Regional geological mapping of the Oak Ridges Moraine, Greater Toronto Area, southern Ontario[1]

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Abstract: Geological maps are keys to communicating earth science information and their use is fundamental to land-use planning. A new 1:200 000 scale surficial geology map synthesizes recent 1:50 000 and 1:20 000 mapping in the Oak Ridges Moraine–Greater Toronto Area. These regional geological data provide consistent mapping across the area in aid of terrain analysis, resource evaluation, and environmental assessment. The mapping provides, for the first time, the basis for developing regional geological models within the area.

The geological mapping synthesizes approximately 20 000 new and archival ground observations that are grouped into 11 deposits or map units. Map units have been organized into major sediment packages depicted in a three-dimensional regional geological model that highlights six principal stratigraphic elements. These regional strata, from oldest to youngest, are: 1) bedrock, 2) lower deposits, 3) Newmarket Till, 4) Channel fill, 5) Oak Ridges Moraine, and 6) Halton Till.

Résumé : Les cartes géologiques constituent un moyen efficace de communiquer l'information géoscientifique et leur emploi est essentiel à la planification et à l'utilisation des terres. Une nouvelle carte de la géologie de surface de la région de la Moraine d'Oak Ridges et du grand Toronto à l'échelle de 1/200 000 fait la synthèse de récents travaux de cartographie dont les résultats ont été publiés aux échelles de 1/50 000 et de 1/20 000. Ces données géologiques à l'échelle régionale permettent de dégager une image cartographique uniforme du territoire, ce qui s'avère utile aux fins d'analyse de terrain, d'évaluation des ressources et d'évaluation environnementale. La cartographie fournit, pour la première fois, une base solide permettant d'élaborer des modèles géologiques à l'échelle régionale.

La carte géologique fait la synthèse d'environ 20 000 observations de terrain, nouvelles ou déjà disponibles, que l'on a attribuées à 11 unités sédimentaires ou cartographiques. Ces unités ont été regroupées en grands assemblages sédimentaires qui sont illustrés dans un modèle géologique tri-dimensionnel de la région mettant en évidence 6 entités stratigraphiques principales. De la plus ancienne à la plus récente, ces entités sont les suivantes : 1) substratum rocheux; 2) dépôts inférieurs; 3) Till de Newmarket; 4) matériaux de remplissage de chenal; 5) Moraine d'Oak Ridges; et 6) Till de Halton.

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[1] Contribution to the Oak Ridges Moraine NATMAP project

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INTRODUCTION

Awareness of earth science is fundamental to rational land-use planning and is a prerequisite for informed debate on resource management, environmental health, and public safety (e.g. Clague et al., 1997). Geological maps are a key means of communicating earth-science information and are important tools for organizing, summarizing, and analyzing data about the spatial pattern of the Earth's landscape and sediments.

A regional, 1:200 000 scale, surficial geology map of the Oak Ridges Moraine (ORM) and Greater Toronto Area (GTA; Sharpe et al., 1997a) summarizes a recent series of twelve 1:50 000 maps for the area (Fig. 1). The regional map also incorporates data from a series of 9 recent 1:20 000 geology maps published by the Ontario Geological Survey (OGS), covering the central area of the ORM (e.g. Barnett, 1996a). Mapping was initiated in response to a number of earth- and water-resource planning and management issues identified by the Ontario Ministry of Natural Resources, ORM Technical Working Committee (1994). Regional mapping was sponsored by the National Geoscience Mapping Program (NATMAP) of the Geological Survey of Canada in collaboration with the OGS and a number of other provincial and municipal agencies and local groups.

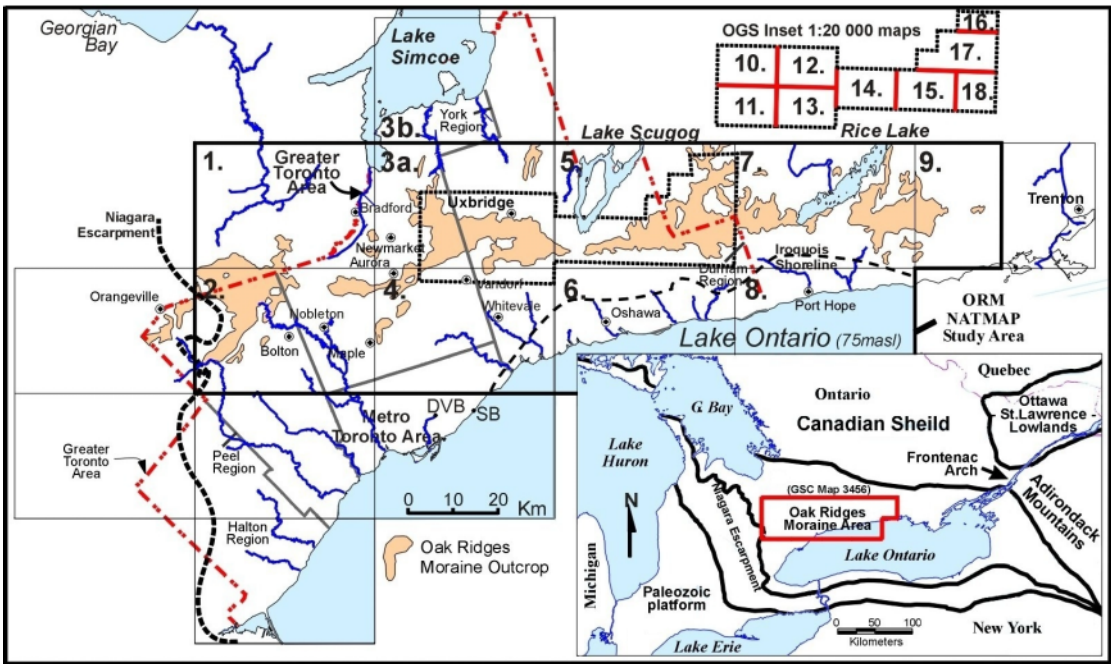

Figure 1. *Location of GTA map area (GSC Open File 3062; Sharpe et al., 1997a) with regional geology inset. The NATMAP study area is covered by GSC Open File 3456 (Sharpe et al., 1997b). Map names and publication numbers for Geological Survey of Canada (GSC) and Ontario Geological Survey (OGS) maps are listed and linked to the index map with numbers:*

1:50 000 scale maps: *1. Alliston: GSC, Open File 3334 (Russell and Dumas, 1997). 2. Bolton: GSC, Open File 3299 (Russell and White, 1997). 3a. Newmarket: GSC, Open File 3329 (Barnett and Gwyn, 1977); 3b. Beaverton: OGS Map 2560 (Barnett and Mate, 1998). 4. Markham: GSC, Open File 3300 (Sharpe and Barnett, 1997). 5. Scugog: GSC, Open File 3330 (Barnett, 1997b); OGS, Map 2644 (Barnett et al., 1996). 6. Oshawa: GSC, Open File 333](Brennand, 1997a). 7. Rice Lake: GSC, Open File 3332 (Gorrell and Brennand, 1997). 8. Port Hope: GSC, Open File 3298 (Brennand, 1997b). 9. Trenton: GSC, Open File 3333 (Gorrell, 1997).*

1:20 000 scale maps: *10. Mt. Albert: OGS, Map 2631 (Barnett and McCrae, 1996a). 11. Stouffville: OGS, Map 2632 (Barnett and McCrae, 1996b). 12. Uxbridge: OGS, Map 2633 (Barnett and Dodge, 1996). 13. Claremont: OGS, Map 2634 (Barnett, 1996a). 14. Port Perry: OGS, Map 2635 (Barnett and Henderson, 1996). 15. Enniskillen: OGS, Map 2636 (Barnett, 1996b). 16. Kendal area: OGS, Map 2637 (Barnett, 1996c). 17. Bethany: OGS, Map 2638 (Barnett, 1996d). 18. Brunswick: OGS, Map 2639 (Barnett, 1996e).*

Objectives and scope of the report

The objective of the regional map, and of this paper, is to present the geology of the ORM-GTA area as baseline data for terrain evaluation, regional planning, resource management, and environmental analysis. This paper is aimed at informed users (e.g. terrain consultants) who can help communicate this geological knowledge to a wider group of users. The report describes 11 map units discussed within the framework of a regional geological model. The mapping provides a consistent geological synthesis across the region as required for standardized land-use and resource evaluation. The map also provides a basis for understanding the surficial geology of the area in three dimensions when used with the geological model (Sharpe et al., 1996). This report describes the geological context for the sedimentary units and their distribution. It also provides a regional geological synthesis for the origin and depositional setting of strata in the ORM-GTA. More detailed accounts of the geology of the ORM area are being published separately (e.g. Barnett et al., 1998; Pugin et al., in press).

