results from the compilation and three-dimensional modeling of subsurface geological data obtained from a variety of government and industry sources for a portion of the Dundas Valley in the Hamilton-Wentworth region. The objective of the three-dimensional modeling exercise is to

---

Geosphere; August 2005; v. 1; no. 1; p. 23–31; doi: 10.1130/GES00007.1; 11 figures.

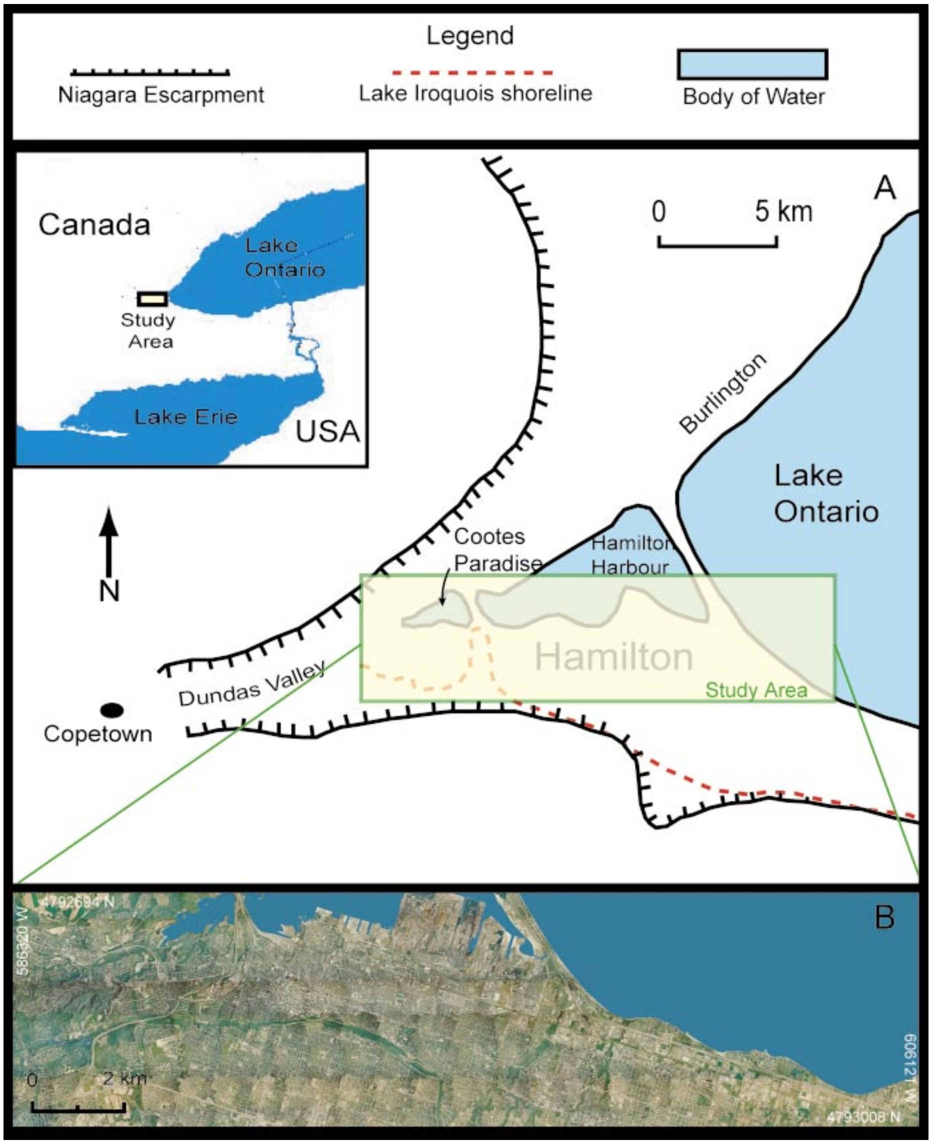


Figure 1. A: Location map of study area (yellow box) within Dundas Valley of Southern Ontario. B: Air photo of study area (courtesy of City of Hamilton, Geographic Information System Services).

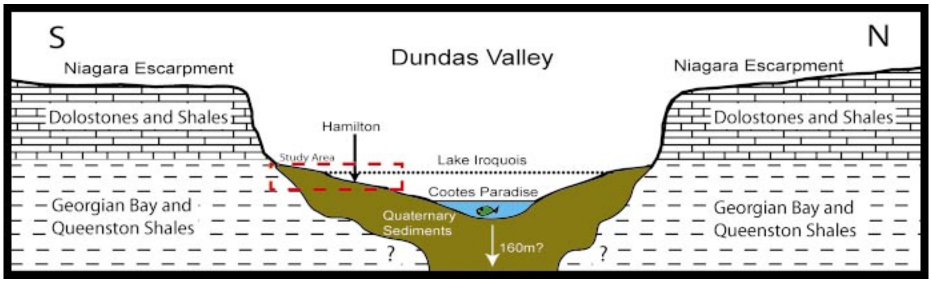


Figure 2. Schematic cross section of Dundas Valley showing bedrock, Quaternary sediment infill, former level of postglacial Lake Iroquois (dotted line), and modern level of Cootes Paradise.

effectively identify, visualize, and analyze subsurface geological units and their geometric form in order to better understand the Quaternary depositional history and hydrostratigraphic characteristics of the region. The illustrations presented here show the types of three-dimensional images that may be created from the compilation of subsurface data from borehole records and construction reports. This type of modeling work is applicable to many other regions of North America and Europe underlain by thick successions of Quaternary sediment where incomplete understanding of subsurface sediment types and distributions severely limits the creation of realistic hydrostratigraphic models (e.g., Hansel et al., 2004; Russell et al., 2004; Bajc et al., 2004; Sarapera and Artimo, 2004; van Haaften et al., 2004).

