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**A revised depositional setting for Halton sediments in the
Oak Ridges Moraine Area, Ontario**

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Abstract

Outcrop and continuous core descriptions, high-resolution seismic profiling and downhole geophysical data, are integrated with detailed mapping to update sedimentary and stratigraphic frameworks for Halton sediment, a complex mud-rich lithofacies succession. Halton sediment has a gradational transition from underlying Oak Ridges Moraine (ORM) sediment and can abruptly overlie Newmarket Till. Halton strata thin and fine upwards from Oak Ridges Moraine sand and gravel to graded sand, silt, and clay rhythmites, with muddy diamicton and sand and gravel inter-beds. These strata fill basin lows and drape ORM sediment lobes and Newmarket Till drumlins. These distinct sedimentary units are here informally referred to as Halton formation. Formal Halton Till is a proposed sub-unit of Halton formation, a clay-rich diamicton mapped from Niagara Peninsula to ORM and eastward. Halton Till has traditionally been inferred to represent a late, climatically-induced re-advance of grounded ice from Lake Ontario basin, which deposited drumlinized till.

Halton sedimentary architecture and facies are interpreted as deposition in an ice-marginal /subglacial lake bounded by Niagara Escarpment, ORM and grounding line oscillation of a semi-buoyant ice shelf /lid over Lake Ontario. Large volumes of transported mud are distal equivalents of ORM high-energy gravelly sand deposits to the east. Glaciolacustrine sedimentation is indicated by mud-rich texture and laminations. Clay-silt rhythmites, diamicton inter-beds, and intra-clasts indicate ponding, debris flow and periodic ice loading. Halton

depositional model may apply to other muddy diamictos in Great Lakes basins. Halton formation facies are not compatible with proposed grounded ice stream events in Lake Ontario basin.

Key words: Ice-marginal sediment, ice shelf, Halton, glaciolacustrine, Oak Ridges Moraine

INTRODUCTION

During deglaciation much of the Laurentide ice sheet was bounded by water bodies formed within isostatically-depressed foreland basins. Deglaciation of the Paleozoic terrain of Southern Ontario was further complicated by deep depressions associated with Great Lakes basins and by regional bedrock escarpments (e.g., Niagara Escarpment). These basins and long scarps helped store water either proglacially or subglacially (e.g., Shoemaker 1992; Evatt et al. 2006). In addition, the basins were pre-disposed to funnel ice flow and to trap basin mud (Karrow 1989), particularly silt-rich carbonate detritus (Dreimanis and Vagner 1971). The long-standing glacial model states that ice flowed preferentially along and from lake basins in a way that flow was enhanced by a substrate of mud deposited in the basin (Dreimanis and Karrow 1972). It has been suggested that glacial reworking of laminated silt-clay glacio-lacustrine sediment can result in a massive clayey silt diamicton (Hicock and Dreimanis 1992). This model of enhanced glacial flow in troughs that trap water and re-work accumulated mud at the glacier bed can be tested against the sedimentary record.

A characteristic feature of Great Lake basins is the widespread occurrence of mud-rich (silt-clay) diamictons (e.g., lakes Ontario and Huron, Fig. 1a), even though many of these basins contain minimal glacial sediment, and adjacent uplands may contain thick sandy sediments. For example, mud-rich Halton sediment is a typical lake bordering sequence. It onlaps thick sand and gravel of the Oak Ridges Moraine (ORM), an elevated deposit up to 300 m above modern Lake Ontario. Halton sediment is varied and consists of a complex stratigraphic package, distinguished by its upward transition from coarse ORM sediment to laminated mud to massive muddy diamicton, mud breccias and sand and gravel interbeds. Traditional interpretation, classification and naming of Halton Till have not included consideration and discussion of these sediment characteristics. Formal use of the term, Halton Till, was completed within a paradigm of till stratigraphy and a model of climatically-modulated ice marginal retreat (e.g., Dreimanis and Karrow 1972). Subsequent work on stratified moraines (Barnett et al. 1998), tunnel valleys (Brennand and Shaw 1994; Russell et al. 2003a,b), the advent of seismic profiles (e.g., Pugin et al. 1996) and continuous sediment cores (e.g., Sharpe et al. 2003; Knight et al. 2008) has radically changed our understanding of the deglacial Laurentide record in the ORM area.

