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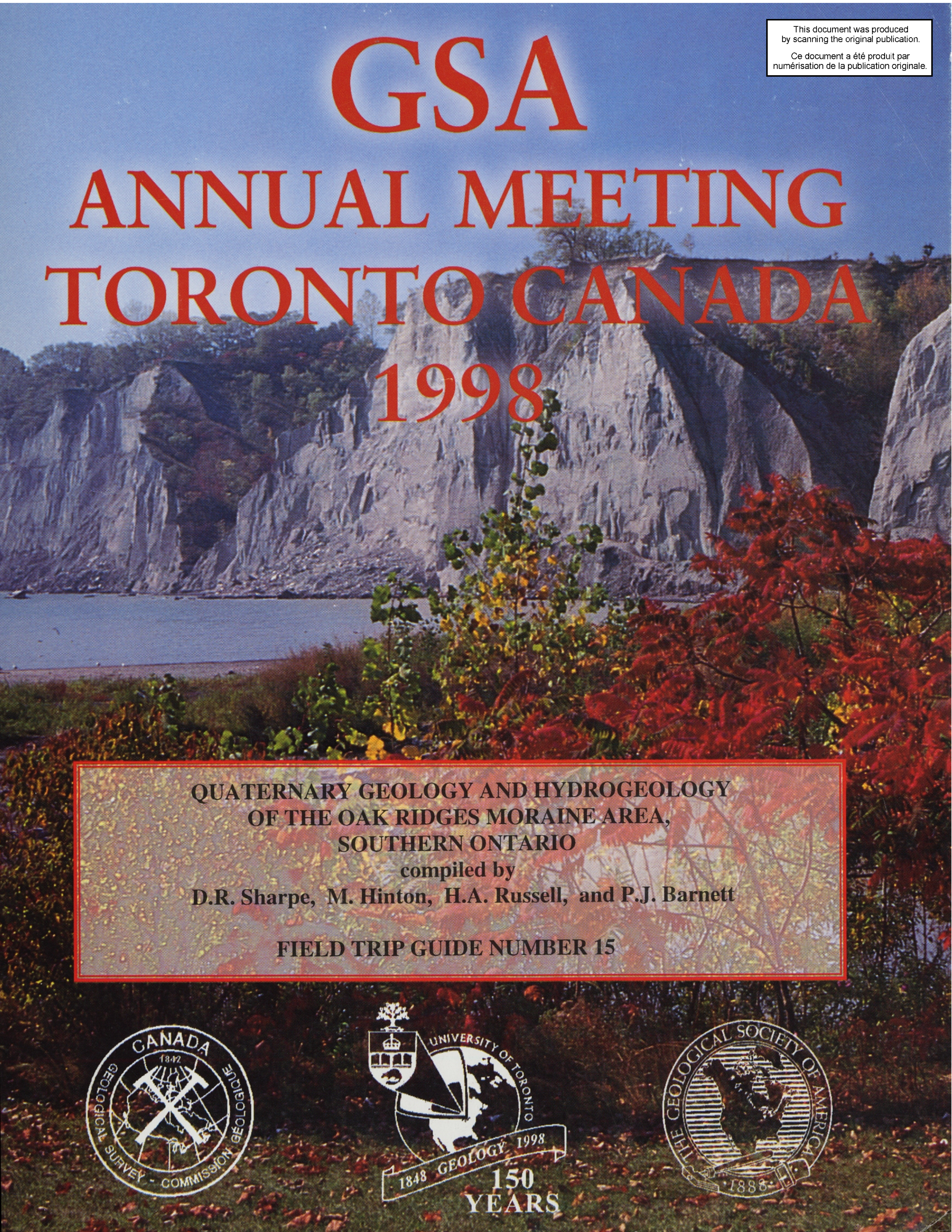

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1998

QUATERNARY GEOLOGY AND HYDROGEOLOGY OF THE OAK RIDGES MORAINE AREA, SOUTHERN ONTARIO

compiled by
D.R. Sharpe, M. Hinton, H.A. Russell, and P.J. Barnett

FIELD TRIP GUIDE NUMBER 15

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Regional Surficial Geology of the Oak Ridges Moraine NATMAP Area

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LEGEND

QUATERNARY PERIOD (~last 2 million years)

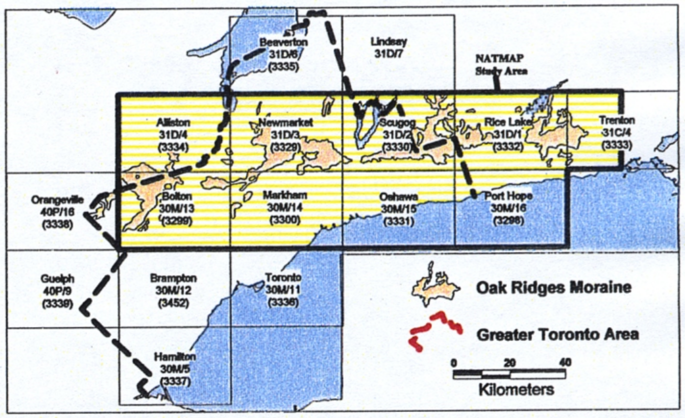
11	**Recent Deposits:** sand, gravel and diamicton:
10	**River Deposits:** sand and gravel
9	**Organic Deposits:** peat, muck and marl,
8	**Glacial Lake Deposits[1]:** sand and gravel
7	**Glacial Lake Deposits[1]:** silt and clay,
6	**Glacial River Deposits[2]:** sand and gravel
5	**Moraine Deposits:** fine sand to gravel
4	**Glacial Deposits (till):** clayey silt to silt,
3	**Glacial Deposits (till):** sandy silt to sand,
2	**Lower (drift) Deposits:** till, fine-medium sand, and laminated silt and clay,

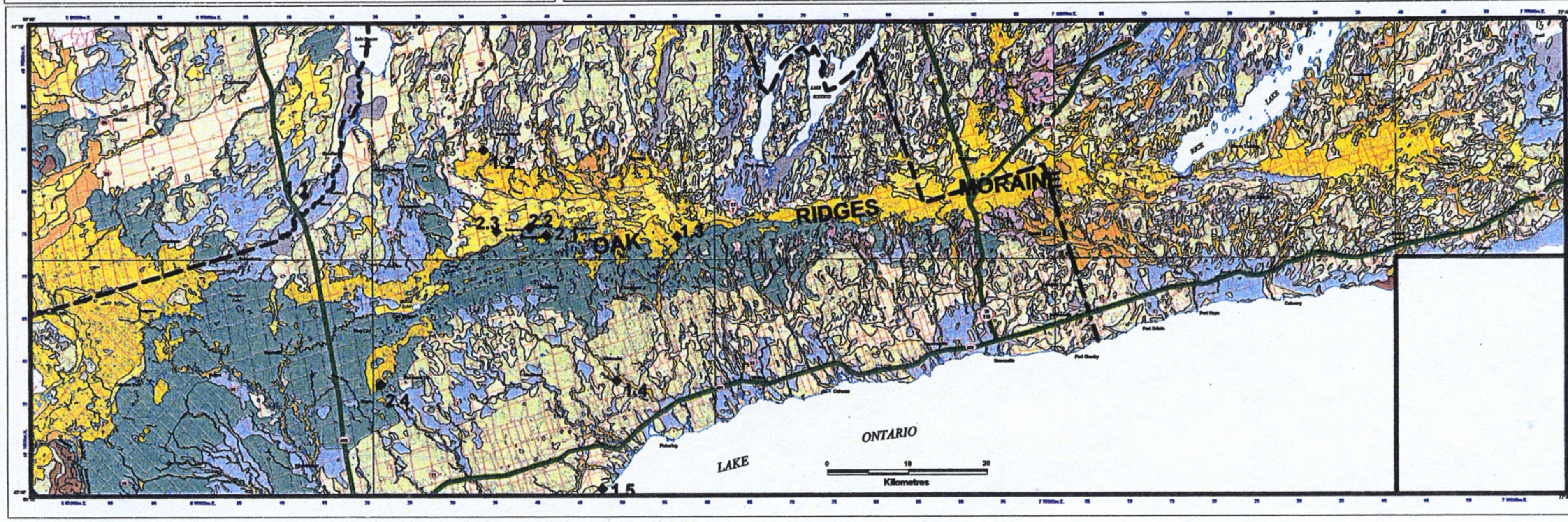
Unconformity ______________(interval with no deposits and/or major erosion)

PALEOZOIC

1	**Bedrock:** limy mudrock and clastic sedimentary rock

A 1:200,000 scale compilation of nine 1:50,000 scale surficial geology maps for the Oak Ridges Moraine study area has been completed by the Geological Survey of Canada (GSC) in collaboration with the Ontario Geological Survey. Note: This map is designed to accompany Geological Society of America Field trip guide 15, 1998





Quaternary Geology and Hydrogeology of the Oak Ridges Moraine Area, Southern Ontario

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ABSTRACT

The Oak Ridges Moraine (ORM) is a prominent, sandy ridge on the north shore of Lake Ontario. It is an important resource in the Greater Toronto Area (GTA) with respect to water resources because of its ability to absorb, store and discharge clean, cool water and support major streams in the area. The ORM is a well-used regional aquifer complex, however, there is a need to define the extent, nature and quality of its surface and groundwater resources. These resources are under pressure due to rapid urbanization.

The ORM area is the focus of a multi-disciplinary hydrogeological study by the Geological Survey of Canada (GSC) and other agencies and groups under the GSC National Geoscience Mapping Program (NATMAP) and Hydrogeology initiatives. The ORM study is part of an effort to enhance regional hydrogeological research at the national level.

The area consists of a complex succession of coarse-grained glacial sediments (aquifers), and extensive fine-grained tills (aquitards), and southwest-trending channels that dissect underlying sediments. This field trip will address the geologic setting and architecture of the ORM while highlighting regional methods, sedimentary models and areas of advancement in hydrogeology.

INTRODUCTION

Groundwater in Canada is a provincial resource, but several federal departments play a role in groundwater. Although the GSC was active in groundwater mapping and research in the first half of the century, there have been no national surveys of groundwater resources similar to those conducted by the USGS Regional Aquifer System Analysis (RASA) program. A review of groundwater research in Canada by the Canadian Geoscience Council recommended that provincial and federal governments establish database standards, delineate aquifers and characterize groundwater resources (CGC, 1993). While no nation-wide program has been initiated in Canada, the Oak Ridges Moraine study is an attempt by the GSC to apply its existing expertise to groundwater issues in Canada and to redevelop its groundwater program and partnerships.

The ORM Hydrogeology study is investigating groundwater issues at the regional scale. While many hydrogeological studies seek to investigate issues related to water supply and contamination over small areas, we seek to adopt a broader approach so that our results address a range of water resource issues. As water resource management becomes more integrated, there are more diverse users of groundwater information. User's interests include land use planning, watershed management, recreation (e.g. golf courses), agriculture, aquatic ecology and aggregate extraction. The ORM study has integrated new and existing data at several scales and the trip will outline the benefits of such a regional approach while reviewing the geology and hydrogeology of the area.

More than 95% of Canada and ~25% of the US has been glaciated. Glacial deposits form important aquifers and aquitards and also influence groundwater flow in bedrock aquifers. The relatively thin, complex and discontinuous nature of glacial aquifers compared to sedimentary bedrock aquifers has, in part, discouraged regional approaches to glacial aquifers in Canada. In the Northeastern US most glacial aquifers occur in individual valleys and do not interact at a regional scale (Randall and Johnson, 1988; Randall, 1997). Elsewhere, in areas similar to the ORM, however, there are thicker and more extensive deposits (up to 200 m thick) that form regional aquifer systems. Studies by RASA of such areas covered ~10, 000-30,000 km^2, 3-10 times the size of the ORM study.

Many regional hydrogeological studies focus on bedrock terrains and involve large sedimentary basins (e.g. Ogallala Formation), with aquifer dimensions much larger than the complex system of aquifers found in glacial terrain. Hence, there is a need to develop appropriate conceptual models for glacial aquifers, especially in Canada. It is anticipated that some of the

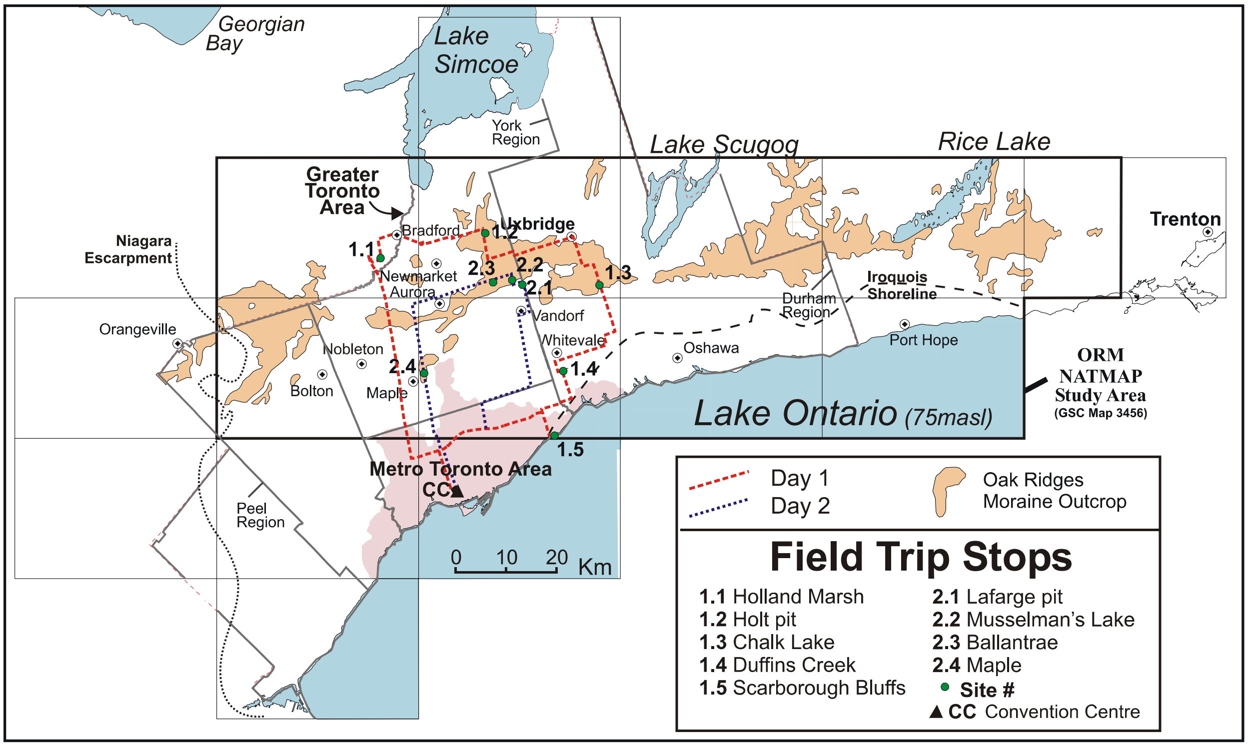


Figure 1. Location map and trip route. The highlighted area is a coloured geology and fieldtrip map inserted at the front of this guidebook.

geological models and methods developed within the ORM study may be applicable to other glaciated regions of Canada and elsewhere.

The ORM is a regional east-west drainage divide running between Lake Ontario and Lake Huron (Georgian Bay; Fig. 1). It is a valuable resource in the Greater Toronto Area (GTA) as the main source of water to 30 major streams, an important source of aggregate, recreation and wildlife habitat. The ORM is also an important water resource in a region of rapidly growing urban and rural population. The ORM aquifer complex provides an example of the need for regional groundwater studies in areas of diverse groundwater uses.

The ORM study is a collaborative effort between the GSC and the Ontario Geological Survey (OGS), with the support of several provincial agencies and regional governments. This project is complementary to other research in the area conducted by the University of Toronto, the Interim Waste Authority (IWA), Hunter-Raven/Beck and other consultants.

Goals of the field trip

1. Present a regional hydrogeology study that is broad in scope and diverse in methodology.
2. Provide an overview of research methods and techniques used in the ORM study.
3. Present a regional geological and hydrogeological model of the ORM by visiting each of the main geologic and hydrogeologic elements of the model.
4. Demonstrate the utility of geological models to hydrogeological investigations, in part by encouraging greater interaction between geologists and hydrogeologists.

Water resource issues

Across Canada, about 25% of the population rely on groundwater for their domestic water supply. In Metropolitan Toronto and suburban areas near Lake Ontario however, 85% of the population obtains their water from the lake via pipeline. The remaining 15%, mostly in urban areas north of Toronto (e.g. Newmarket, Aurora), small towns and rural areas, use groundwater.

Adequate water supplies are essential in planning from the residential scale, to the development and national scales. On a regional scale, the GTA has had sufficient water supplies to enable large population growth to date, without suffering major water shortages. Short-term water supply problems have been experienced, however, in smaller communities where there is an incomplete hydrostratigraphic understanding. Groundwater has proven to be a reliable and economical resource, but the potential of the resource is not well known. The primary concern with respect to water supply is the rapid population growth in areas farther from Lake Ontario. For example, in York Region (Fig. 1), long-term projections indicate that water demand will continue to grow (from 218M L/day in 1991 to 504M L/day in 2011) and groundwater supplies are thought to be insufficient to satisfy demand. Various options for supplying water by pipeline from Lake Ontario or from Georgian Bay are presently being considered (Regional Municipality of York, 1993; 1996). However, new pipeline construction alone is estimated to cost approximately $1 billion without considering the additional operational cost of water transport and treatment.

Even if additional pipelines are built, groundwater use in the ORM is unlikely to decrease. Rural populations are expected to grow; outside of major urban areas pipelines will likely be uneconomical and continued reliance on groundwater supplies is to be expected. Furthermore, the demand for high-value irrigated crops close to urban markets is likely to increase. There are also new groundwater users in the area, such as golf courses, sod farms and the bottled water industry.

In some areas, groundwater may be used to supplement lake water (Gartner-Lee Ltd., 1996) or may simply be more cost-effective since it is available closer to the site of demand at a higher elevation than lake water and will require less treatment. Such a system is presently operating in Durham region (Fig. 1) where Skinner's Spring has supplied 1.5 million L/ day to Bowmanville at low cost since 1914.

Streams are of great importance to residents of the GTA. Most of the green spaces and parks are located along water courses that derive much of their flow from groundwater discharge. These areas are popular for sporting and recreational activities. Most importantly, streams are often the residents' closest contact to the natural environment and one of the few ways they can assess its "health". Consequently, much effort is made to develop stream management programs.

Groundwater is becoming increasingly important for land use development and planning. Both regulators and residents are recognizing the ecological role of groundwater for the numerous streams in the GTA and that groundwater is a potential pathway for contaminant movement. Consequently, concerns about groundwater are more frequently being raised whenever land use changes are considered. Conservation authorities are including groundwater in their watershed management programs. Similarly, government agencies are receiving an increasing number of requests for groundwater information from both conservation authorities and planners.

