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Critical review
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Abstract: Halton Till, mapped south of Oak Ridges Moraine from Niagara Escarpment eastward to Pontypool, has traditionally been inferred to represent a climatically induced readvance of late-glacial ice from Lake Ontario basin that deposited sandy drumlinized till. Basin analysis techniques, seismic profiling, outcrop and core logging, and downhole geophysics, are integrated with detailed mapping to revamp the sedimentary and stratigraphic framework for Halton Till. Integration of glaciological process permits a reinterpretation of Halton Till depositional models.

Field and core data reveal Halton Till as a muddy, clast-poor diamicton with interbeds of graded sediment. It is transitional upward from Oak Ridges Moraine sand and gravel to units of graded sand, silt, and clay rhythmites, with interbeds of sand, gravel, and muddy diamicton. It may abruptly overlie stony, sandy Newmarket Till and cross-sections show that Halton Till sediment fills basin lows and thins across Oak Ridges Moraine sediment lobes.

Halton Till sedimentary architecture and facies are reinterpreted within an oscillating, ice-marginal, glaciolacustrine depositional model. The transitional lower contact with Oak Ridges Moraine sediment and upward-fining into Halton Till sediment records waning flow and deposition within lower-energy, ice-marginal, glaciolacustrine environments. Glaciolacustrine sedimentation is indicated by diminishing (mud-rich) grain sizes and gradational sediment style. Rhythmically laminated mud, diamicton interbeds, and intraclasts indicate ponded, ice-marginal debris flow and semibuoyant ice loading. Paleoflow data indicate westward transport of fine sand and mud from an eastern channellized, high-energy, sandy Oak Ridges Moraine depositional setting. The Halton Till depositional model may be applicable to other muddy diamicton units in the Great Lakes basin.

Résumé : Le Till de Halton, cartographié au sud de la Moraine d'Oak Ridges depuis l'escarpement du Niagara vers l'est jusqu'à Pontypool, était traditionnellement interprété comme le produit d'une réavancée de glace tardiglaciaire provenant du bassin du lac Ontario, causée par les conditions climatiques, qui aurait déposé du till sableux à surface modelée en drumlins. Les techniques d'analyse de bassin, le profilage sismique, la description visuelle de coupes naturelles et de carottes, ainsi que la géophysique en forage sont intégrés à une cartographie détaillée afin de réviser le cadre sédimentaire et stratigraphique du Till de Halton. L'intégration du processus glaciologique permet une réinterprétation des modèles de dépôt du Till de Halton.

Les données de terrain et les données de carottage permettent de décrire le Till de Halton comme un diamicton boueux, contenant peu de clastes, avec des interstrates de sédiments classés. Il présente un caractère transitoire assurant le passage du bas vers le haut des sables et graviers de la Moraine d'Oak Ridges à des unités de rythmites granoclassées de sable, de silt et d'argile, avec des interstrates de sable, de gravier et de diamicton boueux. Il peut parfois reposer abruptement sur les sédiments sableux et pierreux du Till de Newmarket et des coupes transversales montrent que les sédiments du Till de Halton remplissent les dépressions du bassin et s'amincissent sur les lobes de sédiments de la Moraine d'Oak Ridges.

L'architecture et les faciès sédimentaires du Till de Halton sont réinterprétés à la faveur d'un modèle de dépôt glaciolacustre en bordure d'une marge glaciaire oscillante. Le contact inférieur de transition avec les sédiments de la Moraine d'Oak Ridges et la granodécroissance ascendante au sein des sédiments du Till de Halton témoignent du ralentissement du courant et de la sédimentation dans des milieux glaciolacustres proglaciaires à plus faible énergie. La sédimentation glaciolacustre est indiquée par la granulométrie décroissante des débris dans les sédiments (riches en boue) et par le style progressif de la sédimentation. La boue à lamination rythmique, les interstrates de diamicton et les intraclastes indiquent un écoulement de débris proglaciaire dans un bassin fermé soumis à la charge d'une marge de glacier semi-flottante. Les données sur les paléoécoulements indiquent un transport vers l'ouest de sable fin et de boue provenant d'un milieu de dépôt à sédimentation sableuse, chenalisé et à haute énergie de la Moraine d'Oak Ridges, à l'est. Le modèle de dépôt du Till de Halton peut s'appliquer à d'autres unités de diamicton boueux dans le bassin des Grands Lacs.

INTRODUCTION

Southern Ontario has an extensive cover of surficial (tens of metres of glacial) sediment that mainly buries Paleozoic bedrock (Fig. 1). Surficial geological mapping of southern Ontario proceeded from landform mapping (Taylor, 1913; Chapman and Putnam, 1943) to mapping glacial lake shorelines and till sheets (Karrow, 1967). Most work was based on widespread field investigations involving shallow outcrop exposure and aerial photograph interpretation, which resulted in a regional glacial stratigraphy and geological history (e.g. Karrow, 1974). Reflecting geological thinking of the time, the sequence of geological events was interpreted using a climate-driven, ice-readvance model (e.g. Chapman and Putnam, 1943; Karrow, 1967). Thus, Halton Till strata are considered to represent late-glacial, ice-lobe readvances from adjacent lake basins (Fig. 1a). In the past 30 years, two developments require that the fluctuating ice-margin model be reassessed: first, emerging understanding of the complexity of glacial processes, and second, the role of meltwater processes in influencing ice-sheet dynamics (e.g. Gilbert, 1990; Shaw and Gilbert, 1990; Shoemaker, 1992, 1999; Sharpe et al., 2004; Wingham et al., 2006). In addition, increased study of stratified moraines (e.g. Barnett et al., 1998) and adjacent subsurface terrain (Pugin et al., 1999; Sharpe et al., 2002) developed new geological concepts and improved geological understanding of the region with implications on the depositional environment of Halton Till (e.g. Sharpe and Russell, 2007).

Within the traditional investigative framework, tills in southern Ontario have been mapped based on sediment texture (matrix grain size), clast content, and geographic context with moraines (e.g. Karrow, 1987). At a regional scale, till units have been assigned to gravel, sand-rich and muddy, stone-poor end members (Barnett et al., 1991). In the Greater Toronto Area and along the southern flank of the Oak Ridges Moraine two regional till units have been mapped, Newmarket Till and Halton Till (Sharpe et al., 1997, 1999). Some confusion surrounds the extent and stratigraphic relationship of these two units based on surface mapping techniques alone. For example, regional trends in texture in part due to limited stratigraphic control, make regional correlation difficult. In addition, lack of subsurface data has made it difficult to correlate isolated outcrop data.

The need for improved management of groundwater resources in the last approximate 25 years has led to increased hydrogeological investigations and provided key geological data sets with improved spatial and stratigraphic resolution. For example, extensive site studies (e.g. Interim Waste Authority, 1994a, b) and collection of tens of kilometres of core has provided improved, high-quality stratigraphic data. Also, the growth in digital data storage, analysis, and dissemination has provided access to a wealth of archival data for improved regional correlation. High-quality borehole data has also been enhanced by collection and integration of borehole geophysics and seismic-reflection profiles across the region (e.g. Pugin et al., 1999; Pullan et al., 2000). These large sets of subsurface geological data have been integrated into a regional, digital, 3-D geological framework of the area (e.g. Logan et al., 2005).

Under the climate-driven, ice-readvance model (e.g. Karrow, 1967), till units across southern Ontario have been interpreted to be deposited during episodes of ice-marginal fluctuation based on inferred deglacial landforms (Chapman and Putnam, 1984). Thus, Halton Till strata are considered to represent late-glacial, ice-lobe readvances from adjacent lake basins (Fig. 1a). This traditional model has been challenged by the reinterpretation of the origin of the Oak Ridges Moraine region (e.g. Barnett et al., 1998; Pugin et al., 1999; Russell et al., 2003a, b; Sharpe et al., 2004) that suggests regional-scale ice dynamic events and waning meltwater discharges may have significantly influenced the deglacial sequence in southern Ontario. Challenges to the existing climate-based, deglacial model and analysis of recently assembled data sets prompt a revised stratigraphic framework and sediment facies relationships for Halton Till and related sediment.

OBJECTIVE

Through integration of abundant surface and subsurface geological and geophysical data the objective is to present a revised stratigraphic framework and geological model for Halton Till sediments. The traditional conceptual model for Halton Till is tested against new field, laboratory, and archival data. The authors propose an improved genetic landform sediment model for Halton Till sediment based on sedimentary architecture and facies, and context is proposed that will improve understanding of its hydrogeological function.

REGIONAL GEOLOGICAL SETTING

Southern Ontario

A number of sandy and muddy till sheets have been mapped in the thick succession of glacial sediment across southern Ontario (Fig. 1), and they form the primary stratigraphic elements for geological reconstruction (Karrow, 1974; Barnett et al., 1991; Ontario Geological Survey, 2003). Mapping till regionally provides the basis for a simple stratigraphic succession to be assigned across southern Ontario based on six general units (Table 1): 1) sediments that predate regional till, 2) regional sandy till (e.g. Catfish Creek Till, Newmarket Till), 3) glaciofluvial sediment, 4) basin mud, muddy diamicton (e.g. Halton Till, St. Joseph Till), 5) glaciolacustrine deposits, and 6) alluvium and organic material. Till correlation, lithostratigraphy, and paleolake-level mapping provided the basis for regional deglacial reconstructions (Karrow, 1989). Approximately 18 till units have been mapped across southern Ontario (Barnett et al.,

1991) and about 12 of these are muddy diamicton units with low gravel content. Catfish Creek Till, the oldest till unit to be extensively exposed at surface, forms an important regional marker unit across most of southwestern Ontario (Karrow (1989); Barnett et al. (1991); Fig. 1a). Catfish Creek Till, a regional drumlinized, dense, stony, sandy silt diamicton, is overlain by stratified moraines (e.g. Oak Ridges Moraine, Waterloo Moraine, Paris Moraine), muddy and silty diamicton units, and glaciolacustrine deposits. Newmarket Till in the Greater Toronto Area (Fig. 2) is correlative to this regional, drumlinized, Late Wisconsinan till sheet, and has similar overlying stratigraphic units to the regional strata.

Greater Toronto Area stratigraphic framework

The classic Greater Toronto Area stratigraphic framework developed from the Scarborough Bluffs (sub-Newmarket Till, e.g. Scarborough and Thorncliffe formations) has

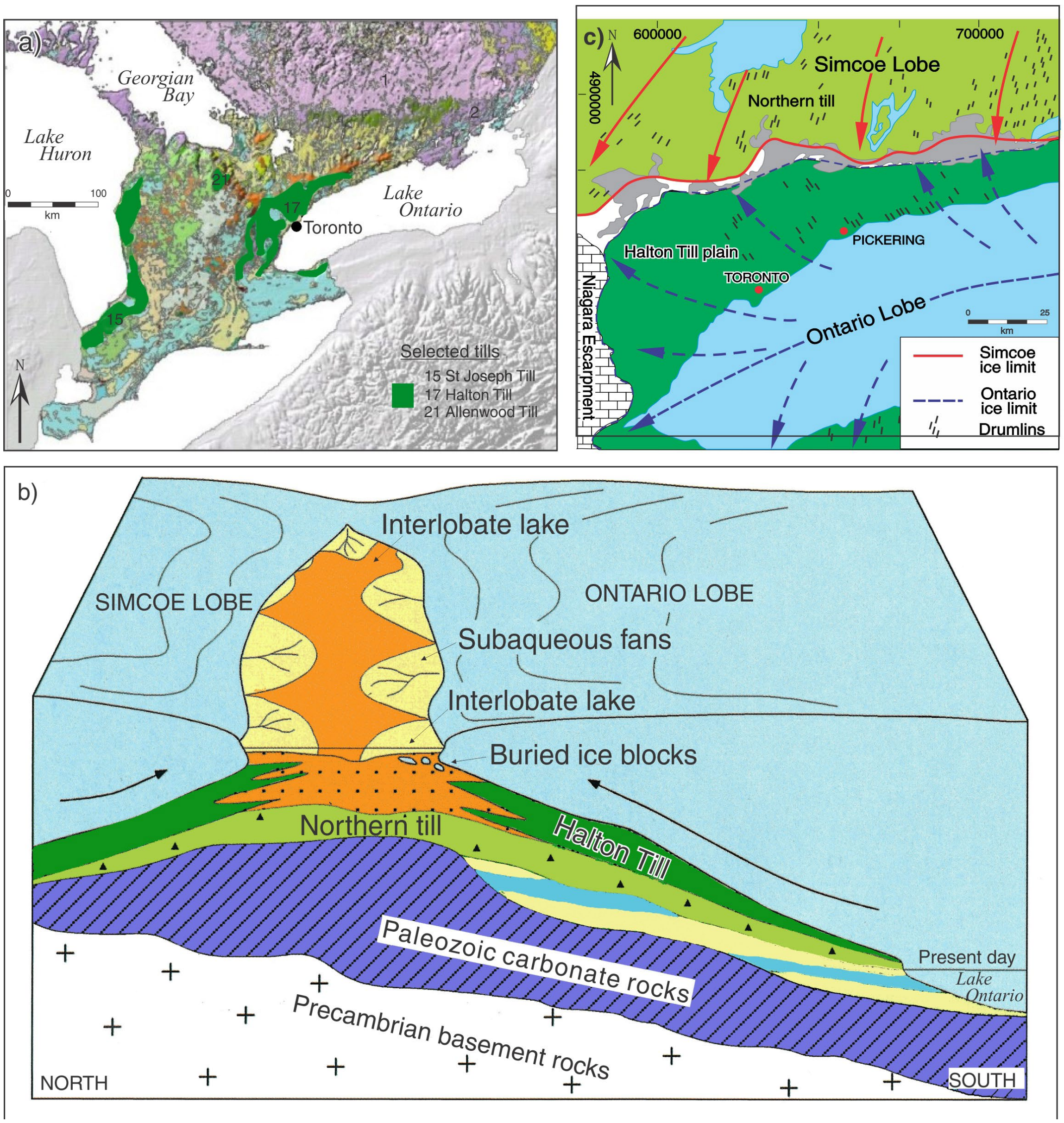

Figure 1. a) Location map and general geology of southern Ontario. Halton, St. Joseph, and Allenwood mud-rich diamictons (tills) and ice and/or lake marginal muddy strata rest on regional sandy tills (Catfish Creek, Elma, Newmarket; *after* Barnett et al. (1991)). Paleozoic bedrock (2) and Canadian Shield (1) have little glacial sediment. **b)** Traditional stratigraphic-depositional model of the Greater Toronto Area (*after* Eyles, 2002) **c)** Flow lines depict the traditional inferred readvance of Ontario lobe ice to deposit drumlinized Halton Till across the area south of Oak Ridges Moraine (*after* Boyce and Eyles, 2000).

been extended northward to near Alliston (Eyles et al., 1985) and has been confirmed by new subsurface data to predate Newmarket Till (Fig. 2a, b; Sharpe et al. (2003)). Newmarket Till has been mapped from Lake Ontario lake bluffs northward beneath the Oak Ridges Moraine to the Canadian Shield (Fig. 2c; Pugin et al. (1999)). Large valleys truncate Newmarket Till and underlying deposits north of the Oak Ridges Moraine and they have been identified in the subsurface beneath the moraine (Barnett, 1992, 1993; Sharpe et al., 1994, 1996, 1997, 1998, 1999; Boyce et al., 1995; Brennand, 1997; Barnett et al., 1998; Pugin et al., 1999; Brennand et al., 2006). The incised valleys retained glaciofluvial sediment following valley erosion (Brennand, 1994; Russell et al., 2003a, b) and in places are covered by Oak Ridges Moraine sediment (Russell et al., 2006). Younger Halton Till, and its equivalent north of the Oak Ridges Moraine, Kettleby Till, overlies the flanks of the Oak Ridges Moraine (Fig. 2a, c, d). Thin glaciolacustrine deposits are scattered across the area and a significant Lake Iroquois scarp truncates Halton Till west of Scarborough Bluffs. Alluvial deposits occur in incised modern valleys. This stratigraphy has been mapped regionally as four isopach maps: 1) sediment underlying Newmarket Till, 2) Newmarket Till, 3) Oak Ridges Moraine sediment, and 4) Halton Till (e.g. Russell et al., 2005; Sharpe and Russell, 2005; Sharpe et al., 2007). Thin, discontinuous units of glaciolacustrine sediment and alluvium were not mapped regionally.