Hence, there is a need to assess the sedimentology, landform association and depositional process models for Halton sediment within a regional event stratigraphic framework that considers the complexities of deglacial processes. For instance, a regional tunnel valley network has been interpreted to have funneled meltwater flow into the Great Lakes basin (Brennand and Shaw 1994), and, Shoemaker (1992) has hypothesized that Lake Ontario ponded water in a subglacial lake, thereby changing the ice sheet profile to an ice lid and dramatically influencing subsequent deglacial processes. The dearth of sediment in the Lake Ontario basin (Lewis and Todd 2015), and the elevated position of the Oak Ridges Moraine (up to 300 m above Lake

Ontario, Russell et al. 2005) and associated glaciolacustrine sediment, required grounded ice to prevent significant sedimentation into the Lake Ontario basin. Grounded ice, with lake-marginal pinning points, was needed to support raised water bodies in subglacial and ice marginal positions (Russell et al. 2003a; Sharpe et al. 2004). A continuous core just west of Lake Ontario appears to capture a complete Halton sedimentation record (Marich et al. 2011). Across Lake Ontario in western New York State, studies of Buffalo, Alden, and Niagara Falls moraines indicate a local glacial meltwater events that led to sand and gravel deposition at the ice sheet margin (Calkin 1970).

Understanding of Halton Till has also been confounded by confusion regarding the mapped extent and its constituent physical properties (Sharpe and Russell 2013). Original surface mapping of clayey silt Halton Till 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 (e.g., Karrow 1974), near Toronto (J.A. Westgate, unpublished Markham map, 1980; Fig. 1). In this area, diamicton originally mapped as Leaside Till was re-classified to Halton Till (Karrow 1974; Boyce et al. 1995). This mistaken re-classification of Halton Till (corrected by Sharpe and Barnett 1997; Fig. 3) as dense, stony, sandy silt till atop Scarborough Bluffs resulted in an incorrect conceptual landform model for this drumlinized unit (see Gwyn 1976; Sharpe et al. 1994, 2004). For example, Karrow (1967) used a depositional landform model for Halton Till based on fluting and drumlin formation to infer ice movement and deposition by ice flow from the southeast out of the Lake Ontario basin (Fig. 1b, c, Table 2). Boyce and Eyles (1991) also inferred that lake-bordering drumlins were formed of Halton Till sediment (see Fig. 1c), and that the drumlins were younger than the Oak Ridges Moraine, a discredited interpretation (Barnett et al. 1998) adapted from Gravenor (1957). In the Scarborough area the drumlinized till near Lake

Ontario is in fact Newmarket Till (Sharpe and Barnett 1997). Shallow W-NW-oriented fluting, however has been identified on the Halton surface southeast of the Trafalgar Moraine (Karrow 2005; Eyles et al. 2010).

Comprehensive re-mapping in the 1990's integrated digital elevation models (DEM) with subsurface data to support correlation and improved characterization of the physical properties of till units across the area (Sharpe et al. 1998). A regional digital elevation model (DEM) linked to a stratigraphic model also helped clarify landform-sediment relationships and provided a critical tool for stratigraphic correlation of Halton and Newmarket till units (Logan et al. 2006). Further, DEMs helped in the visual connection of regional terrain elements, such as the sweeping drumlin field orientation from Peterborough to Scarborough across areas of the ORM where drumlins are buried, including curvature in the flow path from ~NE-SW curving to ~NW-SE.