Previous and present geological mapping

Sediment mapping in the ORM-GTA has been ongoing throughout the twentieth century. Taylor (1913) identified the moraines in the GTA while Coleman (1913, 1932) added three-dimensional geological perspective by examining the lake bluffs along Lake Ontario. Chapman and Putnam (1984) defined the physiography of the ORM/GTA.

Gadd (1950), Watt (1957, 1968) and other GSC workers introduced the early work on geological mapping related to water resources. Singer (1974), Funk (1979), Sibul et al. (1977), and Ostry (1979) provided modern hydrogeological mapping to the GTA. This included the introduction of three-dimensional methods such as drilling and borehole geophysics (Sibul et al., 1977; Fligg and Rodrigues, 1983; Eyles et al., 1985). Recent geological mapping has been summarized by Karrow (1967), Sharpe (1980), Barnett et al. (1991), and Sharpe et al. (1997a).

The nine maps within the NATMAP area (Fig. 1) are based on new fieldwork and conceptual understanding, complemented by archival field data; most maps have approximately 1000 field sites. Maps outside the NATMAP area (Fig. 1) have been remapped with a minimum of new fieldwork, but include reassessed archival data and a standardized legend. All new maps are structured in a Geographic Information System (GIS) with supporting data in a relational database (e.g. Russell et al., 1996). GSC Open File 3062 (Sharpe et al., 1997a) is available digitally, along with related 1:200 000 scale map products (Russell et al., in press).

Table 1. Glacial and Recent sediments shown on GSC Open File 3062.

Map unit	Name (origin)	Sediment	Thickness	Landform type
11	Recent deposits	sand, gravel and diamicton	1-3 m	dunes, lakeshores, slopes
10	River deposits	**a**. gravel, sand, silt, clay, muck **b**. gravel, sand, silt, clay	1-2 m 1-8 m	modern floodplains river and delta terraces
9	Organic deposits	peat, muck and marl	1-7 m	wetlands
8	Glacial lake deposits	**a.** sand and silty sand **b.** gravely sand	1-50 m 1-5 m	basins and nearshore flats raised shorelines
7	Glacial lake deposits	**a.** silt, clay, diamicton **b.** silt and clay	1-10 m 1-5 m	basins basins
6	Glacial river deposits	**a.** sand b. gravel	1-15 m 1-15 m	eskers, fills and terraces eskers, fills and terraces
5	Morainal deposits	**a.** sand, silt, gravel, diamicton, **b.** sand and gravel	1-100 m 1-20 m	broad moraines channels, hills, depressions
4	Glacial deposits (till)	clayey silt to silt, 1–2% stones (e.g. Halton and Kettleby Tills)	1-15 m	plains
------------------------------------erosional unconformity				
3	Glacial deposits (till)	sandy silt, sand, 3–10% stones (e.g. Newmarket Till)	1-50 m	plains and uplands
2	Lower sediments	sand, silt, clay and till	1-100 m	bluffs, buried plains
	g. Upper Thorncliffe Formation/Clarke beds; **h**. Seminary/Meadowcliffe/ Bondhead tills			
	i. Lower Thorncliffe Formation/Clarke beds; **j.** Sunnybrook Till; **k**. Scarborough Formation			
	l. Don Formation; **m**. York Till; **n.** Stratified sediment, sand **o.** Stratified sediment, silt and clay			
Unconformity (long interval with no deposits and/or major erosion)				
Paleozoic				
1	Bedrock	limestone, sandstone, or shale	~50-500 m	Niagara Escarpment; buried valleys
Note: Glacial deposits (till) are grouped as coarse and fine textured.				

SURFICIAL GEOLOGICAL MAP

Geological maps generalize earth-science information, but they are technical documents that portray complex three-dimensional earth relationships in plan view. Hence, there is a need to simplify and explain map content so that it is more accessible to a range of users (e.g. Clague et al., 1997). Geological Survey of Canada Open File 3062 (Sharpe et al., 1997a) presents a 1:200 000 scale map, a simple legend, and side-bar figures showing the regional location, terrain, and geological context of the area. The legend uses 11 classes of sediment and rock to describe the geological landscape in the ORM-GTA (Table 1). Sediments are grouped under terms such as glacial-lake or glacial-river deposits. Unit descriptions and colours on the map emphasize primary sediment textures (e.g. sand, silt, clay, gravel, and diamicton), followed by the thickness, landform type, and origin of material. A digital elevation model of the area allows the land contours and terrain to be more easily recognized (Fig. 2a; Kenny et al., 1999). A three-dimensional block model portrays the regional geology in a manner that allows the structural and functional link between map elements and map units to be clarified (Fig. 3, 4).

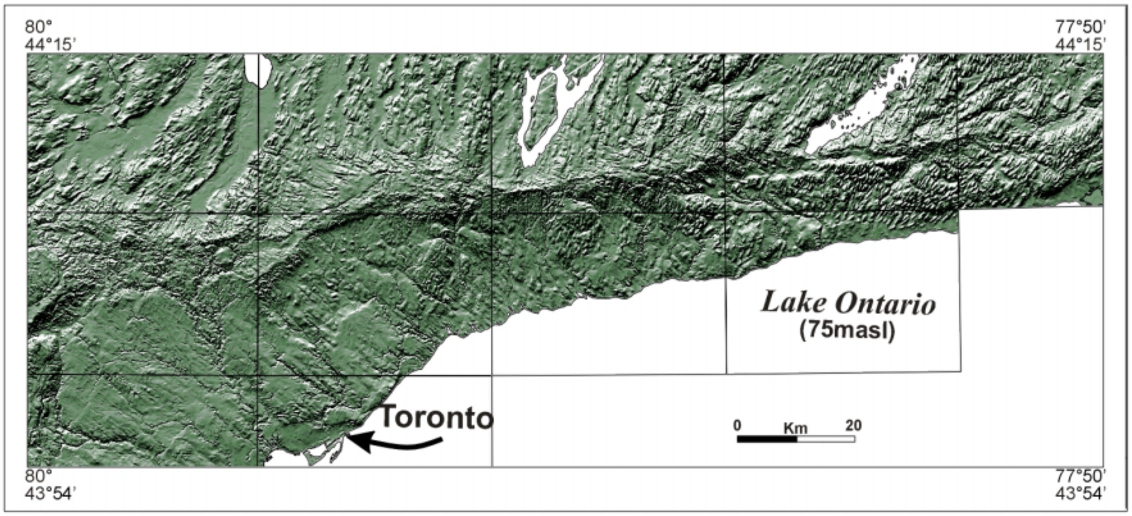

Figure 2. a) *Relief of the central ORM area (Skinner and Moore, 1997)*

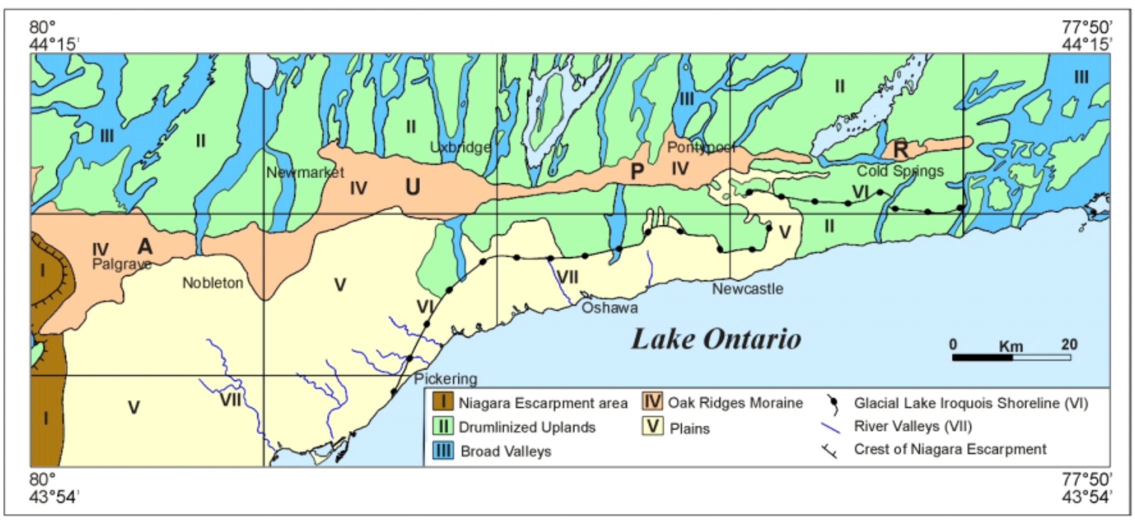

Figure 2. b) *Physiographic units of the GTA/ORM area based on the digital elevation model (DEM)(see Barnett et al., 1998 for additional discussion).*

GEOLOGICAL SETTING

Regional terrain elements include the Precambrian Shield to the north, and underlying flat-lying Paleozoic rocks of the St. Lawrence Lowlands and Great Lakes (Fig. 1). Limestones, shales, and sandstones (Table 1, unit 1) of Ordovician age (Sanford and Baer, 1981), mainly outcrop along the Niagara Escarpment, Lake Simcoe, and in streams close to Lake Ontario (Fig. 5h).