DATA SOURCES AND METHODS

Data for this study have been compiled over a 15-year period for regional groundwater assessment. There are four distinct sources: archival, legacy geological mapping, sedimentological studies (mapping, drilling, outcrop), and geophysical studies (Fig. 2). All data were integrated into a regional stratigraphic database that was maintained in one of two formats, an MS Access relational database or a multi-file archive of GIS data (Logan et al., 2005). Archival data input to the stratigraphic database included approximately 75 000 Ontario Ministry of Environment (MOE) water-well records, and 1000s of Ontario Ministry of Transportation geotechnical data and Ontario Hydro geotechnical data. Higher quality hydrogeological data collected by Interim Waste Authority that included continuous-core data, along with coring completed by GSC and others provided important stratigraphic reference-site data (*see* Logan et al., 2002, 2006, 2008; Sharpe et al., 2003; Russell et al., 2005; Knight et al., 2008). Legacy geological mapping was integrated from Ontario Geological Survey with new 1:20 000- and 1:50 000-scale mapping in the area supported by approximately 1000–2500 ground-truth sites per map area (*see* Sharpe et al., 1998, 2006). In addition, more recent Highway 407 geotechnical data, along a 14.7 km long section from Markham to Whitevale (Fig. 3, M), contributed approximately 1200 borehole logs, 400 grain-size results, and thousands of penetration resistance tests (Ontario Ministry of Transportation, unpub. records, 1999; Golder and Associates, 1999).

Sedimentological analysis provided a common thread for new geological mapping, section descriptions, and core logging (Barnett, 1996; Sharpe et al., 1997; Sharpe and Russell, 2005). This work supported the production of new 1:50 000-scale digital geological mapping across the region (Fig. 3), based on aerial photographic and digital-elevation model interpretation (Sharpe et al., 1997). Geophysical data also were collected: seismic-reflection profiling along road corridors and downhole geophysics in cored boreholes (e.g. Pugin et al., 1999; Pullan et al., 2000).

UNRAVELLING HALTON TILL

Mapping tills in the Greater Toronto Area

Mapping till units and till stratigraphy evolved over many years in the Greater Toronto Area (Table 2). Work by multiple geologists with little regional perspective led to a proliferation of mapped till units with poor stratigraphic control. Uncertainty in particular was related to the distribution and stratigraphic position of Newmarket and Halton tills. A review of previous geological mapping reveals that agreement on the extent and nature of Halton Till has been confounded by unresolved stratigraphic relationships (Table 2; Sharpe et al. (1999)). Three central points of confusion are reviewed: early reliance on surface mapping; lack of 3-D data inland from Scarborough Bluffs; and faulty conceptual models that were not tested with new regional data.

First, clayey silt Halton Till mapped near Hamilton (Karrow, 1963) could not be reliably traced across the region and was incorrectly mapped eastward as a facies transition to sandy silt diamicton near Scarborough (e.g. Karrow, 1974) and Markham (J.A. Westgate, unpub. map, 1980) (Fig. 1c).

Table 1. Simple Quaternary stratigraphy of southern Ontario.

Unit	Age	Description	Lithology
(landform)			
6	Modern	Alluvium and/or organic material	Sand, silt, organic material
5	Late glacial	Basin sand (glaciolacustrine)	Sand, silt
4	Late glacial	Basin mud and/or till	Mud, mud diamicton (lake plain)
3	Late glacial	Glaciofluvial sediment	Sand and gravel
2	Late Wisconsinan	Regional till (e.g. Catfish Creek Till)	Stony, sand-silt till
1	Pre-Late Wisconsinan	Predates regional till sediment	Till, mud, sand-gravel (buried)

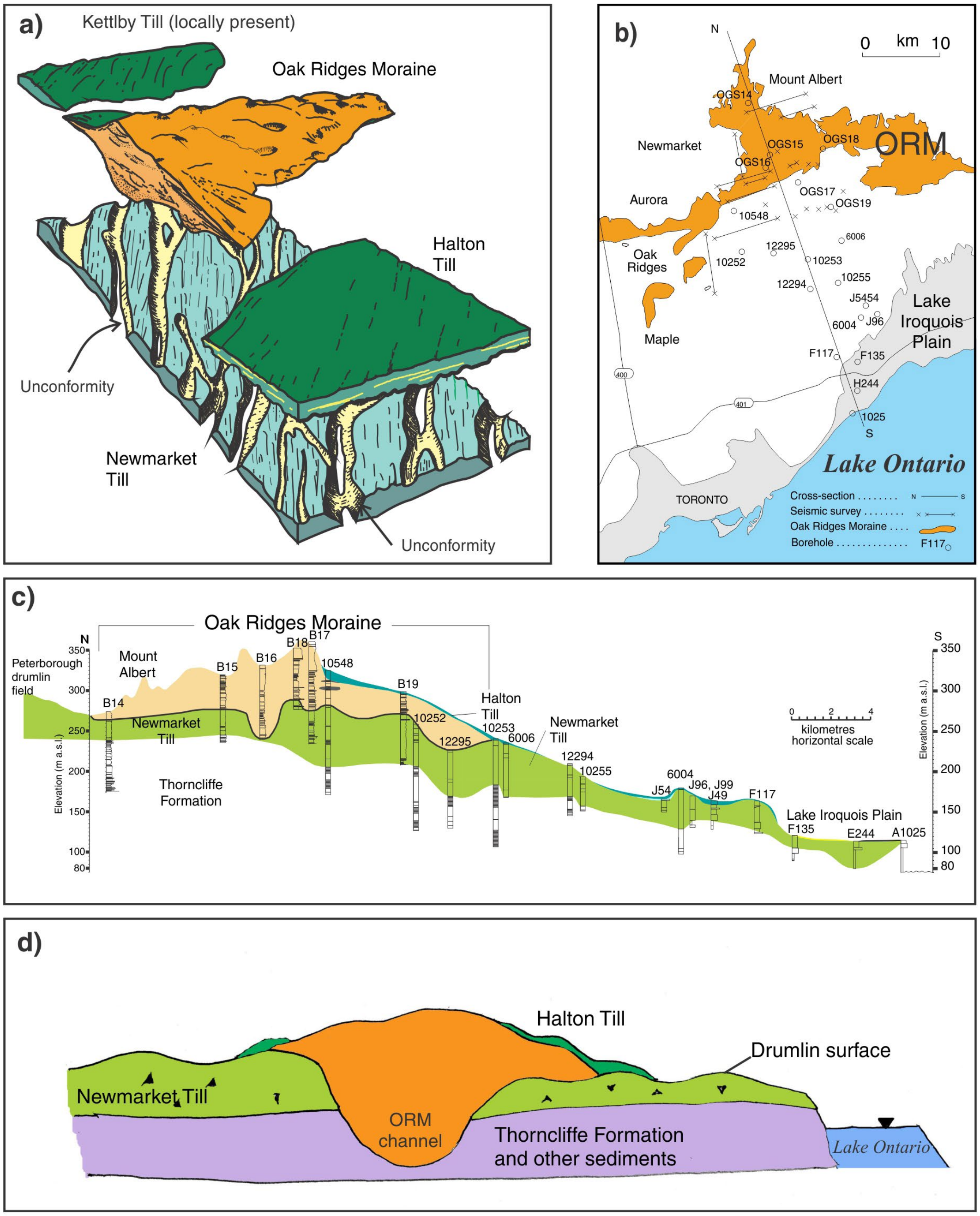

Figure 2. Stratigraphy in the Greater Toronto Area. **a)** Conceptual geological model: shows major strata, (Newmarket Till, channel (yellow) and Oak Ridges Moraine (ORM) sediments, and Halton Till) in the Greater Toronto Area, which rest on older strata (not shown), lower sediments and Paleozoic shale and carbonate. **b)** Location of section N-S. Section extends from north of Oak Ridges Moraine to Lake Ontario east of Scarborough Bluffs. **c)** North-south cross-section (Sharpe et al., 1994; *see also* Barnett et al., 1998) shows regional distribution of Newmarket Till from Lake Ontario bluffs north, beneath the Oak Ridges Moraine, to the drumlinized uplands of the Peterborough drumlin field. Halton Till occurs as thin sediments on the south flank of the Oak Ridges Moraine; thin glaciolacustrine sediments occur on Halton Till and the Newmarket Till plain to the south, above the glacial Lake Iroquois shoreline. Simplified cross-section is based on field mapping (e.g. Sharpe and Barnett, 1997), measured sections (e.g. Karrow, 1967), and deep boreholes (Sibul et al., 1977; P.J. Barnett, unpub. field notes, 1992) and borehole geophysics (Pullan et al., 2000). Older strata include pre-late Wisconsinan deposits such as Thorncliffe Formation and other sediments (Sharpe et al., 2005). **d)** Stylized, cross-section conceptual model for terrain adjacent to Lake Ontario. Halton Till overlies the Oak Ridges Moraine; drumlinized Newmarket Till provides a regional platform upon which channel, Oak Ridges Moraine, and Halton Till sediments rest (*see* Fig. 2c for data support; Barnett et al. (1998)). Note that channel sediments form the lower portion of the Oak Ridges Moraine stratigraphic package.

Second, it was not clearly recognized (Karrow, 1974; Boyce et al., 1995), that the upper till at the Lake Ontario bluffs (Fig. 1b) is not Halton Till (Sharpe et al., 1994). Third, the conceptual model that ice flowed out of Lake Ontario (Fig. 1b, c) to deposit drumlinized, stony, sandy silt till atop Scarborough Bluffs was shown to be faulty (Gwyn, 1976; Sharpe et al., 1994, 2004). For example, Karrow (1967) used a landform depositional model of fluting and drumlin formation to infer ice movement and deposition of youngest glacial Lake Ontario basin till (Fig. 1b, c), Leaside Till, renamed as Halton Till (Karrow (1974); Table 2). Boyce and Eyles (1991) also inferred that lake-bordering drumlins were formed of Halton Till sediment and the drumlins were younger than the Oak Ridges Moraine, a concept proposed by Gravenor (1957). Lithofacies and seismic mapping showed these drumlins to be Newmarket Till, older than Oak Ridges Moraine (Sharpe and Barnett, 1997; Pugin et al., 1999), as illustrated in a revised conceptual model (Fig. 2).

Mapping in the 1990s refined delineation of geological units based on improved subsurface information (Sharpe et al., 1998) and digital data. A regional digital elevation model (DEM) helped clarify landform-sediment relationships and provided a critical tool for stratigraphic correlation of till units (Logan et al., 2006). Elevation models helped in the visualization of terrain conditions such as the sweeping drumlin field orientation from Peterborough to Scarborough. Integration of DEM analysis with GIS data analysis and aerial photograph interpretation provided 3-D map relationships and models. This ability to integrate regional terrain data sets in a geomatics environment over a large area (about 12 000 km^2), and supported by a regional stratigraphic model, enabled resolution regarding the stratigraphic order and spatial correlation of Halton and Newmarket tills.