REGIONAL GLACIAL STRATIGRAPHY

The Quaternary sediment infill of the Dundas Valley probably contains early Wisconsin deposits in the deepest parts, as bedrock valley infills preserved elsewhere in southern Ontario contain deposits of this age (e.g., Scarborough Formation; Karrow, 1967; Eyles and Williams, 1992); unfortunately, the lowermost sediments within the Dundas Valley have not yet been sampled or dated (Karrow, 1987). These lowermost deposits are overlain by a thick succession of glacial and glaciolacustrine sediment that records ice margin fluctuations and changing environmental conditions during the late Wisconsin and early Holocene (Karrow, 1963, 1987). Southern Ontario was completely overridden by the southern margin of the Laurentide Ice Sheet during the late Wisconsin and was also strongly influenced by changing lake levels as outlets to the Ontario basin along the St. Lawrence Valley were episodically blocked by ice (Eyles and Eyles, 1983; Barnett, 1992; Eyles, 2002). Sediments deposited beneath overriding ice during the late Wisconsin include subglacial tills formed either by lodgement processes or as ice deformed previously deposited lacustrine sediments. During episodes of ice advance or retreat, topographic lows on the margin of the Ontario basin, such as the Dundas Valley, would also have been flooded by lake waters allowing silty clays and fine-grained diamicts to accumulate, as a result of ‘‘rain out’’ of suspended sediment and ice-rafted debris, under glaciolacustrine conditions. Glaciolacustrine diamicts can have very similar textural characteristics to deformed subglacial tills and differentiation of the two types of poorly sort-

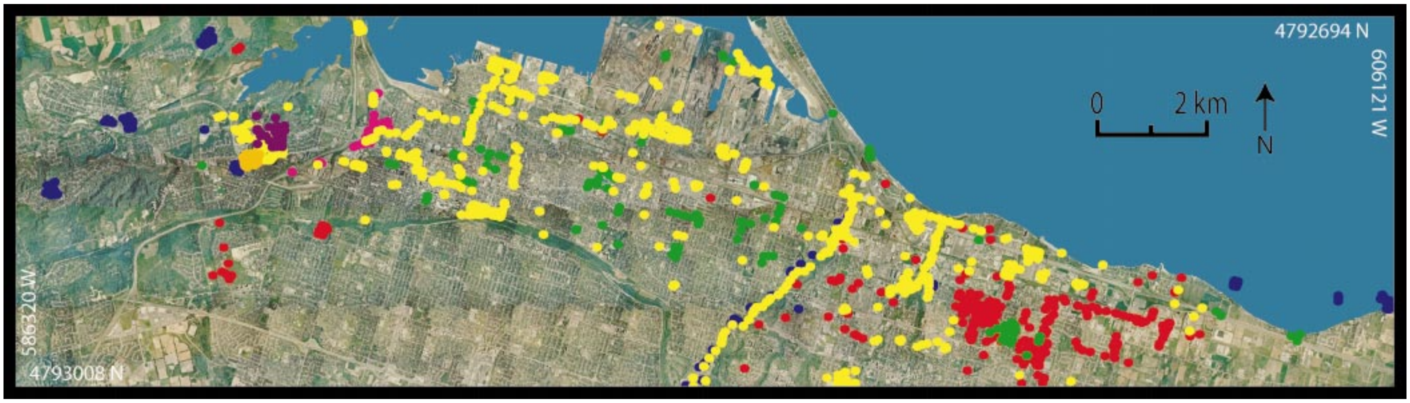


Figure 3. Georeferenced air photograph showing borehole locations (photo courtesy of Hamilton Geographic Information System Services). Over 2000 borehole records were used in this study. Yellow dots—Hamilton Urban Geology Database; pink dots—Ministry of Transportation Database; blue dots—Hamilton Conservation Authority; orange dots—Henkel Canada Ltd. site investigation; red dots—Ontario Water Well Database; green dots—Hamilton geotechnical reports; purple dots—McMaster University construction reports.

ed deposit is extremely difficult, even in surface outcrops (Eyles and Eyles, 1983; Hicock and Dreimanis, 1992).

Near-surface deposits in the lower (eastern) part of the Dundas Valley record the formation and drainage of Lake Iroquois, a high level (45 m above present lake level) postglacial lake that formed in the Ontario basin, and the development of extensive bay mouth bars that isolated Cootes Paradise and Hamilton Harbour from the open lake (Coleman, 1937; Karrow, 1987; Figs. 1 and 2). Small streams also supplied limited amounts of sediment to the valley from early Holocene to recent times (Karrow, 1987).