A major regional unconformity separates the Paleozoic bedrock and overlying sediments. A new map of this surface (Brennand et al., 1997) shows major valleys trending southeasterly across the area, including the ancient Laurentian Valley (Spencer, 1881), but no bedrock ridge beneath the ORM (Eyles et al., 1993). Sediment thickness is highly variable (0–200 m; Russell et al., 1998a), being influenced by bedrock topography and ice-controlled sedimentation. It is thinnest atop the Niagara Escarpment and thickest along Laurentian Valley.

From analysis of surface texture and digital elevation data (Skinner and Moore, 1997; Kenny, 1997), the region can be divided into seven physiographic areas that are significant to understanding the regional geology (Fig. 2b). 1) The Niagara Escarpment is an approximately 100 m topographic rise that affected ice and meltwater flow across the area , particularly during formation of the ORM (Barnett et al., 1998). 2) Drumlinized uplands of the Peterborough drumlin field occur north and south of the ORM (Fig. 2b); they also underlie it (Fig. 4a; Barnett et al., 1998). 3) Large flat-floored valleys are eroded into the drumlin upland north of the ORM (Fig. 2b); some continue south of the moraine, e.g. Duffins Creek (Sharpe and Barnett, 1997; Kenny, 1997). 4) The Oak Ridges Moraine is an east-west drainage divide extending from the Niagara Escarpment to east of Rice Lake (Fig. 2b). 5) Broad, gently sloping plains border the southwestern margin of the ORM (Fig. 2b; Barnett et al., 1991). 6) The Lake Iroquois shoreline truncates this plain (Fig. 2b) at elevations ranging from about 110 m a.s.l. near Hamilton (Karrow, 1987) to ~140 m a.s.l. at the eastern margin of the area. And, 7) river valleys dissect the area (Fig. 2b), rising in drumlinized uplands or in the ORM.

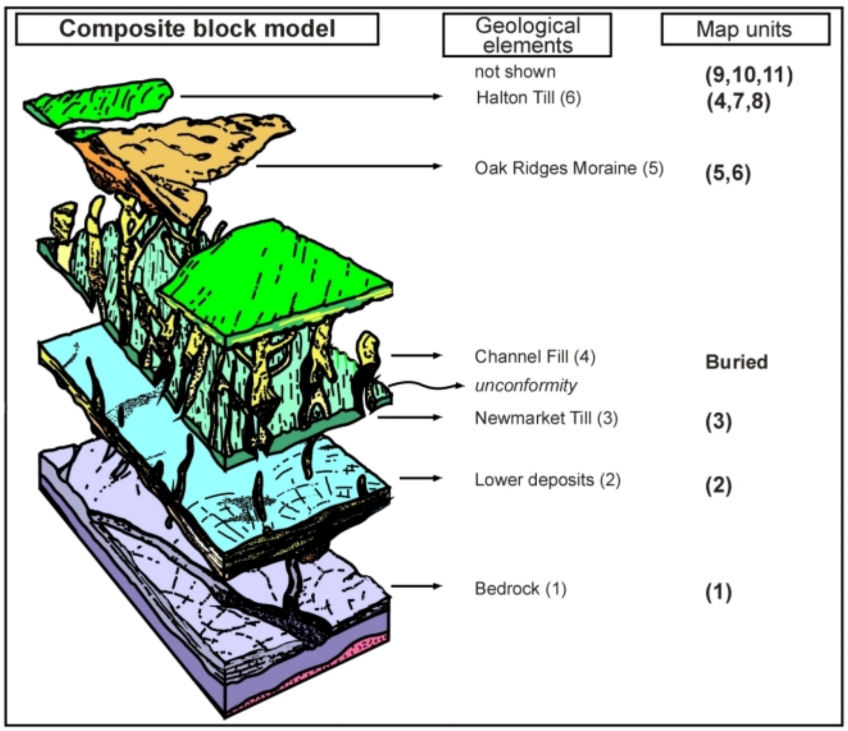

Figure 3. *Geological model of major stratigraphic elements of the GTA, showing relationship of 6 stratigraphic elements to the 11 map units*

SURFICIAL GEOLOGY AND A THREE-DIMENSIONAL GEOLOGICAL MODEL OF THE ORM-GTA

Sediments in the ORM-GTA are described and subdivided using grain size, thickness, landform type, and sediment origin (Table 1; GSC Open File 3062; Sharpe et al., 1997a). More detailed sediment descriptions, which can improve understanding of the processes of formation and their environments of deposition, are published separately (e.g. Russell et al., 1998a). The major sediment packages of the area are displayed as a regional geological model (Fig. 3; Sharpe et al., 1996). Six principal stratigraphic elements are discussed below in chronological order to place the surface map units (Sharpe et al., 1997a) in their appropriate geological and stratigraphic context (Fig. 3).

Lower deposits

Lower deposits comprise thick, complex, sediment packages that rest on bedrock and that occur below the Newmarket Till (Fig. 3, 4). These deposits are poorly exposed at surface and individual sediment sequences can only be mapped at scattered locations. The oldest exposed sediments (unit 2, Table 1) are found along the Lake Ontario bluffs and river valleys (Fig. 5f, g; e.g. Karrow, 1967), in sequences up to 100 m thick. Some units may extend as far north as Lake Simcoe as defined by borehole geophysics (e.g. Fligg, 1983; Eyles et al., 1985) and reflection seismic profiling (Pugin et al., in press). These sediments are mainly sand, silt, and clay, but they also include older tills, and distinctive fossil-bearing beds that form important markers in regional investigations and correlations (Karrow, 1990). Recent mapping has revealed sandy beds near Lake Scugog (unit 2n and 2o; Barnett and Dodge, 1996). Lower sediments were mainly deposited in proglacial lakes. From the base up, the lower sediments include York Till, Don Interglacial beds, Scarborough Formation, Sunnybrook Till, and the Thorncliffe Formation.

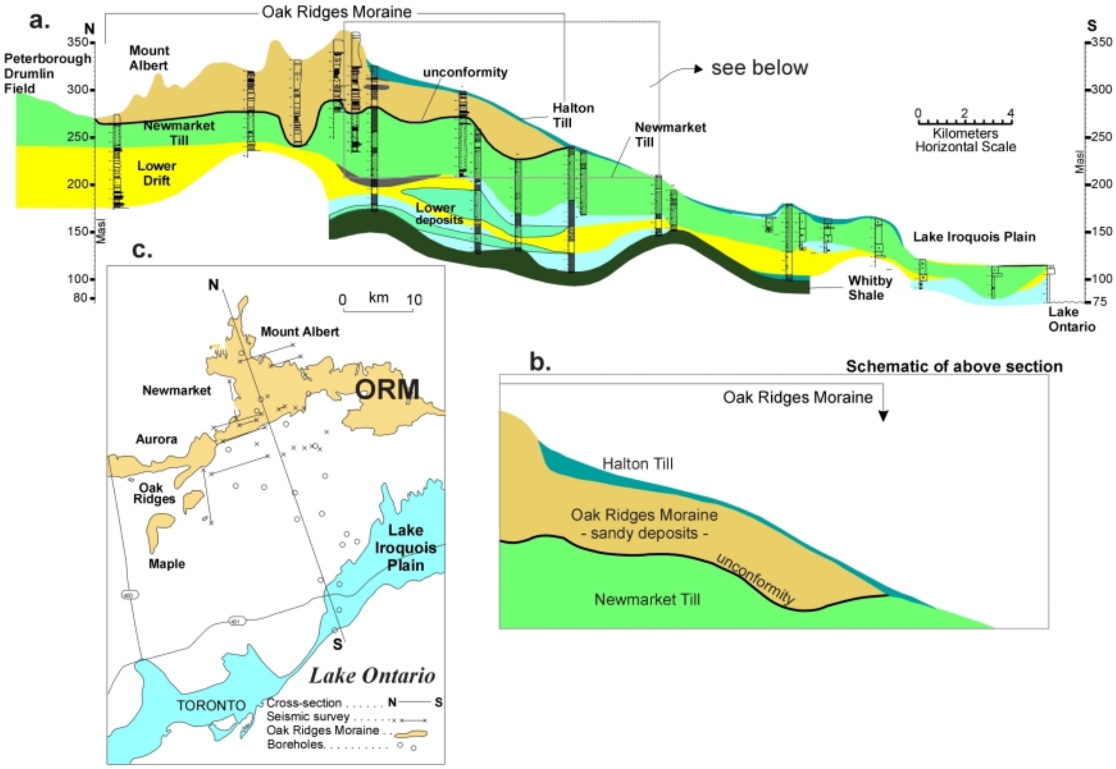

Figure 4. *Cross-section and geological model showing central GTA stratigraphic elements.* ***a)*** *N-S section from Scarborough Bluffs to Mount Albert.* ***b)*** *inset cross-section of Newmarket, Halton and ORM showing the thin and restricted distribution of Halton strata.* ***c)*** *map of borehole control. The regional extent of the Newmarket Till and the broad expanse of ORM sediments below a very thin Halton sediment package (inset) are easily seen in cross-section (from Sharpe et al., 1994). Simplified from original hardcopy publication.*