Newmarket Till

Of tills exposed at the land surface in the Greater Toronto Area, the stratigraphic lowest, Newmarket Till, a regional stony diamicton, was originally mapped north of the Oak

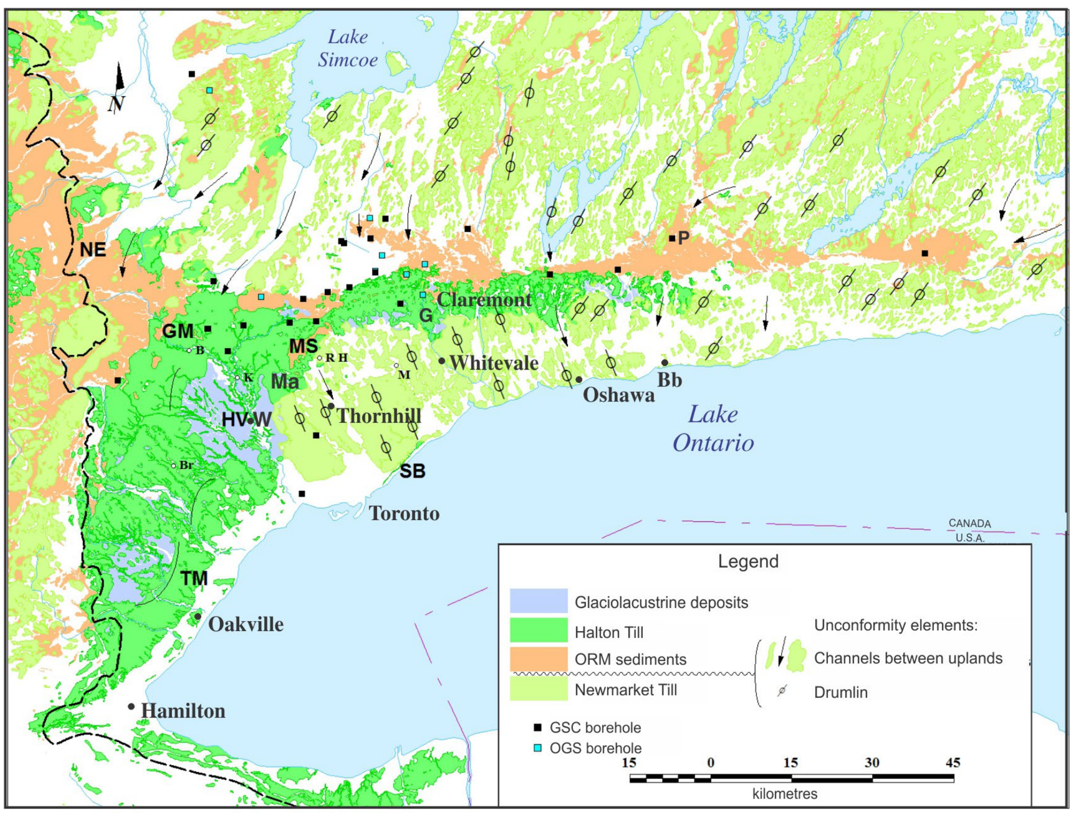

Figure 3. Terrain element geology of the Greater Toronto Area showing the distribution of Halton Till and its relationship with (older) Newmarket Till and Oak Ridges Moraine (ORM) sediments. Notice location of cored borehole data support. Note also, northeast-southwest drumlin orientation north and south of Oak Ridges Moraine along its eastern flanks. These drumlins are part of the Peterborough drumlin field. Northwest-southeast–oriented forms, south of Oak Ridges Moraine, occur on the same till surface (Newmarket) east of the Humber River valley (HV). NE = Niagara Escarpment, GM = Gooseville Moraine, TM = Trafalgar Moraine, B = Bolton, Br = Brampton, G = Glasglow, K = Kleinburg, M = Markham, Ma = Maple, RH = Richmond Hill, SB = Scarborough Bluffs, Bb = Bowmanville bluffs, P = Pontypool, W = Woodbridge. Note that sections in Figure 9 are located at: a) 1 km east of RH, b) 5 km north RH, c) 3–5 km northwest of Maple.

Ridges Moraine (Gwyn and DiLabio, 1973). It was later mapped in the subsurface and south to the Lake Ontario shoreline (Gwyn, 1976; Sharpe and Barnett, 1997). It is commonly drumlinized, with a predominant north-northeast to south-southwest orientation (Boyce and Eyles, 1991; Sharpe et al., 1997). Newmarket drumlins extend from the Peterborough area north of the Oak Ridges Moraine, to west of Lake Simcoe and to the south side of the Oak Ridges Moraine, to the area of Bowmanville bluffs (Brookfield et al., 1982) (Fig. 3). From Scarborough Bluffs eastward, a similar landscape consists of low-relief, stony, sandy till in northwest-southeast–oriented flutings and drumlins (Fig. 3).

Newmarket Till, a dense, stony (about 5–15% gravel) sandy silt diamicton (Fig. 4a) up to 50 m thick, overlies regional beds of Thorncliffe Formation sand and silt (Fig. 2) and underlies Oak Ridges Moraine and Halton Till (Fig. 4b). Seismic data reveal a planar lower contact (Pullan et al., 1994; Boyce et al., 1995; Pugin et al., 1999) on Newmarket Till. It forms a continuous, diagnostic, high-velocity reflector (~2000 m/s) on seismic profiles and downhole-velocity logs (e.g. Hunter et al., 1998; Pullan et al., 2000). Consistent lithology and velocity characteristics make it an excellent regional marker across the area and beneath Oak Ridges Moraine (Sibul et al. (1977); Fig. 2, 3). This predominantly massive till locally consists of beds 3–5 m thick, separated in places by stone lines and rare 1–2 m thick sandy interbeds (Sharpe et al., 1999, 2002; *see* northern till of Boyce and Eyles (2000)).

Highway geotechnical data, along a 14 km section traversing the Markham-Whitevale drumlinized till plain reveal very thin, discontinuous Halton Till and continuous Newmarket Till (Fig. 3, M). These transect data confirm four consistent material properties of Newmarket Till in contrast with Halton Till: high density (N values, 50–100), stoniness (5–15% clast content), sandy (37%), silt diamicton, and low water content (about 10%; Table 3). Deeper borings (5–50 m), 2–3 km apart at road and river intersections,

Table 2. Tills of the Greater Toronto Area.

Name Type area (reference)	**Lithofacies**	**Reported association**	**Correlation**
Kettleby Bolton (White, 1975)	*Silt, clay, mud diamicton*	Mainly mud and mud-rich diamicton with less than 1% clasts. Inferred Halton Till equivalent north of the Oak Ridges Moraine	Halton
Halton[1] near Hamilton (Karrow, 1959)	*Silt, clay, mud, diamicton; local inter-bedded sand-silt diamicton (Fig. 5)*	Silty with less than 1% clasts; correlated with vaguely defined upper Leaside Till in Thornhill (Karrow, 1970,1974). Mapped north into Bolton area (White, 1975). Halton Till could not be mapped in Scarborough (Karrow, 1967) and most of Markham areas (J.A. Westgate, unpub. field notes and map,1980). This mapping gap left no designed main late-glacial till (~25 ka to 12 ka) in Greater Toronto Area (e.g. lower Leaside).	Halton
Wentworth near Hamilton (Karrow, 1959)	*Dense, stony sand-silt till*	From Hamilton to Brampton, Halton Till is difficult to distinguish from underlying Wentworth Till.	(?) Halton It may be (?) Newmarket
Leaside Upper and Lower Scarborough (Karrow, 1967)	*Dense, stony sand-silt till*	Thin (1–2 m), fine sandy-silt surface till was found to locally overlie thick (5–15 m), stony, sand till. Correlated with Halton Till (Interim Waste Authority, 1994a, b), or, Halton and northern tills (Boyce et al., 1995; Boyce and Eyles, 2000). Upper and lower Leaside till division could not be mapped consistently across the region. Most sections were left with no name for sandy till; Leaside name dropped (Karrow, 1974).	Newmarket
Humber till Humber River	*Dense, stony sand-silt till (Fig. 6b)*	At Brampton, Karrow (1991) correlated a dense, stony, sand till (Humber till), identified by Sharpe (1980a) below Halton Till.	Newmarket
Newmarket Till Newmarket (Gwyn and DiLabio, 1973)	*Dense, stony sand till (Fig. 4a)*	Sandy silt, stone-rich drumlinized till. Mapped north of Oak Ridges Moraine (Gwyn, 1976), southward beneath Oak Ridges Moraine (e.g. Bowmanville Till, east of Scarborough (Fig. 3)). North of Scarborough, former Leaside Till was traced (Fig. 2b) beneath Oak Ridges Moraine (Sharpe and Barnett, 1997) and correlated with Newmarket Till (Fig. 3; e.g. Sharpe et al. (1994)).	Newmarket
Bowmanville Till, Bowmanville (Brookfield et al., 1982)	*Dense, stony sand till*	Correlated to Newmarket Till and Catfish Creek Till (Sharpe et al., 1994; Boyce and Eyles, 2000), the main late-Wisconsinan Till recognized across southwestern Ontario (Barnett et al., 1991).	Newmarket
Older till	*Stony sand-silt till (Fig. 6a)*	Dense, sandy till resting on bedrock (west of Toronto) with no overlying sediment can be interpreted as any age. Figure 6a may be older stony till, with overlying Halton Till.	Any age but Halton

Note: The initial assignment of Halton Till (Karrow, 1967) to the latest ice movement out of Lake Ontario (Fig. 1c) meant that the main regional marker bed, and very distinct Late Wisconsinan till, Catfish Creek Till equivalent, was missing in the study area.
[1] Wildfield Till (White, 1975) is a near-surface equivalent of Halton Till that has been identified separately from Halton (White, 1975; Eyles et al., 2010) in the southwest portion of the Oak Ridges Moraine region.

provide stratigraphic context by showing Newmarket Till and deeper underlying strata, such as 5–10 m thick silty sand Thorncliffe Formation beds (*see* Fig. 9a, 11c).

Halton Till distribution

Halton Till was first described in Halton County north of Hamilton (Fig. 3), where it overlies red Queenston shale (Karrow, 1959). Typically the matrix is silt-rich (20–76% silt; Table 3; Fig. 5), interstratified with sand and silt, and, has a high shale content (Karrow, 1987). Halton Till can vary locally with sandy or clayey facies and commonly grades upward into interbedded lacustrine sediment (e.g. Sharpe, 1980). To the west, Halton Till occurs within minor ridges of the Waterdown moraines below the Niagara Escarpment (Fig. 3); westward across the Niagara Peninsula it is a stone-poor, clayey silt till (Fenestra, 1975). Halton Till has been traced across the region eastward from Hamilton using lithological

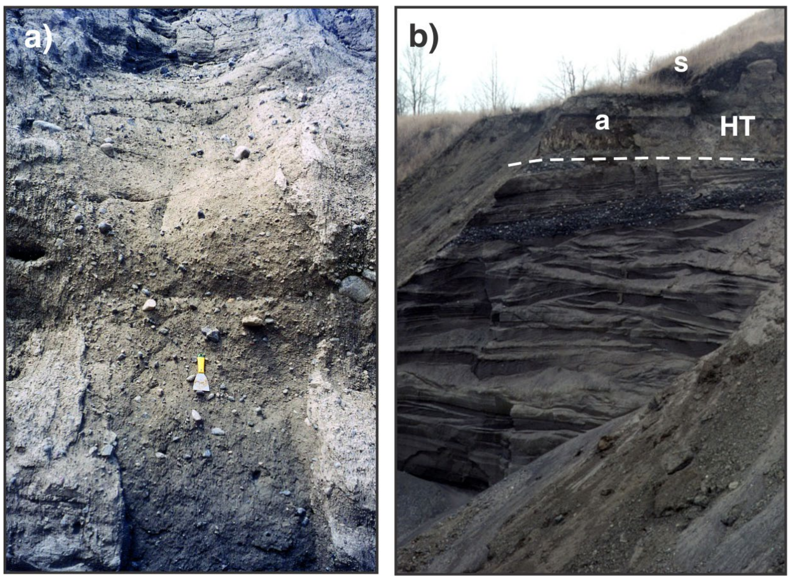

Figure 4. a) Newmarket Till: massive, stony sandy diamicton (trowel is about 10 cm); photograph by D. Sharpe; 2012-140A; **b)** Halton Till (HT) resting conformably on Oak Ridges Moraine crossbedded sand (dashed); S = spoil; a = soil (section is about 8 m high); photograph by D. Sharpe; 2012-140B

Table 3. Grain-size data for Halton Till.

Area	Author	Samples (N)	Sand	Silt	Clay	Gravel (estimated)	Comments
1. Hamilton	Karrow (1987)	39	20	49	31	nd	
2. Brampton	Karrow (1991)	40	25	53	22	1–3	
3. Bolton	White (1975)	98	30	50	20	nd	
4. Thornhill	Karrow (1970)	7	18	44	38	nd	
5. Carville	(Consultant)	11	18	44	38	nd	
6. Vaughan	Interim Waste Authority (1994a, b)	50	20	50	30	5	
7. Markham	Sharpe et al. (1994)	12	19	53	28	1–3	
8. Bolton-Oshawa (GSC, 1994)	Brennand (1997)	24	17	76	7	nd	Silt facies - Humber R.
9. Markham	Sibul et al. (1977)	9	34	45	21	nd	
10. Markham	J.A. Westgate (unpub. field notes and map, 1980)	43	40	44	16	nd	Unpublished data
11. Scarborough	Karrow (1967)	16	50	31	19	nd	Upper Leaside
Newmarket Till							
Highway 407 (Markham)		300	52	37	11	5–15	N = 50–100; W is less than 10%

Percentages should be assessed with • 3% because some of the early studies (<1987) used a 3.9 •m silt-clay boundary (Wentworth classification), whereas later ones used a 2 •m (USDA) boundary. nd = not determined observations from many hundreds of field sites (e.g. Karrow, 1987; Barnett, 1992; Sharpe et al., 1997). Sharpe (1980) and Karrow (1989) mapped Halton Till across the Brampton area as a widespread 1–10 m thick unit with consistent texture, low stone content and silty matrix (53% silt; Fig. 5). Here, Halton Till occurs north of Lake Iroquois shoreline from the Niagara Escarpment to the Humber River, as a 25 km wide band (Fig. 3; Sharpe et al. (1997)). From Humber River eastward it occurs as a narrow belt, a few kilometres wide, eastward along the south flank of the Oak Ridges Moraine to Pontypool (Fig. 3; Barnett (1996); Sharpe et al. (1997)). Near Richmond Hill, 1:5000-scale mapping refined the extent of Halton Till by several kilometres to the southeast along the Maple spur of the Oak Ridges Moraine (W. Morrison, pers. comm., 2000). In the Humber River watershed near Bolton, a subfacies of Halton Till, the Wildfield Till, has been mapped in the Gooseville Moraine (White, 1975) and in the Trafalgar Moraine (Eyles et al., 2010). Along the Oak Ridges Moraine crest, Halton Till occurs in hummocky terrain to elevations over 350 m a.s.l. (Fig. 5f). North of Oak Ridges Moraine, the unit forms scattered small bodies near Alliston and Newmarket where it is mapped as Kettleby Till (Fig. 2d).

Halton Till sediment facies

Halton Till is a complex assemblage of massive diamicton and interstratified sediment with laminated mud, sand, and gravel that is up to 40 m thick (Table 2). A suite of continuous cores (Fig. 3) across the region complement measured lake and river sections with Halton Till. Three main facies characterize Halton Till sediment: diamicton, laminated and/or banded silt-clay; sand and gravel facies that can be interbedded with the first two.