METHODOLOGY

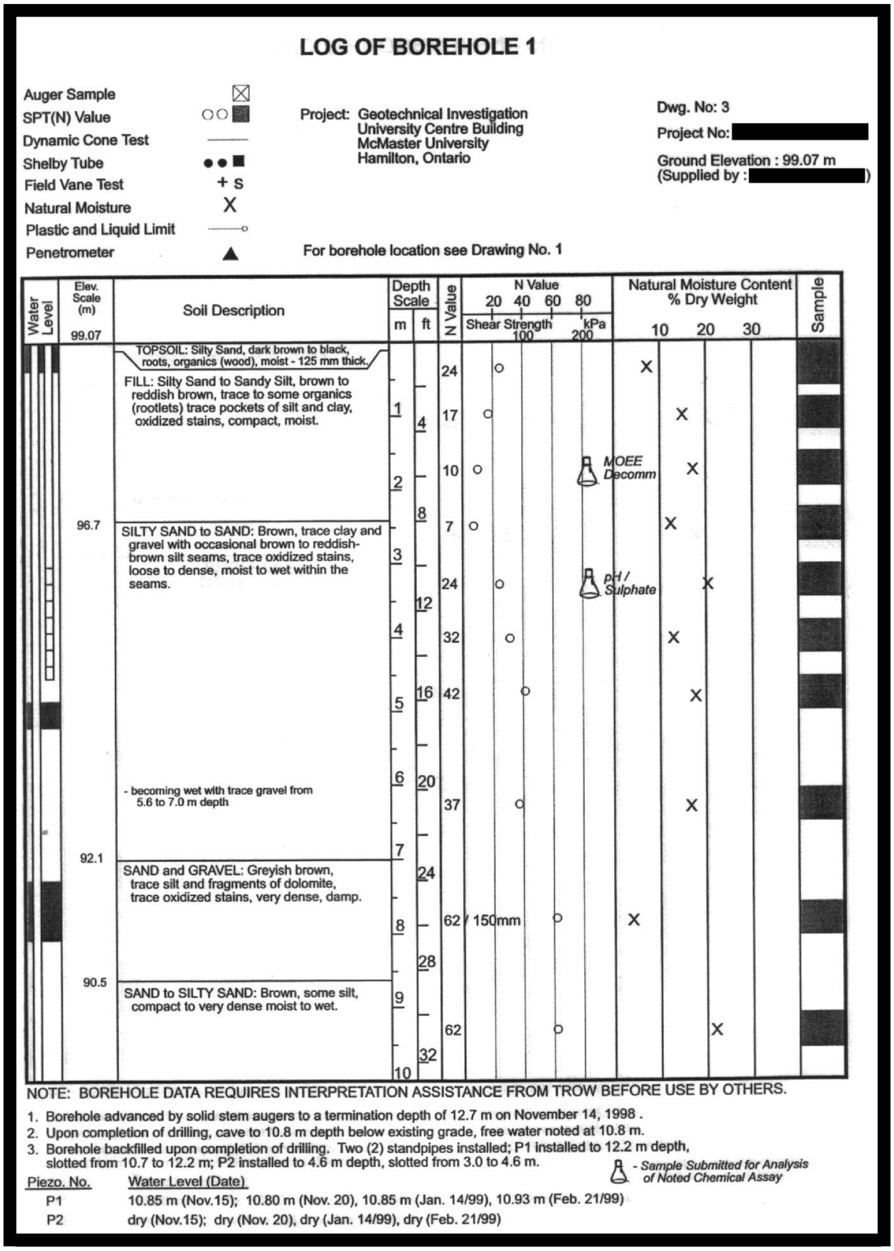
Subsurface geological data used to create the three-dimensional images presented in this paper were obtained from a variety of sources including the Urban Geology Database of Hamilton, Ontario, the Ontario Ministry of Transportation borehole database, and the Ontario Ministry of Environment water well and borehole database, and engineering and construction reports. Over 2000 records were used to create a subsurface database covering an area of over 230 km^2 (Fig. 3).

Borehole locations were established either from borehole records or construction reports; in several instances borehole coordinates were verified on a georeferenced digital topographic map of the Hamilton area or were manually checked using GPS data. The borehole locations were also plotted on a georectified air photo of the study area (Fig. 3). Water well and borehole databases contain coded information regarding sediment texture and the elevation of changes in textural characteristics recorded by the well driller. These data were entered into an Excel spreadsheet and reformatted for entry into RockWorks v.2002, the software package used to model and create three-dimensional images of the subsurface stratigraphy (RockWare, 2002). Geological records from engineering and construction reports (Fig. 4) were also examined and data describing sediment texture and depth below surface were manually entered into the database.

One of the initial steps in three-dimensional subsurface modeling is the identification of appropriate geological units to be used in the modeling process. In this study, a major focus was on the identification and delineation of coarse- and fine-grained lithologic units as textural characteristics provide considerable information regarding depositional conditions and are a primary control on fluid transmissivity and aquifer potential. Individual lithologic units to be used in the modeling process were identified through careful correlation of textural characteristics between adjacent boreholes identified along numerous transects crossing the study area (Figs. 5 and 6). In order to check the consistency of the correlations, many ‘‘closed’’ sections were constructed (starting and ending at the same well) allowing an individual lithologic unit to be traced back to its original stratigraphic position. Identification and delineation of lithologic units also took into consideration the nature and likely genesis of the materials as textural descriptions varied considerably between individual well records. For example, the fine-grained diamict unit (Figs. 7 and 8) includes sediments identified on driller's logs and in borehole records as fine-grained tills, pebbly silty clays or clayey silts with gravel. These poorly sorted lithologic types are difficult to clearly differentiate in core or from auger chips and are most likely the same sediment type, recorded differently by different well drillers.

Data entered into RockWorks v.2002 were then modeled and a number of images showing borehole correlations (Figs. 5 and 6) and three-dimensional box models with different orientations (Figs. 7 and 8) were created. Initial model runs identified correlations between lithologic units that were clearly incorrect (Fig. 5) and required careful checking and relabeling of individual well stratigraphies prior to rerunning the model (Fig. 6). Once again, examination of many ‘‘closed’’ cross sections through the study area was necessary to ensure correct and consistent stratigraphic nomenclature had been applied to the data. The three-dimensional box models (Figs. 7 and 8) show the regional distribution and geometry of subsurface units and can be viewed from any angle or orientation. A digital air photograph of the study area was also draped across the upper surface of the model in order to provide geographic context for the images (Figs. 7 and 8).