Waste management is an issue that has received considerable attention in the GTA over the past decade. As the GTA landfills are reaching their capacity, there is debate over the fate of the city's garbage in the future. This debate has raised awareness about groundwater contamination.

GLACIAL GEOLOGY

Early work on the ORM has been summarized by Duckworth (1979), Gwyn and Cowan (1978) and Chapman (1985). Groundwater studies have relied on analysis of water wells (e.g. GSC Water Supply series, 1940-1950), earlier geologic mapping (e.g. Deane, 1950; Gadd, 1950; Gravenor, 1957), and later work by Ontario Geological Survey (Watt, 1957; Karrow, 1959; 1963; 1967). This geologic mapping was important for regional hydrogeological assessments by Haefeli (1970), the Ontario Ministry of Environment (MOE) (Singer, 1974; Turner, 1997; Sibul et al., 1977; Funk, 1977; Ostry, 1979) and others (e.g. Howard and Beck, 1986; Howard et al., 1997).

Geological setting

The Oak Ridges Moraine forms an elevated ridge of sediment ~250-300 m above Lake Ontario and Georgian Bay, extending 160 km from the Niagara Escarpment to near Rice Lake (Fig. 1). It is a sandy, complex glaciofluvial-glaciolacustrine landform resting unconformably on a regional till sheet, lower sediments and, in places, directly on gently-dipping bedrock.

The ORM and underlying sediments are late Pleistocene in age and unconformably overlie thin Paleozoic platform strata. These in turn overlie Precambrian Shield rocks exposed north of the study area (Fig. 2). Ordovician limestones, in the east, and minor sandstone and shale in the west, underlie the thick glacial sediments of the area. The Niagara Escarpment on the western margin of the area is capped by Silurian dolostones (Fig. 2).

A broad control on groundwater resources and flow patterns in the area is the structure of Precambrian, Paleozoic and Pleistocene strata. A major northeast trending structure in Shield rocks (Easton, 1992) may control the position of lakes on the edge of the Precambrian / Paleozoic contact (Fig. 2) and possibly the orientation of the bedrock valleys that occur in the northern ORM area (Scheidegger, 1980). A complementary set of northwest and northeast trending fracture patterns (Sanford et al., 1985), and preglacial drainage networks (Spencer, 1881), that preferentially eroded softer shale, may also control the position of the Paleozoic bedrock valleys. These lakes and structures have likely been enhanced by glaciofluvial erosion as well (Gilbert and Shaw, 1994). In addition, a network of valleys or channels occur in the thick glacial sequences of the ORM area (Barnett, 1990). Hence, underlying structure and bedrock morphology are controls on regional hydrogeology of the ORM. Finally, small-scale structure, weathering and near surfaces fractures and jointing in bedrock may enhance groundwater flow.

Glacial history of southern Ontario

Recent summaries describe the glacial history of southern Ontario (Barnett et al., 1991), the ORM (e.g. Barnett et al., 1998) and till plains south of the ORM (Fig. 2; Martini and Brookfield, 1995; Boyce et al., 1995). The thick sequences in the ORM region originated from glacial, glaciolacustrine and non-glacial events during the last ~125, 000 years (Karrow, 1989; Table 1).

Quaternary glacial and non-glacial sediments are exposed to the south of the ORM along the Lake Ontario bluffs (e.g. Karrow, 1967; Brookfield et al., 1982) and underlie the ORM (Duckworth, 1979; Sado et al., 1984; Eyles et al., 1985). This complex package of till, glaciolacustrine sand, silt, clay and diamictons, deposited ~12-125 K years BP, is up to 100 m thick. The package includes Illinoian-age till and warm-climate interglacial sediments overlain by early to middle Wisconsinan age (25-90 K years BP) glacial lake sediments (Karrow, 1967).

The last major ice advance (Late Wisconsinan; 25 000 to 12 000 years BP) was from the northeast (Fig. 3) and along the axis of the Great Lake basins. During this interval the ice deposited a thick widespread till sheet or amalgamated sheets (Newmarket Till; stop 1.4). This till overlies thick lower deposits and both sequences continue under the ORM (Fig. 4). This regional till sheet is variable in thickness (Sharpe et al., 1994b); it has been eroded by meltwater to form a regional unconformity consisting mainly of

Table 1. Stratigraphy of the Oak Ridges Moraine area

Stratigraphic unit[1]	Explanation/description	Age (ka)
Quaternary	Period covers last 2 million years (e.g., glacial time)	
Recent (Holocene)	Postglacial period	
Lake Ontario deposits	Deposits along shore of the modern lake (75m asl)	
Alluvium	Sediment deposited by modern rivers	10
Older alluvium	Sediment deposited by rivers in terraces	
Organic deposits	Plant, animal matter, mostly peat, deposited in wetlands	
Pleistocene epoch		2000 - 10
Glacial lake deposits	Iroquois/Algonquin/Peel/Schomberg (sand, silt, clay) (the high glacial lakes of Lake Ontario)	
Glaciofluvial deposits	Deposits of glacial meltwater flow (sand and gravel)	
Late Wisconsinan		25 - 12
Wildfield / Kettleby sediment[2]	Till interbedded with clay, silt and fine sand	
Halton Till (and sediment)	Thick in Humber Valley thins rapidly to the east	
Oak Ridges Moraine sediments	Thick glacial lake deposits on eroded Newmarket Till	
Wentworth / Upper Leaside tills	May grade into Halton Till	
Port Stanley / Tavistock tills	Lake Ontario derived till / Lake Huron derived till	
unconformity	Erosion marked by drumlin formation and channel erosion; channels produced by subglacial floods - Barnett, 1990	
Newmarket / northern Till	Thick regional till extending beneath the ORM	
Middle to Early Wisconsinan (Lower Sediment)		~100 - 25
Upper Thorncliffe Fm.	Deltaic/fan beds along lake bluffs	
Seminary / Meadowcliffe	Thin diamicton separating Thorncliffe sands	
Lower Thorncliffe Fm	Sand and rythmites	~30 - 50
Sunnybrook Fm	May form regional till sheet	
Scarborough Formation	Cool-climate beds (~122m asl at bluffs)	~90
Sangamon		
Don Formation	Warm-climate (+3°C) sand, silt and clay	
Illinoian		
York Till	Illinoian Till from prior to last interglacial	>125
unconformity	Long interval with no deposits and/or major erosion	
Paleozoic (Ordovician)	Limestone, dolostone; sandstone or shale	

1. see Barnett at al., (1991) for stratigraphic scheme of southern Ontario.
2. Wildfield occurs south of ORM; Kettleby occurs north of ORM.

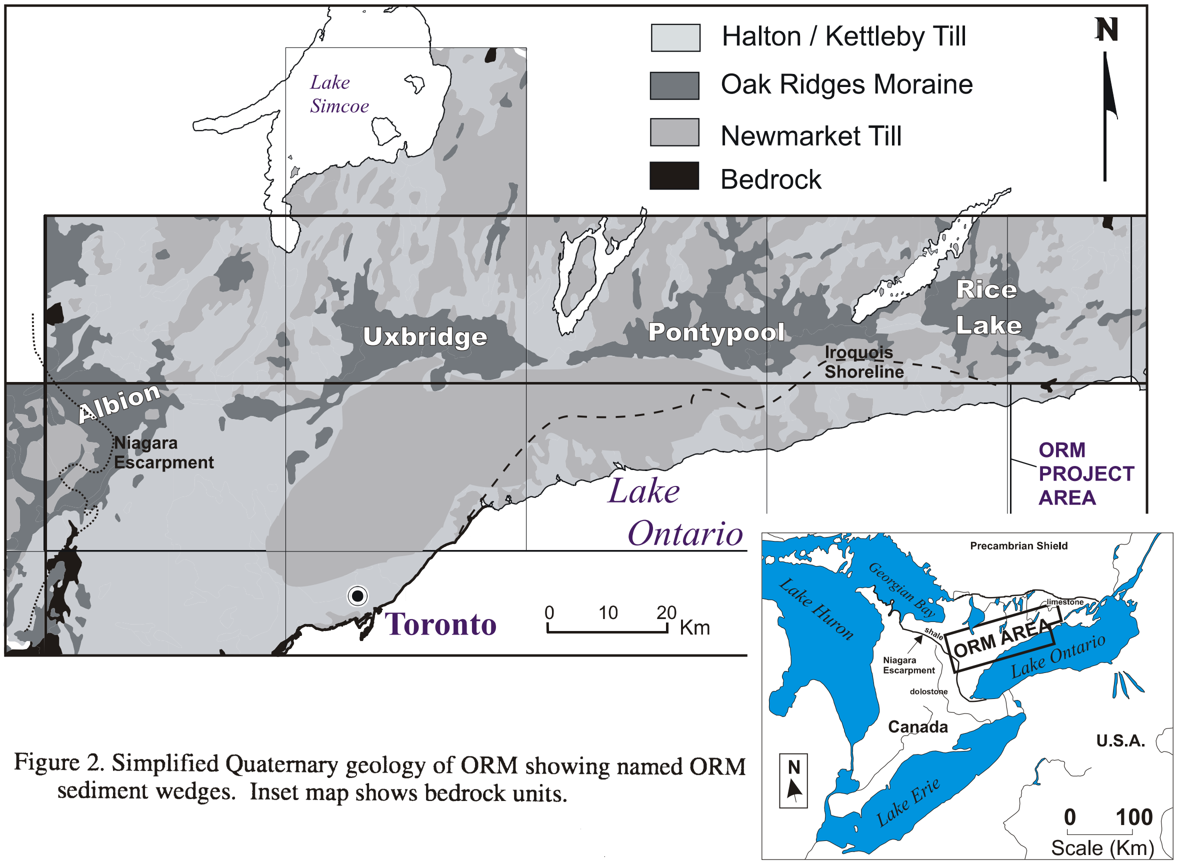


Figure 2. Simplified Quaternary geology of ORM showing named ORM sediment wedges. Inset map shows bedrock units.

drumlins and a network of channels. The ORM rests on this eroded terrain (Fig. 4) and formed ~12 000-13 000 years ago (Gwyn and Cowan, 1978).

The ORM occurs as thick stratified sediments, partly capped by thin Halton Till along its southern flank (Fig. 4). The ORM sediments were deposited rapidly in a glacial lake (e.g. Gilbert, 1997; Barnett et al., 1998) set in a re-entrant or cavity between thick ice of the Laurentide Ice Sheet to the north and low-relief ice occupying the Lake Ontario basin to the south (Fig. 5). ORM deposits may be part of a larger system of ice-controlled meltwater deposition during final deglaciation that includes stratified moraines west of the ORM (Gwyn and Cowan, 1978).

Regional geology

Based on geological mapping (Sharpe et al., 1997) and a need to generalize the complex geological history of the area, four major units and two erosional surfaces (regional unconformities) are identified and described (Fig. 6; Table 2). The unconformities are important as they allows us to correlate stratigraphic units across the area and they often mark major changes in hydraulic properties across their boundaries.

1. *Bedrock surface:* This surface is the regional unconformity separating rock from sediment. The general location of valleys on this surface has been mapped (e.g. Eyles et al., 1993). The best documented of these buried valleys, the Laurentian Channel (Stop 1.1), extends from Georgian Bay to Lake Ontario (Spencer, 1881) and is buried by sediment up to 200 m thick (Stop 2.4). The geometry of the bedrock surface is poorly constrained, as few wells intersect bedrock. Investigations using location-corrected water-wells (e.g. Kenny et al., 1996), hydrogeological borehole data, and seismic reflection profiles indicate a trunk and tributary valley system (Brennand et al., 1997a). In the Bolton area, valleys eroded into the Niagara Escarpment form tributary valleys to the main Laurentian Channel (Hunter et al., 1996). These bedrock valleys may contain productive aquifers.

2. *Lower sediments*: Lower sediments (Don, Scarborough, and Thorncliffe Formations and

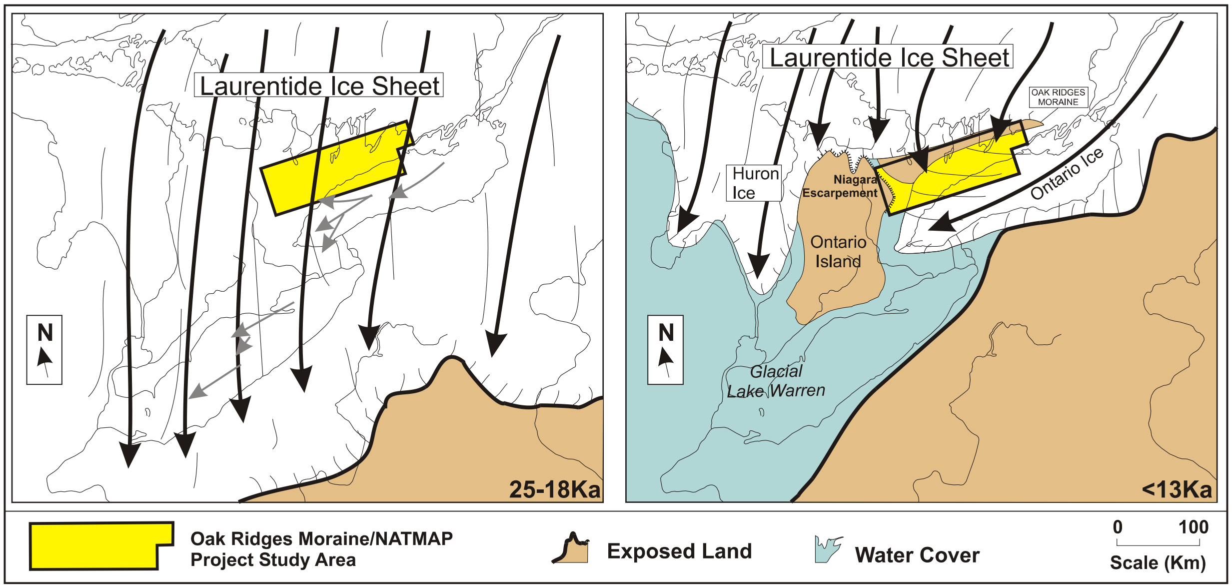


Figure 3. Ice flow at last glacial maximum across ORM: a) 18-25K years, b) <13K years, showing late-glacial configuration of ice masses, glacial lakes and exposed land. (From Dyke and Prest, 1987).

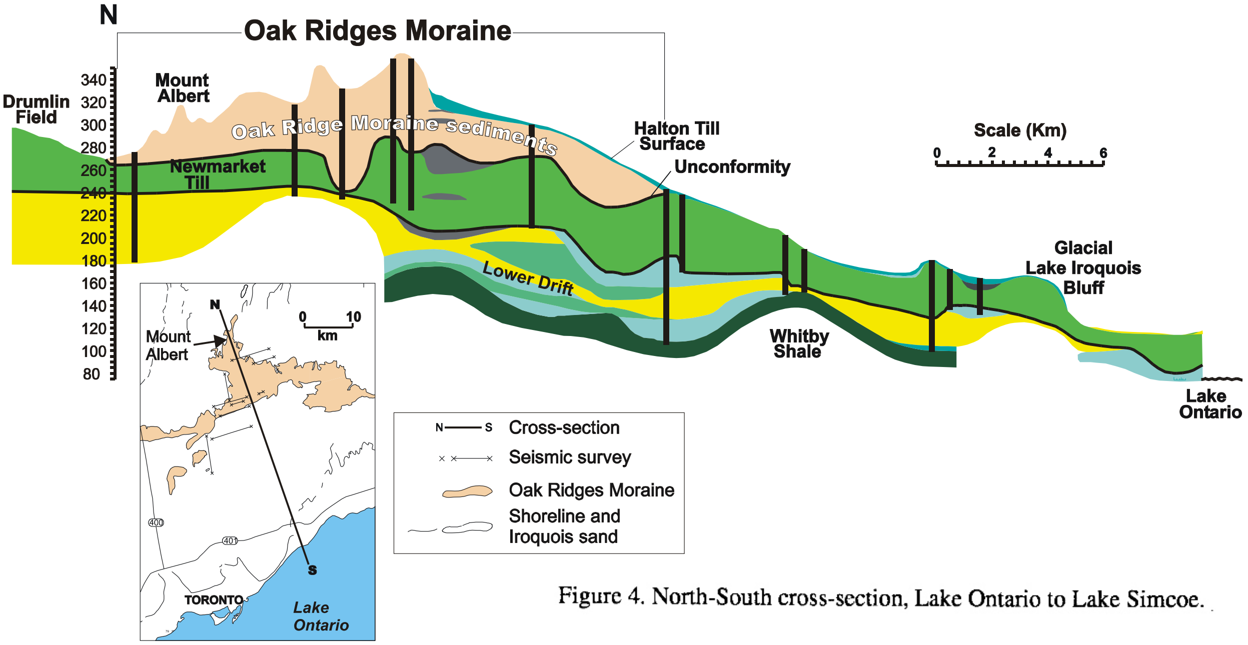


Figure 4. North-South cross-section, Lake Ontario to Lake Simcoe.

Sunnybrook Till, Table 1), exposed at Scarborough Bluffs (Karrow, 1967), extend north of the ORM in the subsurface (Fligg and Rodrigues 1983; Eyles et al., 1985). River bluffs north of Lake Ontario expose lower sediments in places (e.g. White, 1975). The sandy Don sediments have been identified on seismic records near Nobleton (Pugin et al., 1996), extending reports from drillcores (Sado et al., 1984; Stop 2.4). Overlying organic-rich Scarborough sands have been confirmed in boreholes as far north as Vandorf (Fig. 1; Sharpe et al., 1996) and possibly Lake Simcoe (Fenco-MacClaren, 1994). These sand strata have regional extent and are well displayed on seismic profiles (Pugin et al., 1996; stop 2.4). Organic matter and methane gas in the Alliston aquifer (Aravena and Wassenaar, 1993) may indicate thick, organic-rich Scarborough sediments in the Laurentian Channel. The Sunnybrook Till appears in a GSC borehole near Newmarket and forms a regional clayey aquitard contains sands and clayey rhythmites that may be traced from Lake Ontario (stop 1.5) north to Mount Albert, Stop 1.2 (Fig. 4). Where the Newmarket Till is completely eroded, lower sediments may also have been eroded (Pugin et al., in press). The lower

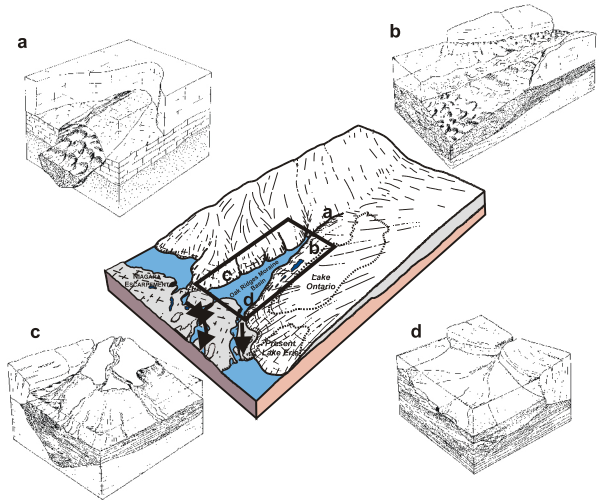


Figure 5. Ice position during formation of ORM showing deep re-entrant lake supported by the Niagara Escarpment. Four depositional settings occurred during moraine formation (from Barnett et al., 1998): a) subglacial (eskerine), b) subaqueous fan, c) fan-delta, d) ice-marginal.

sediment unit is a complex hydrostratigraphic entity that includes both aquifers and aquitards. Nevertheless, several municipal wells are screened in sandy lower sediments (e.g. Aurora-Newmarket).