Diamicton facies

The most common facies occurs across the region as 1–5 m thick beds of clayey silt to fine sandy silt diamicton with low (1–2%) stone content (Fig. 5a, b). It may occur in beds up to 15 m thick within Humber River watershed near Woodbridge (Russell and Arnott, 1997). The massive to faintly laminated diamicton has minor intraclasts of 2–5 mm silt and clay and 5–10 cm sand. Less than 2% sparse gravel occurs coarser than granules (Golder and Associates, 1994). Pebbles are subrounded to subangular carbonate, siltstone, shale, and gneiss. The contact with lower facies is variably sharp, interbedded, or gradational. Diamicton facies become finer grained and more massive upward and there is less gravel and less interbedding upward (Fig. 6a). On downhole geophysical logs, Halton Till sediments have higher gamma and conductivity signatures and lower magnetic susceptibility than Oak Ridges Moraine sediments and Newmarket Till (Pullan et al., 2000).

Laminated facies

This facies comprises 1–3 m thick, fining-upward rhythmic sequences of silt to clay (Fig. 5e), with occasional beds of silt intraclasts. Clay beds are massive and commonly less than 5 mm thick, rarely exceeding 1 cm. Silt beds vary from 1 mm to 3 cm thick. Silt beds are sharp, based with minor sand at the contact. Rare dropstones are 2–3 cm in diameter and smaller.

Sand and gravel facies

Sand, and gravel with thin, interbeds diamicton and laminated silt, clay, are found in sequences 1–10 m thick (Fig. 5c, d, e). Interbedding occurs in transitional contact with underlying Oak Ridges Moraine sand, gravel, silt (Fig. 5c, d), or overlying laminated silt and fine sand beds (Fig. 5e). Sand and gravel facies occur as discontinuous horizons, 30 cm thick that are mainly fine ripple-drift crosslaminated sand, medium-scale, crossbedded, and planar-laminated pebbly coarse sand (Fig. 5g), and minor crossbedded pebble and cobble gravel. The lower contact forms an abrupt transition from diamicton (Fig. 5h). Rare trough structures eroded into underlying beds are filled with Halton Till diamicton or gravel with intraclasts of Halton Till diamicton. Paleoflow is variable, northwest to northeast. These facies are common along southern margins of Halton Till extent where its cover is variable and discontinuous (Russell et al., 2005).

Halton grain-size composition

Halton (Fig. 5a) and Newmarket (Fig. 4a) tills can be clearly distinguished based on over 900 grain-size results reporting clay-silt-sand and gravel for diamicton facies from across the region. Halton Till has a clayey-silt to silt grain size with low (1–2%) stone content, compared to the coarser, stony (5–10%), sandy-textured Newmarket Till (Fig. 7a; Table 3). Newmarket Till has consistent sandy matrix texture across the area (Fig. 7a). Near Markham and Scarborough, Halton Till was reported to have a sandy matrix (*see* Karrow (1967, 1970), Fig. 7b; Table 3), very similar to that of Newmarket Till. This makes distinction difficult as sandy Halton Till facies (Fig. 7b) may include Newmarket Till, or Newmarket Till may be laterally contiguous. Subsurface data show stony, sandy Newmarket Till in areas that can be traced north beneath Oak Ridges Moraine (Fig. 2b, 4). Much of this sandy textured till classified as Halton Till is now considered to be outliers of older Newmarket Till. Consequently, some Halton Till grain-size data were reclassified to exclude this older, misidentified sandy till (Table 3). Textural distinction between Halton and Newmarket tills is most clear when the approximately 4–9% gravel content differential is considered, not just matrix content (Table 3).

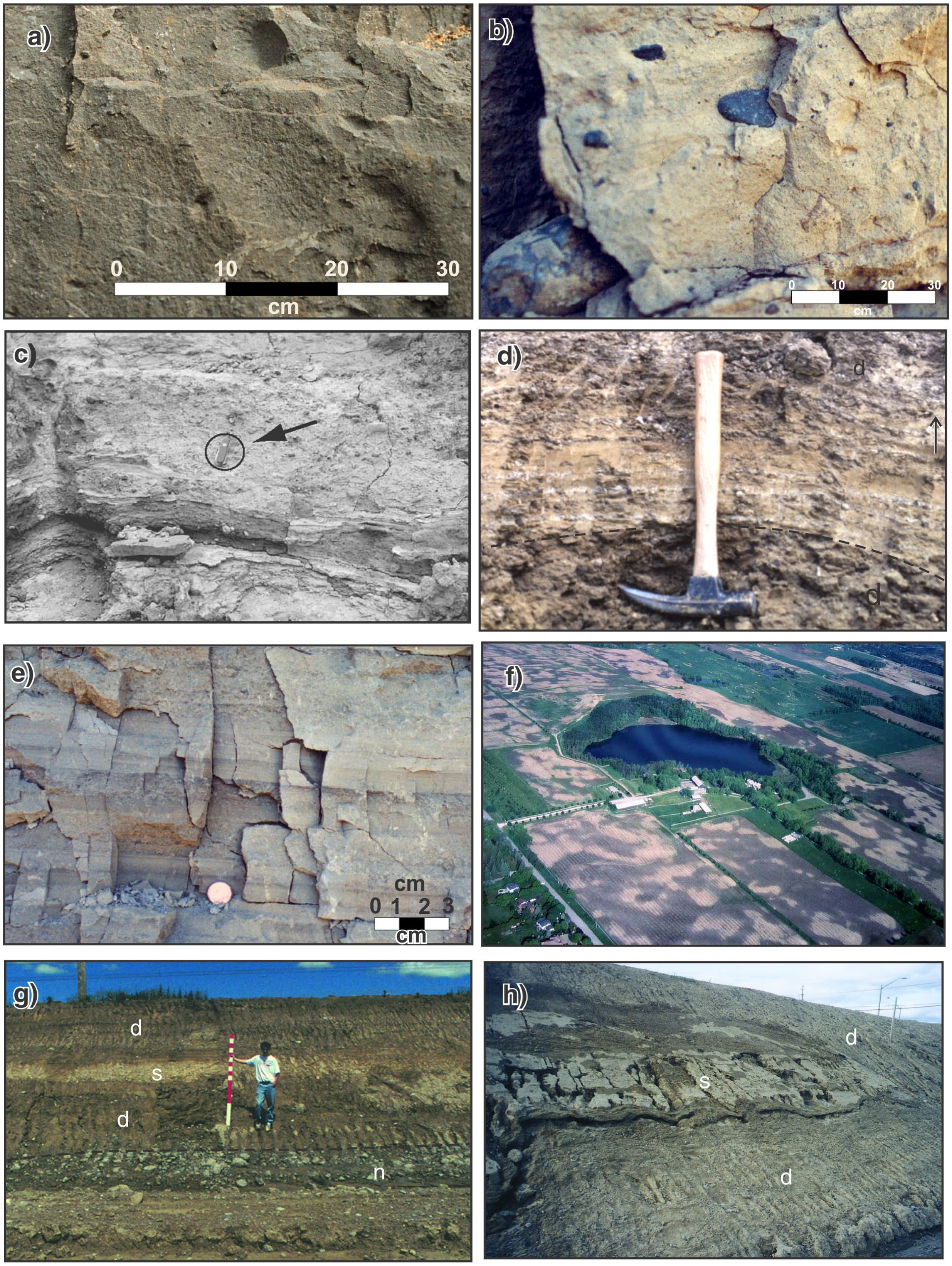

Figure 5. Photographs of Halton Till sediment facies: **a)** Halton Till lithofacies: massive, stone-poor, silty diamicton; photograph by H. Russell; 2012-141A; **b)** Halton Till lithofacies: massive, silt diamicton; 1–2% clasts; photograph by D. Sharpe; 2012-141B; **c)** Halton Till lithofacies: diamicton, interbedded silt, fine sand (knife, *see* arrow, is about 8 cm); photograph by D. Sharpe; 2012-141C; **d)** Halton Till lithofacies: laminated silt; transition to diamicton (d), hammer about 15 cm; photograph by D. Sharpe; 2012-141D; **e)** Halton Till sediment: banded silt and minor clay; photograph by H. Russell; 2012-141E; **f)** Halton Till; hummocky terrain with a kettle lake near Oak Ridges; lake is approximately 400 m wide; photograph by F. Johnson; 2012-141F; **g)** Halton Till (d) with interbedded sand (s) over stony Newmarket Till (n); photograph by D. Sharpe; 2012-141G; **h)** Halton Till (d) with large sand interbed (s); photograph by D. Sharpe; 2012-141H

Halton stratigraphic architecture

The stratigraphic architecture of Halton Till is observed in outcrop and in continuous core. In general, Halton Till occurs as a sediment drape on the flanks of the Oak Ridges Moraine and on Newmarket Till, and it thins over bedrock northwest from Lake Ontario (Fig. 2d, 3). Halton Till sediment is thickest west of Humber River valley (about 40 m; Fig. 8a), where a transect shows sediment cover and thickness diminishing eastward. Southward thinning of Halton Till (Fig. 8b) and presence of Newmarket Till at surface (Fig. 3) marks the subsurface limits of Oak Ridges Moraine sediment as it ‘pinches out’ in this setting. In the Humber River watershed, Halton Till commonly fills depressions in the basin and thins over adjacent highs (Fig. 9c). Halton Till stratigraphic architecture is mark by distinct contact relationships: sharp-based contact with underlying Newmarket Till (Fig. 9a), a gradational (interbedded) contact from basin mud units to

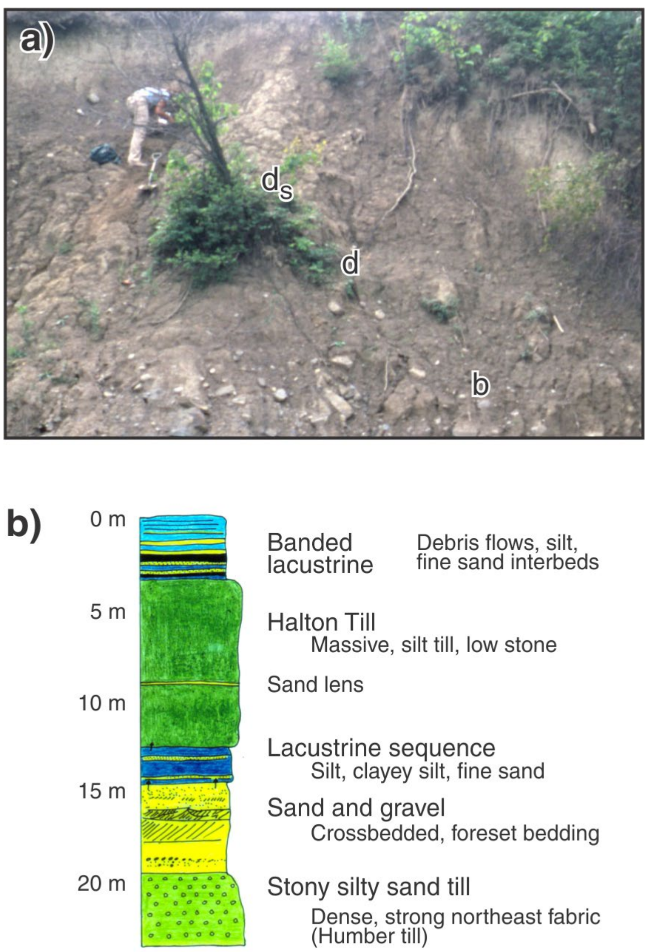

Figure 6. Measured section with Halton Till: **a)** Halton Till, silt diamicton (*see* person at top) is transitional from sandy, stony diamicton (ds), massive diamicton (d) resting on shale, carbonate bedrock (b); Etobicoke Creek, south Humber River valley; photograph by D. Sharpe; 2012–143; **b)** Measured section on Etobicoke Creek, south Humber River valley (Fig. 3) showing Halton Till and related sediments over dense, stony Humber till; this local till is correlated with Newmarket Till.

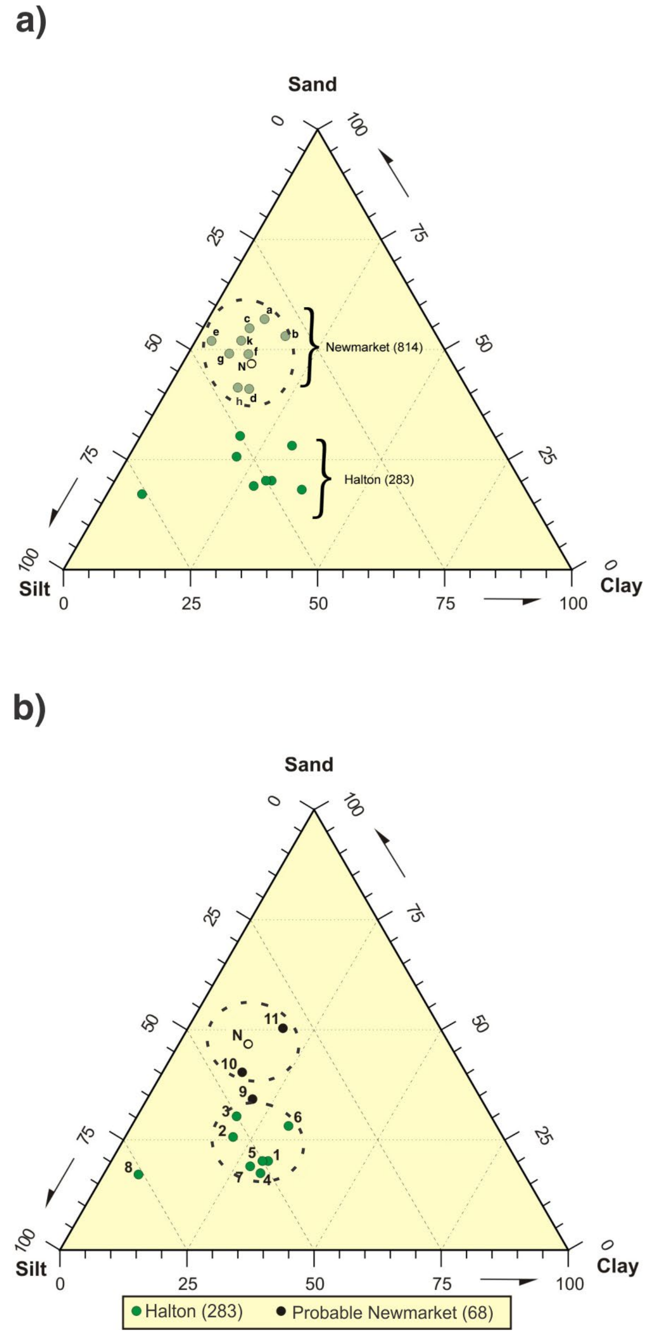

Figure 7. Comparative grain-size plot of Halton and Newmarket tills; **a)** matrix grain-size plots with stratigraphic correction and adjustment for gravel fraction; **b)** grain-size plot of Halton Till showing reclassified samples (black dots, numbers defined below). Note: The plot generalizes Halton (>275) and Newmarket (>700) till analyses. Note: a) Markham (10) (J.A. Westgate, unpub. map, 1980); b) Markham (9) (Sibul et al.,1977), c) Oshawa (Singer, 1974); d) Scarborough (11) (Karrow, 1967); e) Markham (7) (Sharpe et al., 1994); f) Brampton (2) (Karrow, 1991); g) Hamilton (1) (Karrow, 1989); h) Oshawa (8); in Figure 7b only: 6, Vaughan (Interim Waste Authority, 1994a, b); 5, Carville; 4, Thornhill (Karrow, 1970); 3, Bolton (White, 1975). N = average Newmarket Till.