In the past 30 years, two developments necessitate that the fluctuating grounded-ice model be re-assessed: i) emerging understanding of the complexity of glacial processes (e.g., surging and bed deformation in addition to climate controls), and, ii) the role of meltwater storage and discharge events that likely influenced ice-sheet dynamics. These storage and discharge events include sheet floods and low-relief ice lobes (Shoemaker 1992; 1999, cross-cutting meltwater floods (Algonquin and Ontarian events) in the Lake Ontario basin including a curved flow path from NE to NW mapped from drumlins in and east of Toronto (Fig. 3, Shaw and Gilbert 1990; Lewis and Todd, 2015); a regional meltwater unconformity beneath ORM and across southeastern Ontario, Sharpe et al. 2004; subglacial lakes, Evatt et al. 2006; Wingham et al. 2006). The increased recognition of non-steady state meltwater discharge events to the formation of stratified moraines (e.g. Barnett et al. 1998) and the importance of high-quality data in deciphering events

in subsurface terrain (Pugin et al. 1999; Sharpe et al. 2002) is particularly significant to understanding Halton sediment.

In light of the complexity of glaciers interacting with water bodies in and around the Great Lakes, particularly Lake Ontario, and the control on deposition with respect to glacial sediment, process and chronology, there are three objectives for this paper:

- 1) document the sedimentary record and landform context of Halton sediment and related terrain elements on the north side of Lake Ontario,
- 2) assess the formative mechanisms for Halton sediment (and potential similar lake-bordering muddy sequences in Great Lake basins),
- 3) integrate Halton sediment into an event-sequence reconstruction for the Laurentide Ice Sheet deglacial history of the Lake Ontario basin, and
- 4) introduce the informal term, Halton formation, to cover the range of sediment facies that comprise Halton Till and associated sediment.

REGIONAL CONTEXT

Southern Ontario Quaternary framework

Southern Ontario has extensive, mainly glacial, sediment that covers Paleozoic bedrock (Fig. 1). Surficial geological mapping, in general, proceeded from landform mapping (Taylor 1913; Chapman and Putnam 1984) to mapping glacial lake features and till sheets (Karrow 1967). Widespread field investigations of shallow outcrops linked to aerial photograph interpretation resulted in a regional till stratigraphy and glacial geological history (e.g., Karrow 1974). The

surficial geology has been mapped on the basis of 18 units (OGS, 2003), such as till, glaciofluvial sand and gravel, and, glaciolacustrine sands and mud related to respective Great Lakes basins. This stratigraphic succession can be simplified to six units based on texture and stratigraphic relationships (Table 1; Fig. 3) to effectively characterize glacial sediments across southern Ontario (Fig. 1). The six units form primary stratigraphic elements for geological reconstruction, and include: i) sediments that predate regional (sandy) till, (e.g., Don, Scarborough, Thorncliffe formations), ii) regional sandy till (e.g., Catfish Creek, Newmarket tills), iii) glaciofluvial sediment (e.g. stratified moraines, Waterloo, Oak Ridges; spillways), iv) basin mud and muddy diamicton (e.g., Halton, St. Joseph tills), v) glaciolacustrine deposits, (e.g., Peel Ponds), and, vi) alluvium and organic material.

Prior to the 1990's, surface till correlation, lithostratigraphy, and paleo-lake-level mapping provided the basis for regional deglacial reconstructions (Karrow 1989). Many till units (2/3) mapped across southern Ontario (Barnett et al. 1991) are muddy diamictons with low gravel content (e.g., St. Joseph, Port Stanley, Allenwood, Halton, Wildfield, Kettleby). All of these units can be considered to be part of the clayey-silt basin mud and muddy diamicton unit and have similarities with Halton Till, such as stratigraphic position, texture, and facies associations (Table 2). A regional till unit, Catfish Creek Till, is extensively exposed at surface, and forms an important regional marker across most of southwestern Ontario (Karrow 1989; Barnett et al. 1991; Fig. 1a); east of Niagara Escarpment its equivalent is Newmarket Till (Sharpe et al. 2005). These two till units consist regionally of dense, stony, sandy silt diamicton that has been drumlinized. Catfish and Newmarket tills are overlain by stratified moraines (e.g. Oak Ridges Moraine, Waterloo Moraine, Paris, Orangeville and Oro Moraines), muddy and silty diamictons (e.g. Halton Till), and, glaciolacustrine deposits.