3. *Newmarket Till:* This sediment, a dense, stony, silty sand diamicton, is up to 60 m thick and has been traced lithologically beneath the moraine (e.g. Gwyn, 1976; Barnett et al., 1991). It contains locally significant (1-2m; up to 5 m) sandy interbeds (see stop 1.4). In rare instances, it contains thin rhythmites or isolated clay laminae. The Newmarket Till has a planar, generally-undeformed lower contact between the till and underlying (Thorncliffe) rippled and interbedded sand and silt, based on logged sections and seismic profiles. Newmarket Till is characterized by high seismic velocities in downhole seismic logs obtained over wide areas, and the contrast in velocities between it (2000-3000 m/s) and overlying sediments (1500-2000 m/s) makes it a prominent reflector on seismic profiles (Pullan et al., 1994; Boyce et al. 1995; Pugin et al., in press). The base of the unit typically occurs ~ 200-220 m asl across the central part of ORM (Fig. 4). The extent and stratigraphic relationship of Newmarket Till to other till sheets has been discussed (e.g.Table 1; Sharpe et al., 1994b; Boyce et al., 1995).

The sedimentary character of this till indicates some loading from overlying ice but not enough, in most places, to rearrange underlying, widespread fine sedimentary structure. The diamicton is locally interbedded and appears to have formed as debris flows. In other places, discontinuous boulder pavements may be found with striated upper surfaces. In total, this diamicton complex includes thick, massive sequences to bedded and interbedded layers of diamicton that formed by a variety of subglacial processes.

The Newmarket Till surface undulates north of the ORM (Gwyn and DiLabio, 1973), and carries both drumlins and channels as part of a regional unconformity. This erosional surface is considered to have been formed by subglacial sheetflows, producing drumlins (Shaw and Sharpe, 1987) followed by waning-stage, entrenched flow, producing channels (Brennand and Shaw, 1994). Newmarket Till is a regional aquitard separating near-surface aquifers from deeper, lower aquifers (Fig. 4).

4. *Tunnel channels and channel fill:* A network of south-southwest-oriented channels that occurs north of the Oak Ridges Moraine (Figs. 7, 8), is cut into Newmarket Till. The surface expression of the channels disappears beneath the ORM (Fig. 8). Mapping (Barnett, 1993), drilling (Barnett, 1993), and seismic reflection profiling (Pugin et al., 1996) show that channels continue beneath the ORM. The channels may be confined within the Newmarket Till, or may have eroded through it into lower sediments (Fig. 4). The channels at surface are 1-4 km wide and tens of metres deep. In the subsurface, their geometry is 1-2 km wide and tens of metres deep (Pugin et al., in

Table 2. Lithologic units and unconformities of the regional model and stop locations

	Depositional or erosional event	Stop
6)	Halton / Kettleby sediments	2.4
5)	Oak Ridges Moraine sediments	1.1, 1.2, 1.3, 2.1 - 2.4
4)	Tunnel channels (unconformity) and channel fill	1.1, 1.2, 2.4
3)	Newmarket Till	1.2, 1.4, 1.5
2)	Lower sediments	1.4, 1.5, 2.4
1)	Bedrock surface (regional unconformity)	1.1, 2.4

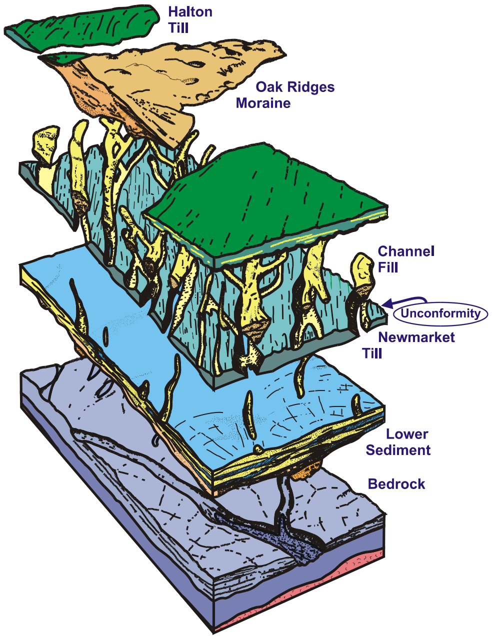


Figure 6. Geological model of the ORM. Major lithological elements and two regional unconformities, one on bedrock and one on Newmarket Till are shown.

press). The lowest, coarse sediment fills show NE-SW trends (parallel to surface channels, Fig. 7). The channels mainly contain sandy sediments (Russell et al., 1998); however, some channels contain thick (10-15 m), cross-bedded gravels (Shaw and Gorrell, 1991; Pugin et al., in press; stop 1.2). The channel network is attributed to subglacial floods (e.g. Barnett, 1990; Shaw and Gilbert, 1990) and the fill is attributed to waning flow (e.g. Shaw and Gorrell, 1991). These channels may be hydrogeologically significant as high yield aquifers (e.g. Ballantrae, Stop 2.3; Sharpe et al., 1996) or as hydraulic connections to lower beds.

5. Oak Ridges Moraine sediments: The ORM is an extensive stratified sediment complex 160 km long and 5-20 km wide, arranged as four sediment wedges (Fig. 2), each widening westward. The wedges sit distal to large channels extending from: 1) Holland Marsh, 2) Lake Scugog, and 3) Rice Lake (Figs. 2,7). The ORM may be more extensive (~ 5km) and may reach thicknesses of 150 m in the subsurface (Fig. 4), particularly beneath Halton sediments (Stop 2.4). The lower contact of the ORM sits on a channelized, regional unconformity found on lower sediment or on bedrock (Figs. 4, 6). ORM sediments occur primarily within fan-shaped bodies on the scale of 10-100 m thick, 100-5000 m long and 10-1000 m wide; they are arranged from coarse to fine downflow and upsection. Core logging shows that moraine sediments may consist of a 2-3 fining-upward sequences (Gilbert, 1997; Russell et al., 1997). Rhythmically interbedded fine sands and silts are the dominant sediments, but coarse, diffusely-bedded sands and heterogeneous gravels are prominent locally, at the apex of fans and at depth in channels. ORM sediments have predominant NE-SW to E-W paleoflow indicators. The deposits are interpreted as glaciofluvial, transitional to glaciolacustrine subaqueous fan, and delta sediments, deposited in a glacial lake ponded between the ice and the >400-m-high Niagara Escarpment to the west (Fig. 5). The ORM forms the dominant aquifer and recharge-discharge complex in the region (Turner, 1977).

6. Halton/Kettleby sediments: Halton and Kettleby sediments are the most recent stratigraphic unit (Figs. 4,6), occurring as surface tills and lake sediments south (Halton) and north (Kettleby) of the ORM (Fig. 2). The Halton complex is thickest (20-30 m) in the Humber Valley (Stop 2.4; Figs. 4 and 6); it thins towards the north and east. Where these sediments onlap the flanks of the ORM they are marked by a zone of hummocky terrain and depressions (stop 2.2). The unit is dominantly a clayey silt to silt till with interbedded sand and silt. Its extent is reduced south of the Uxbridge wedge (Fig. 2) based on regional mapping (Sharpe et al., 1997; Brennand, 1997b). This limited extent south of ORM has important hydrogeologic implications as Halton Till is often mis-identified (IWA, 1994) and ORM sediments are less extensive than reported. The Halton/Kettleby sediments are predominantly aquitards but as they are thin, jointed and contain sandy lenses, their local permeability is often enhanced.

HYDROGEOLOGICAL SETTING

GSC first compiled water well records in the ORM in a series of reports (1940's, 1950's) on the groundwater conditions encountered in local counties (e.g. Gadd, 1950). Inland Waters Branch, successors to the earlier GSC activity, examined regional flow systems to consider the potential for flow between Lake Simcoe and Lake Ontario, and groundwater discharge into Lake Ontario (Haefeli, 1970). In the 1970s, the Ontario Ministry of the Environment published a series of reports and maps that compiled existing water well information and, in some studies, collected new hydrostratigraphic data (Ostry, 1970; Funk, 1977; Sibul et al., 1977) and delineated and characterized

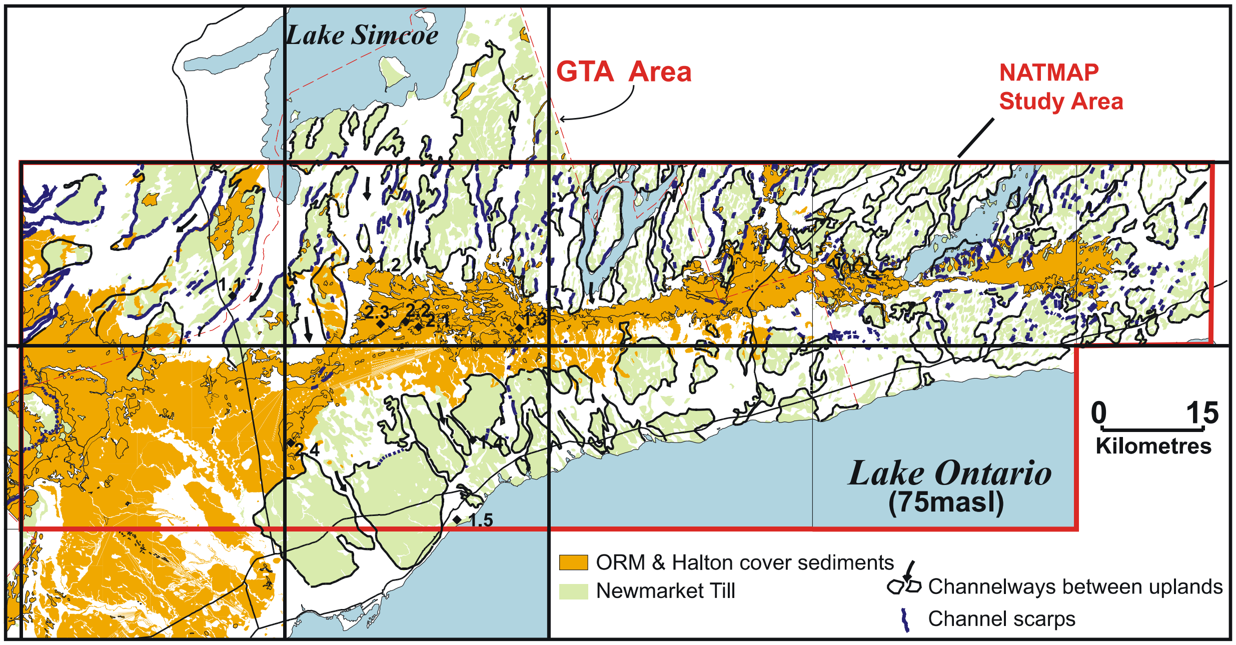


Figure 7. Channels of the ORM area. The ORM and Halton sediments obscure the channel network in the central and southwestern portions of the area.

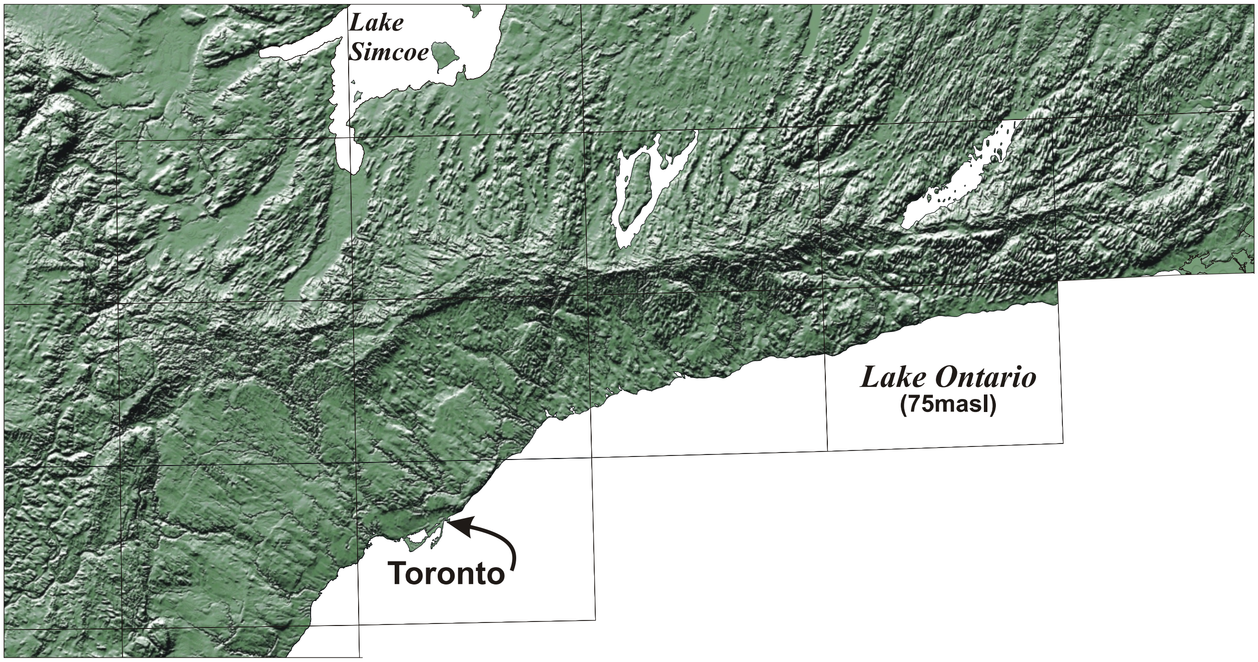


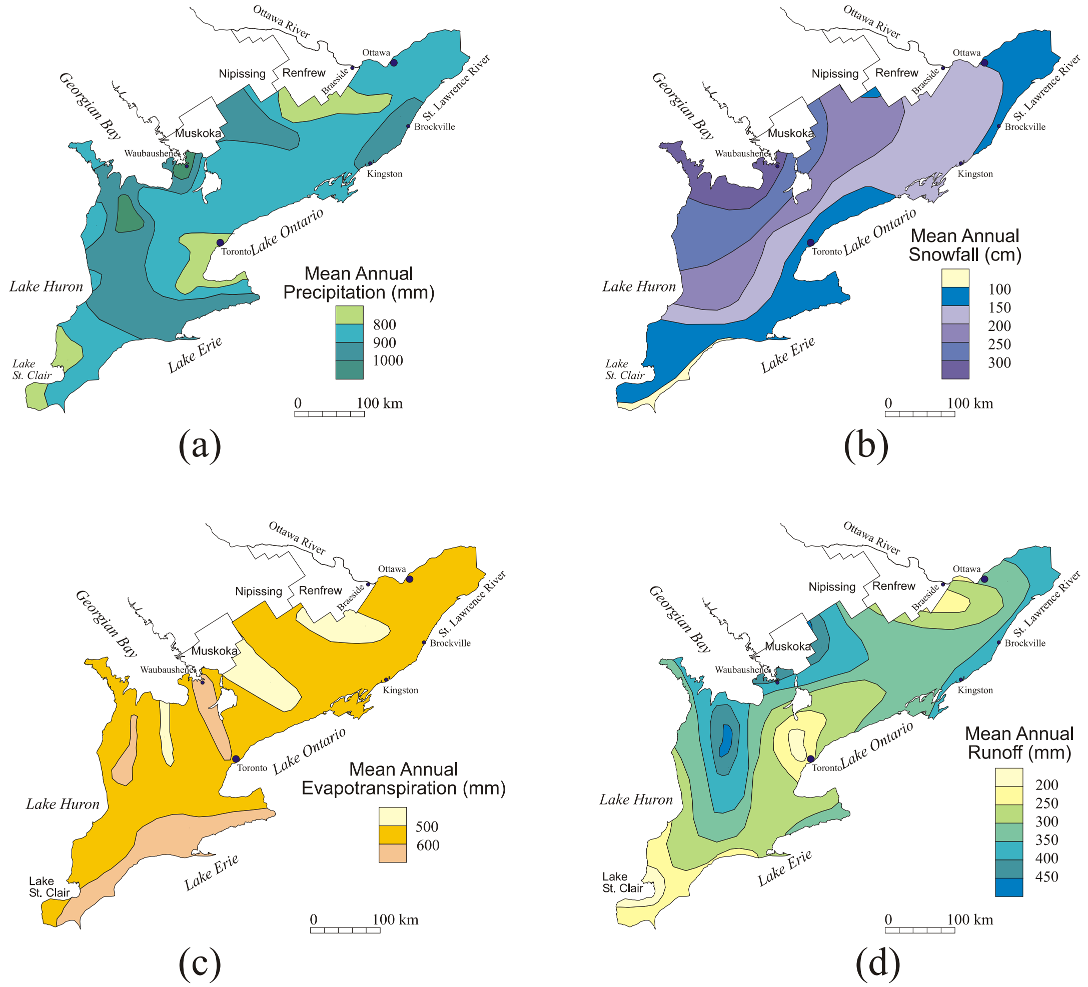
Figure 8. Shaded-relief digital elevation model (DEM) of ORM. Rectangular grid matches map grid on Figure 1. Compare geometry of ORM ridge to ice positions in Figure 5.

aquifers at the watershed scale. More recently, workers at the University of Toronto (Howard and Beck, 1986; Howard et al., 1993; Smart, 1994; Gerber and Howard, 1996a,b), have investigated groundwater recharge, discharge, flowpaths and contamination through field studies and the use of groundwater models. Studies conducted for landfill sites have provided detailed geologic and hydrogeologic data (e.g. Dillon, 1994). A recent government of Ontario study compiled and analysed existing ORM hydrogeological data (Hunter et al., 1996).

Hydrology

Southern Ontario has a temperate climate (Fig. 9) and the ground freezes for ~ 4 months / year. The annual precipitation in the ORM area is ~ 800-900 mm/yr (Fig. 9a; Singer et al., 1997) with 120-240 mm/yr falling as snow (Fig. 9b). There are frequent mid-winter thaws but the major hydrologic event is usually spring snowmelt in March and April. Lowest stream discharge occurs in July - August when evapotranspiration is highest. Lake evaporation is ~ 700-800 mm/yr but actual evapotranspiration over entire watersheds ranges from less than 500 mm/yr to more than 600 mm/yr (Fig. 9c). Mean January temperature is –8°C whereas mean July temperature is 20°C.

Streams are absent or of low order on the crest of the ORM (Fig. 10a). Low order streams are usually ephemeral in areas where clay or till occurs at surface, and are perennial in or downstream of sand and gravel outcrops. Higher order streams are perennial and drain watershed areas up to 900 km^2. Stream discharge varies between watersheds and is ~ 200-500 mm/yr (Fig. 9d).