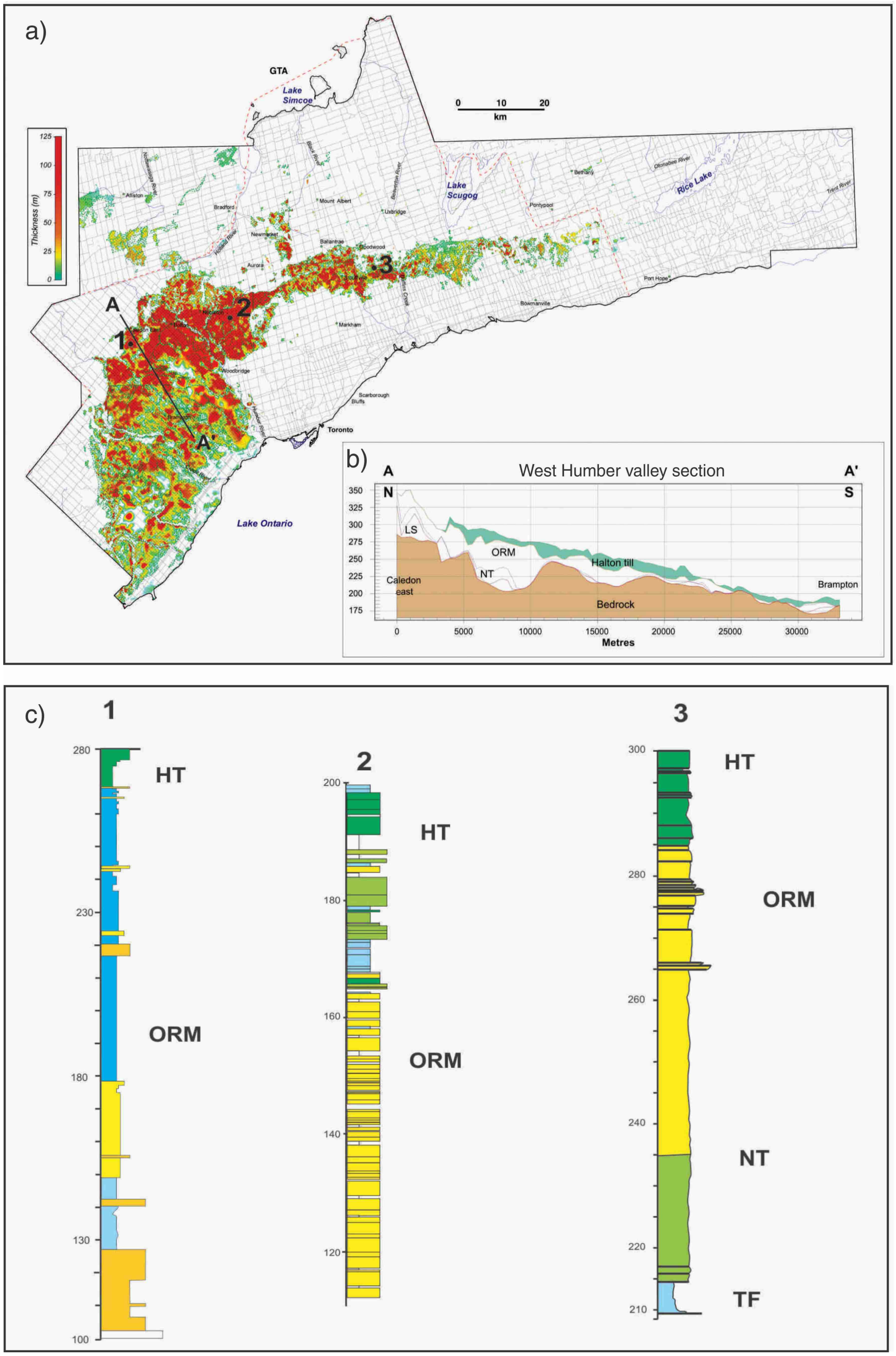

Figure 8. Thickness of Halton Till: **a)** isopach map shows thickness of Halton Till sediments based on regional stratigraphic data (Logan et al., 2002, 2005); note distribution of thickness is similar to Oak Ridges Moraine extent (Fig. 3), except for the southwest. **b)** North-south section A-A' shows Halton Till draped on Oak Ridges Moraine sediment in the north and on bedrock in the south. LS = lower sediment. **c)** Thick sediment sequences show transitions from Oak Ridges Moraine to Halton Till sediments in continuous cores from Credit River valley (1), Vaughan (2), and Glasglow (3); ORM = Oak Ridges Moraine, GTA = Greater Toronto Area, HT = Halton Till, NT = Newmarket Till, TF = Thorncliffe Formation.

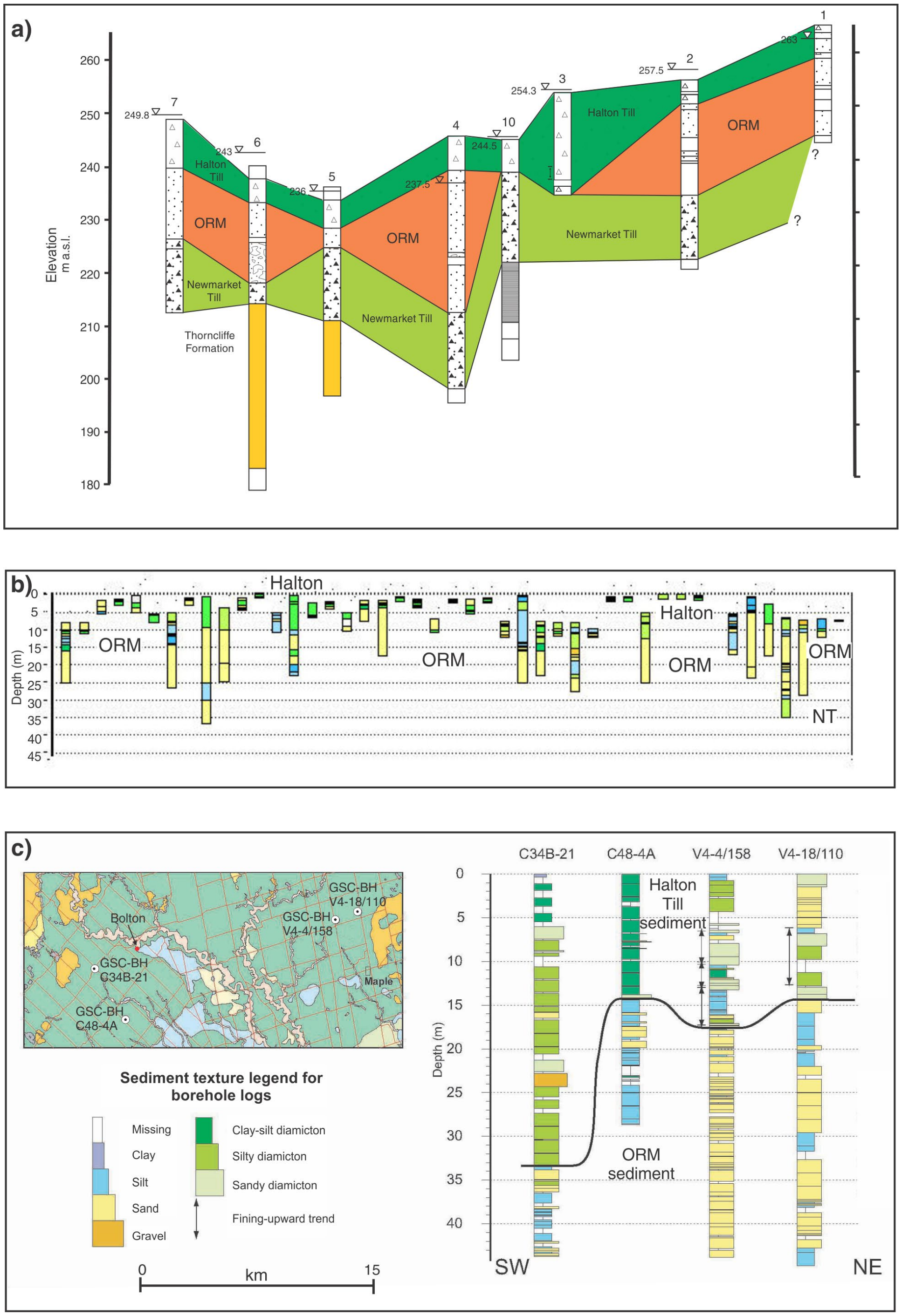

Figure 9. Stratigraphic sections on Oak Ridges Moraine (ORM) (*see* Fig. 3 for locations; or inset): **a)** southeast Richmond Hill: plot of eight cored boreholes (10–60 m) shows undulating drumlin surface (Newmarket Till) that provided depositional space for Oak Ridges Moraine, Halton Till, and interbedded stratified sediments. **b)** Northwest Richmond Hill: plot of about 50 cored boreholes shows 2–20 m thick Halton Till. Interbedded stratified sediments show as multiple units within borehole logs, resting conformably on thick (<40 m) Oak Ridges Moraine sand and silt, overlying Newmarket Till and Thorncliffe Formation sand. Note: colours in Figures 9b and 9c indicate lithology illustrated below on the map in Figure 9c. **c)** Cross-section near Maple shows interbedded Halton Till diamictons and sorted sediment in transition upward from Oak Ridges Moraine sediment. Halton Till strata thicken westward into a basin-fill geometry (*after* Russell et al., 2005, Fig. 7). No colour = missing, orange = gravel, yellow = sand, light blue = silt, dark blue = clay, dark green = clay-silt diamicton, medium green = silty diamicton, NT = sandy diamicton (Newmarket Till).

silt diamicton (Fig. 10, photographs 1, 2), and a gradational (interbedded) contact from Oak Ridges Moraine sand to sandy silt diamicton (Fig. 10 sediment log).

Transitional character between Oak Ridges Moraine and Halton Till

The stratigraphic setting and subsurface character of Halton Till relative to Oak Ridges Moraine sediment is documented based on geotechnical drilling in a range of landform (ridge, slope) and depositional (basin) settings.

At Richmond Hill, on a south-facing ridge of the Oak Ridges Moraine, about 50 borehole records reveal 2–20 m thick, clayey-silt diamicton intercalated with sandy Oak Ridges Moraine ridge sediment (Fig. 9b; Thompson and Beatty (2000); Sharpe et al. (2001)). The diamicton includes 1–5 m thick massive beds and discontinuous, 0.2–3.0 m thick, clay, silt, sand, and gravel interbeds (e.g. Fig. 5h). These occur with preserved primary bedding and lamination (Fig. 5c, d, e). Halton Till beds are conformable with and transitional from the underlying sand as indicated by interbedding at the contact and draping of diamicton where sand is thick (Fig. 9b) or, where kettle depressions occur.

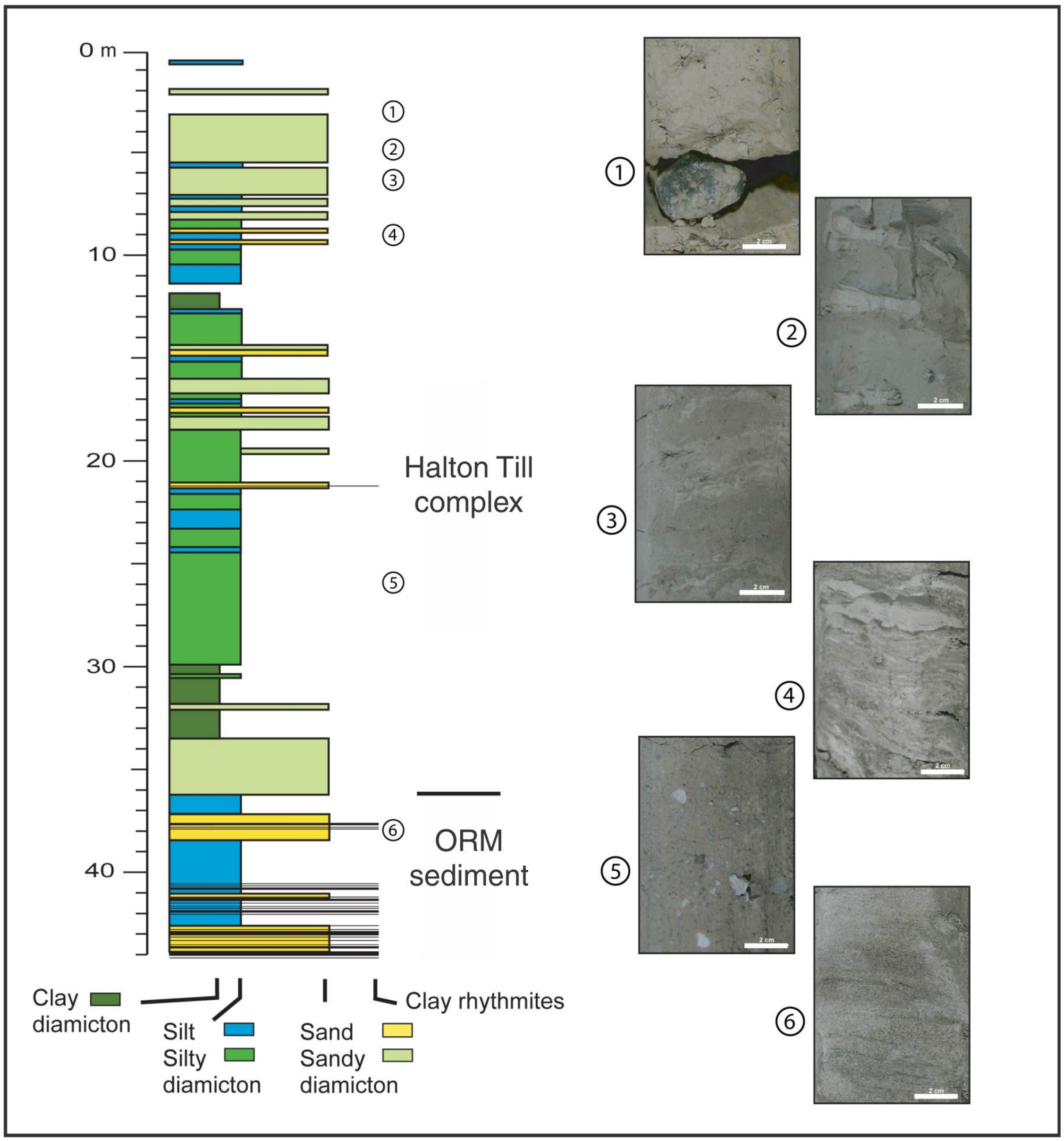

Figure 10. Kleinberg continuous core and photographs. Sediment log shows upper 44 m, extending from Oak Ridges Moraine (ORM) sand and silt, upward to interbedded Halton Till diamicton and laminated sediment. Photographs illustrate key variable sediment facies. Photograph by C. Logan. 2012-142

Halton Till is 1–2 m thick or absent on southern slopes of Oak Ridges Moraine sediments, perhaps indicating instability on original depositional slopes or subsequent erosion. Halton Till and Oak Ridges Moraine sediment appears to fill-in local undulating topography on Newmarket Till (Fig. 9a).