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 nearby 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 (GTA) and along the southern flank of the Oak Ridges Moraine (ORM) two regional till units have been mapped, Newmarket Till and Halton Till (Sharpe et al. 1997, 1999). However, some confusion surrounds the extent and stratigraphic relationship of these two units based on surface mapping techniques alone (Karrow 1974; Eyles 2002). For example, lack of subsurface data and isolated outcrops has resulted in regional correlation of disparate textural trends as facies transitions rather than as separate stratigraphic units (Sharpe and Russell 2013).

Under the climate-driven, oscillating grounded-ice model (e.g. Karrow 1967), till units across southern Ontario were interpreted as episodes of deposition during ice marginal fluctuation based on inferred deglacial landforms (Chapman and Putnam 1984). Thus, Halton Till strata (and similar strata bordering Great Lakes, e.g., St. Joseph, Port Stanley, Allenwood) were considered to represent late-glacial, ice-lobe re-advances that over-rode and re-worked fine-grained sediment that occurred between adjacent lake basins to the ORM (Fig. 1a). In the GTA, this traditional model has been challenged by the reinterpretation of the origin of the ORM and related strata (e.g. Barnett et al. 1998; Pugin et al. 1999; Russell et al. 2003a, b; Sharpe et al. 2004) that suggest that regional-scale meltwater storage and discharges events may have significantly influenced glacier dynamics (e.g., thinner ice sheets with lower gradients) and the style of the deglacial sequence. Nevertheless, recent studies of Halton formation (Halton Till and related sediments; Meyer and Eyles 2007; Eyles et al. 2010; MacLachlan and Eyles 2011) conclude that Halton formation formed as deforming beds in ice streams as the grounded Ontario

Lobe re-advanced during the Port Huron stadial, aided by ponded water against or above the Niagara Escarpment.

Other mechanisms have been proposed to explain lake-bordering flow patterns in addition to stadial advance-interstadial retreat include: marginal oscillation (Barnett 1992); surging (Clayton et al. 1985); subglacial floods (Shaw and Gilbert 1990; Colgan et al. 2003); floods influenced by subglacial lakes (Shoemaker, 1999); and ice streaming (Ross et al. 2006). These challenges to, or variations of, the existing climate-based, deglacial model, and analysis of recently assembled high-quality datasets prompt a revised stratigraphic framework and sediment facies relationships for Halton formation.

Greater Toronto Area stratigraphic framework

In the GTA the classic stratigraphic framework was developed from the Scarborough Bluffs (sub-Newmarket Till, e.g. Scarborough and Thorncliffe formations; Karrow 1967), inferred to extend northward to near Alliston (Eyles et al. 1985) and was confirmed by new subsurface data to pre-date the regional Newmarket Till (Figs. 2a, b; Karrow et al. 2001; Sharpe et al. 2003). Newmarket Till has been mapped as a regional unit from Lake Ontario 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; 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; Barnett et al. 1998; Pugin et al. 1999; Brennand et al. 2006). The incised valleys are partly infilled by glaciofluvial sediment following valley erosion (Brennand and Shaw 1994; Russell et al. 2003a) and in places are buried by Oak Ridges Moraine sediment (Russell et al. 2006a). Younger Halton Till, and its equivalents, Kettleby Till, and Wildfield Till, north and south of the Oak Ridges Moraine respectively, overlie the flanks of the

Oak Ridges Moraine (Figs. 2a, c). Thin, post-glacial, glaciolacustrine deposits are scattered across the area and a significant Lake Iroquois scarp (Figs. 2b, c) truncates Halton Till west of Scarborough Bluffs. Alluvial deposits also occur in incised modern valleys. This stratigraphy forms a regional event-stratigraphic framework mapped as four key units: i) sub Newmarket sediment (older sediment), ii) Newmarket Till, iii) ORM sediment, and iv) Halton Till sediment (now formation) (e.g. Russell et al. 2005a, b; Sharpe and Russell 2005a, b; Sharpe et al. 2007).