A note on the limitations of three-dimensional models—It is important to note that the three-dimensional box models shown in Figures 7 and 8 do not give an entirely accurate representation of subsurface geological conditions in all parts of the study area. RockWorks v.2002 extrapolates the mapping of subsurface lithologic units to all extremities of the study area, despite the lack of data from certain sectors. In the Dundas Valley, there are few data points available for the area covered by Lake Ontario, Hamilton Harbour, and Cootes Paradise and the modeled subsurface



LOG OF BOREHOLE 1

Auger Sample	☒
SPT(N) Value	○ ○ ■
Dynamic Cone Test	——
Shelby Tube	● ● ■
Field Vane Test	+ S
Natural Moisture	X
Plastic and Liquid Limit	——○
Penetrometer	▲

Project: Geotechnical Investigation
University Centre Building
McMaster University
Hamilton, Ontario

Dwg. No: 3
Project No: [redacted]
Ground Elevation : 99.07 m
(Supplied by : [redacted])

For borehole location see Drawing No. 1

Elev. Scale (m)	Soil Description
99.07	TOPSOIL: Silty Sand, dark brown to black, roots, organics (wood), moist - 125 mm thick.
	FILL: Silty Sand to Sandy Silt, brown to reddish brown, trace to some organics (rootlets) trace pockets of silt and clay, oxidized stains, compact, moist.
96.7	SILTY SAND to SAND: Brown, trace clay and gravel with occasional brown to reddish-brown silt seams, trace oxidized stains, loose to dense, moist to wet within the seams. - becoming wet with trace gravel from 5.6 to 7.0 m depth
92.1	SAND and GRAVEL: Greyish brown, trace silt and fragments of dolomite, trace oxidized stains, very dense, damp.
90.5	SAND to SILTY SAND: Brown, some silt, compact to very dense moist to wet.

NOTE: BOREHOLE DATA REQUIRES INTERPRETATION ASSISTANCE FROM TROW BEFORE USE BY OTHERS.

1. Borehole advanced by solid stem augers to a termination depth of 12.7 m on November 14, 1998 .
2. Upon completion of drilling, cave to 10.8 m depth below existing grade, free water noted at 10.8 m.
3. Borehole backfilled upon completion of drilling. Two (2) standpipes installed; P1 installed to 12.2 m depth, slotted from 10.7 to 12.2 m; P2 installed to 4.6 m depth, slotted from 3.0 to 4.6 m.

- *Sample Submitted for Analysis of Noted Chemical Assay*

Piezo. No.	Water Level (Date)
P1	10.85 m (Nov.15); 10.80 m (Nov. 20), 10.85 m (Jan. 14/99), 10.93 m (Feb. 21/99)
P2	dry (Nov.15); dry (Nov. 20), dry (Jan. 14/99), dry (Feb. 21/99)

Figure 4. Typical borehole log from a construction report.

conditions below these sites should be considered as unreliable at present. Future model runs, using data filters available in RockWorks v.2004 (RockWare, 2004), will establish boundaries that essentially remove certain geographic areas from consideration by the model and will produce more reliable output in areas of limited data coverage. Despite these limitations, the modeled three-dimensional subsurface stratigraphy below most of the study area is consistent with known geological conditions and can be applied with confidence.

STRATIGRAPHIC UNITS

Individual lithologic units identified on the three-dimensional box models were vertically separated to emphasize the geometry of individual horizons and to aid in the identification of distinct stratigraphic units (Fig. 9). 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. For example, the close vertical association of fine-grained diamicts and pebbly silty clays across the region suggests they formed at similar times, possibly in laterally juxtaposed environments. The depositional origin of the two sediment types is probably similar (see below) and they are therefore considered as a single stratigraphic unit (unit 3; Fig. 9). Analysis of the vertical stacking of sediment types is important for both paleoenvironmental reconstruction and hydrostratigraphic work and the stratigraphic units identified within the Dundas Valley infill are considered to record significant changes in environmental conditions over time.

Five distinct stratigraphic units can be identified within the portion of the Dundas Valley examined in this study, each recording different depositional conditions (Fig. 9). Bedrock (unit 1) lies at a depth of between 1 and 50 m and consists of red and gray 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). Quaternary sediments immediately overlying bedrock include discontinuous sandy gravels (unit 2), which, given their coarse texture and distribution, infilling lows in an eroded bedrock valley, are probably of fluvial origin (Fig. 9). These sandy gravels, together with the fractured bedrock surface, form a discontinuous confined aquifer in the region. Unit 3 consists of gray silty clays and fine-grained diamicts that form an extensive lower aquitard. These silty clays and diamicts appear to have formed either by subglacial reworking of previously deposited lacustrine sediments during the final stages of late Wisconsin glaciation or as glaciolacustrine deposits formed by rain out processes during the early stages of postglacial Lake Iroquois (Fig. 9). 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.

The extensive unit of coarse sands and gravels (unit 4) that overlies the fine-grained diamicts and silty clays of unit 3 formed under high-energy conditions and is probably associated with shoreline environments of postglacial Lake Iroquois (Fig. 9). This unit forms an important and laterally continuous aquifer beneath the Hamilton urban area (Figs. 7 and 8). The uppermost sedimentary unit in the study area (unit 5) consists of silts and silty sands formed in lagoonal environments created at the western end of Lake Iroquois by the growth of shoreline bars (Fig. 9). Although unit 5 is a relatively permeable stratigraphic

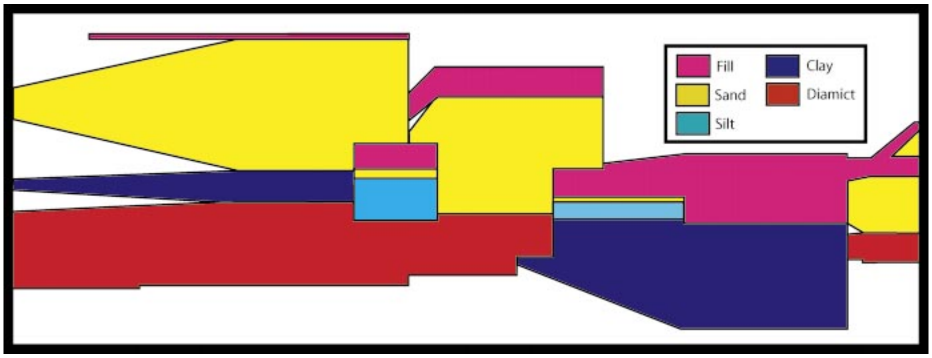


Figure 5. Borehole correlation diagram showing initial correlations made between incorrectly labeled lithologic units below a section of the study area. Original logs and lithologic classifications were rechecked and units relabeled correctly prior to rerunning correlation program. Image is shown at 20× vertical exaggeration.