On the slope of the Oak Ridges Moraine near Maple, approximately 20 cored boreholes reveal Halton Till as a clayey-silt to sandy-silt diamicton, 2–25 m thick sequence in transition from Oak Ridges Moraine sediment (Fig. 9c; Interim Waste Authority (1994a). Halton Till sediment contains numerous slightly deformed and contorted water-bearing sand and silt lenses. It conformably overlies over 50 m thick Oak Ridges Moraine sand and silt (Interim Waste Authority, 1994a; Russell et al., 2006). Oak Ridges Moraine sediment sequences fine upward from sand to laminated silt-clay, then to Halton Till diamicton and sandy interbeds (Fig. 9c). Interbedding of variable sediment indicates a transitional contact from Oak Ridges Moraine sediment to Halton Till sediment, which appears to be filling a basin (C34B-21, Fig. 9c; Russell et al. (2003a)).

At Kleinberg, in a basin setting, a transition occurs from sandy Oak Ridges Moraine sediment to interbedded Halton Till diamicton and laminated fine sediment in continuous core (Fig. 10). Several other continuously cored boreholes show the transitional and interbedded character of Halton Till sediment from Oak Ridges Moraine sediment. This transitional style extends from Glasglow in the east (Fig. 11a) to Credit River valley in the west (Fig. 8c). Interbedded laminated and diamicton sediment is also widespread across Halton Till and/or Oak Ridges Moraine ridge and basin settings (Gilbert, 1997). Predominant east to west paleoflow directions in the Oak Ridges Moraine sediment beneath Halton Till sediment (Duckworth, 1975, 1979; Sharpe and Russell, 2005) can be linked to sand to silt interbedding and sediment fining along east-west Oak Ridges Moraine settings.

The Oak Ridges Moraine and stratigraphic correlation

The Oak Ridges Moraine plays an important stratigraphic role in distinguishing Halton and Newmarket tills. As Halton Till sediments become thinner along the lower parts of Oak

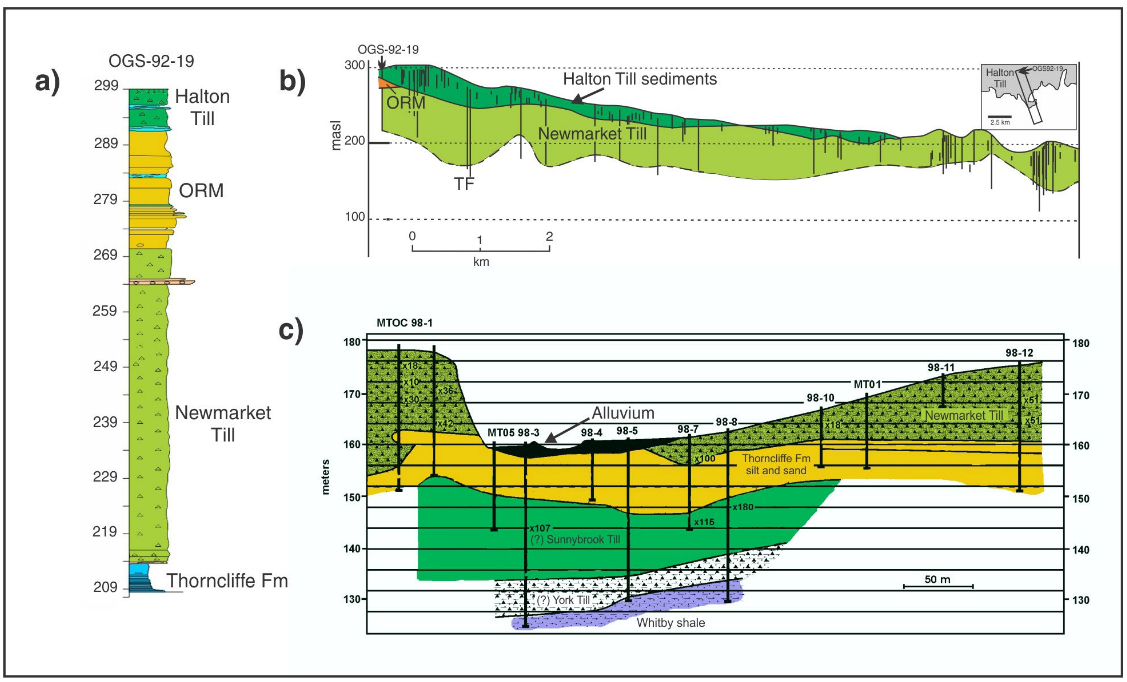

Figure 11. Stratigraphic sections related to the Oak Ridges Moraine: **a)** Cored borehole sediment log (OGS-92-19) at Glasgow shows Oak Ridges Moraine sediments transitional to Halton Till sediment (OGS-92-19: P.J. Barnett, unpub. data, 1993). The Glasgow reference site occurs north of Newmarket Till plain, exposed in section along West Duffins near Whitevale. North-south stratigraphic section provides context for reference site OGS-92-19 with a transect from Glasglow to Whitevale (*see* Fig. 3). Halton Till was mapped as a stone-poor, silt till with laminated silt, clay, and fine sand interbeds at tens of field sites along this transect (*see* Barnett and Dodge, 1996). **c)** Highway 407 at Rouge River: portion of about 15 km transect across Newmarket Till is shown at the surface of the former Halton Till plain (e.g. Karrow (1970); Boyce and Eyles (2000); Fig. 2b, d), now identified as a drumlinized Newmarket Till surface. Section shows stratigraphic sequence to bedrock: Newmarket Till–Thorncliffe sand–(?) York Till–Whitby shale.

Ridges Moraine flanks, and on the adjacent till plain, it can be difficult to differentiate Halton Till from Newmarket Till where there is little or no intervening Oak Ridges Moraine sediment (e.g. Fig. 11b). Three sites illustrate subsurface variability and control on the southern till plain stratigraphy (Fig. 8). A 62 m deep cored borehole located on the south flank of the Oak Ridges Moraine at Glasglow (OGS 19/B19 in Fig. 2; Barnett, 1992; P.J. Barnett, unpub. notes, 1992), shows about 7 m of silty Halton Till (1–2% stone), overlying about 23 m of Oak Ridges Moraine sand and silt and about 40 m of stony (10–15%) sand to silty sand Newmarket Till (Fig. 11a). South of the Oak Ridges Moraine topographic slope, revealed in 2–3 m thick clayey silt beds, isolated outliers, valley settings and in drilling for subway and highway right-of-ways (Golder and Associates, 1994, 1999), Halton Till may be present as outliers where Newmarket Till occurs at the surface (Fig. 3). These outliers are difficult to map without drill core and often occur in depressions on eroded surfaces of Newmarket Till (e.g. Markham basin, Fig. 3) where they contain 0.3–1.5 m thick, fine sand, silt, clay, and Halton Till diamicton beds (Sibul et al., 1977).

Preliminary hydrogeological differences in tills

Hydrogeological studies, mainly landfill investigations in the Greater Toronto Area provided hydraulic conductivity and recharge data that distinquish Halton and Newmarket tills (e.g. Funk, 1977; Golder and Associates, 1994, 1999; Fenco-MacLaren Inc., 1994; Dillon, 1994; Gerber and Howard, 1996; Gerber et al., 2001). In general, significant differences occur between the hydrogeological properties of each till (Table 4). Significant quantities of detailed, stratigraphically-constrained data are available from three Interim Waste Authority sites in the Humber River and Duffins Creek watersheds. Data from the Humber River watershed are available from two distinctly different geomorphological and stratigraphic settings, the Palgrave area of hummocky, thick, mud-rich Halton Till, and the Vaughan site on the Oak Ridges Moraine flanks with thin, interbedded Halton Till with a strong glaciolacustrine character. Massive lithofacies have vertical hydraulic conductivity (Kv) ranging from 1 x 10^{-6} cm/s to 8 x 10^{-7} cm/s (Golder and Associates, 1994). Significantly higher K (hydraulic conductivity) values of 4–5 x 10^{-4} cm/s are found for interbedded lithofacies, particularly with sand and gravel (Golder and Associates, 1994). These local studies provide an indication of the range of potential subsurface fluid-flow conditions within Halton Till sediment. Regions of dissected hummocky terrain (Palgrave Moraine; Fig. 3) are capped by thinner, more interbedded diamicton, whereas the lowland plains are associated with a thicker, less interbedded diamicton sequence. Similar lithofacies in each setting have similar K values.

In Duffins Creek watershed, Newmarket Till occurs as a thick surface till across studied landfill sites (Fig. 3). Hydraulic conductivity values are very low (Kv ranges from ~5 x 10^{-7} cm/s to 5 x 10^{-8} cm/s) for massive till when it is below the near-surface (3–6 m) fracture zone (Dillon, 1994). Despite the fact that Gerber and Howard (1996, 2000) have inferred much higher Kv values for Newmarket Till based on isotope results, estimated recharge fluxes are three to ten times greater in Halton Till than those in Newmarket Till (Table 4).

INTERPERTATION

The extent of Halton Till (Fig. 3) is much reduced from previous regional maps (e.g. Sharpe, 1980, 1988) where it was drawn as a continuous unit from Lake Ontario to Oak Ridges Moraine (Fig. 1a; Barnett et al. (1991); Boyce and Eyles

Table 4. Hydrogeological data for Halton and Newmarket tills.

Sediment	Thickness (m)	Lithology	Kv (cm/s)	Recharge estimates	Comment
Halton Till (Diamicton)	About 2–20	Clay silt (weathered) Clay silt (massive)	2 x 10^{-3} 1 x 10^{-7} to 8 x 10^{-7}	125–350 mm/a	Drapes Oak Ridges Moraine
(Diamicton)		Sandy silt (massive)	2 x 10^{-7}	Varies with terrain	Limits recharge Local aquifers
(Interbeds)	About 1–3	Sand and gravel	4 x 10^{-4} to 5 x 10^{-4}		Lateral drains
Newmarket Till	About 2–50	Silty sandy (dense)	5 x 10^{-7} 5 x 10^{-8}	35–50 mm/a (fractures)	Underlies Oak Ridges Moraine Overlies and/or protects lower aquifers
Note: depth of observed weathering and fractures is about 3–6 m in both units					

(2000)). This revised interpretation has a wealth of support based on mapping, sedimentary and geotechnical properties, structure, sedimentary architecture, and stratigraphic relationships with adjacent sequences, especially Oak Ridges Moraine (Fig. 2b, 9b, c). Detailed surface mapping (Sharpe and Barnett, 1997) combined with other high-quality data, e.g. continuous borehole logs (Barnett et al., 1998), downhole geophysics (Pullan et al., 2000), all integrated in 3-D geological models (Logan et al., 2006), document the reduced extent and facies transitions of Halton Till and related sediment (Russell et al., 2005). These data and improved analysis support two key interpretations: Halton Till sediment has strong affinities to Oak Ridges Moraine, and Halton Till sediment did not result from significant ice flow from the glacial Lake Ontario basin as has been traditionally inferred (e.g. Karrow, 1967; Boyce and Eyles, 2000). Both of these inferences relate to the strong lacustrine character of Halton Till sediment.

The revised map (e.g. Fig. 3) shows Newmarket Till as the predominant sediment in the east on till plains south of Oak Ridges Moraine (Sharpe and Barnett, 1997). Halton Till sediment has a pronounced east to west trend as scattered outliers with limited extent in the east become more widespread and thicken westward, particularly in Humber River valley (Fig. 8a). There is also a pronounced north to south trend with Halton Till thinning southward, and it occurs rarely adjacent to Lake Ontario east of Humber River. Halton Till sediment distribution is similar in extent to the Oak Ridges Moraine sediment distribution (Fig. 3, 8) east of Humber River. West of Humber River valley, Halton Till drapes Oak Ridges Moraine sediment in the north, but is very thin on bedrock, and insignificant in the south (Fig. 8b). Halton Till sediment also includes facies transition from Oak Ridges Moraine sediment upward to laminated lacustrine muds, diamicton interbeds and to more massive Halton Till sediment (Fig. 8c). The westward fan-shaped geometry is accompanied by east to west paleoflows in sandy, gravelly Oak Ridges Moraine sediment. Oak Ridges Moraine is predominantly sand and gravel, yet it grades to mud upward and westward (Fig. 8c). The transitional basal contact of Halton Till indicates that Halton Till sediment was deposited in ice-marginal or subglacial glaciolacustrine conditions within a distal, deep-water basin setting. This setting allows more accommodation space for transitions from sandy Oak Ridges Moraine to muddy Halton Till sediment in deeper western extents of the basin (tens of metres, Fig. 8c). These results clearly identify the need for a revised Halton Till landform sediment model that reassesses the long-standing paradigm that a lake-bordering drumlinized till surface records late-glacial flow and deposition of Halton Till from the glacial Lake Ontario basin (Fig. 1b; Karrow (1967); Boyce and Eyles (2000)).