DATA SOURCES AND METHODS

Data for this study were compiled for regional groundwater assessment over a 20-year period (Table 2) from five distinct sources: i) archival well records, ii) legacy geological mapping, iii) sedimentological studies (e.g., mapping, drilling, outcrop), iv) hydrogeological investigations, and v) geophysical studies (Fig. 2). All data were integrated into a regional stratigraphic database that was maintained in one of two formats, a 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), location-corrected, water-well records and 1000's of Ontario Ministry of Transportation and Ontario Hydro borehole sites with geotechnical data. Higher quality hydrogeological data collected at IWA landfill sites (e.g., ~ 90 boreholes at ~12 sites, Interim Waste Authority 1994a,b, Fenco-MacLaren Inc. 1994; Gerber and Howard 2001; Gerber and Howard 1996) that included kilometres of continuous-core data, along with cores collected by Geological Survey of Canada (GSC) and others, provided important stratigraphic reference-site data (*see* Logan et al. 2002, 2006, 2008; Sharpe et al. 2003; Russell et al. 2005a,b; Knight et al. 2008). Legacy geological mapping was integrated from Ontario

Geological Survey with recent 1:20 000- and 1:50 000-scale mapping in the area (e.g., Barnett, and Dodge 1996) supported by approximately 1000–2500 ground-truth sites per 1: 50,000 scale map sheet (*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 (N value, Ontario Ministry of Transportation, unpublished records; Golder and Associates 1999).

Sedimentological analysis and a reference stratigraphic framework provided common threads for new geological mapping, section descriptions, and core logging (e.g., Barnett and Dodge 1996; Sharpe et al. 1997; Sharpe et al. 2003; Logan et al. 2008). Specifically, a suite of continuous cores (Fig. 3) across the region complement measured lake and river sections. This work supported the production of 1:50 000-scale digital geological maps across the region (Fig. 3), based on aerial photographic and digital elevation model interpretation (Sharpe et al. 1997). Geophysical data included: high-resolution seismic reflection (HRSR) profiling (> 50 line-kms) along road corridors and downhole geophysics in cored (~20) boreholes (e.g. Pugin et al. 1999; Pullan et al. 2000; Pugin et al. 2011). These large subsurface data sets have been incorporated into a regional, digital, 3-D geological framework of the area (e.g. Logan et al. 2005; Sharpe et al. 2007).

STUDY AREA: UNRAVELLING HALTON TILL

Mapping tills in the Greater Toronto Area

Work on shallow exposures by multiple geologists during the course of geological mapping in the 1960's and 70's (e.g. Karrow 1963,1974; Singer 1974; White 1975), with little regional perspective, led to a proliferation of mapped till units (e.g., Halton, Leaside, Humber, Wildfield, Newmarket, northern) with poor stratigraphic control in the GTA. 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 relate to early reliance on surface mapping, lack of 3-D data inland from Scarborough Bluffs, and use of inadequate conceptual models that were not tested against regional data. As a consequence, there has been a high degree of uncertainty in understanding the distribution and stratigraphic position of Newmarket and Halton tills (Fig. 4).

Halton Till distribution and terrain features

Halton Till was first described in Halton County north of Hamilton (Fig. 3), where it overlies red Queenston shale (Karrow 1959). It has a silt-rich matrix (20–76% silt; Table 3; Fig. 5), is interstratified with sand and silt, and has high shale content (Karrow 1987). Halton Till varies locally to sandy or clayey facies and is transitional upward into inter-bedded lacustrine sediments (Fig.5d). Costello and Walker (1972) noted at Cheltenham that glaciolacustrine sediment, varved clay, passes gradationally upward into the Halton Till. To the west below the Niagara Escarpment (Fig. 3), Halton Till occurs within small ridges of the Waterdown and Trafalgar moraines; minor fluting (southeast-northwest oriented) has been reported near the Trafalgar