(a) (b)

(c) (d)

Figure 9. Climate of southern Ontario: a) precipitation, b) snowfall, c) evapotranspiration, d) runoff (from Singer et al., 1997).

Hydrostratigraphy

The conceptual geological model developed for the ORM (Fig. 6) may be used as a regional hydrostratigraphic model. Halton and Newmarket tills and shale bedrock are aquitards whereas ORM, channel fills and lower sediments are aquifers. The wide range of hydraulic conductivities (K; Table 3) demonstrate that permeable interbeds may be present within aquitards and lower-permeability sediments are also encountered in the ORM. The K values in the lower sediments (Table 3) demonstrate that in some locations (stop 2.4), there are two distinct aquifers (Thorncliffe and Scarborough Formations; Table 1) separated by an aquitard (Sunnybrook Till). Additionally, clayey silt glacial lake sediments (e.g. Peel Ponds) are surficial aquitards whereas nearshore Lake Iroquois sands are shallow local aquifers.

Table 3. Hydraulic conductivity of stratigraphic units (ms^{-1}) (Source: IWA 1994 a-e)

Halton Till	$10^{-9} – 10^{-4}$
Oak Ridges Moraine	$10^{-8} – 10^{-2}$
Newmarket Till	$10^{-12} – 10^{-6}$
Lower Sediments	
- Thorncliffe Formation	$10^{-8} – 10^{-3}$
- Sunnybrook Till	$10^{-9} – 10^{-7}$
- Scarborough Formation	$10^{-8} – 10^{-4}$
Weathered Bedrock	$10^{-6} – 10^{-5}$
Bedrock (unweathered)	$10^{-8} – 10^{-5}$

An important aspect of the geology of the area is the presence of tunnel channels eroding into or through the Newmarket Till. Where they breach the Newmarket Till, they may provide hydraulic windows between the ORM and the lower sediments such that vertical flow may be enhanced (Fig. 11; Desbarats et al., 1998). Even where tunnel channels do not breach the Newmarket Till, they may be significant as coarse sediment fills within these channels and can be productive aquifers (stop 2.3). Most domestic wells in the ORM obtain their water from the upper aquifer complex (Turner, 1977). In areas adjacent to the Moraine most domestic and municipal wells obtain their water from lower sediments (Fig. 4). Bedrock aquifers are exploited where glacial sediments are thin: west of Toronto, along the Lake Ontario shoreline and near Lake Simcoe and Rice Lake (Fig. 2). Water yields from shale are low and of poor quality. Most bedrock wells obtain water from the uppermost 3-5 m of weathered or fractured rock (Singer et al., 1997). Consequently, hydrogeological studies in the ORM area focus mainly on groundwater resources in sediments.

Groundwater recharge

Although groundwater is widely used in parts of the ORM, there is insufficient understanding of groundwater recharge rates and the spatial distribution of groundwater recharge. Knowledge of groundwater recharge is needed both at the local scale for land use planning and at the regional scale for water resource assessment. Because there are wide differences in surface sediments, topography and land use, groundwater recharge is extremely variable (30-450 mm/yr), based on water balances or hydrograph analysis (Gerber, 1994). It is generally recognized that the ORM is the main source of recharge in the region, particularly near the crest of the moraine (Fig. 10a). An estimated volume of 1900 M litres per day recharges the ORM area (Hunter et al., 1996).

Groundwater flow

The regional hydrologic divide is the ORM: to the south, groundwater and streams flow to Lake Ontario; to the north, they flow to Lake Simcoe, Lake Scugog, and Rice Lake (Fig. 10). However, the groundwater divide may not correspond locally with the topographic divide due to subsurface geology or groundwater pumping on one side of ORM (Stop 2.2 Hunter et al., 1996).

Glaciofluvial deposits of the ORM, where exposed at surface, form unconfined aquifers. These aquifers become confined on the south side of the moraine by Halton Till and, on portions of the north side, by Kettleby Till (Fig. 4). Artesian conditions are common on the southern margin of the moraine (stop 1.3) where ground elevations decrease rapidly and both the shallow and deeper aquifers are confined.

On the flanks of the ORM, lower sediment aquifers are confined by the Newmarket Till (Fig. 4). Shallow unconfined aquifers are observed locally along the glacial Lake Iroquois shoreline of Lake Ontario (Figs. 2, 4). Because the sediments are often thin near Lake Ontario and hydraulic gradients are small, most of the groundwater recharged in the ORM area discharges to streams before reaching the lakes. Groundwater discharge directly to Lake Ontario is small (~2%) relative to total stream discharge (Haefeli, 1970; Smart, 1994), but it is difficult to assess.

Groundwater discharge and stream baseflow

A dense stream network drains north and south from the ORM (Fig. 10a). Groundwater discharge to many of these streams is high and supports cold water aquatic communities and fisheries.

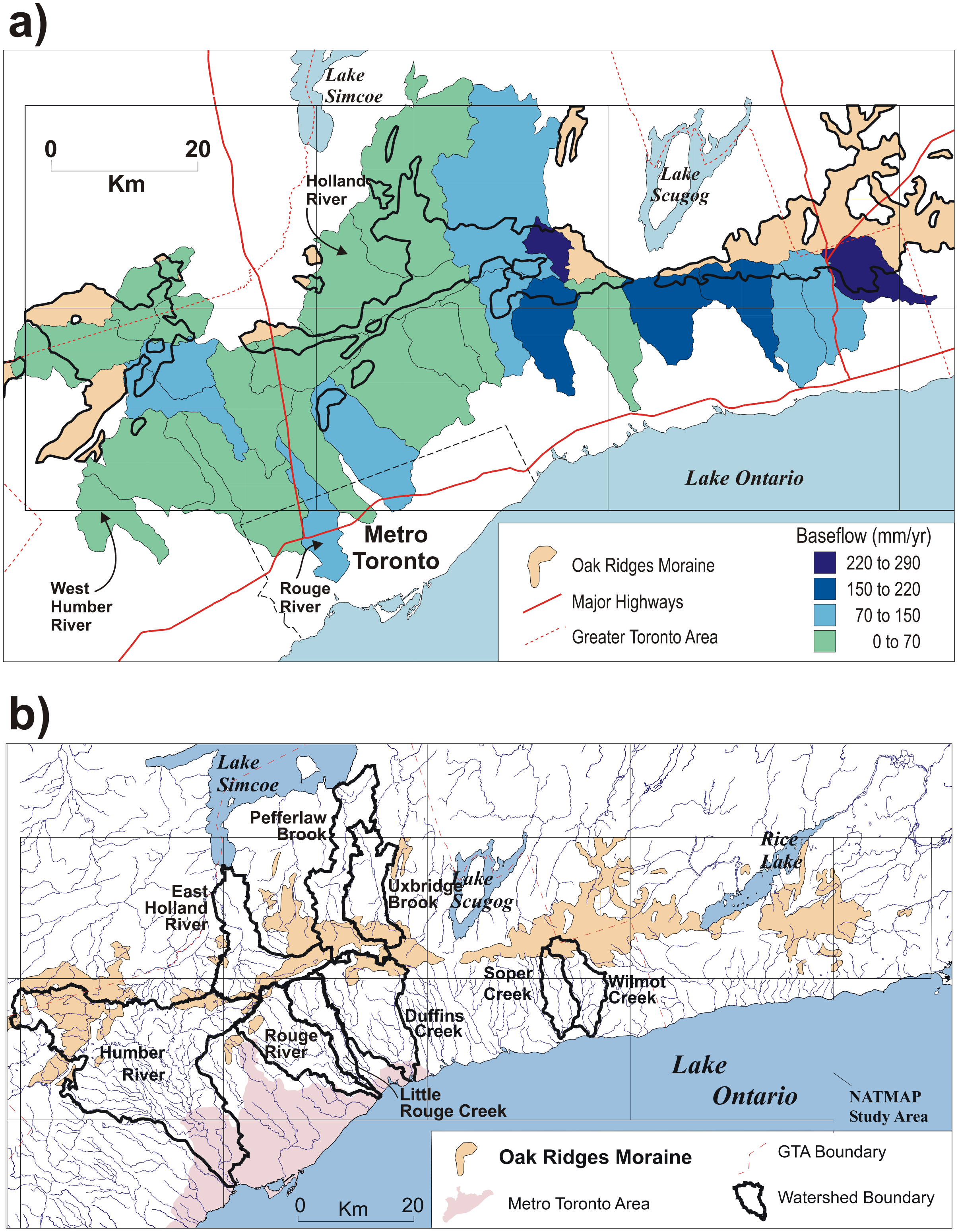


Figure 10. Stream baseflow in key drainage basins of the ORM area: a) data from Water Survey of Canada, b) basins used for detailed baseflow surveys completed by GSC.

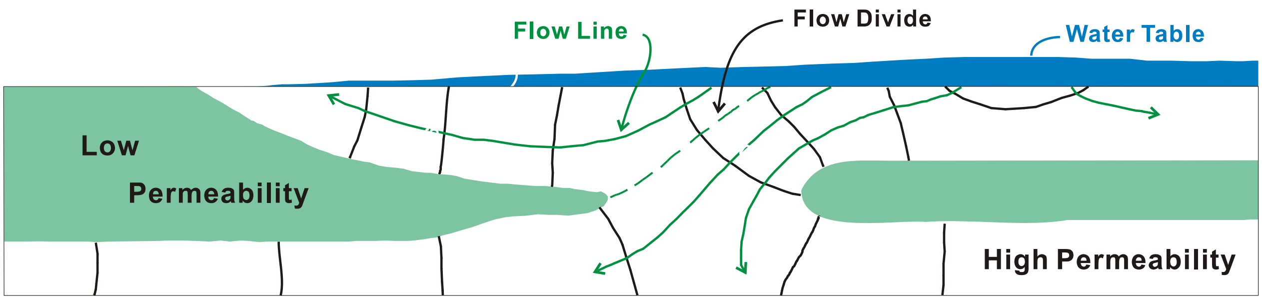


Figure 11. Groundwater flow model for breaches in the low-permeability Newmarket Till; shows enhanced flow to lower aquifers.

In contrast to groundwater recharge, more is known about groundwater discharge. Most of this knowledge comes from stream discharge records. The Water Survey of Canada monitored ~ 70 stream locations within the area with several records that span more than 30 years. Baseflow varies across the region; it is lower in western watersheds and higher in eastern watersheds (Fig. 10b). Differences in baseflow per unit watershed area suggest spatial differences in groundwater recharge rates and/or significant groundwater flow across topographic divides (Hinton, 1996). Significant spatial differences in baseflow are also noted within individual basins (see stop 1.3).

Groundwater chemistry

Groundwater quality is generally good within the ORM area and reflects the interaction with abundant carbonate minerals. Uncontaminated waters in the sediments are calcium-bicarbonate in type. Howard and Beck (1985) observed a gradual evolution towards sodium-bicarbonate waters as a result of cation exchange. Total dissolved solids are ~ 200-600 mg/L. Groundwater in shale terrain is of poorer quality with higher Na and Cl concentrations.

Natural water quality declines in some sediment aquifers where hardness and Fe can exceed recommended water quality guidelines. High dissolved organic carbon (~18 mg/L) or methane are found in the Alliston aquifer where buried peat likely occurs (Aravena and Wassenaar, 1993). Anthropogenic groundwater contamination has been observed in the form of elevated Na, Cl and NO_3 values. Road salt, domestic septic systems and agricultural fertilizers are suspected. Most large water pollution control plants are located adjacent to the Great Lakes although a few smaller plants still discharge to streams. Groundwater chemistry will be further discussed at stop 1.3.

REGIONAL METHODS

A range of methods may be used in regional hydrogeological studies. A key sequence of activities used in the ORM, however, includes: i) archival data assembly, ii) geologic and hydrogeologic review, iii) data assessment, iv) working model development, v) new data collection and testing, vi) data analysis, vii) model evaluation and presentation, and viii) application to hydrogeologic problems. Many current studies appear to start at step v), with an apparent loss of early perspective for those studies (Legrand and Rosen, 1998).

Scale is an important issue in hydrogeology. Recent efforts in North America have focused on site-specific studies, particularly point-source groundwater contamination and waste disposal (Cherry, 1996). This trip emphasizes the regional geologic context for site-specific studies.

Literature review and the use of archival data aid hydrogeological investigations. Existing qualitative or semi-quantitative data can provide a large portion of total hydrogeologic information needed at an average site (Legrand and Rosen, 1998). Therefore, new data collection can benefit from the use of archival data sources and the early direction they provide.

The above data assessment allows development of a conceptual geologic model. Such models provide valuable tools for analysis in the earth sciences (e.g. models are well established aids to petroleum and mineral exploration). Such geologic models however, are under-developed in recent hydrogeologic investigations (Cherry, 1996; Legrand and Rosen, 1998). The process of model development may include an early working model and the application of sedimentological and stratigraphic concepts to regional models.

The model built for the ORM (Fig. 6) is based on basin analysis (terrain mapping, sedimentology, geophysics, remote sensing and GIS) with limited integration of constraint by hydrological data. A high resolution DEM (Fig. 8; Kenny et al., 1996; Kenny, 1997) helped complete a regional landform analysis (Barnett et al., 1998) and provide an elevation datum to integrate hydrological and geological data. Of a variety of geophysical methods tested in the ORM (Pullan et al., 1994), three have advanced knowledge of this glaciated basin: 1) seismic profiling (Pugin et al., in press), 2) borehole geophysics (Hunter and Burns, 1991; Hunter et al., 1997), and 3) ground-penetrating radar (Pilon et al., 1995). Sedimentological work (Peterson, 1995; Barnett, 1997; Brennand, 1997a; Russell et al., 1997). These methods have provided for a better understanding of the close relationship between hydrogeological properties, lithology, and sedimentary architecture (e.g. Stephenson et al., 1988; Liu et al., 1996).

Hydrogeologic methods

Collection of regional hydrogeologic data is incomplete in the ORM area (e.g. Howard et al., 1997). New stream baseflow discharge and chemistry surveys (Fig. 10) allow the spatial patterns of discharge and chemistry to be related to geology. A regional survey of groundwater chemistry from domestic wells and streams allows one to assess regional groundwater quality and flow (stops 1.3 and 1.4).

Groundwater recharge is more difficult to study regionally. Piezometer nests installed in kettle lakes help to determine their recharge role and to model local flow (stop 2.2). Measurement of groundwater recharge to the ORM at an instrumented site allows the quantity and timing of groundwater recharge to be assessed using various methods (hydraulic gradients, CFC concentrations and water level fluctuations). Groundwater recharge through the Newmarket Till is also being investigated at the University of Toronto using tritium profiles (stop 1.4).

Long-term groundwater level monitoring is sparse across the ORM and most monitors of regional aquifers are in the vicinity of the municipal pumping wells. The most spatially extensive dataset is the water well records. However, these groundwater levels, collected at the time of drilling and spanning 40 years, are the least accurate.

Databases

The ORM study has assembled a relational database, GIS layers and flat files (e.g. geophysical data) (Russell et al., 1996). The database is used to: (i) evaluate other available data; (ii) improve the ORM model; and (iii) devise a hydrostratigraphic model (Fig. 6). Most ORM data are point data (e.g. ~75,000 waterwell records) with limited time series data.

Remotely sensed data are available for the study area (e.g. Landsat TM, SPOT, ERS-1) and thermal imagery of the ORM (Dyke et al., 1997) allows one to map springs. The key data to develop geological and hydrogeological models are borehole records: a) with continuous core, b) from geotechnical reports, and c) from water wells. Boreholes with continuous core allow reliable sediment description. The ORM study has ten cored boreholes (~60-190 m). Recent landfill searches have produced 80 continuously cored boreholes, logged to ASTM soil standards (e.g. Golder and Associates, 1994). Boreholes from geotechnical reports are shallow and were not continuously sampled. Hence, most sediment descriptions are not reliable for sediment mapping; however, the records may be useful for hydrostratigraphic mapping (Russell et al., 1998b).

Regional data synthesis and analysis is completed in a relational database and GIS. Data are linked to a GIS for error-trapping, and cross-verification. The data are then filtered and weighted according to data quality for interpolation and production of thematic, structural, and isopach maps along with cross-sections (e.g. sediment thickness, Russell et al., 1998a).

Summary

The goal of the trip is to review progress in understanding the regional hydrogeology of the Oak Ridges Moraine area. Efforts are directed towards regional scale approaches. Geologic models are emphasized in an attempt to demonstrate their utility to hydrogeologic understanding. The need for credible geologic models illustrates the way in which geologists and hydrologists may work together on hydrogeologic problems, particularly the geological context in complex glacial terrain.

Regional hydrologic methods are briefly evaluated. Regional water-quality datasets are poor. Some important work on groundwater recharge has occurred. However, the spatial variation of recharge is poorly understood and this hampers regional water resource management. New baseflow surveys are providing insight into geological and topographic controls on groundwater discharge and stream management. Groundwater discharge from small areas can account for a large proportion of the watershed discharge, including capture from adjacent basins.

There is also a lack of regional water level data to test emerging hydrostratigraphic models. Modeling efforts to date can only advance if both the hydrologic and stratigraphic datasets are improved, particularly for deep channel systems beneath the ORM. This should allow the current reliance on surface watershed water budgeting to include subsurface structures which may control groundwater flux across watershed boundaries.

Regional geologic methodologies have been used to provide hydrogeological insights in glaciated terrain. These methods focus on the use of basin analysis (geophysics, sedimentology, continuous deep drilling and coring) and synthesis with archival 3-dimensional data. An important adjunct to these field-intensive and office techniques is the integration of remote sensing, GIS and database management methods to advance regional water resource knowledge.

STOPS DESCRIPTIONS

The trip stops and access are located on a coloured trip map at the front part of this guidebook.

Trip overview

This guide describes nine sites (Fig. 1), covering the central portion of the ORM. The trip provides an overview of a geologic and hydrogeologic model for the ORM area (e.g. Sharpe et al. 1996) and a regional context for hydrogeologic modeling (e.g. Desbarats et al., 1998). This trip and guide complement two earlier guidebooks for the west central (Sharpe et al., 1994b) and eastern ORM (Sharpe and Barnett, 1997).

Day one examines the regional unconformity and platform (erosional uplands, channel system sediments) upon which the ORM is built. We also discuss groundwater discharge and chemistry. Day two focuses on landform-sediment relationships of the ORM related to hydrogeology, in particular recharge and municipal water supply.

Stop 1.1 provides a view of the Holland Marsh, a large channel eroded through drumlinized Newmarket Till, an upland terrain north of the ORM. A long-term pump-test maps out a major aquifer system beneath the marsh. Stop 1.2 reveals a sediment complex on the flank of a large valley. A shallow reflection seismic profile helps define buried channels. Following lunch, Stop 1.3, located at a popular spring on the exposed southern margin of the ORM, affords discussion of recharge and discharge by the ORM and a regional groundwater chemistry program. Stop 1.4 is located south of the ORM and displays a regional Newmarket Till sheet and aquitard complex and its relationship to underlying lower sediments. Stop 1.5 reveals a view of spectacular lower sedimentary sequences along Scarborough Bluffs.