Halton Till stratigraphic and sediment model

A new stratigraphic model (Fig. 2) provides an updated setting for a revised Halton Till sediment model. This stratigraphic setting and the abundant field evidence of sediment facies, distribution and thickness (Fig. 4, 5, 8), illustrate how Halton Till strata are closely linked to, and are transitional from, Oak Ridges Moraine sediments. Halton Till strata comformably rest on, and are intercalated with, Oak Ridges Moraine sediment (Fig. 8) rather than being explicitly associated with a glacial Lake Ontario basin ice advance (Fig. 1b, c). A grounded-ice advance from Lake Ontario would be expected to have deposited till across most lake-bordering areas, as previous Halton Till models imply.

The depositional setting (Fig. 12) for Halton Till sedimentation provides the process framework to explain Halton Till sediment facies and architecture. A semibuoyant ice shelf in the glacial Lake Ontario basin is illustrated to control the westward flux of sediment along the Oak Ridges Moraine axis and then rework these sediments with ice grounding, debris flow, and other ice-marginal processes (Fig. 12). The Halton Till depositional setting is primarily glaciolacustrine, with proglacial and subglacial glaciolacutrine settings in deep water contained by the Niagara Escarpment. The sediment model is dominated by subaqueous, gravity-driven debris-flow, underflow, and suspension processes, as shown by common interbedding, graded beds, facies transitions, and a fining-upward sedimentary style; however, where Halton Till sediment is absent or discontinuous, grounded glacier ice was likely clean and allowed little if any space for sedimentation during a period of late, limited ice fluctuation.

The new sediment model explains why Halton Till and Oak Ridges Moraine sediments fan out and get thicker from east to west (Fig. 3, 8, 12), particularly westward across Humber River watershed. The pre-existing model (Fig. 1b, c) shows sediment influx from the north and south that should have produced equal sedimentation along an east to west corridor. Paleoflow directions in the underlying Oak Ridges Moraine sediment are predominantly east to west (Duckworth, 1975, 1979; Sharpe and Russell, 2005), and explain the east to west sediment trends in Halton Till sediments; for example the westward fan-shape widening, thickening, and fining-upward sediment wedge (Fig. 3, 8).

The new model links Oak Ridges Moraine sedimentation to Halton Till sedimentation. Thus, Halton Till strata exhibit a sand-to-mud facies transition upward from underlying Oak Ridges Moraine sandy facies (Fig. 8c, 9b, c, 10), as well as the east to west sand-mud transition. Halton Till sediment also drapes Oak Ridges Moraine ridges, hummocks, and flanks, and fills depositional basins and kettles on the moraine (Fig. 2b, 8b). Halton Till debris was also resedimented as buried ice blocks melted after being trapped in rapidly deposited Oak Ridges Moraine sediment. Halton Till is also transitional upward into overlying glacial-lake sediments (Russell et al., 2006). Widespread interbedded, mud-rich, laminated sediment across Halton Till ridge and basin settings point to deposition within standing water (Fig. 10), perhaps up to 100 m deep in places (e.g. Gilbert, 1997).

The new Halton Till landform-sediment model (Fig. 12) is in strong contrast to existing Halton Till models based on key sedimentological constraints as summarized below (Table 5). Presented Halton field data do not provide sedimentological support for an active ice model (major retreat and readvance) nor much sediment with grounded-ice properties (Table 5). There is no direct evidence for climate forcing (readvance due to cooling) in the Halton Till sediment model. It is commonly inferred that sandy beds within and/or below near-surface diamictons represent Mackinaw interstadial deposits (e.g. Meyer and Eyles, 2007); however, such bedded sediments are common in glaciolacustrine basins with seasonal sedimentation and ice-marginal dynamic events.

In short, late-glacial conditions as reconstructed better explain the presented three-dimensional geological, sedimentological, and stratigraphic data of Halton Till in the Greater Toronto Area (Fig. 8, 9, 10, 11). The tabulated results (Table 5) and reconfigured paleo-geographic setting (Fig. 12) related to deposition of Halton Till sediments can be related to a plausible succession of events (Table 6) that are compatible with the key Halton Till sedimentary data (Table 5). A detailed discussion of the Oak Ridges Moraine–Halton Till event sequence model is not within the scope of this paper.

HYDROGEOLOGICAL IMPLICATIONS OF HALTON SEDIMENT

The sedimentological data for Halton Till glacial sediment has practical implications in the Greater Toronto Area. Halton Till sediments vary at the site, watershed, and regional scales, and so its hydrogeological parameters have similar variability (Freeze and Witherspoon, 1967). Thus, improved understanding of the architecture and depositional setting of Halton Till sediment, should help guide discussion of hydrogeological implications. Key attributes that may influence hydrogeological function include: thickness, lithological character and variation, and directional properties. These attributes are best assessed at a number of Interim Water Authority (IWA) sites where extensive hydrologeological data were collected as part of landfill site characterization studies of the early 1990s. For example, two

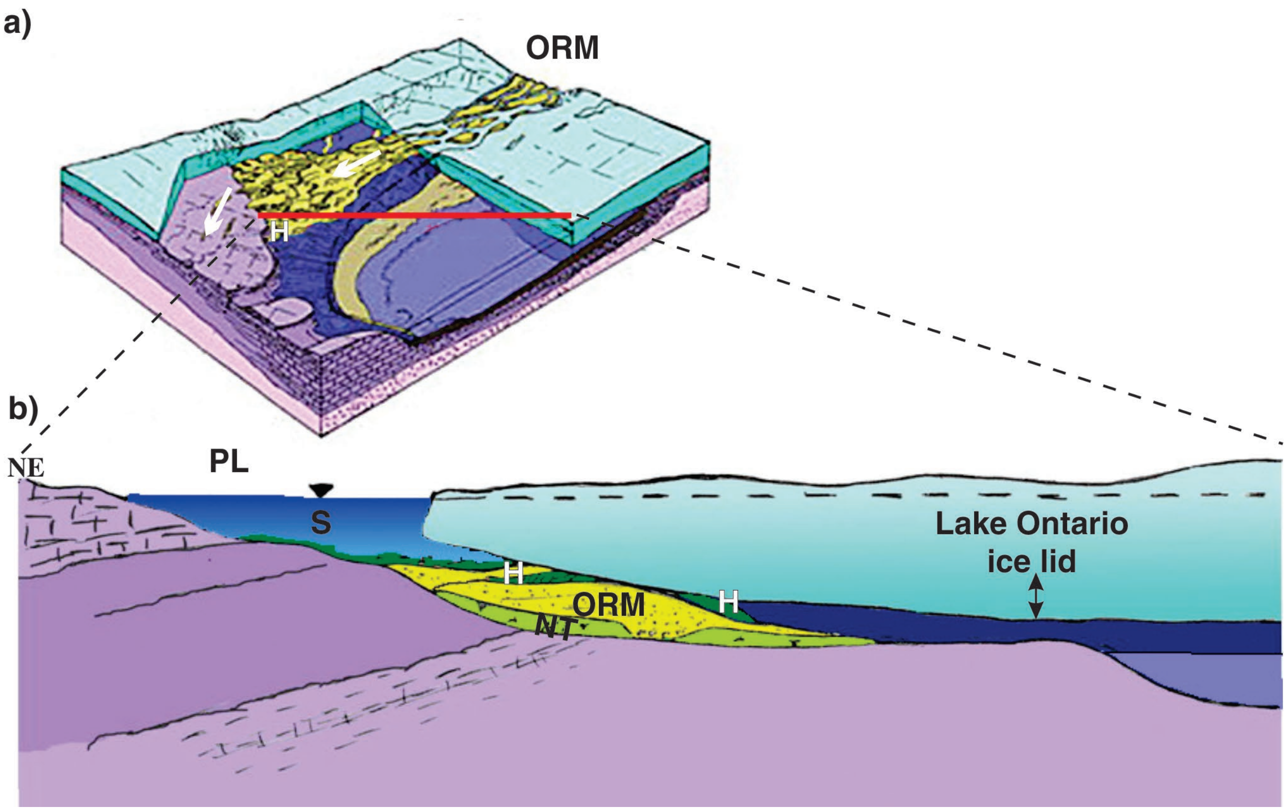

Figure 12. Halton Till (H) depositional setting: **a)** Oak Ridges Moraine (ORM) paleogeographic setting shows a Lake Ontario floating ice lid grounded along the lake margin; east to west flow (white arrow) focused mud to western regions after formation of Oak ridges Moraine; **b)** cross-section of Halton Till grounded-ice position as buoyant forces suspend the floating ice lid to minimum contact on marginal Oak Ridges Moraine sediments. Suspended mud (S) from waning Oak Ridges Moraine sedimentation in Figure 12a is reworked by grounded Halton Till ice, debris-flow, and other ice marginal processes. The section is oriented approximately east-west. PL = proglacial lake, NT = Newmarket Till, NE = Niagara Escarpment.

Table 5. Summary of sedimentary attributes and implications regarding Halton (Till) sediment.

1.	Halton Till is discontinuous south of Oak Ridge Moraine and east of Humber River; extent closely matches extent of underlying Oak Ridges Moraine sediments (Fig. 3).
2.	Halton Till has a conformable, fining-upward, interbedded and transitional relationship with underlying rapidly deposited, east-trending sandy Oak Ridges Moraine sediments (Fig. 8c, 9c).
3.	Halton sediment mainly reflects passive, subaqueous underflow and/or debris flow deposition; not active ice features (preconsolidation, ice-tectonic structures, and striated bullets) as part of readvance deposition (Karrow, 1967, 1974, 1987, 1991).
4.	Newmarket Till, mapped as Halton Till by some, underlies and is stratigraphically older than Oak Ridge Moraine (Fig. 2d, 3).
5.	Dense, stoney till, Newmarket Till, is found in drumlinized till plains, south of Oak Ridges Moraine (Fig. 2d, 3).
6.	Drumlins and/or fluting south of Oak Ridges Moraine are not depositional landforms[1] composed of Halton Till; they are erosional landforms cut into Newmarket Till[1], and form part of Peterborough drumlin field (Sharpe et al., 2004).
7.	Halton Till partially fills drumlin swales and tunnel channels cut into Newmarket Till[2] (Fig. 11); it also partially fills ice-block depressions or kettles in the Oak Ridges Moraine surface.
8.	A major drumlin-forming readvance of late-glacial ice from Lake Ontario basin (e.g. Karrow, 1967, 1970; 1974) is not in accord with presented map, sedimentary and stratigraphic data, or by theory (Shoemaker, 1999) (Fig. 12).
9.	Due to the transitional facies relationship between Oak Ridges Moraine and Halton Till sediment, prominent sandy interbeds are readily explained as basin depositional facies (drainage events) not linked to climate forcing; thus, it is not reasonable to infer interbeds as Mackinaw interstadial deposits.

[1] Drumlins are erosional (Shaw and Sharpe, 1987; Boyce and Eyles, 1991), as indicated by truncation of till and horizontal stones lines within drumlin forms (Sharpe et al., 2004).

[2] Eroded drumlin surfaces with gravel lags and the bases of tunnel channels are part of a regional unconformity (Sharpe et al., 2004).

Table 6. Regional event sequence for Halton Till sedimentation.

i)	Oak Ridge Moraine formed during a rapid sequence of high-energy, west-flowing meltwater events (e.g. Russell et al., 2003a, b; Sharpe et al., 2004), that led to transitional deposition of Oak Ridge Moraine to Halton Till sediment (e.g. Fig. 10). Ice blocks were deposited in rapidly deposited Oak Ridges Moraine sediment.
ii)	Subglacial meltwater (lakes) accumulated in lake basins under late glacial melting, during and following events that formed Oak Ridge Moraine (e.g. Shoemaker, 1992; Russell et al., 2003a, b; Evatt et al., 2006); this stored water in Lake Ontario (Fig. 12) floated the glacier and effectively ended glacier shear stress and ice flow from the lake basin.
iii)	Lake-bordering grounded ice helped control meltwater ponding and sedimentation patterns leading into Halton Till deposition (Fig. 12).
iv)	Sediment was dispersed from east to west along the axis of the ridge during Oak Ridge Moraine formation (Fig. 12a); this included meltwater channels that drained westward above Niagara Escarpment (e.g. Barnett et al., 1998); there was no major northward sediment flux on land from the Ontario basin.
v)	Sedimentary features indicate deposition into high lakes during Oak Ridge Moraine–Halton Till transition (Fig. 12; Gilbert, 1997; Russell et al., 2005); this required a seal by grounded glacier ice on land north of Lake Ontario (point iii).
vi)	As high-energy, east to west Oak Ridge Moraine sedimentation waned, suspended muddy sediment was mainly transported westward; trapped mud was reworked by Halton Till ice-marginal processes (Russell and Sharpe, 2002; Fig. 12).
vii)	Eskers mainly supplied sediment from the east (Gorrell and Brennand, 1997), and late modest supply of sediment along the system, including rare northwest-trending, low-energy, esker sediments near Brampton (Saunderson and Jopling, 1980).

different settings, the Oak Ridges Moraine southern flank in Vaughan and the till plain in Peel, highlight variable Halton Till sediment and hydrologic properties.

Along the flanks of the Oak Ridges Moraine in Vaughan (site 2, Fig. 8), Halton Till strata commonly include interbedded sand, mud, and diamicton beds in an area of topographic relief and hummocky terrain with kettle lakes. Sand interbeds are gradational to glaciolacustrine mud. The coarsest interbeds found within Halton sediment occur in this setting of sandy Oak Ridges Moraine mounds and lobes. Horizontal K values of 1 x 10^{-6} cm/s to 1 x 10^{-8} cm/s are reported for massive diamicton (Fenco-MacLaren Inc., 1994). Higher K values, 1 x 10^{-4} cm/s are found for interbedded diamicton and sand-gravel (Fenco-MacLaren Inc., 1994). Sand-bed connectivity (Fogg, 1986) is critical as it can act as a horizontal drain. In such beds, combined with thin (<5 m thick) sediment, unsaturated conditions, weathering, and fracturing of fine-grained Halton Till sediment, vertical connectivity can be enhanced between surface and subsurface interbeds (e.g. Fig. 10, 13b). Hydraulic properties vary where Halton Till overlies hummocky, kettled Oak Ridges Moraine terrain, (Fig. 5f, 8c). Such hummocky terrain captures surface run-off within internally drained areas, which promotes ponding, sustains saturated conditions, and promotes ongoing infiltration (Fig. 13a, b), particularly from spring snow melt.