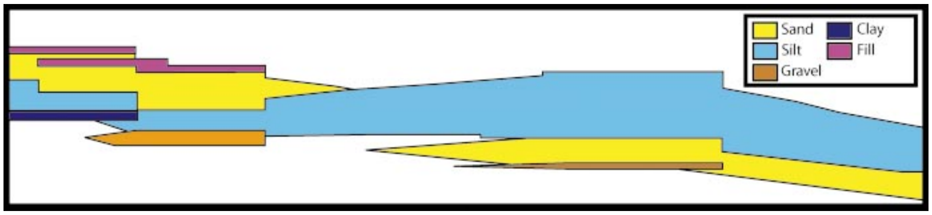


Figure 6. Corrected borehole correlation diagram showing lateral continuity and cross-sectional geometry of individual lithologic units identified below a section of the study area. Image is shown at 40× vertical exaggeration.

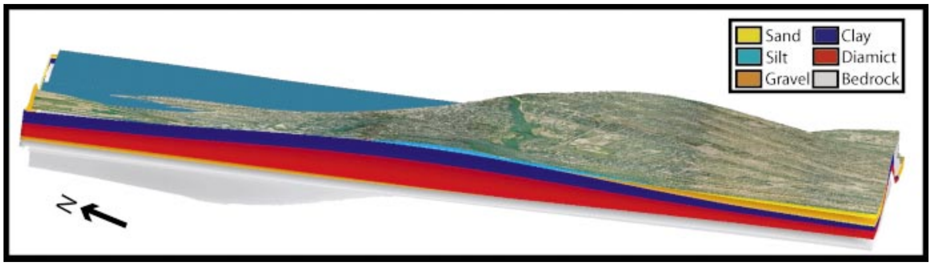


Figure 7. Three-dimensional box model (looking toward the east) showing lithologic units underlying study area. Note lateral continuity of diamict and clay units within valley infill. Image is shown at 20× vertical exaggeration.

unit, it lies predominantly within the unsaturated zone above the regional water table and is not considered as a productive regional aquifer.

GROUNDWATER APPLICATIONS

The Hamilton-Wentworth region is densely populated and heavily urbanized and there are serious concerns regarding contamination of groundwater from sources such as industrial and municipal waste disposal sites and buried storage tanks. Three-dimensional modeling of subsurface sediment units can be effectively used to identify and delineate aquifers below such an urbanized area to better constrain potential contaminant migration pathways and assist in the planning of mitigation programs.

Case Study: Aquifer Geometry Beneath the Henkel Site

The Henkel site is an abandoned industrial site in west Hamilton (Fig. 10), extensively contaminated with gasoline products and chemicals used in the food processing industry (Groundwater Technology Canada Ltd., 1994). These contaminants were known to be migrating offsite in subsurface aquifers but the form and extent of the aquifers were poorly understood. Borehole data obtained from Groundwater Technology Canada Ltd. (1994) and from the McMaster University campus were used to create detailed three-dimensional images of the stratigraphy below the Henkel site and adjacent areas and to delineate major subsurface aquifer and aquitard units; a three-dimensional fence diagram showing an oblique view through the subsurface data (modeled using RockWorks v. 2002) is presented in Figure 11.

The geology below the Henkel site is very similar to that of downtown Hamilton (Figs. 7, 8, and 9). However, few boreholes penetrate to bedrock in this area and the full thickness of Quaternary sediment is not known; units 1 (bedrock) and 2 (discontinuous sands and

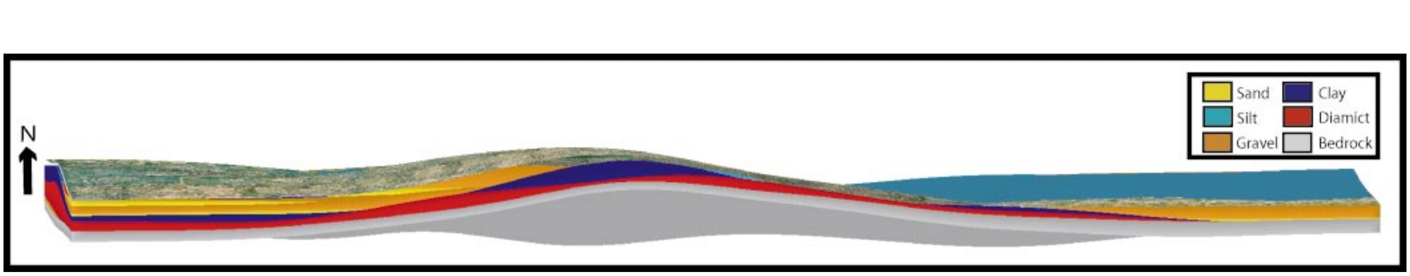


Figure 8. Three-dimensional box model (looking north) showing lithologic units underlying study area. Bedrock ‘‘high’’ in central area connects southward with base of Niagara Escarpment. Within study area, buried bedrock surface is highly irregular with over 50 m of relief. Image is shown at 20× vertical exaggeration.