The York Till is dense, clay-sand diamicton with 5–10% gravel. It occurs at Don Valley Brickyards (Karrow, 1967), Woodbridge (White, 1975) and in boreholes to the north near Nobleton (Russell and Arnott, 1998). In places (e.g. Etobicoke Creek; Watt, 1968), this till is difficult to distinguish from younger tills (e.g. Newmarket). The Don Formation is found at the Don Valley Brickyards (Fig. 1; Karrow, 1967), near Woodbridge, and in boreholes. It consists of fine sand, silt, and clay with warm-climate fossils interpreted as a fluvial environment (Karrow, 1990). The Scarborough Formation forms approximately 50–100 m high bluffs along the Lake Ontario shore and adjacent creeks (Fig. 1). It is recognized in drill core north of Lake Ontario between 120–150 m a.s.l. It consists of a lower 30 m of silt-clay rhythmites and massive silt, overlain by 20 m of sand (Kelly and Martini, 1986). Disseminated organic material and wood fragments are common, making it a subsurface marker bed across the area (Fig. 5f). The Sunnybrook Till , a clayey-silt diamicton with low stone content (~1%), is prominent at Scarborough Bluffs and river valleys south of Woodbridge (Karrow, 1967; White, 1975). It can include rhythmites (Karrow, 1967) and massive clay that indicate glacial-lake affinities (Eyles and Eyles, 1983), but striated stones at its base suggest that it may be a till. The Thorncliffe Formation is also exposed along lake and rivers bluffs and extends in the subsurface well to the north, as recorded by thick sequences interpreted on seismic profiles (Pugin et al., 1996) and in drill core. Thorncliffe beds extend east along the Port Hope lake bluffs (Brookfield et al., 1982). Thorncliffe sediments consist of lower silt-clay rhythmites (Fig. 5g) and cross-laminated and cross-bedded sands. The package is up to 50 m thick at Scarborough, thinning to 20 m thick at Duffins Creek (Karrow, 1967). The extent and thickness of this formation makes it a significant aquifer in the area (Sibul et al., 1977; Gerber and Howard, 1996).

Newmarket Till

The Newmarket Till (Table 1, unit 3; Gwyn and DiLabio 1973) can be traced across the GTA as a distinct and consistent lithology (Fig. 5e), making it an excellent regional marker unit (Fig. 3a, 4a). It was mapped as the Leaside till near Toronto (Karrow, 1967) and its correlatives have been identified across the area (Sharpe et al., 1994; Gerber and Howard, 1996; Boyce et al., 1995) after it was recognized to underlie the ORM (Gwyn and Cowan, 1978) and extend into Lake Ontario (Lewis et al., 1998). This widespread till sheet forms the main sediment in the regional (Peterborough) drumlin field (Fig. 4) and is extensive in the Markham area. It is a dense, stony (~5–15% gravel), silty sand to sandy silt diamicton that occurs as beds 3–5 m thick, separated in places by stone lines and sandy interbeds, 1–5 m thick; total thickness is 5–50 m.

The Newmarket Till commonly has a planar lower contact on undisturbed rippled sand (Thorncliffe Formation); in places sand is interbedded. This planar contact is present on seismic profiles (Pullan et al., 1994; Boyce et al., 1995; Pugin et al., in press) at elevations ranging from approximately 210–190 m a.s.l. where it shows as a continuous, high-velocity reflector (2500–3000 m/sec on downhole velocity logs (Hunter et al., 1998)). The advance of the Late Wisconsinan ice sheet from the north and along the Lake Ontario basin lead to initial deposition of Newmarket Till into standing water.

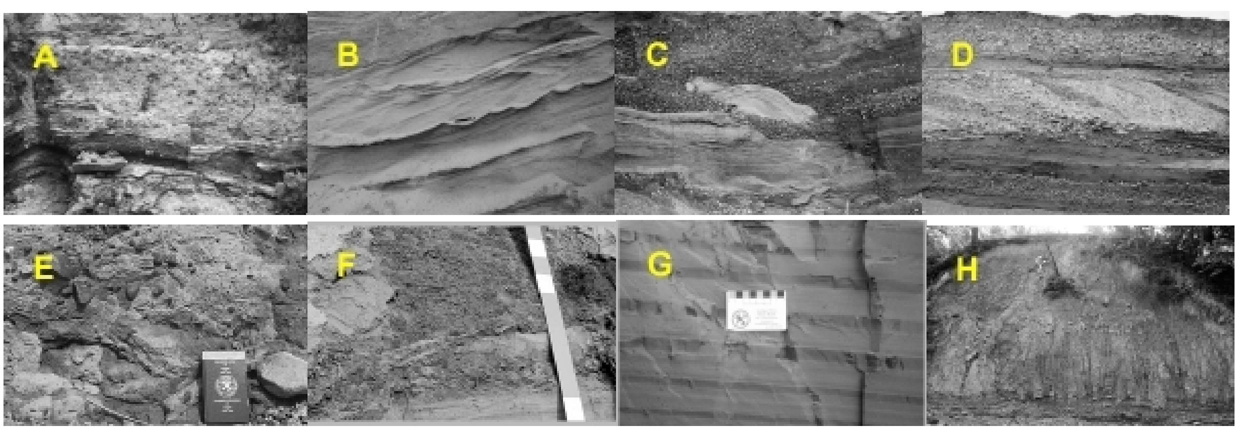

Figure 5. *Major types of sediment and rock in the ORM/GTA* ***a)*** *Halton interbedded sediments;* ***b)*** *ORM fine sand and silt;* ***c)*** *ORM gravel;* ***d)*** *channel gravel;* ***e)*** *Newmarket Till;* ***f)*** *lower sediments, Scarborough sand and organics;* ***g)*** *lower sediment, rhythmites;* ***h)*** *Shale-carbonate bedrock (below shovel) overlain by Newmarket and Halton Tills, Etobicoke Creek*

Regional unconformity

Cutting across the Newmarket Till, and into Lower deposits in places, is an unconformity (Table 1); a regional erosion surface marked by channels and drumlins (Fig. 3, 4; Barnett et al., 1998). The channels form a south-southwest-oriented network (Fig. 2) cut into Newmarket Till north of the Oak Ridges Moraine (e.g. Barnett 1990; Brennand and Shaw 1994). The link between channels and adjacent drumlin fields on this regional erosion surface is interpreted from landforms (Shaw and Sharpe, 1987) and displayed on reflection seismic profiles (Pugin et al., in press). The unconformity and channel fill sediments are part of a closely-linked event sequence that scoured Newmarket Till and deposited coarse-grained sediment on parts of the erosional surface (Barnett et al., 1998).

Channel fill sediments

The tunnel channels of the regional unconformity form an extensive network with valleys 1–5 km across, tens of kilometres long and 50–100 m deep (Barnett, 1990). They contain thick buried deposits (Fig. 3), several with 10–25 m thick gravel sequences (Fig. 5d; Shaw and Gorrell 1991; Pugin et al., 1996). However, channels fills are mainly 10–75 m thick sandy sediments that fine upwards to silt and clay (Barnett et al., 1998). Surface sediments within the buried channels contain fine sand, silt, and organic material. Both channels, and eskers within them, appear to be related to the ORM complex (Barnett et al., 1998); channel fills form the lower portions of the ORM sediment package and eskers are linked to upper ORM sediments. The coarse channel sediments were deposited during waning flow from inferred regional meltwater floods (e.g. Shaw and Gorrell, 1991). Sediments deposited during subsequent seasonal meltwater flow (Brennand and Shaw, 1994) form eskers, exposed at small surface outcrops areas in the area (unit 6a). Other near-surface glaciofluvial channels sediments (unit 6; Table 1) are found atop the ORM (Sharpe and Barnett, 1997a).