moraine (Karrow 2005). Across the Niagara Peninsula, it is a stone-poor, clayey silt till, in part forming minor moraines (Fort Erie, Niagara, Vineland, Fenestra 1975). Halton Till has been traced across the region eastward from Hamilton using lithological 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); it conformably overlies the short, sandy Brampton esker (Saunderson and Jopling 1980). In this area Halton Till occurs as a 25 km wide band north of Lake Iroquois shoreline from the Niagara Escarpment to the Humber River (Fig. 3; Sharpe et al. 1997). From Humber River eastward to Pontypool it occurs as a progressively narrower belt a few kilometres wide along the south flank of the Oak Ridges Moraine and ~10 km north of the Iroquois shoreline (Fig. 3; Barnett and Dodge 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 (Fig. 3; Morrison personal communication, 2000). Along the Oak Ridges Moraine crest, Halton Till occurs in hummocky terrain to elevations over 350 m a.s.l. (Fig. 5h; Russell et al. 2005a); eastward however, Halton Till occurs along Lake Ontario at ~ 100 m asl.

In the Humber River watershed near Bolton a subfacies of Halton Till, Wildfield Till, has been mapped in the Gooseville Moraine (White 1975) and in the Trafalgar Moraine (Eyles et al. 2010). Halton Till identified beneath Trafalgar Moraine by Eyles et al. (2010) is not Halton Till; coarse grain size and northern provenance, compared to regional data, indicate it is more appropriately correlated with Newmarket Till (northern till of Boyce and Eyles 2000). This coarse-grained till is a sandy silt diamicton (51% silt, 36% sand, 8% clay; compare in Table 3,

this study) with granite and gneiss clasts from the Canadian Shield, 150 km to the north. The till described in the Trafalgar Moraine, Wildfield Till, has sediment properties of Halton Till (clast-poor, fine-grained texture: 18-34% clay 38-50% silt and 18-36% sand; compare with Table 3), and high gamma count); it has local provenance of lacustrine mud and Queenston shale (Eyles et al. 2010). Due to these properties we group Wildfield Till (White 1975; Watt 1968) with Halton sediment.

Newmarket Till

Newmarket Till, a regional stony (~5–15% gravel), dense, sandy-silt diamicton, can be clearly distinguished from Halton Till (Sharpe et al. 2005a). Of tills exposed at the land surface in the GTA, Newmarket Till is stratigraphically the lowest. It was originally mapped north of the Oak Ridges Moraine (Gwyn and DiLabio 1973) and it was later mapped in the subsurface and south to the Lake Ontario shoreline (Gwyn 1976; Sharpe and Barnett 1997; Fig. 6). Newmarket Till is commonly drumlinized, with a predominant north-northeast to south-southwest orientation (Boyce and Eyles 1991; Sharpe et al. 1997) that extend from Peterborough 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) on Lake Ontario (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, (Fig. 4a) is up to 50 m thick, or more, overlies regional beds of sand and silt of the Thorncliffe Formation (Fig. 2c) and underlies the Oak Ridges Moraine and Halton Till (Fig. 4b). Seismic data reveal a planar basal contact with underlying Thorncliffe Formation

sediments (Boyce et al. 1995; Pugin et al. 1999). It forms a continuous, diagnostic, high-velocity reflector (~2000 m/s) on seismic profiles and downhole-velocity logs (e.g., 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; Figs. 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 inter-beds (Sharpe et al. 1999; 2002b; 2005; *see* northern till of Boyce and Eyles 2000).

Geotechnical data collected along a 14 km section of highway traversing the Markham-Whitevale drumlinized till plain, portray very thin, discontinuous Halton Till and thick, continuous Newmarket Till (Fig. 3, M). These transect data confirm four consistent material properties of Newmarket Till in contrast with Halton Till: i) high density (N values, 50–100), ii) stoniness (5–15% clast content; Fig. 4a), iii) sandy (37%), silt matrix, and, iv) low water content (about 10%; Table 3). Deeper borings (5–50 m), 2–3 km apart at road and river intersections, provide stratigraphic certainty of Newmarket Till correlation and underlying silty sand Thorncliffe Formation beds (*see* Figs. 9a, 11c).