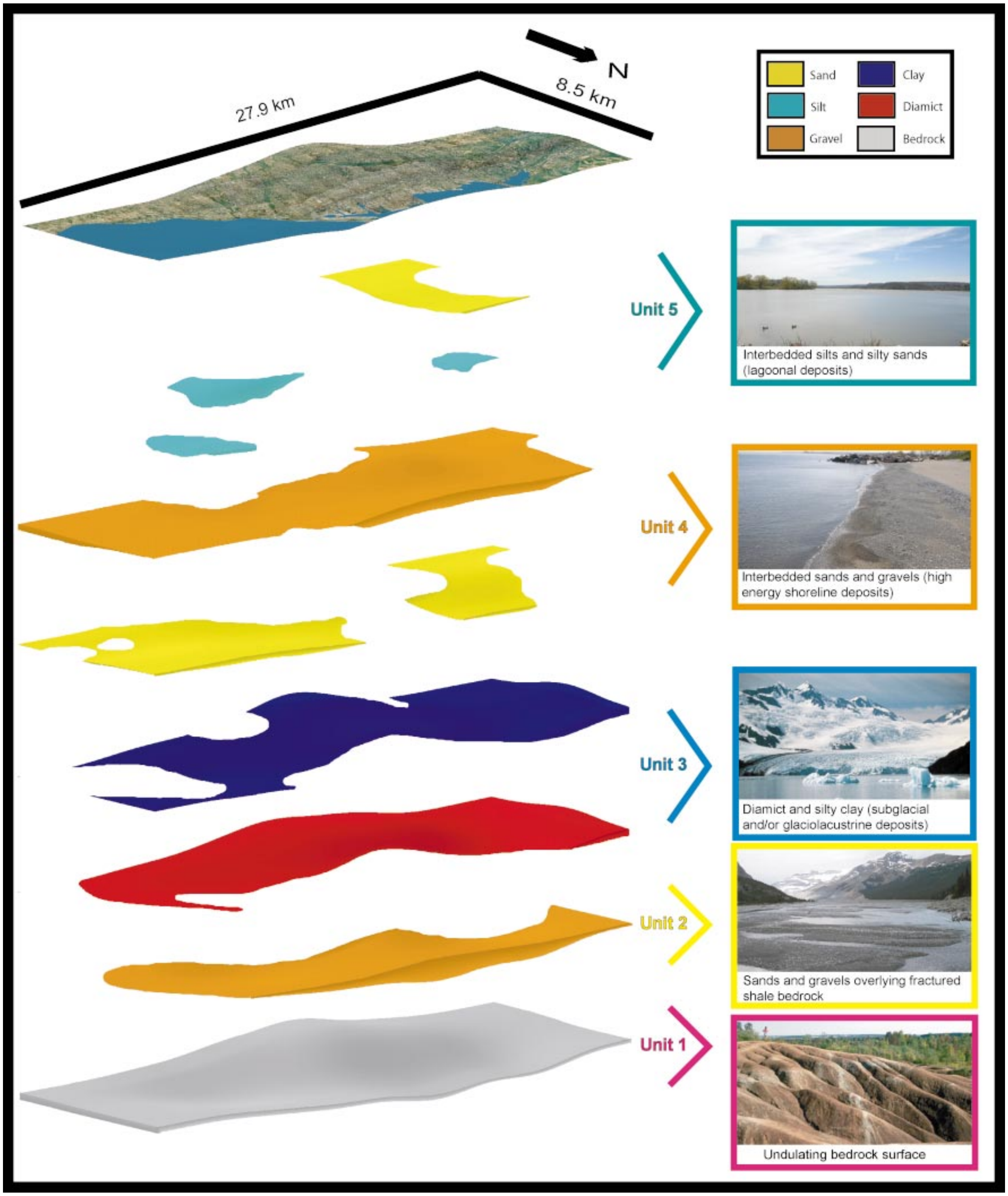


Figure 9. Three-dimensional model of stratigraphic units (units 1–5) beneath study area showing each unit as a vertically separated layer. Each stratigraphic unit records deposition under different environmental conditions; modern analogues of interpreted depositional environments are shown in photographs at right. Image is shown at 20× vertical exaggeration.

gravels) could not be accurately modeled. The lowermost stratigraphic unit recorded by most boreholes consists of fine-grained silts and clays (unit 3) that form a continuous lower aquitard with an irregular surface topography (Fig. 11; note: the thickness of unit 3 should be considered as a minimum due to limited borehole penetration). Unit 3 is overlain by coarse-grained sands and gravels of unit 4, which infill lows and pinch-out toward the southwest (Fig. 11). The southwestern limit of these sands and gravels probably represents the ancient shoreline of Lake Iroquois. Unit 4 forms the major aquifer below the Henkel site and provides the most significant transportation pathway for off-site migration of contaminants. Contaminants are unlikely to migrate toward the southwest due to aquifer pinch-out but are more likely to migrate within unit 4 deposits toward surface water bodies such as Cootes Paradise in the northeast. The relative-