Oak Ridges Moraine and morainal deposits

On Open File 3062 (Sharpe et al., 1997a), stratified sediment ridges are shown as morainal deposits (unit 5), including the ORM and several similar, but smaller, deposits found to the north of the ORM.

The ORM is an extensive deposit, 160 km long, 5–15 km wide and more than 100 m thick (Fig. 3), but it is not identified with a precise line on Open File 3062. This is because it may be more extensive (5–10 km) in the subsurface, where it underlies Halton Till (Russell and Arnott, 1997) and the ORM comprises several map units (Fig. 3). The ORM consists of four major wedges of stratified sediment (Fig. 1, 2b) forming plains, hummocks, kettles, narrow beads, and gaps. The lower contact of the ORM is an irregular, scoured surface (channel and drumlin unconformity), which, in part, controls the thickness and distribution of ORM sediments. Rhythmically interbedded fine sands and silts are the dominant near-surface sediments (Fig. 5b), but coarse sands and gravels (Fig. 5c) are prominent locally, at depth, and in fans (Barnett, 1995; Paterson and Cheel, 1997). Some areas of the ORM consist of a few fining-upward packages of tens of metres (e.g. Sharpe et al., 1996; Gilbert, 1997; Russell et al., 1998b), which grade from medium sand to silt-clay laminae. Composite landform relations (Barnett, 1995), textural trends, and structural data indicate formative meltwater flow from the northeast, changing to westward during later fan- and delta-building stages (e.g. Barnett, et al., 1998; Duckworth, 1979). ORM sediments were deposited in a deep glacial lake (Gilbert, 1997) ponded between the ice and the Niagara Escarpment, where spillover channels formed at elevations around 425–250 m a.s.l. (Chapman, 1985; Barnett et al., 1998). On Open File 3062 (Sharpe et al., 1997a), several similar, but small, stratified sediment ridges are found to the north of the ORM.

Halton Till

The Halton (and Kettleby) Till and related sediments (unit 4, Table 1) occur as thin (~10–20 m) surface tills and interbedded lake sediments that onlap the south (Halton) and north (Kettleby) flanks of the ORM. The Halton sediment complex covers 150–200 km^2 as predominantly clayey silt to silt till with interbedded sand, silt and clay (Fig. 5a). The Kettleby Till covers a smaller area and occurs as a thin (1–2m) clayey diamicton, interbedded with fine sand, silt, and clay. The Halton sediments are approximately 20–40 m thick along the Humber Valley (Russell and Arnott, 1997), and they thin towards the north and east (Fig. 4). Where these sediments onlap the south flank of the ORM (Bolton to Port Perry) they are characterized by a zone of hummocks and kettles (Fig. 2). Toward the end of final glacial cover, Halton ice melted back into Lake Ontario (Fig. 4, 6b) and deposition apparently ceased when ice floated off a local grounding position or it became stagnant, signaling, in broad terms, the end of ORM-building events.

Table 2. Stratigraphic elements of the ORM-GTA.

		Stratigraphic unit[1] (youngest on top)	Map units	Explanation/description[2] (reference to stratigraphic name)
Quaternary				Period covering last 2 million years of glacial climates
	Recent			Last 10 000 years B.P. following glacial climates
		Lake Ontario deposits	11	Deposits along shore of modern lake (75 m a.s.l.)
		Alluvium (river deposits)	10a	Sediment deposits by modern rivers in Recent time
		Organic deposits	9	Plant and animal matter accumulating in wetlands
		Older alluvium	10b	Sediment deposited by rivers in modern valleys during glacier melt
	Pleistocene			Time of advance and retreat of the great ice sheets (~2 million - 10 000 years BP)
		Peel/Schomberg pond deposits	7,8	Two of a series of lake beds deposited as melting ice blocked drainage (~180 m a.s.l.)
		Lake Iroquois/ Algonquin deposits	7,8	Largest of postglacial lakes in Lake Ontario/Lake Huron basins
		Glaciofluvial deposits	6	Deposits of high-energy streams or currents issuing from a glacier (may form core of ORM)
		a. Wilfield/Kettleby Till[3,4]	4a	
		b Halton /Boucette Till[5]	4b	Clay, silt till; few stones; thick in Humber Valley, thins rapidly to the east; Karrow, 1959
		c. Oak Ridges Moraine	5	Thick fine sand, silt and gravel resting on eroded Newmarket Till; Chapman and Putnam, 1943
		d. Wentworth/Leaside[6] Till	3d	Sandy, stony till: may grade upward into Halton Till; Karrow, 1959; Leaside, Karrow, 1967
		e. Port Stanley/Tavistock Till	3e/4c	Port Stanley: Lake Ontario sandy stony till; Tavistock: Lake Huron silt till
	Unconformity[7]			Major erosional episode marked by channel cutting and scouring; produced by subglacial floods (cf Barnett et al., 1998)
		f. Newmarket /northern Till	3f	Sandy, stony till extending beneath the ORM; Gwyn and Dilabio, 1973; Sharpe et al, 1994
		g.Thorncliffe Formation / Clarke Beds	2g[8]	Sandy beds found at Scarborough Bluffs, Karrow, 1967; and at Bowmanville, Singer, 1974
		h. Seminary/Meadowcliffe/Bond head Tills	2h	Thin mixed sediment separating thick Thorncliffe sands at lake bluffs; Karrow, 1967
		i. Thorncliffe Formation/ Clarke Beds	2i	Beds are considered to be 30–50,000 years old (see above)
		j. Sunnybrook Till /Port Hope	2j	Clay till with very few stones; Karrow, 1967; Brookfield, 1982
		k. Scarborough Formation	2k	Cool-climate (-5°C) raised lake beds (122 m a.s.l.) may be ~90 000 years old; Karrow, 1967
		l. Don Formation	2l	Warm-climate (+3°C), raised lake beds with interglacial fossils; Karrow, 1967
		m. York Till	2m	Dense, sandy till from glacial interval prior to last major warm period; Karrow, 1967
		n. Lower sediment[9]	2n	Undifferentiated stratified sediment, mainly sand
		o. Lower sediment[9]	2o	Undifferentiated stratified sediment, mainly silt and clay
	Unconformity			Major interval of time and erosion
Paleozoic		Bedrock		Ancient marine sand, silt, and limey mud rocks formed ~450 million years ago
		a. Bedrock-drift complex		Map unit with thin 9 (<1 m) cover of glacial deposits on lime bedrock.
		b. Clastic (sandstone or shale)		Rocks made from grains of sediment cemented together; Georgian Bay/Queenston shale
		c. Carbonate		Limestone and dolostone rocks found respectively east and west of the Niagara Escarpment

[1] See Barnett et al., 1991 for stratigraphic scheme of southern Ontario
[2] Lithology of older sediment is described
[3] Wilfield occurs south of ORM; Kettleby occurs north of ORM
[4] Till is mixed sediment (sand, silt, clay, stone) deposited by glaciers; till, lower case, indicates local name
[5] Units in italics refer to names for strata found east of Oshawa; see Brookfield et al., 1982.
[6] May correlate with Newmarket Till; Wentworth may have been deposited from retreat phase of "Newmarket ice"
[7] Erosional episodes may be present between and within other units e.g. boulder pavements
[8] Unit 2 comprises lower sediment in block model (Fig. 3)
[9] Uncertain age designation