HALTON DATA

Halton sediment facies (formation)

Halton formation sediment forms a stratigraphic entity that comprises a complex assemblage of massive diamicton (Halton Till) and inter-stratified sediment with laminated mud, sand, and gravel that is up to 40 m thick. Halton sediment is highly variable and includes muddy, clast-

poor diamicton with inter-beds of stratified sediment and graded sand, silt, and clay rhythmites, with inter-beds of clayey-silt diamicton, sand and gravel. Due to this variability in facies and sedimentary setting, we refer to these sediments as the Halton formation.

The full breath of facies variability was observed from a suite of continuous cores (e.g., Figs. 3, 5, 6, 7, 9) and measured lake and river sections. The basal contact of the Halton sediment unit is defined by a sharp, abrupt transition where it is underlain by Newmarket Till and is commonly a gradational contact from small-scale cross-laminated sands and laminated muds to massive mud with increasing gravel content, initially granules with increasing pebble content upward where it overlies ORM (IWA 1994a, b; Russell et al. 2006a). Where gradational, Halton formation is considered to start with the transition from sand to mud. Overall, four facies, characterize Halton formation: i) diamicton, ii) laminated and/or banded silt-clay; iii) sand and gravel facies often inter-bedded with the first two; iv) deformed facies.

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 (Figs. 5a, b). It may occur in beds up to 15 m thick within Humber River watershed near Woodbridge. The contact with lower facies is variably sharp, inter-bedded, or gradational yet is rarely observed at the surface. The massive to faintly-laminated diamicton has minor silt and clay intra-clasts of 2–5 mm and sand intra-clasts of 5–10 cm (Fig. 7). Less than 2% of the gravel component is coarser than granules (Golder and Associates 1994). Pebbles are sub-rounded to sub-angular and consist of carbonate, siltstone, shale, and gneiss. Clasts occur in rare striated stone lines in south Humber River close to Lake Ontario and near Richmond Hill. Diamicton facies become finer grained and more massive upward; there is little gravel (<1%) and less inter-bedding upward (Fig. 7). Based on downhole geophysical data, Halton sediments display higher gamma and conductivity

signatures and lower magnetic susceptibility compared to ORM 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 intra-clasts. Rhythmite counts are in the order of < 100 silt-clay couplets. Silt beds vary from 1 mm to 3 cm thick and are sharp-based with minor amounts of sand at the contact (Figs. 5 c, d). Clay beds have gradational bases from silt, are massive and are commonly less than 5 mm thick, rarely exceeding 1 cm. Rare, 2–3 cm in diameter and smaller, dropstones are observed.

Sand and gravel facies: sand and gravel with thin inter-beds of diamicton and laminated silt-clay occur in sequences 1–10 m thick (Fig. 5c, d, e). Inter-bedding is observed in transitional contact with underlying Oak Ridges Moraine sand, gravel, and silt (Figs. 7), or in overlying laminated silt and fine sand beds. Sand and gravel facies occur as discontinuous horizons, 30 cm thick that are mainly fine ripple-drift laminated sand, medium-scale, cross-bedded and planar-laminated pebbly coarse sand (in part shown in Fig. 5g), and minor cross-bedded pebble and cobble gravel. The lower contact with diamicton facies is invariably abrupt (Fig. 5g). Rare trough structures eroded into underlying beds are filled with diamicton facies or gravel with intra-clasts of Halton diamicton. Paleoflow measurements have a range in orientation from northwest to northeast. These facies are common, yet discontinuous, mainly along southern margins of Halton formation.

Deformed facies: deformed laminated and diamicton facies are the least common sediment across the region and occur as 1–2 m thick contorted beds of silt and clay, locally overturned, yet intercalated with undeformed laminated sediment (Fig. 7). Diamicton may contain numerous,

slightly deformed and contorted water-bearing sand and silt lenses (Fig. 5f). Deformed diamicton inter-bedded with silt and clay laminations also occur in isolated mounds and ridges south of ORM. Near Oshawa, surface sandy silt diamicton reveal complex measured fabric patterns (Brennand, personal communication, 2013).