The first three stops of day two show the use of landform sediment models to hydrogeology. Stop 2.1 is on the crest of the ORM at one of its largest sand and

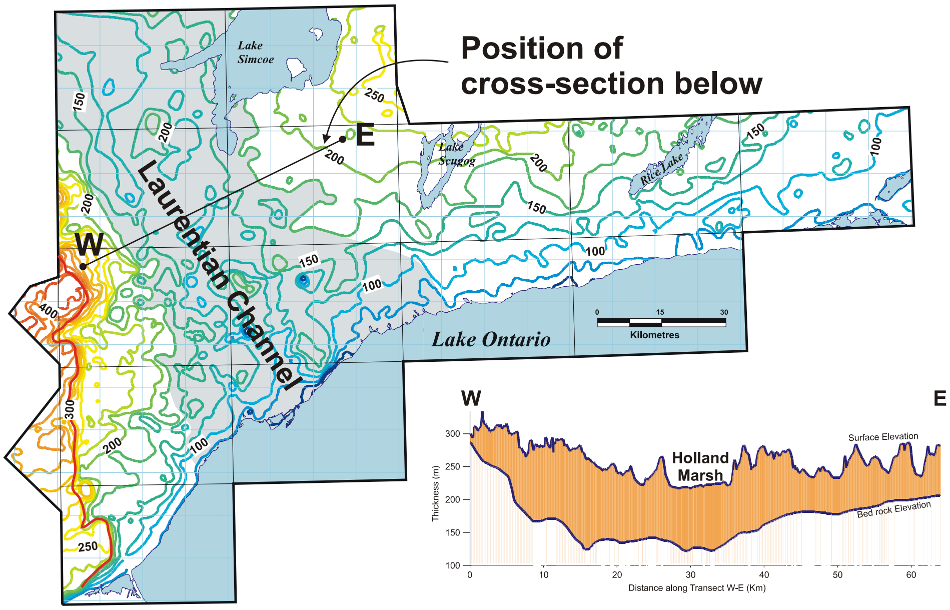


Figure 12. Bedrock topography around Holland Marsh site shows that it overlies a large bedrock valley, the Laurentian Channel. Depth scale is metres above sea level.

gravel pits, revealing thick sequences of sand and gravel. A borehole drilled at the site adds the lower hydrostratigraphic context. Stop 2.2 visits Musselman's Lake, a kettle lake used for recreation, one of many kettles lakes in the area that enhances recharge to the ORM complex. Stop 2.3, Ballantrae, rests on the latest, deltaic phases of ORM sedimentation. The site is underlain by a deep buried channel filled with gravely sediments, a source for new municipal water supply. At Stop 2.4 we will examine a 193 m deep borehole core from the deepest and most complete sequence in the ORM.

DAY 1

Stop 1.1: Holland Marsh channel and unconformity

(D. Sharpe and P. Barnett; Alliston NTS 31D/1)
[612250E 4801500N]

This stop introduces the ORM geologic model and highlights tunnel channels, one of the most significant elements of the regional hydrostratigraphy.

Geologic setting

As we look to the southeast across the deep SW-trending channel of the Holland Marsh, we can see the same upland surface on the south side of the channel as that we are standing on. The channel cuts this drumlinized upland and defines a regional unconformity (Fig. 4). Higher, hummocky terrain of the ORM is present in the distance. The ORM rises about 125 m above the Holland Marsh, and thus provides a gradient for groundwater flow to the lower terrain.

About 100 m below the Holland Marsh lies a broad bedrock low, the Laurentian Channel (Fig. 12). This depression likely captured thick lower sediment (stops 1.2 and 1.5), sand and silt that is widespread and susceptible to glaciofluvial erosion.

The Holland Marsh is part of a tunnel channel network (Barnett, 1990; Fig. 7) that dissects drumlinized uplands and continues below the ORM (Barnett, 1990). Channels can be filled with glaciofluvial, glaciolacustrine, and /or organic sediments. The Holland Marsh channel fill can only be assessed in general as seismic data and well records reveal tabular units of probable sand and silt across the central part of the marsh. Newmarket Till appears to be missing and sands and gravel show in a few deep wells above bedrock.

The complex anabranched pattern of the channel network is not related to modern drainage (Fig. 7), but does suggest a fluvial origin. In places, channels exhibit undulating long profiles and upslope flow paths, truncate drumlin strata and contain subglacial eskers. In places, gravel lags or large (~15m) bedforms are present on the channel floors (Stop 1.2; Shaw and Gorrell, 1991). In summary, a subglacial meltwater origin is favoured to explain this set of features. The powerful subglacial meltwater flows then partly filled the eroded channel as flows waned.

In addition to the hydrostratigraphic data, a three-month pump test was run at the north end of the Marsh (Jagger-Hims, 1996). It reveals a response-zone that

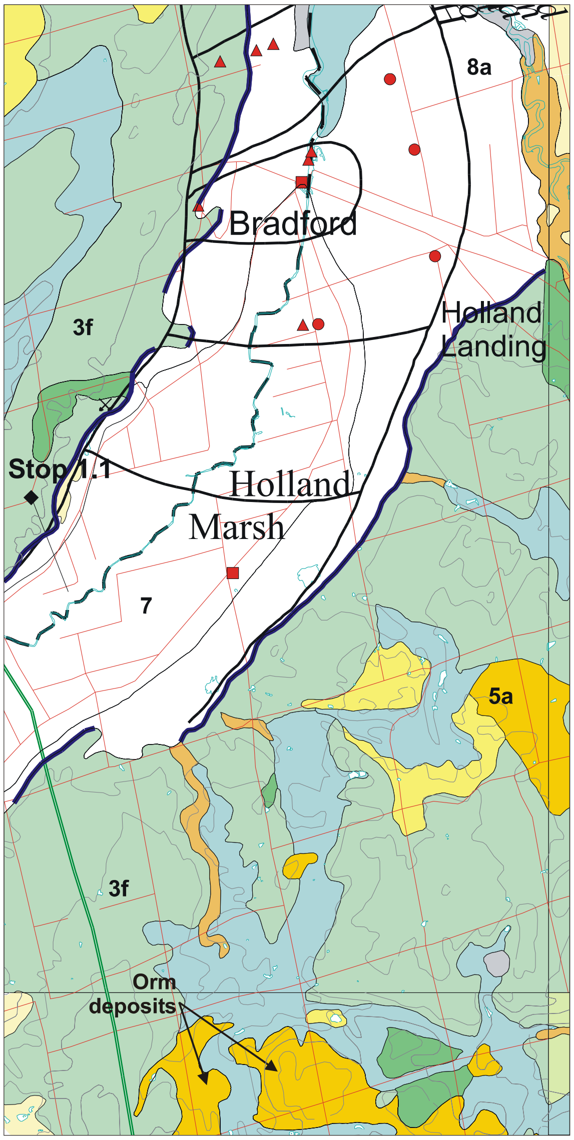


Figure 13. Lines of equal drawdown from 3 month pump-test results based on monitors (circles) and test wells (triangles and squares) defining a deep (~100m) aquifer oriented parallel to the Holland Marsh tunnel channel (after Jagger-Hims, 1996)

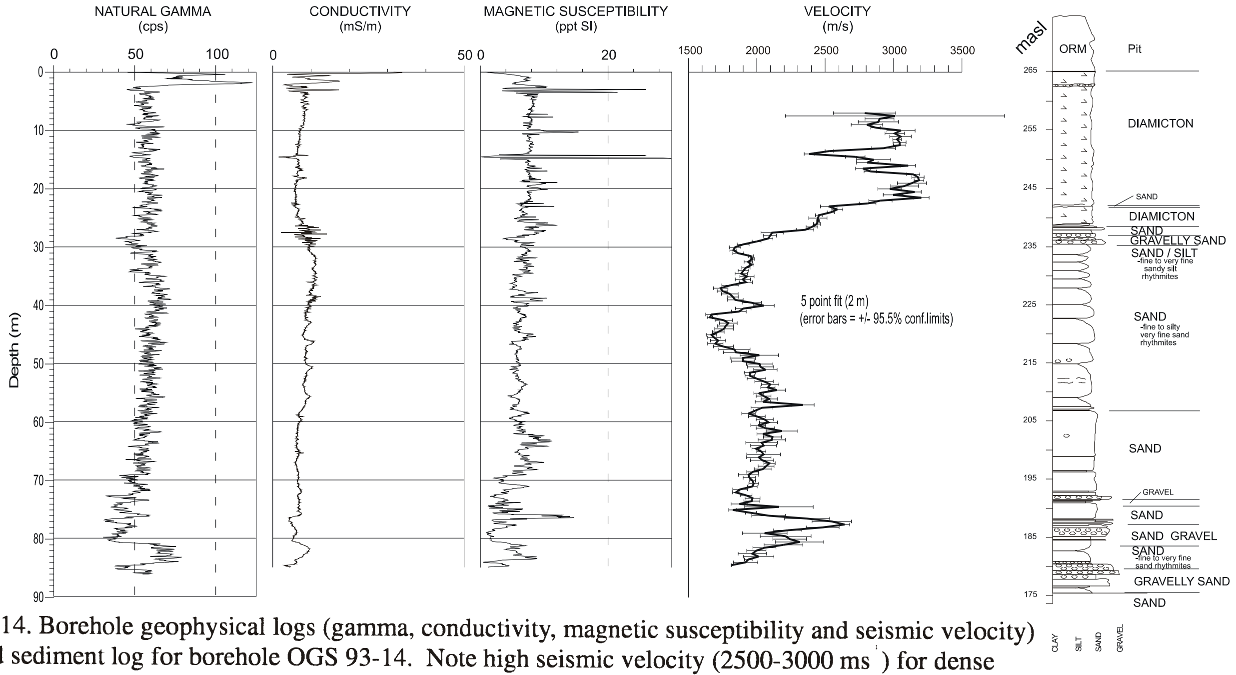


Figure 14. Borehole geophysical logs (gamma, conductivity, magnetic susceptibility and seismic velocity) and sediment log for borehole OGS 93-14. Note high seismic velocity (2500-3000 ms^{-1}) for dense Newmarket Till (diamicton). Lower sediments fine upwards from gravelly sand to silty sand.

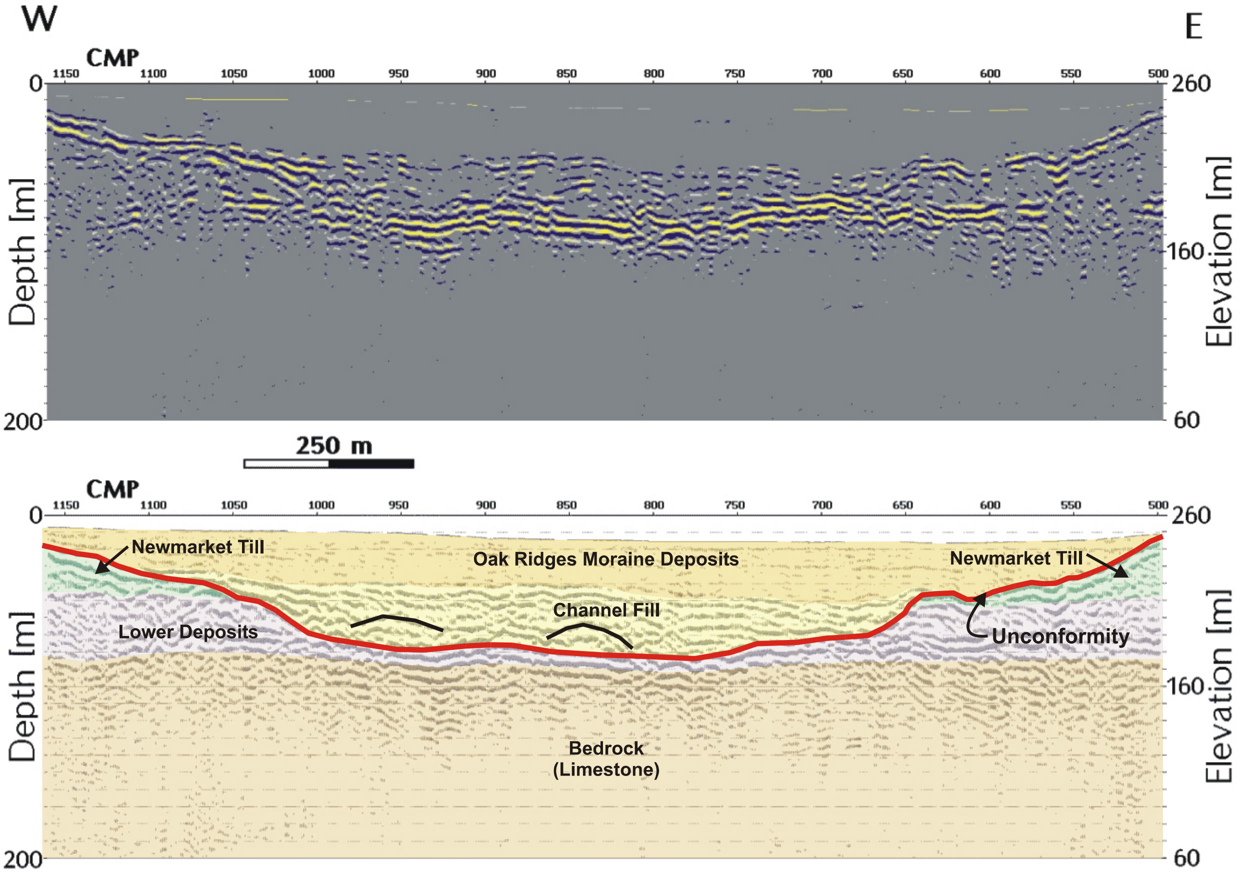


Figure 15. Herald Road seismic profile: top, processed data; bottom, interpreted data showing channel, Newmarket Till and surface forming regional unconformity. Channel fill consists of mound-like forms overlain by more planar sediment packages. Mounds may be possible gravel bedforms observed at stop 1.2.

sits beneath a portion of the north end of the Holland Marsh (Fig. 13).

Aquifer extent

Most pump tests that are conducted in the ORM area are of short-duration (<48 hours, often 2-3 hours) with monitoring close to the pumping well (<50 m). These tests are conducted to determine well capacity and local transmissivity around the well. As a result, these pump tests do not provide much information about hydraulic connections between aquifers or aquifer boundaries.

A rare longer duration pump test was conducted for two municipal wells to the southwest of Bradford, to amend the Provincial 'Permit-To-Take-Water'. The purpose of the test was to identify potential interference from an increased pumping rate. The pumping wells are screened within a gravel zone > 10 m thick in the central portion of the confined Bradford aquifer at a depth of 90 m (130 masl) within a broad bedrock valley (Fig. 12).

Examination of the well logs suggested that the Bradford aquifer extends at least 10 km in a north-south direction and 4 km in width (Fig. 13). The pump test results confirmed the hydraulic connection over the entire north-south extent of the aquifer (Fig. 13). Groundwater levels in the adjacent Newmarket-to-Aurora aquifer (Fig. 1) to the east (45-75 m depth, 165-195 masl), did not respond to pumping. This indicates no hydraulic connection between the two aquifers.

Stop 1.2. Holt pit - channel and sediment complex

(P. Barnett and S. Pullan; Newmarket NTS 31D/2)
[633000E 4885900N]

At this stop we will examine the flanks of a tunnel channel and the overlying permeable sediments of the ORM as seen from pit exposures, a seismic profile and borehole data.

Site Geology

The Preston sand and gravel pit is located near the northern edge of the ORM (Fig. 1). The pit is excavated into coarse sediment on the western edge of the Mount Albert channel (Fig. 7). In the western end of the pit, sand and gravel overlies a drumlin composed of stony, sandy Newmarket Till, the dominant sediment on the uplands north of the ORM (Fig. 2). In the eastern end of the pit, the channel has eroded the till. The lower bench of the pit has yet to intersect this till. At the north end of the pit, gravel mounds 25-100 m across and 5-15 m high occur and they compare with forms observed on seismic profiles.

Exposed sediments grade from gravel and gravely sand to rhythmically bedded fine sand and silt at the top of the pit. There is also a distinct fining trend away from source, north to south. Rip-up clasts eroded from the underlying till, occur in the sand and gravel. The sediments are interpreted as being deposited in a sub-ice conduit that fed a subaqueous fan (Fig. 5b). Deposition occurred vertically and laterally toward the valley. Sedimentation of the upper units was directed into an expanding ice-marginal lake (Fig. 5c).

Geophysical surveys

Seismic profiling and downhole geophysics help delineate the subsurface strata; aquitards, aquifers and buried valleys. The Herald Road profile (Fig. 15), an east-west seismic line across a small valley 4 km to the east (Fig. 1), shows a channel (~ 1.5 km wide and at least 40-50 m deep) beneath the valley floor. The channel base forms an unconformity where Newmarket Till and perhaps most of the lower sediments have been removed. Within the channel fill sequence, the seismic profile (Fig. 14) shows arched reflectors along the base of part of the channel. The arched reflectors have similar dimensions (~100 x10 m) to those of the mounds in the pit.

The geophysical logs collected in the borehole (Fig. 14) help link the core to the seismic profile. These data show thick diamicton (Newmarket Till) to be characterized by high seismic velocities (2500-3000 m/s). The high contrast in velocity between this unit and overlying ORM sediments makes the top of Newmarket Till a high-amplitude reflection on seismic reflection profiles. This seismic character can be traced regionally (Pugin et al., in press).

In summary, this stop reveals regional elements of the sub-moraine stratigraphy and the style of moraine sediments set within a tunnel channel.

Stop 1.3. Chalk Lake springs and regional groundwater chemistry

(M. Hinton and L. Dyke; Newmarket NTS 31D/2)
[655850E 4876400N]

At the site where the public collects spring water, we discuss groundwater discharge (springs, baseflow surveys) and regional groundwater chemistry.