In the low-relief Halton Till plain setting in Peel west of the Humber River (Fig. 9c), are the thickest, most fine-grained, and most homogeneous Halton Till. Sediment may be up to 30 m thick (site C34B-21, Fig. 9c); however, it can thin to less than 5 m where the till plain meets the Oak Ridges Moraine (Russell et al., 2005). Halton Till has a gradational basal contact, laminated interbeds, and it becomes more massive and richer in gravel upward. Massive diamicton has horizontal hydraulic conductivity (K) of 1 x 10^{-5} cm/s to 1 x 10^{-3} cm/s and vertical K of 1 x 10^{-6} cm/s to 1 x 10^{-7} cm/s (Table 4; Golder and Associates, 1994). Interbedded sand and gravel sediment has K values of 1 x 10^{-4} cm/s, whereas interbedded sand-gravel and diamicton has K values of 1 x 10^{-3} cm/s (Golder and Associates, 1994). In general, low gradients on thick muddy Halton Till sediment promote direct run-off to streams rather than infiltration to groundwater.

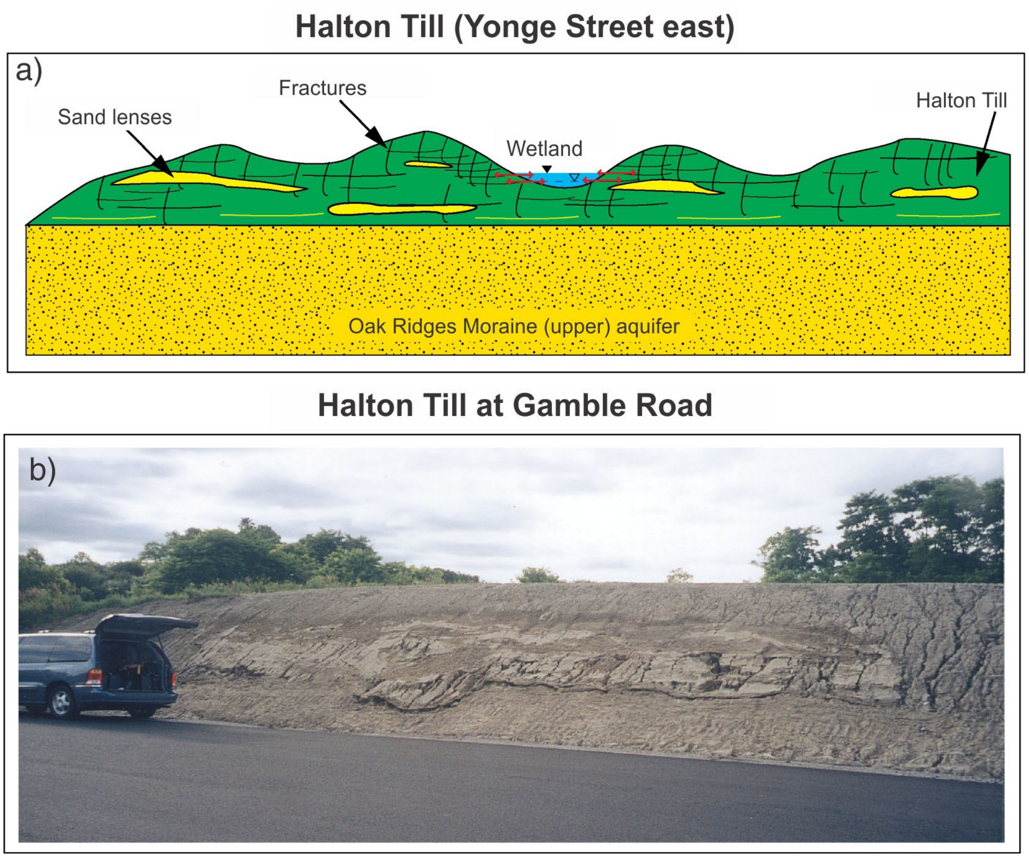

Figure 13. Halton Till hydrogeological setting: **a)** sketch of hummocky Halton Till with sand lenses and fractures, resting conformably on Oak Ridges Moraine sand; **b)** large sand lens (about 15 m) in Halton Till; photograph by D. Sharpe; 2012-144

Directional properties of Halton Till sediment

Halton Till and related sediment display directional lithological and structural change, vertically, horizontally and along paleoflow, within mapped sequences. Because Halton Till sediment was mainly deposited by gravity-driven debris-flow, underflows, and suspension processes, the underlying topography controls distribution, thickness, and sediment trends within the formation (i.e. Fig. 9a, 11b, 13). In this way, basin settings (e.g. Peel) accumulated thick, fine-grained, interbedded sediment, trending westward, yet with variable directions locally on mounds or lobes of sandy Oak Ridges Moraine fan sediment (e.g. Vaughan setting). Most Oak Ridges Moraine sediment lobes trend southeast to northwest. Thus sand beds within Halton Till sediment may be better connected in southeast to northwest directions. Such Halton Till sediment controlled directional trends in hydraulic properties may alter well-head protection zones related to capture of water to pumping wells.

Secondary hydraulic properties

Weathering of Halton Till sediment in the near surface (<5 m) can alter its typical hydrological properties. Halton Till is affected by vadose zone processes and weathering, such as desiccation and fracturing of muddy diamicton or glaciolacustrine beds. Muddy textured Halton Till can lead to large variation in K (2 x 10^{-7} cm/s to 2 x 10^{-3} cm/s; Table 4), related to desiccation and root development (e.g. Hendry, 1988). Weathered, clayey till tends to develop microfractures that are linked to higher hydraulic conductivity in these settings across southern Ontario (Husain et al., 2007); this process was also invoked by Gerber and Howard (2000) to infer enhanced vertical connectivity in Newmarket Till. Site investigations in Peel indicate that fracturing in clayey sediment extends to depths of about 3–5 m (Golder and Associates, 1994). Mud-rich units would typically be assigned a low infiltration rate compared to more sandy sediment, if the extent and nature of weathered clayey sediment was not considered to enhance infiltration (Fig. 13a). Increased bulk hydraulic conductivity may result in an increase in hydraulic connectivity by a factor of two (e.g. Hendry, 1988). Thick muddy sediments would likely result in greater run-off or develop shallow groundwater flow at the vadose zone weathered-unweathered sediment boundary (e.g. Fig. 8a). As such, thick mud-rich sediment with decreased infiltration may help protect aquifers below the fracture zone. Fractures, on the other hand, may also connect to interbeds and underlying sandy Oak Ridges Moraine aquifer sediment and further contribute to enhanced infiltration and recharge.

Hydrogeological applications

Most hydrogeological data are site specific and additional geological mapping is required to support the extrapolation of parameter values beyond known sites when new development is initiated. Because existing information, and in particular geological maps, rather than new subsurface data are used to site key facilities such as landfills and sewer lines, it is instructive to assess the importance of enhanced geological information on successful site development in the Greater Toronto Area. The recognition, testing, and use of sound conceptual geological model are also important to appropriate hydrogeological understanding, even when new site data are collected.

Geotechnical implications of Halton Till

The importance of applying a sound conceptual geological model, such as the stratigraphy and distribution of Halton and Newmarket tills, is illustrated by the Interim Waste Authority landfill search and in a later section on the trunk sewer installation by York region. The proposed regional Greater Toronto Area landfill facilities (Durham, Peel, and York) were sited, in part, based on the conceptual model that Halton Till formed a simple till plain with predictable sediment and low-permeability properties and known thickness (Dillon, 1994; Fenco-MacLaren Inc., 1994; Golder and Associates, 1994; Interim Waste Authority, 1994a, b). Note that the Durham site is now known to occur on the Newmarket Till plain (Fig. 1, 3).

Inspection of the borehole logs for the planned Vaughan landfill (Fig. 9a, V4-4 and V4-18) illustrates variable facies and properties present in Halton Till sediment. This variety of sediment texture and layering was not predictable from the 'till plain' conceptual model and limited water-well information. In addition, the fact that Halton Till sediment was transitional upward from coarser, sandy Oak Ridges Moraine sediment was not recognized (e.g. Turner, 1977). With a planned excavation depth of about 15 m (Interim Waste Authority, 1994a, b), the presence of sandy Halton Till interbeds, and the transition from sandy Oak Ridges Moraine aquifer sediments, provided little if any 'natural' protection to lower aquifers from any landfill leakage. Neither did the siting model anticipate that the Halton Till was part aquifer rather than all aquitard in the Vaughan Oak Ridges Moraine slope setting. In contrast to the Vaughan setting, the Peel investigation encountered thick, fine-grained Halton Till sediment with few sandy interbeds based on the till plain model, although variable sediment thickness (form >20 m to <5 m) was an important issue. In summary, the simple application of an untested till-plain, landform-sediment predictive model proved to be unreliable.

Recharge

The scarcity of site-specific hydrogeological data requires regional mapping to support the extrapolation of recharge estimates across large areas. Estimates of recharge in the Oak Ridges Moraine area (e.g. Gerber and Howard, 2000; Gerber et al., 2001) can be generalized over larger areas where accurate geological and hydrometerological data allow. Thus, spatial variability in unit thickness, texture, and interbeds can have a significant influence on the reliability of such regional extrapolation. For example, Halton Till sediment becomes finer-grained and thicker to the west, and regional trends in recharge estimates and other hydrogeoogical properties may be anticipated.

Sandy interbeds are frequent and prominent in some areas within Halton Till. At one property near Richmond Hill, 90% of new boreholes (~20) showed beds of at least 10 cm thickness in the top 5 m of weathered till (Fig. 11b; Sharpe et al., 2001). Near-surface sandy interbeds are frequently intersected by vertical pathways, roots, worm holes, and enhanced infiltration results. Thus, sedimentary features, and weathered Halton Till may yield recharge rates as high as about 350 mm/a for hummocky Halton Till (Gerber and Howard, 2000) when surplus water is available. Reported estimates as low as about 125 mm/a more likely relate to Halton Till where there is no hummocky terrain and where sediment is transitional to lacustrine silt and clay, and sand interbeds are thinner or absent, such as the Peel Interim Water Authority setting (Fig. 9a). These relationships (e.g. Halton Till drapes Oak Ridges Moraine; hummocky terrain; sandy interbeds; sediment thickness is less than 5 m) all enhance recharge; hence, recharge estimates are more predictable where surface mapping includes subsurface detail.

Groundwater flow

The amount of stream discharge that can be attributed to groundwater flow (baseflow) has been correlated with geological units in southern Ontario (Piggott and Sharpe, 2007). Thus, Halton Till affects groundwater discharge based on base-flow surveys carried out under low-flow (minimal precipitation) conditions depending on its setting in this region (e.g. Hinton, 2005). Baseflow in the Rouge River is less than 5 L/s where it is floored in Halton Till (e.g. Fig. 11c). It increases to 10 L/s where headwater streams intercept Oak Ridges Moraine aquifer sediment below Halton Till. Similarly in the Humber River watershed, base flow is closely linked to geology with little discharge on Halton Till compared to Oak Ridges Moraine sediment areas; there are about two orders of magnitude less base flow in areas of Halton Till (Hinton et al., 1998). In contrast, south of the Halton Till plain, base flow from streams flowing on Newmarket Till are less than 1 L/s if there is any flow at all. Base-flow discharge increases to about 25–50 L/s where stream incision occurs to adequate depth to intercept underlying sandy Thorncliffe Formation sediment along the Rouge River bed south of Markham (Sharpe et al., 2001). It is noteworthy that Halton Till is missing and the eroded surface till unit is Newmarket Till in this area.

Construction and land development

Application of an untested, simple conceptual geological model can contribute to serious hydrogeological construction problems. Plans for deep trunk-sewer excavation in the study area relied on poor geological understanding that incorrectly anticipated that the prevailing surface geological model, a simple till plain, provided a predictable setting for subsurface excavation. The area of trunk-sewer excavation was assumed to be Halton Till plain (e.g. Husain et al., 2007); however, it was actually underlain by older, Newmarket Till (Sharpe et al., 2011) and had much different sediment properties and stratigraphy than areas of Halton Till plain (Fig. 9a; Table 3). Excavation and breaching of the surface till aquitard resulted in interception of confined groundwater hydraulic conditions (in Thorncliffe Formation) beneath Newmarket Till rather than Oak Ridges Moraine aquifer sediment beneath Halton Till. The confined hydraulic conditions of Thorncliffe Formation aquifers have base-flow estimates that are more than five to ten times greater than those in Halton Till settings and up to five times base-flow contributions from Oak Ridges Moraine slope settings. Understanding the differences in stratigraphic content, sediment properties, and hydrogeological behaviour between Halton (thin with sand seams) and Newmarket (thick and dense) tills might have avoided the expensive dewatering program that was required to rescue the deep trunk-sewer excavation development in York region (Husain et al., 2007).

CONCLUSIONS

A revised depositional model for Halton Till sediment explains its stratigraphic setting, reduced extent, sediment thickness, variable lithology, and predominant glaciolacustrine character. This revised origin also explains its form and facies trends such as upward transition from, and interbedding with, underlying sandy Oak Ridges Moraine sediment derived from high-energy meltwater discharge events. The glaciolacustrine sedimentation and stratigraphic model provides a predictive framework to improve understanding of near-surface hydrogeology of the region. Sedimentary form, hummocks, kettles, and basins affect surface hydrology and infiltration location and rates of flow to aquifers. Knowledge of sedimentary properties also affects recharge and water balances related to sediment facies, thickness, lithology, and directional properties around construction sites, landfills, and well-head protection zones in the Greater Toronto Area. For example, the significant east-to-west transport of Oak Ridges Moraine sediment, particularly late-stage mud, provided much source sediment for Halton Till strata, and controlled its resultant form, lithological character, and hydrogeological properties in the region.

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