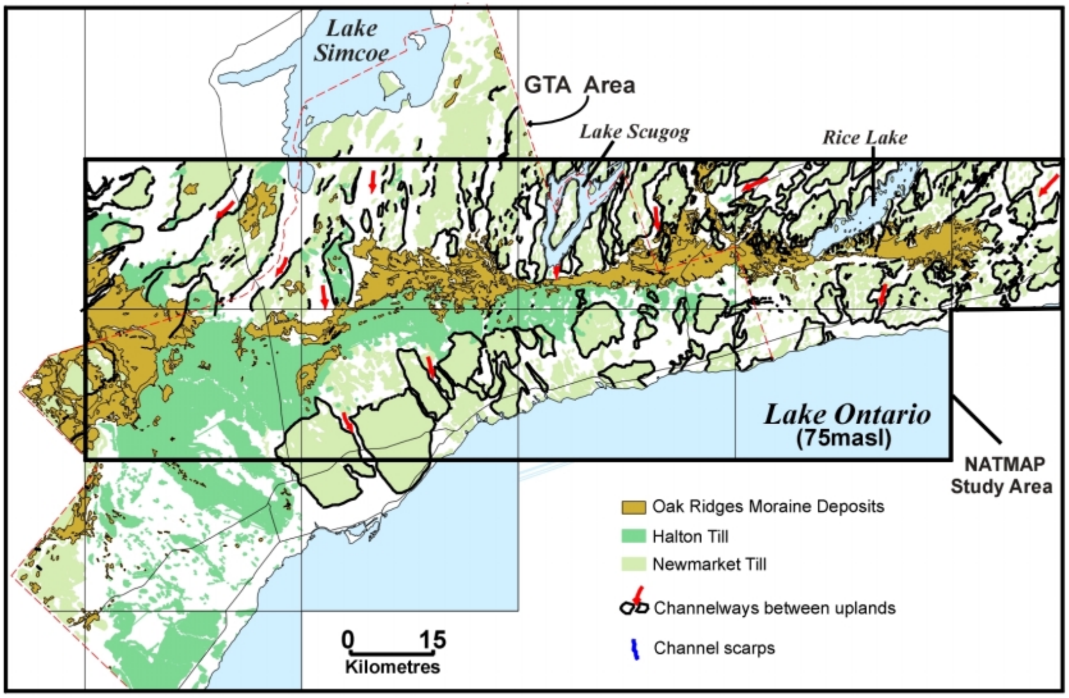

Figure 6. *Generalized terrain and geology map of the ORM-GTA emphasizing three regionally extensive units and channel network of the stratigraphic model, Figure 3. (See Figure 1 for context).*

Extent of Halton Till redefined

The extent of Halton sediments has been overestimated in recent correlations (e.g. M.M. Dillon, unpub. rept.,1994; Gerber and Howard, 1996) and is now redefined east of the Humber watershed (Fig. 6), on the basis of continuity, texture, and a well defined stratigraphy (Fig. 4). Halton forms a thin, narrow sequence that onlaps the Oak Ridges Moraine between Bolton and Oshawa (Fig. 1 and 4, inset). Halton sediments occur as patchy outliers as far south as Highway 401, but these small areas are not all shown on 1:50 000 scale maps (e.g. Sharpe and Barnett, 1997). Its distinct fine texture, low stone content, and interbedded relationship with lacustrine beds (Fig. 5a) contrasts markedly with the coarse-textured, stony, generally massive, amalgamated beds of Newmarket Till (Fig. 5c). This new regional mapping results in a more extensive surface exposure of Newmarket Till (e.g. Sharpe and Barnett 1997a). The restricted, thin, distribution of Halton sediment constrains the southern extent of the underlying ORM sediments (Fig. 4).

Glacial deposits (till)

Open File 3062 groups heterogeneous glacial sediment into two broad till classes, clayey and sandy, to simplify sediment types for applied users (Table 1). This simplification means that some tills are not in chronological order on the legend (Table 1) but their precise stratigraphic position is shown in Figures 3, 4, and Table 2. Not all tills are discussed here, but coarse Newmarket Till and fine-textured Halton Till (above) have been described in stratigraphic order.

MAP UNITS NOT HIGHLIGHTED ON THE REGIONAL GEOLOGICAL MODEL

Remaining map units on Open File 3062 are briefly discussed below, but for simplicity, they are not highlighted on the regional geological model (Fig. 2).

Glacial Lake Deposits

Glacial lake deposits are widespread in the GTA (Fig. 3). They form broad plains within channels and below raised lake shorelines (e.g. Glacial Lakes Algonquin and Iroquois, units 7 and 8, Table 1). These glacial lake sediments comprise sand and interbedded silt and minor clay in successions that are 3–20 m thick (Barnett, 1996a). In places, they contain interbedded diamictons, deposited during slump events. At surface, younger glaciolacustrine sediments can be difficult to distinguish from older, bedded sand and silt deposits (e.g. Thorncliffe and Scarborough sediments) where Newmarket and Halton till units are missing. Organic material within the lower deposits (e.g. Aravena and Wassenaar, 1993) is one characteristic that allows these sediments to be distinguished.

As the ice retreated eastward in the Lake Ontario basin, Glacial Lake Iroquois was impounded within the basin to a level of approximately 110–150 m a.s.l. across the area. At its margin, the lake eroded till uplands and longshore currents reworked these sediments into gravely beaches, baymouth bars, and spits (Table 1). Nearshore deposits are dominantly sand and gravel (unit 8). Offshore deposits occur in topographic lows and include massive to laminated silt and clay (unit 7). Lower, Post-Iroquois, lake levels (75–120 m a.s.l.) are locally recorded by sand spits and gravel beaches.

Postglacial deposits: slope, organic, eolian and river sediments

Recent deposits formed following deglaciation and lowering of post-glacial lakes. Slope and wind erosion was active, as was the accumulation of organic sediment and the work of modern rivers. However, the extent of organic and fluvial sediments in the area warranted their identification as separate map units (Table 1). Slope erosion produced deep gullying and landsliding from run-off, and from groundwater seepage (e.g. south of Claremont; Barnett, 1997a). Holocene organic deposits (unit 9) accumulated in poorly drained basins, kettles, wetlands and groundwater discharge hollows, particularly in the large valleys north of the ORM (e.g. Pefferlaw creek). Rivers discharged water to lowering lake levels, dissected the glacial landscape, and deposited sediment on their floodplains. As the lake level fell further, these rivers incised deeper, leaving raised terraces (unit 10b) and creating new floodplains (unit 10a). While much of the area is covered with a thin veneer of wind-blown silt and sand, nearshore sands were locally reworked into sand dunes when the area was deforested for a short time, for example, northeast of Vandorf (Barnett and Dodge, 1996). Other recent deposits (unit 11) include the Lake Ontario beach, baymouth bars and spits, in addition to fill.

HYDROGEOLOGICAL CONSIDERATIONS

The new geological mapping and the related three-dimensional reconstructions (Fig. 3) have important applications to hydrogeology (e.g. Sharpe et al., 1996). Three aspects are briefly highlighted: 1) regional stratigraphic models; 2) sediment variation within major hydrostratigraphic elements, and 3) the application of sediment mapping to regional water-budget estimates.

Prior to this work there were no comprehensive geological models in the ORM-GTA area applicable to define the regional hydrostratigraphic setting (e.g. M.M. Dillon, unpub. rept., 1994). The new systematic mapping allows hydrogeological units to be put in a regional geological context (Fig. 3, 4). For example, at least four sedimentary strata form potential aquifer targets and at least two regionally significant aquitards (Sharpe et al., 1996; Howard and Gerber, 1996) are mapped.

Major hydrostratigraphic units in the area are treated as homogeneous elements (e.g. Howard et al., 1997). The ORM is a major aquifer and recharge complex (Turner, 1977) that was traditionally considered to be a uniform hydrogeological unit. Now that its architectural (e.g. Pugin et al., in press) and sedimentological variation (e.g. Paterson and Cheel, 1997; Russell et al., 1998b; Barnett et al., 1998) has been mapped in detail, it will permit improved hydrolgeological understanding and modelling. The Newmarket Till forms a thick regional aquitard apparently possessing low, predictable, regional permeability. However, enhanced secondary permeability (Gerber and Howard, 1996) or major permeability contrasts from channel erosion (e.g. Desbarats et al., 1998) indicate significant inhomogeneities in this hydrostratigraphic map unit.

Systematic sediment mapping across the GTA may allow for infiltration estimates to be made in a more consistent manner in support of regional water-budget calculations. For example, variations in mapped sediment (soil type) and topography have a dramatic impact on estimated rates of percolation (recharge) to groundwater needed for water budget assessment (e.g. Hunter and Associates, unpub. rept., 1996). Further, the combination of digital sediment maps (Russell et al., in press), topography (Kenny, 1997) and land cover (Kenny et al., 1999) could greatly improve regional water budget calculations across the GTA.