This stop is a local water supply from ORM springs and it demonstrates the public perception concerning the quality of groundwater versus that of surface water. Many people who collect water at these

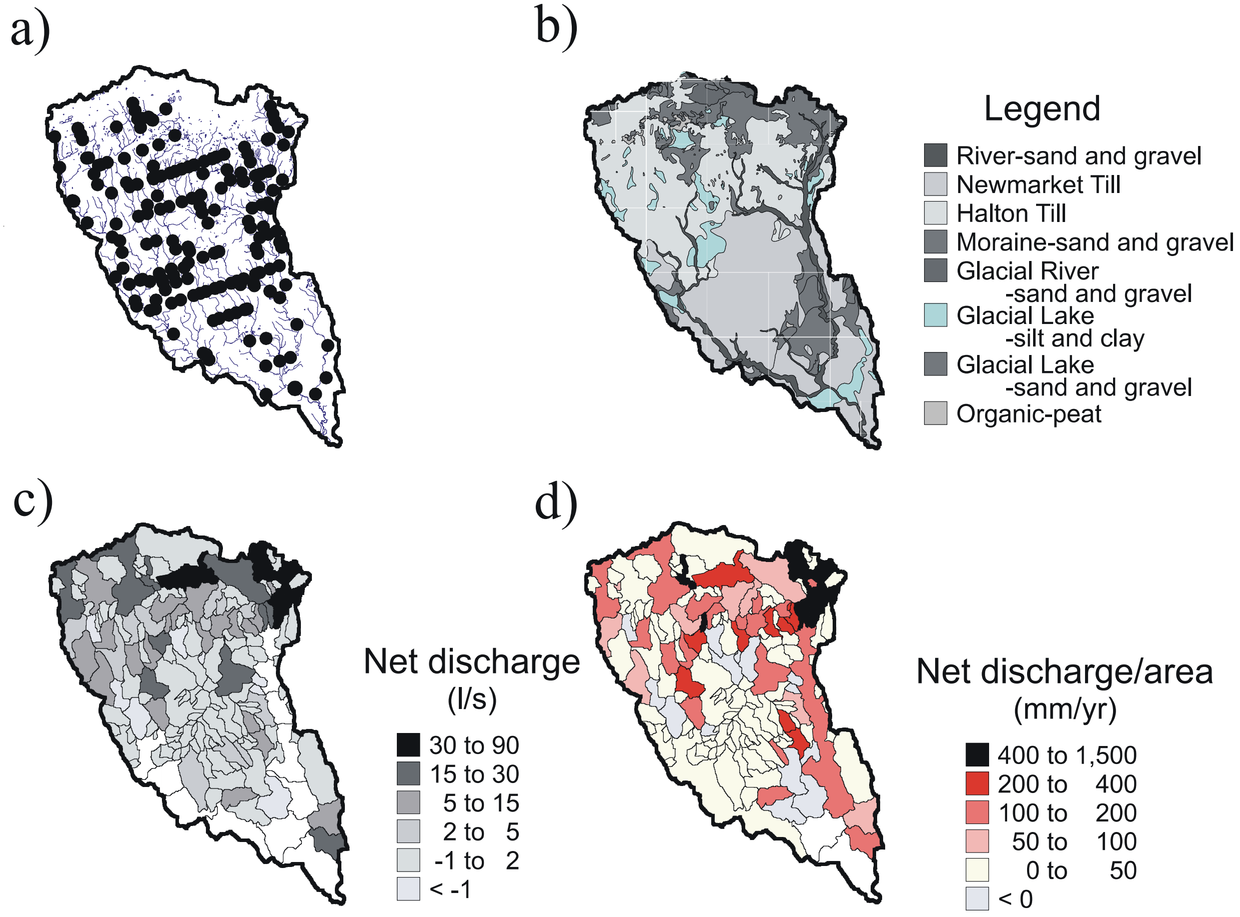


Figure 16. Baseflow surveys Duffin's Creek watershed: a) stations, b) geology, c) net discharge, L/s, shows high % of discharge in small headwater areas, d) net discharge in mm/year, high areas exceed annual input and indicate inter-basin transfers.

springs are residents of cities serviced by municipal water supply originating from Lake Ontario. There are also several companies that market bottled beverages with reference to their use of groundwater from ORM.

The high hills around the site are composed of ice-contact sand and gravely sand of the ORM (Fig. 2). The ridge south of the site marks the northern extent of Halton Till that provides a thin cover (< 3 m) over the ORM sediments (Fig. 4).

Baseflow surveys

This spring-fed stream is typical of many high-groundwater-discharge zones that are found on the flank of the ORM (Dyke et al., 1997). Groundwater discharge among these headwater streams shows that stream baseflow is variable. Baseflow surveys conducted in 1995, 1996 and 1997 delineated areas of high and low groundwater discharge (Fig. 16). Some of the high discharge streams indicates that the groundwater discharge is often concentrated in very small areas. In each of the south facing watersheds, 40-50% of the baseflow discharge originates from the ORM near the headwaters of these watersheds. This result is contrary to the general expectation that groundwater discharge should increase in the lower reaches of the watersheds. These results show that Newmarket Till has a significant influence on regional groundwater flow. Some discharge zones appear to be related to the presence of channel fills deposited within channels eroded into Newmarket Till.

Stream baseflow surveys assist in watershed management. They help: 1) locate areas of high groundwater discharge, 2) find point or non-point sources of contamination, 3) detect water usage from streams, and 4) document stream conditions prior to development.

Regional groundwater and stream water chemistry

In summer 1994, water from 400 private wells and 150 stream sites was sampled to assess groundwater quality and determine if chemical changes are occurring on a scale that would indicate regional groundwater flow. Considerable groundwater quality data exist for the ORM, including analyses of well waters by GSC in the late 1930's, selected watershed surveys (e.g. Funk, 1977; Howard and Beck, 1986), and a regional data compilation (Hunter et al., 1996). The present sampling was done to acquire a regional assessment of ORM water quality in a short time interval. Stream sampling was done during an interval of little or no rainfall in mid- to late June to sample stream baseflow supplied by groundwater discharge. Chloride and other results are discussed.

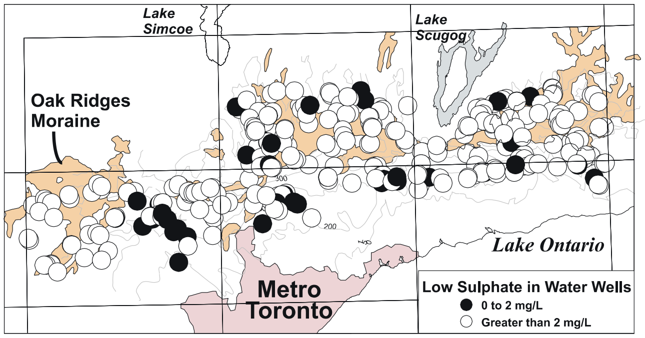


Figure 17. Location of water well samples for the 1994 survey, showing wells having 2 or >2 mg/L SO_4 .

Chloride in water well samples shows a wide range in concentration. A few samples have chloride concentrations of 500 - 1000 mg/L, but most are under 50 mg/L, and one quarter contain less than 2 mg/L. This wide range means that well intakes may intersect chloride plumes originating from surface sources such as road salt and septic field leachate. The highest values tend to concentrate in the western, more urbanized part of the area. This is consistent with the more extensive use of road salt in this area. Stream water values are similar to those for wells. There are however, few stream samples with chloride values of less than 2 mg/L. Very low chloride values for streams will be rare because of the ease with which chloride can reach streams by runoff or shallow groundwater flow.

Streams show the highest nitrate values in the eastern, rural part of the area, suggesting an influence from agricultural nitrate sources. As with the comparison between chloride in streams and wells, nitrate in well waters shows no grouping of high values corresponding to the general pattern for stream samples. About 5 % of the well samples exceed provincial water quality objectives of 45 mg NO_3/L. However, no values exceed 70 mg NO_3/L . Most well samples are below 40 mg NO_3/L and slightly over one-third are below 2 mg NO_3/L.

Sulphate in wells has a bimodal distribution. Concentrations below 2 mg SO_4/L make up 15 % of the wells sampled whereas sulphate concentrations between 2 and 10 mg/L are rare. As with hardness, sulphate is a component most likely acquired by groundwater travel rather then from a surface source. The most likely source for sulphate is pyrite distributed throughout the sediments. Therefore a distribution of concentrations around a mean value, above zero, should result. This is the case with hardness and sulphate, with the addition of the near-zero values.

The very low sulphate concentrations suggests that sulphate is being removed from groundwater rather than simply not encountered. With downward movement in recharge areas, sulphate that is produced by oxidation of pyrite is later reduced to sulphide and precipitated or transformed to HS^- or H_2S. The distance over which this change takes place is probably highly variable but the location of wells with the very low values gives an indication of this distance. Most wells with very low readings are below a surface elevation of 300 m, at the base of or below the lowest elevation of ORM exposure (Fig. 17).

Stop 1.4. Clarke's Hollow - Newmarket Till plain

(D. Sharpe, R. Gerber, M. Hinton; Markham NTS 30M/14) [650200E, 4859000N]

This river bluff site highlights the hydrostratigraphy and permeability of the broad Newmarket till plain extending from beneath and south of the ORM (Fig. 4).

Stratigraphy and lithofacies (D. Sharpe)

Clarke's Hollow exposes a 25 m thick sequence of Newmarket Till and lower sediments (Fig. 7) in West Duffins Creek, a prominent stream issuing from ORM (Fig. 10b). The section records three lithofacies: diamicton (Newmarket Till), sand, and silt-clay rhythmites (Thorncliffe beds; Table 1), traceable to Lake Ontario (stop 1.5) a few km to the south.

From the top of the section, the sequence is: i) 10-12 m of dense, stony, silty sand diamicton; ii) 8- 10 m of rippled, fine to medium sand; iii) 5 m of silt-clay rhythmites. The rhythmites are regularly spaced silt-clay couplets, 1-2 cm thick. Clay caps are 0.5 -1 cm

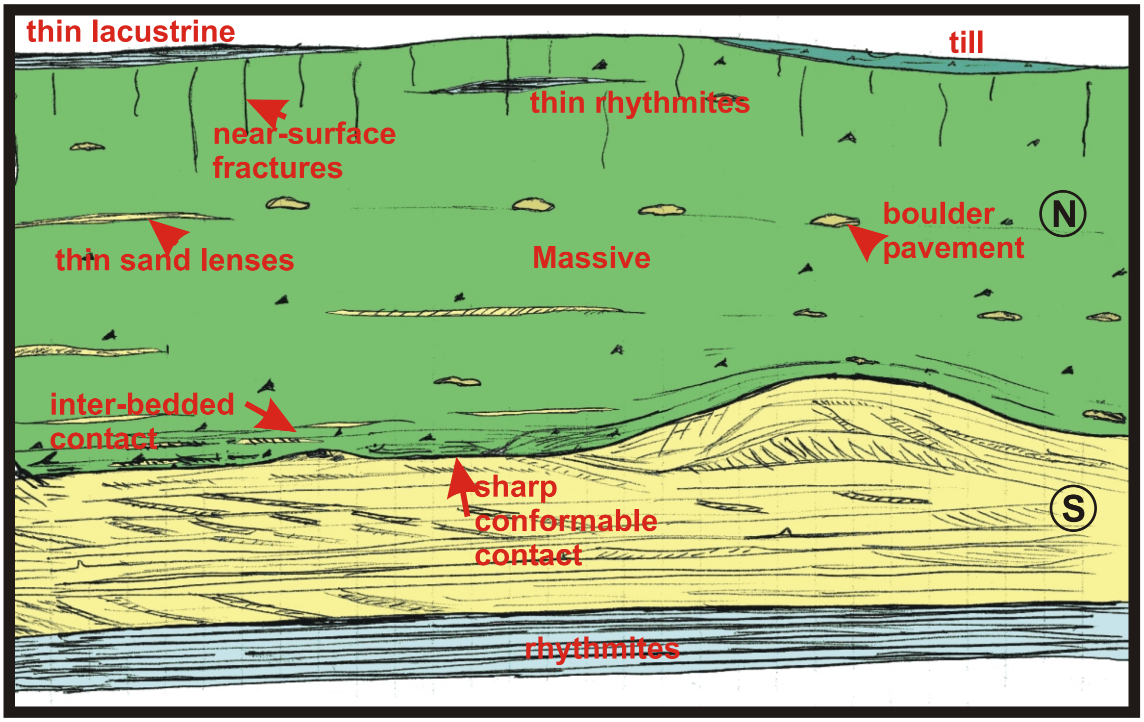


Figure 18. Newmarket Till (N) is commonly found on Thorncliffe sand (S) and displays a regional and local planar contact. Interbedded sand and sand lenses increases horizontal permeability; rare sand dykes and near-surface fractures increase vertical permeability.

thick. This rhythmite-sand sequence can be correlated over a wide area (km^2).

The sandy Thorncliffe beds consist of climbing ripples or graded sets in fine to silty fine sand, 10-50 cm thick. A few clay caps are present. The beds contain clay rip-up clasts, ball-and-pillow and dewatering structures (Walsh, 1995). Paleoflows indicators are variable in this area: many trend north-northeast but at this stop paleoflows are south-southeast in ripple-drift sand. They are westerly in pebbly, trough cross-beds. The diamicton-sand contact is planar with minor structural breaks. A wet zone, common at the base of the sands, is groundwater seepage along the contact with the underlying rhythmites. With no direct connection to ORM, this groundwater discharge appears to be local in origin and conforms with the low seepage through Newmarket Till.

The structure of Newmarket Till is important to understanding its permeability variation (Table 3). Newmarket Till is massive, stony (3-10 %) and consistently dense. It contains thin, 2-5 cm thick, interbeds of sand and silt at its base (Fig. 18) and near-surface jointing. Here, it also contains small injections, dykes, breccia and rafts from lower sandy beds. In nearby outcrops, discontinuous sand beds up to 1-2 m may be present. Thin rhythmites or isolated clay laminae may also occur. In other places, discontinuous boulder pavements may be found. They lack continuity and suggest that beds may have amalgamated following episodes of erosion.

The sandy texture, thickness and high seismic velocity (~2500 m/sec) of Newmarket Till, and the regional erosion surface it carries, are recognized regionally (e.g. Sharpe et al., 1997). South of ORM, it occurs as a subdued till upland with intermittent lacustrine cover (Fig. 2; Sharpe and Barnett, 1997). However, the widespread extent and consistency in regional properties, local inhomogeneities and variable thickness (channels) all indicate that the Newmarket Till complex is a significant regional hydrostratigraphic unit (e.g. Sharpe et al., 1994b; Gerber and Howard 1996a). We will discuss some of the effects of the Newmarket Till complex on groundwater recharge and discharge at this stop.

Regional groundwater flow and recharge (R. Gerber)

Outcrops at and near this site provide an opportunity to study the Newmarket Till (aquitard) and Thorncliffe Formation aquifer-aquitard. The Newmarket Till (or northern till) aquitard controls the amount and quality of leakage to deeper aquifers.

Hydrogeologic investigations conducted by M.M. Dillon Limited (M.M. Dillon Limited, 1990; IWA, 1994a-e) and continued by R.E. Gerber (1998; Gerber and Howard, 1996c) suggest that the Newmarket Till can be considered a dual porosity medium with bulk hydraulic conductivity (K) controlled by non-matrix structures or pathways. Horizontal pathways include sand and gravel interbeds and boulder pavements marking erosional surfaces identified in the Newmarket Till in outcrop and shallow seismic reflection profiles (Boyce et al., 1995; Boyce et al., 1997). Vertical pathways include fractures, sand dykes and steeply-dipping shear surfaces. Isotopic data (^{2}H, ^{18}O and ^{3}H) and regional water balance/groundwater flow modeling (Gerber, 1998) suggest vertical bulk K values on the order of 5×10^{-9} to 10^{-10} m.s^{-1}. Matrix K estimates from triaxial permeability and slug testing, in contrast, yield much lower estimates ranging from 10^{-11} to 10^{-10} m.s^{-1}. Vertical leakage through Newmarket Till is estimated at 30-40 mm/yr.

Baseflow surveys (M. Hinton)

Groundwater discharge to West Duffins Creek is confirmed by several groundwater seeps such as the one present on the river bluff at this stop. However, baseflow surveys show that groundwater discharge along the lower reaches of West Duffins Creek produce only a proportion (<5%) of the total watershed discharge. Most of the stream discharge in West Duffins Creek originates from its headwaters. Smaller fluxes of groundwater discharge are also associated with sands and gravels deposited along the shoreline of glacial Lake Iroquois to the south (Fig. 1). Where Newmarket Till is the surface unit (60 % of watershed), groundwater discharge to the stream is small (Fig. 16).

Stop 1.5. Scarborough Bluffs lower sediments

(D. Sharpe and M. Hinton (Markham NTS 30M/14) [647650E 48463500N]

The well-known Scarborough Bluffs reveal extensive sub-Newmarket, lower sediments of regional importance to the hydrostratigraphy of the area.

Regional geology

Newmarket Till occurs at the top of the Bluff section as a stony sandy silt diamicton. It can be traced as an eroded drumlin upland from stop 1.1 and 1.2 north of the ORM, to the till plain at stop 1.4, south of the ORM (Fig. 4). This regional marker bed helps define the beds below it as lower sediments in the regional hydrostratigraphic model (Fig. 4). On this section (Fig. 19), Newmarket Till feathers out against an increasingly thicker package of lower sediments forming the highest bluffs to the west. These extensive lower deposits are thick Scarborough Formation clay and sand packages (Table 1). These beds form planar tabular units to the west, but are missing in an eroded interval east of this stop. The channel-like geometry of this erosion suggests that it may be analogous to the channels observed north of the ORM (stops 1.1 and 1.2). Here, the feature is older than the channels at earlier stops, as it occurs below Newmarket Till. However, it alerts us to significant regional erosion affecting the stratigraphy of the area. It is also of note that no deep channels appear to be cut into the Newmarket Till at the lake bluffs such as those at stops 1.1 and 1.2. The tunnel channels appear to have changed to a broader and shallower form (Sharpe and Barnett, 1997; Fig. 7).

The bluffs to the west reveal a wet, vegetated seepage zone, within the Scarborough beds (Fig. 19), marking the contact between sands above, and muds below. To the east, a measured section reveals, gravel fining up to sand, silt and clay. This is transitional to the overlying Newmarket Till. This sequence is

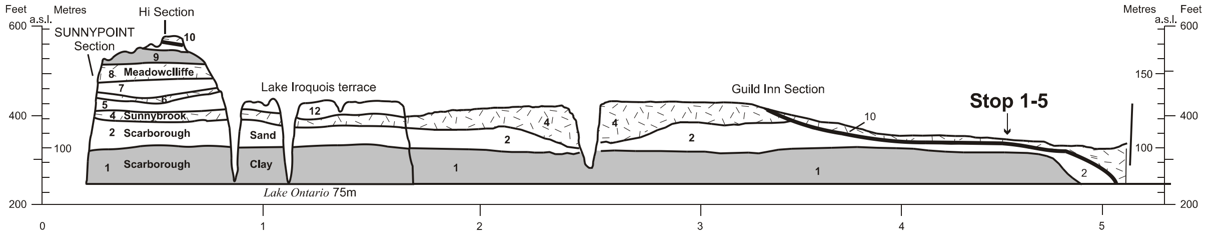


Figure 19. Lithostratigraphy of the Scarborough Bluffs (after Karrow, 1967). Most of the sequence consists of the lower sediments of the regional model (fig. 6). Note channel structure within lower sediments East of Stop 1.5. Units 5, 7 and 9 = Thorncliffe Formation. Unit 10 = Newmarket Till.

analogous to the lower sediments below Newmarket Till at stop 1.2. The passive and planar contact relationship at the base of Newmarket Till is similar to that exposed at stop 1.4. This relationship is widespread (Pugin et al., in press) and allows regional correlation of Newmarket Till-lower sediments.