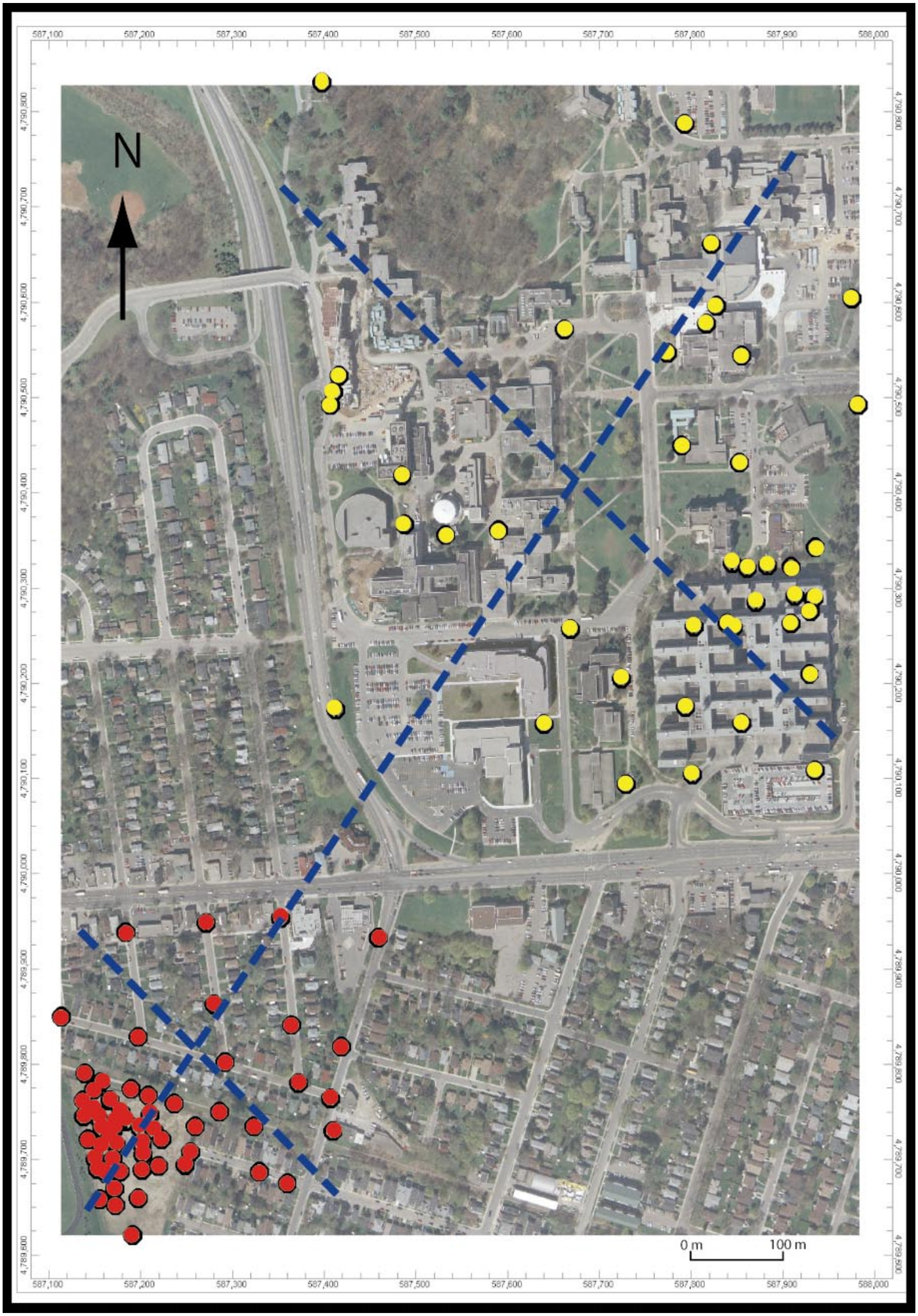


Figure 10. Georeferenced air-photograph showing location of boreholes on McMaster University campus (yellow dots) and Henkel site (red dots) used in three-dimensional subsurface modeling process. Dashed lines indicate position of the cross sections used to create fence diagram shown in Figure 11.

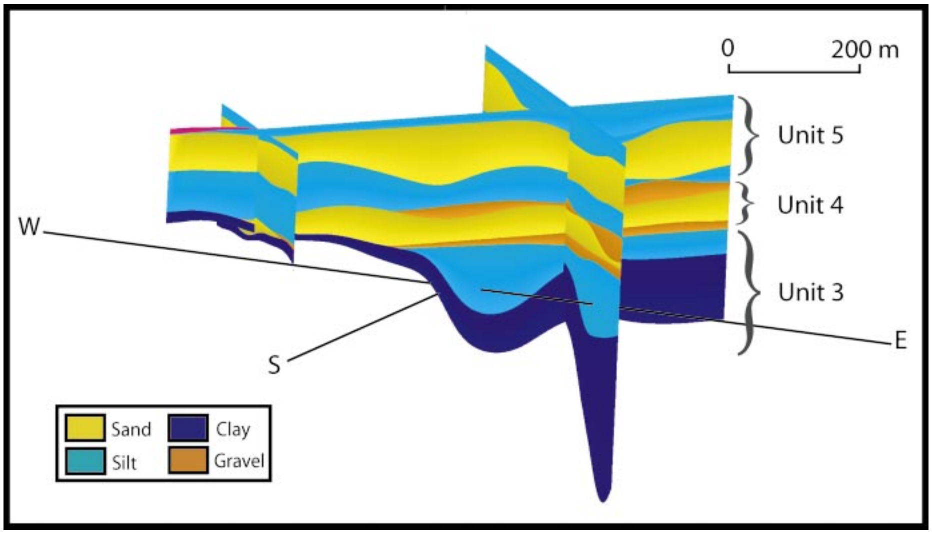


Figure 11. Fence diagram showing three-dimensional geometry of subsurface sediment types and stratigraphic units in area underlying McMaster University campus and Henkel site (see Figure 9 for details of stratigraphic units). Full thickness of lowermost unit (unit 3) is not shown as few boreholes penetrate to bedrock. Note pinch-out of unit 4 toward southwest. Borehole data from Groundwater Technology Canada Ltd. (1994) and McMaster University Physical Plant. Image is shown at 20× vertical exaggeration.

ly permeable sediments of unit 5 lie above the local water table and have facilitated the infiltration of water and contaminants from surface sources. The Henkel site example illustrates the value of using three-dimensional imaging of aquifer form and distribution to predict potential contaminant migration pathways and to help design remediation programs.

SUMMARY AND CONCLUSIONS

This study identifies the methods and tools that may be used to effectively visualize and analyze the subsurface characteristics and three-dimensional distribution of Quaternary sediments in a buried bedrock valley. 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 three-dimensional stratigraphic model to describe the infill of the broader valley.

The model indicates that in the portions of the Dundas Valley examined in this study, the irregular bedrock surface is overlain by a patchy veneer of gravel which probably records deposition under fluvial conditions. In the absence of any dating control it is not possible to determine an age for these fluvial deposits, which may predate the last glacial advance in the region. The overlying fine-grained diamicts and silty clays record flooding of the valley and deposition under glaciolacustrine or subglacial conditions. The widespread extent of these fine-grained deposits (Fig. 7) suggests that the valley was flooded by water many tens of meters above present day lake levels. This may have been caused either by 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. Further analysis of the spatial relationship between silty clays and diamicts within unit 3 is needed to better constrain the extent of glacial influence in the valley at this time.