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REFERENCES

Aravena, R., and Wassenaar, L.I.
1993: Dissolved organic carbon and methane in a regional confined aquifer, southern Ontario, Canada: carbon isotope evidence for associated subsurface sources; Applied Geochemistry, v. 8, p. 483–493.
Barnett, P.J.
1990: Tunnel valleys: evidence of catastrophic release of meltwater, central-southern Ontario, Canada; *in* Abstracts with Programs, Northeast Section, 25th Annual Meeting, Geological Society of America, Syracuse, New York, 3 p.
1995: Geology of the Oak Ridges Moraine area, parts of Peterborough and Victoria counties and Durham and York regional municipalities, Ontario; *in* Summary of Fieldwork and Other Activities 1995; Ontario Geological Survey, Miscellaneous Paper 164, p. 177–182.
1996a: Quaternary Geology, Claremont area; Ontario Geological Survey, Map 2634, scale 1:20 000.
1996b: Quaternary Geology, Enniskillen area; Ontario Geological Survey, Map 2636, scale 1:20 000.
1996c: Quaternary Geology, Kendal area; Ontario Geological Survey, Map 2637, scale 1:20 000.
1996d: Quaternary Geology, Bethany area; Ontario Geological Survey, Map 2638, scale 1:20 000.
1996e: Quaternary Geology, Brunswick area; Ontario Geological Survey, Map 2639, scale 1:20 000.
1997a: Piping: an important process in the postglacial landscape development of southern Ontario; *in* Program with Abstracts, Geological Association of Canada–Mineralogical Association of Canada Annual Meeting, Ottawa, Ontario, p. A8.
1997b: Surficial geology of the Scugog area, southern Ontario; Geological Survey of Canada, Open File 3330, scale 1:50 000.
Barnett, P.J. and Dodge, J.E.P.
1996: Quaternary Geology, Uxbridge area; Ontario Geological Survey, Map 2633, scale 1:20 000.
Barnett, P.J. and Gwyn, Q.H.
1997: Surficial geology of the Newmarket area, NTS 31 D/3, southern Ontario; Geological Survey of Canada, Open File 3329, scale 1:50 000.
Barnett, P.J. and Henderson, L.A.
1996: Quaternary geology, Port Perry area; Ontario Geological Survey, Map 2635, scale 1:20 000.
Barnett, P.J. and McCrae, M.K.
1996a: Quaternary Geology, Mount Albert area; Ontario Geological Survey, Map 2631, scale 1:20 000.
1996b: Quaternary Geology, Stouffville area; Ontario Geological Survey, Map 2632, scale 1:20 000.
Barnett, P.J. and Mate, D.J.
1998: Quaternary geology of the Beaverton area; Ontario Geological Survey, Map 2560, scale 1:50 000.
Barnett, P.J., Dodge, J.E.P., and Henderson, L.A.
1996: Quaternary Geology, Scugog area; Ontario Geological Survey, Map 2644, scale 1:50 000.
Barnett, P.J., Henry, A.P., and Cowan, W.R
1991: Quaternary geology of Ontario, southern sheet; Ontario Geological Survey, Map 2556, scale 1:1 000 000.
Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Gorrell, G., Pullan, S.E., Brennand, T.A., and Kenny, F.M.
1998: On the origin of the Oak Ridges Moraine, Canadian Journal of Earth Sciences, v. 35, p. 1152–1167.
Boyce, J.J., Eyles, N., and Pugin, A.
1995: Seismic reflection, borehole and outcrop geometry of Late Wisconsin tills at a proposed landfill near Toronto; Canadian Journal of Earth Sciences, v. 32, p.1331–1349.
Brennand, T.A.
1997a: Surficial geology of the Oshawa area, southern Ontario; Geological Survey of Canada, Open File 3331, scale 1:50 000.
1997b: Surficial geology of the Port Hope area, southern Ontario; Geological Survey of Canada, Open File 3298, scale 1:50 000.
Brennand, T., and Shaw, J.
1994: Tunnel channels and associated landforms: their implication for ice sheet hydrology; Canadian Journal of Earth Sciences, v. 31, p. 502–522.
Brennand, T.A., Moore, A., Logan, C., Kenny, F., Russell, H.A.J., Sharpe, D.R., and Barnett, P.J.
1997: Bedrock topography of the Greater Toronto and Oak Ridges Moraine NATMAP areas, southern Ontario; Geological Survey of Canada, Open File 3419, scale 1:200 000.

Brookfield, M.E., Gwyn, Q.H.J., and Martini, I.P.
1982: Quaternary sequences along the north shore of Lake Ontario: Oshawa–Port Hope; Canadian Journal of Earth Sciences, v. 19, p. 1836–1850.
Chapman L.J.
1985: On the origin of the Oak Ridges Moraine, southern Ontario; Canadian Journal of Earth Sciences, v. 22, p. 300–303.
Chapman, L.J., and Putnam, D.F.
1943: The moraines of southern Ontario; Transactions of the Royal Society of Canada, v. 37, p. 33–41.
1984: The physiography of southern Ontario; Ontario Geological Survey, Special Volume 2, 270 p. (third edition).
Clague, J.J., Turner, R.J.W., and Groulx, B.J.
1997: Reinventing the geological map — making geoscience more accessible to Canadians; Geoscience Canada, v. 24, no. 4, p. 161-172.
Coleman, A.P.
1913: Geology of the Toronto region; *in* The Natural History of the Toronto Region, Ontario, Canada; Canadian Institute, Toronto, p. 51–81.
1932: The Pleistocene of the Toronto region; Ontario Department of Mines, Annual Report XLI, pt. 7, map 42g, scale 1:63 360.
Desbarats, A.J., Hinton, M.J., Logan, C., Russell, H., and Sharpe, D.
1998: Geostatistical modeling of leakance in the Newmarket till aquitard; *in* Abstracts with Program, Geological Society of America, Annual Meeting 1998, Toronto, Ontario, p. A402.
Duckworth, P.B.
1979: The late depositional history of the western end of the Oak Ridges Moraine, southern Ontario. Canadian Journal of Earth Sciences, v. 16, p.1094–1107.
Eyles C.H. and Eyles, N.
1983: Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada; Geology, v. 11, p. 146–152.
Eyles, N., Boyce, J.I., and Mohajer, A.A.
1993: The bedrock surface of the western Lake Ontario region: evidence of reactivated basement structures?; Géographie physique et Quaternaire, v. 47, p. 269–283.
Eyles, N., Clark, B.M., Kaye, B.G. Howard, K.W.F., and Eyles, C.H.
1985: The application of basin analysis techniques to glaciated terrains: an example from the Lake Ontario basin, Canada; Geoscience Canada, v. 12, p. 22–32.
Fligg, K., and Rodrigues, B.
1983: Geophysical well log correlations between Barrie and the Oak Ridges Moraine; Water Resources Branch, Ontario Ministry of the Environment, Map 2273.
Funk, G.
1979: Geology and water resources of the East and Middle Oakville Creeks IHD representative drainage basin; Ontario Ministry of Environment, Water Resources Report 12, 68 p.
Gadd, N.R.
1950: Groundwater resources of Uxbridge Township, Ontario County; Geological Survey of Canada, Water Supply Paper 307, 25 p.
Gerber, R.E. and Howard, K.W.F.
1996: Evidence for recent groundwater flow through Late Wisconsinan till near Toronto, Ontario; Canadian Geotechnical Journal, v. 33, p. 538–555.
Gilbert, R.
1997: Glaciaolacustrine environment of part of the Oak Ridges Moraine, southern Ontario; Géographie physique et Quaternaire, v. 51, p. 55–66.
Gorrell, G.
1997: Surficial Geology of the Trenton area west half), southern Ontario; Geological Survey of Canada, Open File 3333, scale 1;50 000.
Gorrell, G. and Brennand, T.A.
1997: Surficial geology of the Rice Lake area, southern Ontario; Geological Survey of Canada, Open File 3332, scale 1:50 000.
Gwyn, Q.H.J. and Cowan, W.R.
1978: The origin of the Oak Ridges and Orangeville Moraines of southern Ontario; Canadian Geographer, v. XXII, no. 4, p. 345–351.
Gwyn, Q.H.J. and DiLabio, R.N.W.
1973: Quaternary geology of the Newmarket area; southern Ontario; Ontario Division of Mines, Preliminary Map P836, scale 1:50 000.
Howard, K.W.F., Eyles, N., Smart, P., Boyce, J., Gerber, R., Salvatori, S.L., and Doughty, M.
1997: The Oak Ridges Moraine of southern Ontario: a ground-water resource at risk; *in* Environmental Geology of Urban Areas, (ed.) N. Eyles; Geological Association of Canada, p.153–172.
Hunter, J.A., Pullan, S.E., Burns, R.A., Good, R.L., Harris, J.B., Pugin, A., Skvortsov, A., Goriainov, N.N.
1998: Downhole seismic logging for high resolution reflection surveying in unconsolidated overburden. Geophysics, v. 63, p. 1371–1384.
Karrow, P.F.
1959: Pleistocene geology of the Hamilton area; Ontario Department of Mines, Geological Circular no. 8.
1967: Pleistocene geology of the Scarborough area; Ontario Department of Mines, Maps 2076, 2077, scale 1:50 000.
1987: Quaternary geology of the Hamilton–Cambridge area, southern Ontario, Ontario Geological Survey, Report 25, 94 p.
1990: Interglacial beds at Toronto, Ontario; Géographie physique et Quaternaire, v. 44, p. 289–297.