Lower sediment aquifers

The thick sand and clay of the lower sediments indicate the complex aquifer-aquitard conditions that may occur beneath Newmarket Till. North and south of ORM, the lower sediment aquifers are often the primary source of groundwater. These aquifers can be very productive with some municipal wells capable of producing up to 6500 m^3/d (1000 Igpm). However, south of the moraine, groundwater usage from lower sediment has decreased due to a shift to reliance upon surface water piped from Lake Ontario. North of the moraine, many communities and rural areas still rely on groundwater supply from the lower sediment aquifers.

While thickness estimates of lower sediments has improved, less is known of the extent, configuration, sedimentology and hydrostratigraphy of the lower sediment aquifers. The best exposures occur along the Lake Ontario bluffs as well as in river valleys, and the Don Valley brickyards. Elsewhere, data on the lower sediment aquifer comes from drilling and new reflection seismic surveys (stop 1.2). Near Lake Ontario and in several areas south of the Moraine, the lower sediments consist of two main aquifers (Thorncliffe and Scarborough Formations-Table 1) separated by Sunnybrook Till (and silts and clays of the Thorncliffe Formation). To the north, the lower sediment aquifers may be hydraulically connected (Sibul et al., 1977), where thicker bodies of fan sediments (gravel, sand and silt) occur. At a GSC borehole near Aurora (Fig. 1), lower sediment consists of 75 m of sand and gravel above bedrock.

The source areas for groundwater in the lower sediment aquifers appear to be a combination of recharge from the ORM and some leakage though the Halton and Newmarket Tills. Eyles and Howard (1988) measured modest flow in the sand aquifers to the west of this stop and attribute most of the flow to local recharge based on the chemical signature of local contaminants (road salt) in the flow system. Groundwater modeling (Smart, 1994) suggests that nearly half of the recharge (~170 mm/year) to the lower

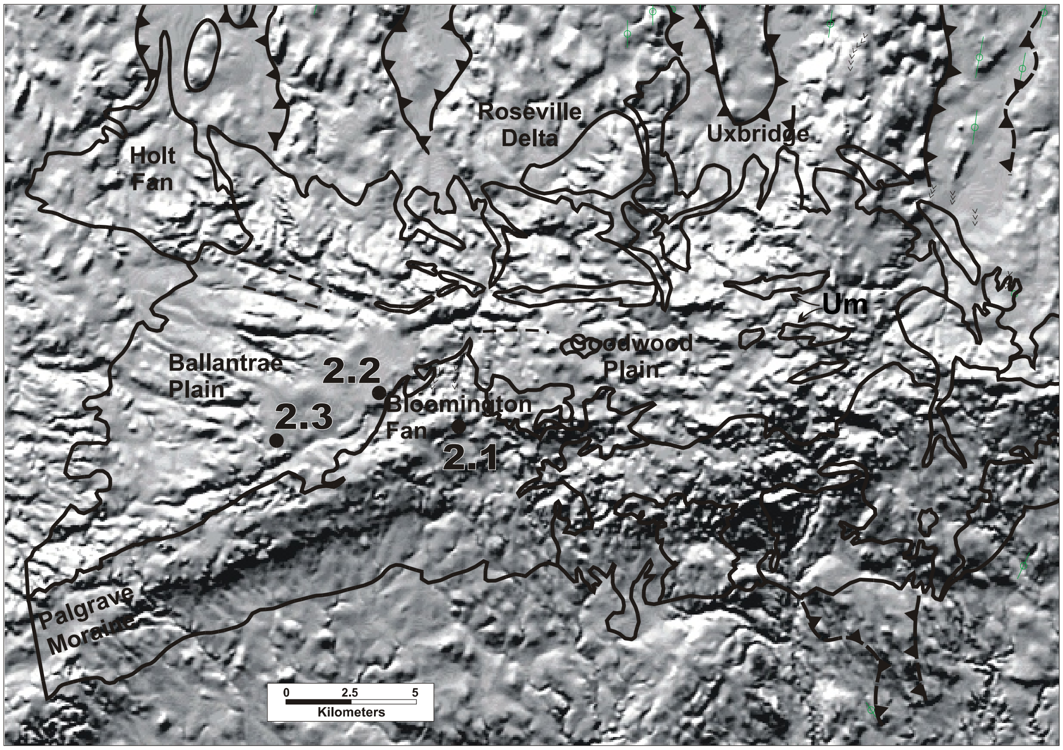


Figure 20. Landforms of the Uxbridge sediment wedge of the ORM shown overlying a shaded-relief digital elevation model (Kenny, 1997). Moraine (Um) and ice-contact slopes (dashed lines) mark former ice marginal positions during wedge formation. Lines with triangles are tunnel channel margins.

aquifers originates from the ORM. Hunter et al., (1996) estimate an underflow component (not measured by stream gauging) from the ORM to regional groundwater flow of ~80 mm / year, some of which may be flowing through the coarser lower aquifer sediments such as those found in the channel structure to the east of this stop (Fig. 19).

DAY 2

Geologic setting for stops 2.1, 2.2 and 2.3 on the ORM

The purpose of these stops is to demonstrate the utility of sedimentary models to groundwater studies. Detailed geological mapping of sediment distribution, variation, and landform elements (Barnett, 1995a,b; 1996) helps decipher complex glacial landforms such as the ORM.

The Uxbridge wedge (Figs. 2, 20) is the best known of the ORM sediments. It contains most of the stages in the formation of the ORM (Barnett et al., 1998) and can be divided into several landforms. Each has its own dominant processes of formation and resulting sediment character and structure (Fig. 5) that can be linked to hydrogeologic parameters (e.g. Fogg, 1986; 1998).

Bloomington fan

This fan forms the central, highest, and southwesterly-oriented part of the Uxbridge sediment wedge (Fig. 20, Stop 2.1). It is interpreted, based on sedimentological studies, to be a large subaqueous fan (transitional to delta) that formed at the mouth of a major sub-ice conduit (Fig. 5b). Meltwater issuing from this conduit entered a narrow lake (Fig. 5b). It flowed to the southwest thus explaining the southwestward elongation of the landform (Fig. 20) and the distribution of observed sediment facies, structures and paleoflow measurements. Evidence of the meltwater corridor remains as narrow, steep-crested esker ridges found north of the fan (stop 2.1).

Ballantrae plain

This plain (Fig. 20, Stop 2.3) is underlain by thick sand, and at depth, by silts and clays. It is composed of coalescing, sandy delta sediments that extended westward into the deeper part of the ice-supported lake (Fig. 5d). A series of plains that decrease in elevation to the north, were developed along its northern margin: a result of progressively lower lake levels as the ice margin receded northward (Fig. 5). Along the plain's western edge, a steep depositional slope is preserved, separating the Ballantrae plain from a lower altitude basin to the east (Fig. 20). Locally, the plain is irregular as a result of wind activity which eroded blow-outs and built dunes.

Goodwood plain

This plain (Fig. 20) is dissected and underlain by sand and gravel. It represents the glaciofluvial river/delta topset component of the Ballantrae plain. A thick unit of rhythmites within the sand and gravel provides variability within these sediment sequences.

Uxbridge moraines

These moraines (Fig. 20) are made up of several prominent ridges of gravel and sand. They are interpreted as moraines, kames and subaqueous fans. They become increasingly buried by sands of the Ballantrae plain toward the west, but can be traced by following the lines of kettle holes or the edges (ice-contact slopes) of the various levels of the Ballantrae plain (Fig. 20). The Uxbridge moraines mark former ice marginal positions of the northerly-retreating ice and formed before that part of the ORM was deposited.

Palgrave moraine

The Palgrave moraine is a distinct ridge within and along the southern flank of the ORM (Fig. 20). It is an area of hummocks and closed depressions often containing wetlands. An abundance of flowtills, melt-out tills and sorted sediment give the Halton Till an interbedded nature. The Palgrave moraine likely formed in response to instability along the margin of the Ontario ice that resulted in a local advance, over-extension and ice stagnation. Northern ice deposited Kettleby Till (Fig. 2) within the Aurora basin, temporarily dammed lower outlets and caused a rapid rise in water level within the interlobate zone. A thick sequence of silt/clay rhythmites was deposited over the sand and gravel of the Goodwood plain (Fig. 20) and over stagnant ice.

Holt fan

The Holt fan is a large fan-shaped body of sand and gravel (south of Holt, Stop 1.2) that rests upon drumlinized Newmarket Till (Fig. 20). It marks the northern mapped extent of the ORM (Chapman, 1985). It is a smaller version of the Bloomington fan and probably formed in much the same way, as a subaqueous fan at the mouth of a conduit issuing from the ice margin (Fig. 5b). At Holt, however, the southern ice margin was probably many kilometres away and ORM probably formed the southern shore of the lake.

Utica delta

The Utica delta (Fig 20) consists of fan-shaped bodies of sand and gravel that were deposited by northward flowing rivers issuing into an ice-marginal lake dammed between the northern flank of the moraine and the receding ice margin.

Stop 2.1 ORM sediments - Lafarge Sand and Gravel pit

(Barnett, Gorrell and Hinton; Newmarket NTS 31D/2) [640500E 4876000N]

The site reveals core sediments of ORM and provides a picture of the recharge potential of thick, sandy sediments ~300 m above Lake Ontario.

The Lafarge sand and gravel pit provides a panoramic view from the crest of the ORM, south to Lake Ontario and northeast to a tunnel channel. The pit reveals the core of one (Uxbridge; Fig. 2) sediment wedge of the ORM. The feature has an elevated fan-shape which broadens toward the southwest (Fig. 20). The pit exposes glaciofluvial and glaciolacustrine beds fed by meltwater from the north. The meltwater sediments are overlain by Halton Till deposited by ice flowing northward. The pits provide continuous exposure for 2 km along the axis of the fan and 1 km across its axis. Some descriptions and illustrations were provided by J. Paterson as part of an MSc thesis (Paterson, 1995; Paterson and Cheel, 1997) at Brock University, supervisor, R. Cheel.

Pit description

The exposed pits contain a variety of sediment, ranging from coarse gravels to laminated silts and clays (Fig. 21). These sediments are characterized by dramatic lateral facies changes but display more gradual change in facies vertically in the pits. Gravel deposited near source is dominated by thick sequences of clast-supported, pebble to boulder sediment with poorly-defined bedding dipping gently to the south (Fig. 21, section s13). Laterally continuous interbeds of rippled and trough cross-bedded sand are regularly spaced throughout the gravel. These cycles are suggestive of sedimentation pulses from meltwater-discharge cycles due to diurnal, seasonal or annual variations.

Rapid lateral transitions occur from proximal gravel to thick (~ 12 m) accumulations of climbing ripple-drift sands (Fig. 21, section S7). Proximal-to-mid fan sediments contain numerous large, well-defined, and relatively broad channels filled with decimetre-scale, sandy pebble gravel cross beds and larger metre-scale planar tabular cross beds (Fig. 21, section L4). Numerous depression-fill sequences are exposed, formed in openings resulting from melting of buried ice blocks. These fills are characterized by fining-upward trends; pebbly cross-bedded sands to rippled and laminated sands.

Deposits exposed 500 m to the southwest are not as variable as in the Lafarge Pit: they were laid down on more distal portions of the fan (Fig. 21). These deposits are characterized by laterally continuous beds which dip gently to the southwest and display horizontally-bedded sands, planar-tabular and trough, cross-bedded sands (Fig. 21, sections L2 and L17). They are occasionally cut by steep-walled channels filled with massive sands.

This evidence suggests that the deposit is a subaquatic fan (Fig. 5b). The lack of vertical trends suggests that the spatial organization of the sediment facies must have remained relatively stable during sedimentation or that deposition was rapid. The fan sediments were subsequently overridden by ice flowing 1-2 km toward the north as indicated by overturned strata, shear planes and incorporation of subsole

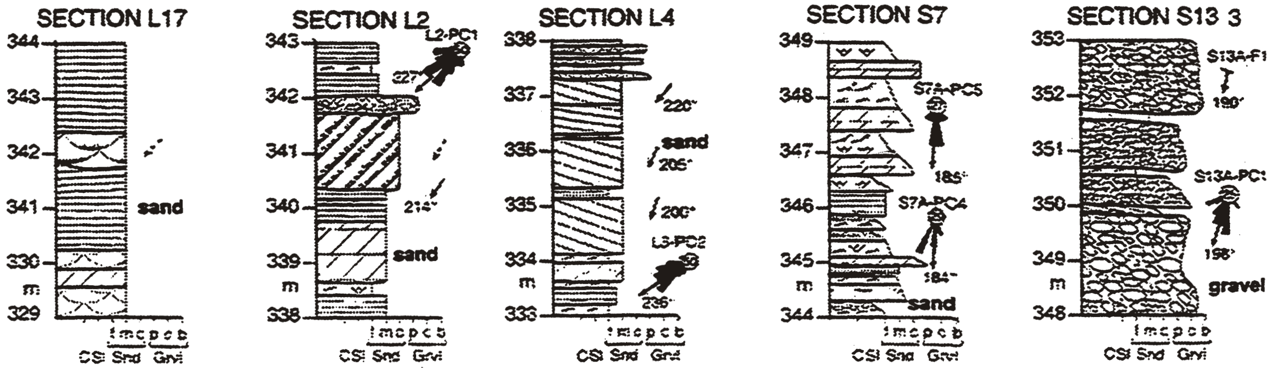


Figure 21. Measured sections in Lafarge Sand and Gravel Pit (S7 and S13) and Lee Sand and Gravel (sections L2, L4 and L17). (From Paterson, 1995).

sediments. Rippled sands with northward paleoflow indicate that the overriding ice also contributed meltwater discharges. The limit of this advance is marked by a narrow zone of hummocks and kettle lakes and, by the surface distribution of Halton Till.

A rotosonic borehole drilled from the floor of the pit (Barnett, 1993) encountered ~93 m of rhythmic fine sand of the ORM, overlying sandy Newmarket.

Oak Ridges Moraine aquifer complex

The ORM aquifer is the main source of water supply in rural areas and it is a significant source of recharge to most other confined aquifers. The grain size and structure of ORM sediments can vary significantly over short distances from silt and clay to coarse gravel. Hence, the ORM is not a single aquifer. While domestic water supplies can be obtained in most areas of the ORM, with yields commonly in excess of 0.8-3.5 L/s (10-50 Igpm) (Sibul et al., 1977), it is clear that sedimentary models (Fig. 5) can help locate high-yield areas of the ORM and help assess groundwater flow.

Most or the ORM is exposed at the ground surface and forms an unconfined aquifer (Fig. 4). In some areas, the water table is deep and ORM is unconfined; in other areas, particularly at lower, southern elevations, the ORM is confined by this overlying Halton Till (Fig. 4). The variability in sediment texture and the presence of the Halton Till are important controls on groundwater recharge. While the topographic position and the prevalence of coarse sediments in the ORM makes this an important area of groundwater recharge, it is likely that groundwater recharge is not uniform across the moraine. Recharge will generally be lower beneath the Halton Till but may also be restricted in areas underlain by silt or clay. Local geology is needed to identify the relative importance of different recharge areas within the ORM.

Stop 2.2 Musselman's Lake-ORM recharge-discharge area

(L. Dyke and M. Hinton; Newmarket NTS 31 D/2)
[638500E 4876800N]

The hydrogeological function of Musselman's Lake, a kettle lake, is of interest because it is situated near the crest of the sandy ORM ~250 m above Lake Ontario.

Musselman's Lake occurs at the junction of unconfined ORM aquifer sands and the northern limit of silty Halton Till, which overlies ORM sediments to the south. The highly permeable nature of these surface deposits is reflected in the lack of developed surface drainage channels (Hunter et al., 1996). Most precipitation rapidly infiltrates the soil, resulting in low runoff.

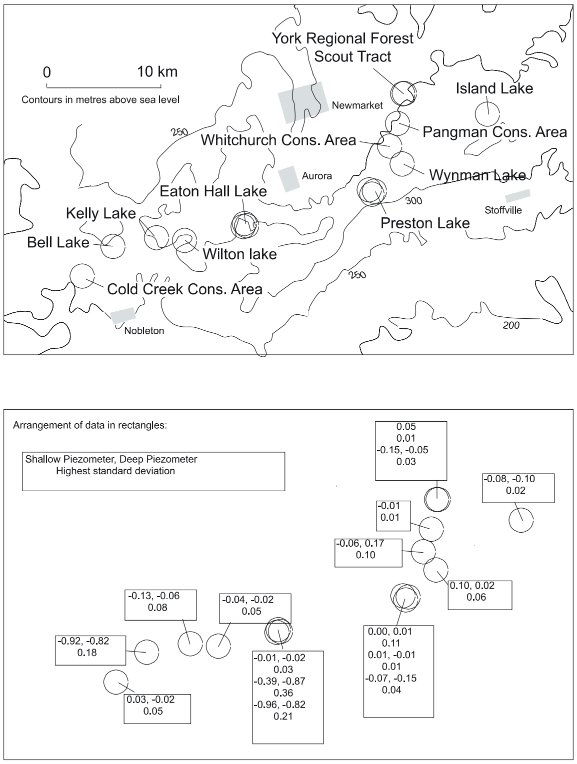


Figure 22. Multi-level piezometres in or near kettle lakes: a) locations; b) average hydraulic gradients and standard deviations for all piezometres.

Kettle lakes

Small lakes (0.1-1 km), are common along the broad crest of the ORM between the Niagara Escarpment and Lake Scugog. These lakes are mainly located in hummocky terrain where Halton Till overlies the ORM. Similar, but dry depressions are also common on ORM. The term 'Kettle' implies melting of buried ice, and although many of the lake-filled depressions may be of this origin, uneven glacial sedimentation may have produced others. Nevertheless, these lakes may constitute a source of recharge to the ORM because of the high elevation at which most lie.

To assess the degree to which these lakes serve a recharge function, 10 lakes were instrumented with piezometers, installed in pairs at the lakeshore (Fig. 22). These installations provide a measure of the vertical hydraulic gradient which can be used to interpret the relationship of the lake to groundwater flow. The direction of groundwater flow has obvious implications for groundwater recharge, lake water quality and land use near these lakes.

Ten out of 16 installations show downward flow with 3 installations showing gradients close to -1 (Fig. 23). Steep hydraulic gradients suggest that these piezometers are screened either in or below aquitards, and that the water elevation of the lake is elevated with respect to the regional head in the underlying aquifer. Therefore, some of these kettle lakes may represent mounds in the groundwater table or they could indicate that the underlying aquifer is drained, by surface springs or highly permeable zones, to elevations well below the lake level.

Musselman's Lake is the largest of the kettle lakes on the ORM. It has a north-south regional groundwater divide 2 km to the north (Kaye, 1986). The northward shift of the divide may be a result of lower-permeability sediments near the lake producing a groundwater mound. Mini-piezometers showed that Musselman's Lake is a flow-through lake with shallow groundwater recharge and discharge areas (Kaye, 1986). However, at the regional scale, the lake is in a groundwater recharge zone with downward flow to lower aquifers. Vertical gradients help demonstrate which strata limit groundwater recharge and affect groundwater flow; gradients are large across shallow silt and clay layers and are very low across more permeable sediments.