Coarse-grained sediments of unit 4 are interpreted as shoreface deposits formed around the margins of postglacial Lake Iroquois during recession of ice from the Ontario basin; the 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 (Figs. 8 and 9). This aquifer provides a major conduit for the migration of pollutants from contaminated sites toward the major surface water bodies in the region.

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

This study illustrates the importance of three-dimensional subsurface modeling in areas underlain by thick successions of poorly exposed Quaternary sediment. Better understanding of the sedimentary infill of buried bedrock valleys, such as the Dundas Valley, will allow more accurate reconstruction of late Quaternary paleoenvironmental change and the identification and delineation of major aquifers, aquitards, and contaminant migration pathways. This type of three-dimensional imaging and analysis of subsurface sediments may be applied to other regions where relatively thick Quaternary sediments overlie bedrock.

ACKNOWLEDGMENTS

Research was supported by a McMaster University Entrance Scholarship to MacCormack, an Ontario Graduate Scholarship to Maclachlan, and a Discovery Grant from the Natural Sciences and Engineering Research Council to Eyles. We thank Mark Radomski and Viktor Terlaky for many valuable and insightful discussions, and Steve Hicock, an anonymous reviewer, and the editors for valuable comments on the manuscript.

REFERENCES CITED

Bajc, A.F., Endres, A.L., Hunter, J.A., Pullan, S.E., and Shirota, J., 2004, Three-dimensional mapping of Quaternary deposits in the Waterloo Region, Southwestern Ontario: Illinois State Geological Survey Open-File Series 2004-8, p. 12–15.

Barnett, P.J., 1992, Quaternary geology of Ontario, *in* Thurston, P.C., Williams, H.R., Sutcliffe, R.H., and Stott, M.T., eds., Geology of Ontario: Ontario Geological Survey Special Volume 4, Part 2, p. 1011–1090.

Birks, J., and Eyles, C.H., 1996, Leachate from landfills along the Niagara Escarpment, *in* Eyles, N., ed., Environmental geology of urban areas: Geological Association of Canada Special Publication, p. 347–363.

Coleman, A.P., 1937, Lake Iroquois: Ontario Department of Mines, 1936 Annual Report, v. 45, 36 p.

Edgecombe, R.B., 1999, Bedrock topography and sedimentary infill of the Dundas Valley, Hamilton, Ontario [M.Sc. thesis]: Hamilton, McMaster University, 122 p.

Eyles, C.H., and Eyles, N., 1983, Sedimentation in a large lake: A reinterpretation of the Late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada: Geology, v. 11, p. 146–152, doi: 10.1130/0091-7613(1983)11<146:SIALLA>2.0.CO;2.

Eyles, N., 2002, Ontario rocks: Three billion years of environmental change: Toronto, Canada, Fitzhenry and Whiteside, 339 p.

Eyles, N., and Williams, N.E., 1992, The sedimentary and biological record of the last interglacial/glacial transition in southern Ontario, Canada, *in* Clark, P.U., and Lea, P.D., eds., The last interglacial-glacial transition in North America: Geological Society of America Special Publication 270, p. 119–137.

Greenhouse, J.P., and Monier-Williams, M., 1986, A gravity survey of the Dundas buried valley west of Copetown, Ontario: Canadian Journal of Earth Sciences, v. 23, p. 110–114.

Groundwater Technology Canada Ltd., 1994, Environmental site investigation, second phase: Groundwater Technology Canada Limited, v. 1–2, 81 p.

Hansel, A.K., Stiff, B.J., and Barnhardt, M.L., 2004, Three-dimensional geologic mapping in rapid-growth areas: A case study from Lake County, Northeastern Illinois: Illinois State Geological Survey Open-File Series 2004-8, p. 23–27.

Hicock, S.R., and Dreimanis, A., 1992, Sunnybrook Drift in the Toronto area, Canada; reinvestigation and reinterpretation, *in* Clark, P.U., and Lea, P.D., eds., The last interglacial-glacial transition in North America: Geological Society of America Special Paper 270, p. 139–161.

International Joint Commission, 1985, Report on Great Lakes water quality: International Joint Commission, Great Lakes Water Quality Board, 68 p.

Karrow, P.F., 1963, Pleistocene geology of the Hamilton Galt Area: Ontario Department of Mines, Geological Report 16, 68 p.

Karrow, P.F., 1967, Pleistocene geology of the Scarborough Area: Ontario Department of Mines, Geological Report 46, 108 p.

Karrow, P.F., 1987, Quaternary geology of the Hamilton-Cambridge area, southern Ontario: Ontario Geological Survey, Mines and Minerals Division, report 255, 94 p.

RockWare, 2002, RockWorks v. 2002: A computer program providing broad, integrated geological data management, analysis, and visualization tools for downhole data: RockWare, 305 p.

RockWare, 2004, RockWorks v. 2004: An updated computer program for spatially analyzing data and visualizing three-dimensional subsurface models: RockWare, 348 p.

Russell, H.A.J., Pullan, S.E., Hunter, J.A., Sharpe, D.R., and Holysh, S., 2004, Buried-valley aquifers: Delineation and characterization from reflection seismic and core data at Caledon East, Ontario: Illinois State Geological Survey Open-File Series 2004-8, p. 73–76.

Sarapera, S., and Artimo, A., 2004, Updating of the three-dimensional hydrogeological model of the Virttaanakangas area, Southwestern Finland: Illinois State Geological Survey Open-File Series 2004-8, p. 77–80.

van Haaften, S., Shirota, J., Gao, C., and Brunton, F., 2004, Depth to bedrock: Three-dimensional bedrock and overburden thickness methodology for mineral aggregates and groundwater heology mapping in Ontario: Illinois State Geological Survey Open-File Series 2004–8, p. 98–100.

MANUSCRIPT RECEIVED BY THE SOCIETY 20 JANUARY 2005
REVISED MANUSCRIPT RECEIVED 10 JUNE 2005
MANUSCRIPT ACCEPTED 18 JULY 2005

Printed in the USA