Kelly R.I. and Martini, I.P.
1986: Pleistocene glacio-lacustrine deltaic deposits of the Scarborough Formation, Ontario, Canada; Sedimentary Geology, v. 47, p. 27–52.
Kenny, F.M.
1997: A chromostereo enhanced digital elevation model of the Oak Ridges Moraine area; southern Ontario; Geological Survey of Canada and Ontario Ministry of Natural Resources, Geologoical Survey of Canada, Open File 3423, scale 1:200 000.
Kenny, F.M., Paquette, J., Russell, H.A.J., Moore, A.M., and Hinton, M.J.
1999: A digital elevation model for the Greater Toronto Area, southern Ontario and Lake Ontario bathymetry; Geological Survey of Canada, Open File D3678, 1 CD-ROM.
Lewis, C.F.M., Mayer, L.A., Cameron, G.D.M., and Todd, B.J.
1998: Drumlins in Lake Ontario; *in* Glaciated Continental Margins: an Atlas of Acoustic Images, (ed.) T.A. Davies, T. Bell, A.K. Cooper, H. Josenhans, L. Ployak, A. Sonheim, M.S. Stoker, and J.A. Stravers; Geological Survey of Canada, Contribution Series, 1996170.
ORM Technical Working Committee
1994: Oak Ridges Moraine: a strategy for the Greater Toronto Area: An ecological approach to the protection and management of the Oak Ridges Moraine, Ontario Ministry of Natural Resources, 106 p.
Ostry, R.C.
1979: The hydrogeology of the IFYGL Forty Mile and Oakville Creeks study area; Ontario Ministry of the Environment, Water Resources Report 5b, 44 p.
Paterson, J.T. and Cheel, R.J.
1997: The depositional history of the Bloomington Complex, an ice-contact deposit in the Oak Ridges Moraine, southern Ontario, Canada; Quaternary Science Reviews, v. 16, p. 705–719.
Pugin, A., Pullan, S.E., and Sharpe, D.R.
1996: Observations of tunnel channels in glacial sediments with shallow land-based seismic reflection; Annals of Glaciology, v. 22: p. 176–180.
Pugin, A., Pullan, S.E., and Sharpe, D.R.
in press: Seismic facies of the Oak Ridges Moraine area, southern Ontario, Canadian Journal of Earth Sciences.
Pullan, S.E., Pugin, A., Dyke, L.D., Hunter, J.A., Pilon, J.A., Todd, B.J., Allen, V.S., and Barnett, P.J.
1994: Shallow geophysics in a hydrogeological investigation of the Oak Ridges Moraine, Ontario; *in* Proceedings, Symposium on the Application of Geophysics to Engineering and Environmental Problems; (ed.) R.S. Bell and C.M Lepper,Boston, Massachusetts, v. 1, p. 143–161.
Russell, H.A.J. and Arnott, R.W.C.
1997: Halton Complex, Humber watershed; *in* Where is the Water? Regional Geological/ Hydrogeological Framework, Oak Ridges Moraine Area, southern Ontario, (ed.) D.R. Sharpe and P.J. Barnett; Geological Association of Canada-Mineralogical Association of Canada, Joint Annual Meeting, Field Trip A1 Guidebook, p 18–22.
1998: Jokulhlaup deposits in subaqueous fans: examples from the western Oak Ridges Moraine; Geological Society of America Annual Meeting, Toronto, Ontario, October 26–29.
Russell, H.A.J. and Dumas, S.
1997: Surficial geology of the Alliston area, NTS 31 D/4, southern Ontario; Geological Survey of Canada, Open File 3334, scale 1:50 000.
Russell, H. A. J. and White, O. L.
1997: Surficial geology of the Bolton area, NTS 30 M/13, southern Ontario; Geological Survey of Canada, Open File 3299, scale 1:50 000.
Russell, H.A.J., Logan, C., Brennand, T.A., Hinton, M., and Sharpe, D.R.
1996: A regional geoscience database: an example from the Oak Ridges Moraine NATMAP / Hydrogeology Project; *in* Current Research 1996-E; Geological Survey of Canada, p. 191–200.
Russell, H.A.J., Moore, A., Logan, C., Kenny, F., Brennand, T.A., Sharpe, D.R., and Barnett, P.J.
1998a: Sediment thickness of the Greater Toronto and Oak Ridges Moraine NATMAP areas; southern Ontario; Geological Survey of Canada, Open File 2892, scale 1:200 000.
Russell, H.A.J., Sharpe, D.R., and Arnott, R.W.C.
1998b: Sedimentology of the Oak Ridges Moraine, Humber River watershed, southern Ontario: a preliminary report; *in* Current Research 1998-C; Geological Survey of Canada, p. 155–166.
Russell, H.A.J., Stacey, P., Sharpe, D.R., and Moore, A.
in press: Digital data compilation I: Oak Ridges Moraine Project; Geological Survey of Canada, Open File D3699, 1 CD-ROM.
Sanford, B.V. and Baer, A.J.
1981: Geological map of southern Ontario; Geological Survey of Canada, southern Ontario sheet 30 S, 1335A, scale 1:1 000 000.
Sharpe, D.R.
1980: Quaternary geology of Toronto and surrounding area; Ontario Geological Survey, Map P. 2204, scale 1:100 000.
1988: The internal structure of glacial landforms: an example from the Halton till plain, Scarborough Bluffs, Ontario; Boreas, v. 17, p. 15–26.
Sharpe, D. and Barnett, P.J.
1997: Surficial geology of the Markham area, NTS 30 M/14, southern Ontario; Geological Survey of Canada, Open File 3300, scale 1:50 000.

Sharpe, D.R., Barnett, P.J., Brennand, T.A., Finley, D., Gorrell, G., and Russell, H.A.J. and Stacey, P.
1997a: Surficial geology of the Greater Toronto and Oak Ridges Moraine areas, compilation map sheet; Geological Survey of Canada, Open File 3062, scale 1:200 000.
1997b: Surficial geology of the Oak Ridges Moraine NATMAP area; Geological Survey of Canada, Open File 3456, scale 1:200 000.
Sharpe, D.R., Barnett, P.J., Dyke, L.D., Howard, K.W.F., Hunter, G.T., Gerber, R.E., Paterson, J., and Pullan, S.E.
1994: Quaternary geology and hydrogeology of the Oak Ridges Moraine area. Geological Association of Canada-Mineralogical Association of Canada, Joint Annual Meeting, Field Trip A7: Guidebook
Sharpe, D.R., Dyke, L.D., Hinton, M.J., Pullan, S.E., Russell, H.A.J., Brennand, T.A., Barnett, P.J., and Pugin, A.
1996: Groundwater prospects in the Oak Ridges Moraine area, southern Ontario: application of regional geological models; *in* Current Research 1996-E; Geological Survey of Canada, p. 181–190.
Shaw, J. and Gorrell, G. A.
1991: Subglacially formed dunes with bimodal and graded gravel in the Trenton drumlin field, Ontario, Canada; Géographie physique et Quaternaire, v. 45, p. 21–34.
Shaw, J. and Sharpe, D.R.
1987: Drumlin formation by subglacial meltwater erosion; Canadian Journal of Earth Sciences, v. 24, p. 2316–2322.
Skinner, H. and Moore, A.
1997: A digital elevation model of the Oak Ridges Moraine, southern Ontario, Geological Survey of Canada, Open File 3297.
Sibul, U., Wang, K.T., and Vallery, D.
1977: Ground-water resources of the Duffins Creek–Rouge River drainage basins; Water Resources Report 8, Ministry of the Environment, Water Resources Branch, Toronto, Ontario.
Singer, S.
1974: A hydrological study along the north shore of Lake Ontario in the Bowmanville–Newcastle area; Ontario Ministry of Environment, Water Resources Report 5d, 72 p.
Spencer, J.W.
1881: Discovery of the preglacial outlet of the basin of Lake Erie into that of Lake Ontario, Canadian Naturalist (New series), v. 10, p. 65–79.
Taylor, F.B.
1913: The moraine systems of southwestern Ontario; Canadian Institute, Transactions, v. 10, p. 1–23; Toronto.
Turner, M.E.
1977: The Oak Ridges aquifer complex; Ontario Ministry of the Environment, Water Resources Branch, Hydrogeological Map 78-2, scale 1:100 000.
Watt, A.K.
1957: Pleistocene geology and groundwater resources of the Township of North York, York County; Ontario Department of Mines, Annual Report 1955, v. 64, pt. 7, 64 p.
1968: Pleistocene geology and groundwater resources of the Township of Etobicoke; Ontario Department of Mines, Geological Report 59, 50 p.
White, O.L.
1975: Quaternary Geology of the Bolton area; Ontario Geological Survey, Report 117, 119 p.