A lake at Cold Creek (Fig. 22) also was instrumented to provide a detailed pattern of piezometric levels within a depression (Romano, 1998). Overland flow, stream runoff, and evapotranspiration are the major controls on water

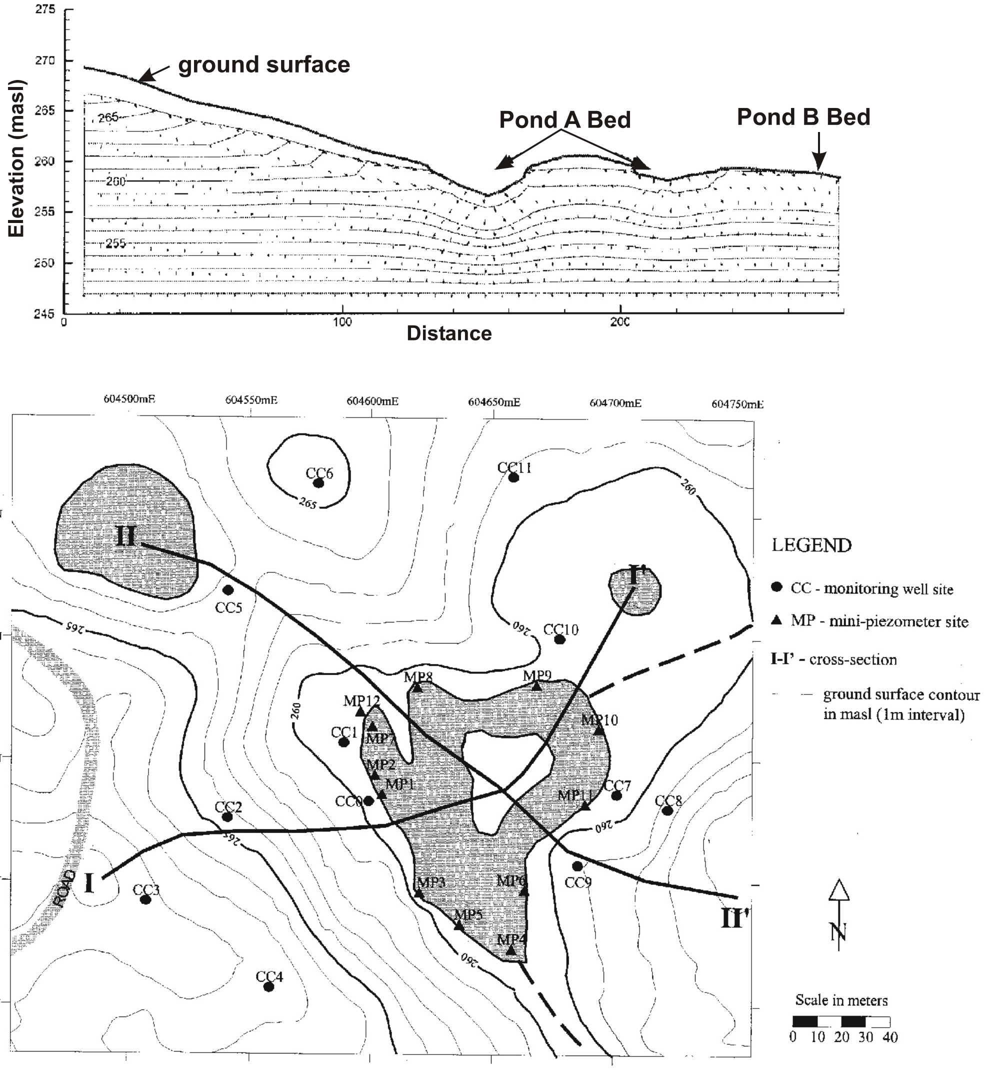


Figure 23. Model of velocity vectors from piezometer installations, Cold Creek.

levels in the lake. Vertical downward gradients are large and hydraulic conductivities of Halton Till below the lake are low 10^{-7} to $<10^{-10}$ms^{-1}). The absence of tritium at 11 m depth adjacent to the lake shows that groundwater recharge is less than 100 mm/year (assuming a measured porosity of 0.42). Groundwater modeling shows that groundwater flow in the vicinity of the lake is predominantly vertical and that groundwater fluxes into the lake are a small part of the total water balance (Fig. 23; Romano, 1998).

Stop 2.3 Ballantrae sand plain and ORM water supply

(P. Barnett, L. Dyke, M. Hinton, S. Pullan; Newmarket NTS 31 D/2) [634700E 4876350N]

This stop reviews the deep geologic structure of ORM and reports on the sediments, geophysics and pump test results that helped to identify buried channel aquifers.

Geologic setting

The major east-west re-entrant in the ice sheet (Fig. 5), focused deposition of extensive sediments within an expanding proglacial lake. Subaqueous fans and deltas developing along the ice margins coalesced, forming a large, thick sandplain in the Ballantrae area ~330 m asl (Fig. 20). Paleoflow directions were predominantly westward, paralleling the growing re-entrant. These deltaic sediments cover the core of the ORM and any of its deep structures, landforms and sediment sequences.

Searching for buried channels

The Ballantrae sand plain lies near the crest of the ORM. Here, it is a thick unconfined aquifer that supports many domestic wells but few sustainable municipal wells. ORM consists of thick sediment sequences (Barnett et al., 1998) that require deep prospecting methods to assess their hydrogeologic function and find water supplies. It was suspected that large surface channels north of the ORM (Fig. 7) extended beneath the ORM in this area (Barnett, 1993). The absence of Newmarket Till and the presence of 90 m of sandy sediments in an exploratory borehole drilled at this site in 1993 hinted at the presence of a buried channel and suggested the need for a more thorough search beneath ORM. In two nearby boreholes, Newmarket Till was only 14 m thick (1 km N and 5 km E of this site) and about 45-50 m below the surface. Was a channel present?

Seismic surveys

North-south and an east-west seismic profiles were run to intersect close to the 90 m borehole position. The 1.5 km east-west seismic profile was run to intersect a channel system trending northeast from Vandorf (Fig. 1). The data acquired at this site, on surface sands, resulted in poorer data quality than elsewhere in ORM area where surface soils are clayey. However, a 159 m deep borehole drilled on this seismic line and cored within metres of bedrock provides control for the seismic facies (Pugin et al., in press). The interpreted profile delineates the western margin of a channel based on dipping reflectors that cross-cut the high-velocity Newmarket Till. The channel is wider and shallower than the channel observed to the south at Vandorf. While the erosion of this channel removed Newmarket Till over an east-west distance of >1 km, it did not cut deeply into the lower drift sequence.

A subsequent borehole intersected 15 m of coarse (bouldery) gravel at a depth of 90 m. Downhole geophysical logging characterized the different channel fill sediments including the gravel sequence, with high seismic velocity (~2200 m/sec). Hence, the borehole core and geophysics (profile and log) revealed a broad channel (Pugin et al., in press) and a complex channel fill consisting of lower-channel gravel overlain by finer sandy ORM sediments. The orientation of the Ballantrae channel is thought to trend north-south or northeast. This appears to be confirmed by the fact that a municipal-well-search 1.5 km due north of the site, encountered the same gravel sequence at ~240 masl (Sharpe et al., 1996). This work was followed by a municipal pump test that showed hydraulic connection between the gravel units and across the channel.

Tunnel channels as aquifer targets

A study of water wells in Ballantrae found that over 70% of the wells tested had elevated concentrations of chloride, sodium and nitrate (Kaye, 1986). In 1987, a program of test-hole drilling and pump testing was carried out (IWS, 1988) to identify deep aquifers. The results of a 24-hour pump test suggested that the "local" transmissivity of an aquifer at 106-117m depth (220-231 masl) is 520-595 m^2/d (35000-40000 Igpd/ft) (IWS, 1988). This drilling strategy eventually lead to production wells at the site in 1995-96, aided by the above hydrostratigraphic analysis. However, the identification of a deep channel aquifer system with a program of geophysical mapping and high-quality core recovery should set the stage for more focused water supply studies and testing of this and other aquifers in the ORM.

In review, the existence and location of tunnel channels are important for two reasons. First, channels that are filled with coarse sand and gravel can be aquifers for municipal supply (e.g. Ballantrae). Second, where the channels have completely eroded Newmarket Till, they provide hydraulic windows between upper ORM aquifers and lower sediment aquifers (Fig. 11).

Stop 2.4. Nobleton borehole in the Laurentian Channel

(H. Russell and S. Pullan; Bolton NTS 30M/11)
[611100E, 4864650N]

This stop provides an overview of the regional stratigraphy and highlight sedimentological and geophysical logging of a continuously cored, 193 m borehole.

The Nobleton borehole is located in the northeastern part of the Humber River watershed (Fig. 10), south of the ORM. The borehole was sited based on a seismic profile completed across the Laurentian Channel (see Fig. 12) and it provides geologic control for the seismic data. There was also a need for a continuously cored hole for lithofacies analysis and for monitoring of municipal pump tests. The hole is collared at 260 masl and ends in bedrock at 67 masl for a total length of 193 m. Except for Newmarket Till, the borehole intercepted all stratgraphic units of the geologic model (Fig. 6). Discussion will focus on regional stratigraphic units, downhole geophysical signatures, and commentary on hydrogeological properties.

Each of the recorded lithostratigraphic units consists of one or more lithofacies (gravel, cross-bedded sand, small-scale cross laminated sand, silt, and clay). These individual lithofacies can then be grouped into facies assemblages, defining the architecture of the sediments. The dominant facies association is a tripartite sequence of sand-silt-clay forming rhythmites. The hydraulic character of each lithofacies is controlled by grain-size, sorting, composition, and structure.

Stratigraphic units

Halton Sediments: This unit consists of silt to silt-clay diamicton that is interbedded with sand, gravel and clay-silt (Russell and Arnott, 1997). At the borehole site this unit is ~ 7 m thick (Fig. 24) and has an interbedded lower contact with ORM sediment. The depositional environment was ice marginal with deposition of diamicton from debris flows, ice-rafting, and subglacial lodgement (Fig. 5d). Sand and gravel were deposited by glaciofluvial discharge while the silt-clay was deposited by underflows and suspension sedimentation in an ice-contact lake. On downhole geophysical logs, Halton sediments have higher gamma and conductivity signatures and lower magnetic susceptibility than ORM sediments (Fig. 24).

In this area, massive diamicton has horizontal hydraulic conductivity (K) of 10^{-7} m.s^{-1} to 10^{-5} m.s^{-1} and vertical K of 10^{-8} m.s^{-1} to 10^{-9} m.s^{-1} (Table 3; Golder Associates, 1994). Interbedded sand and gravel sediments have K values of 10^{-6} m.s^{-1}, whereas, interbedded diamicton and sand-gravel have K values of 10^{-5} m.s^{-1} (Golder Associates, 1994). To the east, horizontal K values of 10^{-8} to 10^{-10} m.s^{-1} are reported for massive diamicton (Fenco-MacLaren, 1994). Higher K values, 10^{-6} ms^{-1} are found for interbedded diamicton and sand-gravel (Fenco-MacLaren, 1994).

Oak Ridges Moraine Sediments: The ORM sediments form a 60 m thick (Fig. 24) fining-upward sequence from gravel to fine sand-silt with minor clay and diamicton (Russell et al., 1998a). The ORM sediments unconformably overlie lower sediments (Fig. 4). The gravels were deposited under high-energy glaciofluvial conditions (Fig. 5a,b) prior to or synchronous with moraine sedimentation. The remaining fine sand-silt sediments were deposited within a glaciolacustrine subaqueous fan environment (Fig. 5b) and record rapid bottom-current and suspension sedimentation. This is characterized by small-scale cross-lamination produced by density underflows and turbidite currents. On downhole geophysical logs (Fig. 24), the ORM sediments have a monotonous signature; gamma readings are low (< 60 cps).

Sand-silt lithofacies in the core are analogous to sediments in the main aquifer unit at the Vaughan landfill site (Fenco MacLaren, 1994). Hydraulic conductivity ranges from 10^{-2} to 10^{-6} ms^{-1}. Here, K varies spatially according to a trend from coarse to fine (proximal-distal and fining-upward) at the site and variations in the coarseness of the sand.

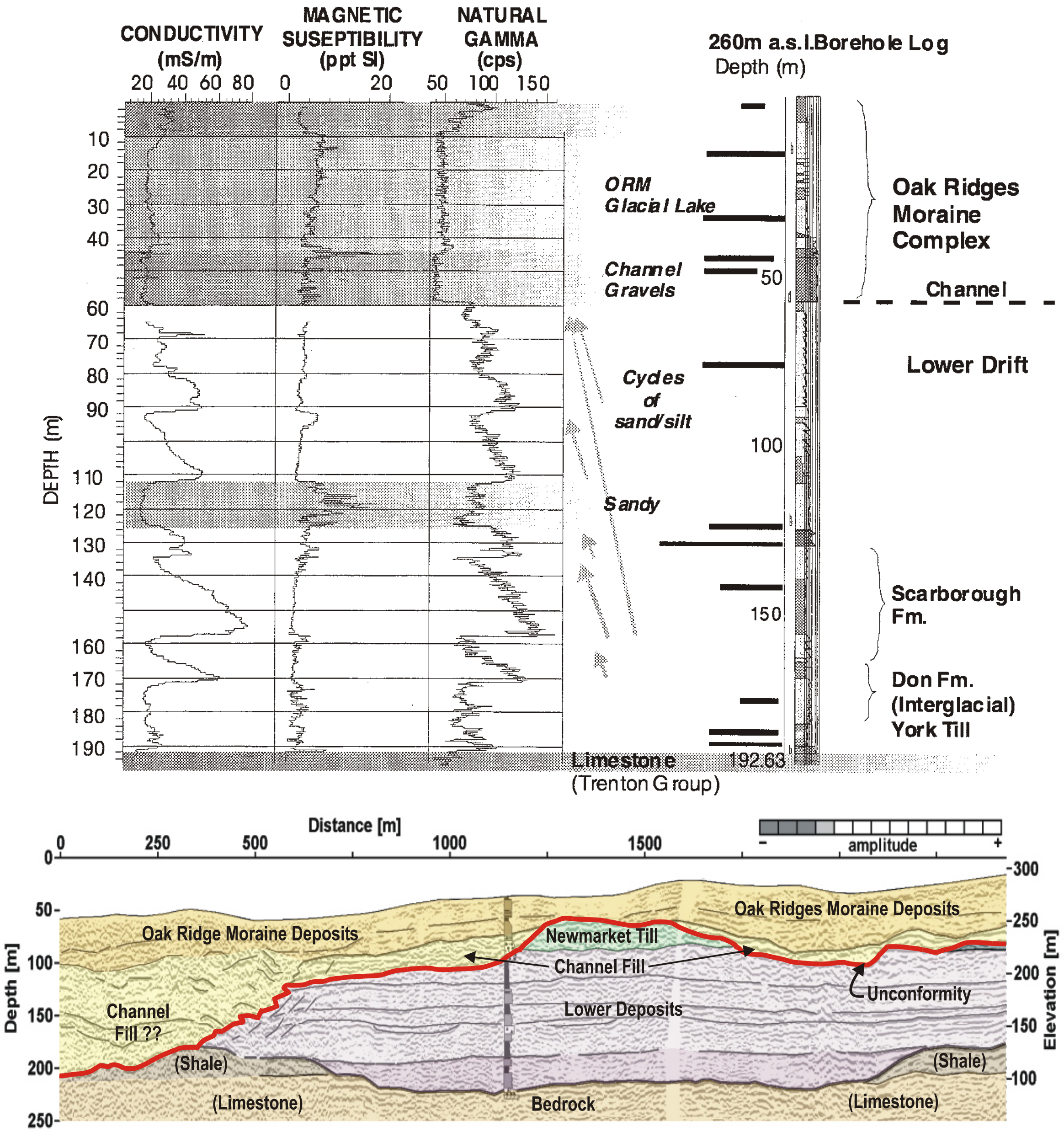


Figure 24. Nobleton borehole sediment and geophysical logs (gamma, conductivity, magnetic susceptibility and seismic velocity). Geophysical logs show marked trends with sediment variation (coarsening upwards) in the lower sediments. Seismic profile provides context.

Lower Sediments: The Scarborough Bluffs type section (Fig. 19), suggest that lower sediments in the core be assigned to four formations (Thorncliffe, Sunnybrook, Scarborough and Don). No hydrogeological data are available for these units from other sites due to a lack of comparable lithofacies logging (e.g. Dillon, 1994a-e).

Thorncliffe Formation: This formation is 65 m thick and has been logged as ~2300 units, forming ~ 1000 graded couplets of fine sand-silt to clay (Fig. 24). The couplet thickness averages 5 cm with the capping clay having a thickness of ~1.1 cm. Sedimentary structures are dominated by micro-laminations and, small-scale cross laminations in the fine sand. The unit is comprised of a number of cycles that are well defined by geophysical records. A 10 m sand package at the base of the unit is characterized by low gamma and conductivity, and, high magnetic susceptibility. Higher in the core, coarsening-upward cycles are well-defined on the gamma and conductivity logs. These cycles are related to changes in couplet thickness and increasing fine sand content. In summary, a distal delta-basin depositional setting is inferred (Fig. 5c). Hydrogeologically, this unit is an aquitard with confined fine-sand aquifers at various levels. The base of the unit has a 10-15 m sequence of fine sand and the top 1-2 m of the coarsening-upward cycles is mainly fine sand.

Scarborough Formation: This formation is 39 m thick and has been logged as ~1260 units forming ~ 500 couplets of fine sand to clay. The fine sand and silt are micro-laminated to small-scale cross laminated. Detrital organic material is common in sand. The sequence is characterized by an overall fining-upward trend with secondary cycles that coarsen upwards. A proximal delta environment is inferred. Geophysical logs, particularly gamma and conductivity profiles identify coarsening-upward cycles (Fig. 24). Regionally, this unit is a major aquifer. Lack of detailed lithofacies logging however, precludes correlations between the facies observed in this core and possible producing horizons in the Alliston aquifer (Turner, 1977).

Don Formation: This formation is ~23 m thick and has been logged as ~60 units. It is composed of three lithofacies: pebble gravel, cross-bedded sand and silty fine sand. Organic material (shells, wood fragments, and detrital fibres) is common and hosted in fine to coarse sand. These deposits may represent deposition in a shallow, high-energy, sandy littoral setting.

This unit appears to have a regional distribution and, with the exception of the ORM sediments, is the coarsest unit in the core. Both the Scarborough and Don formations have water-quality problems related to methane and dissolved organic carbon. This problem is most prominent in the Alliston aquifer north of the ORM (Aravena and Wassenaar, 1993).

Summary

The sediment and geophysical logging completed on this core, and re-logging of nearby IWA core permits inter-core correlations based on clear sedimentological criteria and recognition of common depositional processes. Consequently, hydraulic data can be integrated between sites and conceptual depositional models may be constructed for sediment packages (e.g. Fogg, et al., 1998).

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