Halton Till grain-size composition

Halton (Fig. 5a) and Newmarket (Fig. 4a) tills can be clearly differentiated based on data collected from over 900 grain-size results for clay-silt-sand and gravel for diamicton facies. Halton Till has a clayey-silt to silt matrix grain-size with low (1–2%) stone content, compared to the coarser, stony (5–10%), and consistently sandy-textured Newmarket Till (Fig. 8a; Table 3). Near Markham and Scarborough, Halton Till was reported to have a sandy matrix (*see* Karrow (1970, 1967), Fig. 8b; Table 3); however, it has been remapped by Sharpe and Barnett (1997) as Newmarket Till. This apparent confusion is clarified by the correlation of borehole and river section data of sandy till northward beneath Oak Ridges Moraine (Fig. 2c, 4a,) and confirmation of Newmarket Till using outcrops with both units superimposed (Figs. 5g, 6). Consequently, some Halton Till grain-size data were re-classified to exclude this older, mis-identified sandy till (Table 3). Textural distinction between Halton and Newmarket tills is most obvious when gravel content (~4–9%) differential is considered, in conjunction with matrix texture (Table 3).

Grain size trends in Halton sediments are linked to paleoflow trends observed in underlying ORM gravelly sediments. Along an ~70 km EW transect, using continuous core (Fig. 9c), ORM sediments have increasing amounts of silt-clay westward: little silt or clay at Pontypool (Russell et al. 2003), <2 m at Glasgow (Fig. 11a), ~15 m at Bolton (Fig. 9c) and >25 m, silt-clay at Credit valley (Russell et al. 2006b). This trend in ORM sediment is reflected in

Halton formation texture described with increasing mud content from east to west. This regional east to west sediment fining appears to be linked to the upward-fining transition from ORM to Halton sediment and also to the observed thicker silt-clay sediment downflow to the west (e.g., Caledon, Fig. 9c).

Halton formation stratigraphic architecture

The stratigraphic architecture of Halton formation varies from west to east and north to south. In plan view, it forms a general comma-shaped body, most extensive in the west and curving northeastward along the ORM flanks (Figs. 3, 9). This distribution is marked by Halton draping to progressively higher elevations northward and by a transition in landscapes from a low-relief till plain to progressively more hummocky terrain (Fig. 5h) at higher elevations on the ORM (Fig. 9b). A regional-scale isopach surface highlights variable Halton sediment thickness with thinner sediment in the far east and southwest and thickest sediment northwest in the Caledon-Bolton area (about 40 m) and along the moraine flank (Fig. 9). This distribution in thickness is evident in local borehole clusters and surficial geological mapping (Figs. 3, 10). Where there is a gradational transition from underlying ORM strata, Halton sediment drapes the underlying ORM form by thinning over highs and filling lows and depressions (Fig. 10c). South of the ORM, Halton may discontinuously overlie drumlinized Newmarket Till, and it thins over bedrock in the southwest (Figs. 2c, 3). There is, thus, a pronounced north to south trend as Halton strata thin southward away from ORM; east of Humber River, they rarely occur adjacent to Lake Ontario (Fig. 3). Where Halton Till directly overlies Newmarket Till, with no intervening ORM sediment, stone content can best differentiate these tills (Figs. 5g, 6). For example, outcrops of Halton sediment, some with deformed sediment, are scattered across the

Newmarket Till surface between ORM and Lake Ontario (Brennand 1997; Sharpe 1988; Golder and Associates 1999).

INTERPERTATION

Halton formation linked to ORM sediments

New stratigraphic relationships (Figs. 2c; 7, 9c, 10, 11), improved resolution on regional sediment texture and physical characteristics (Figs. 5, 8), and 3D map extents (Figs. 3, 9) provide the basis to reconsider the interpretation of Halton sediment deposition. A central element of this understanding is the transitional basal contact, based on extensive core data, from sandy ORM sediment to laminated Halton sediment, and, stratigraphically upward to Halton diamicton and inter-bedded sorted sediment (Figs. 7, 9, 10, 11). Traditional interpretations of Halton Till have used near-surface sediment texture, low clast content and a depositional model of grounded ice advancing out of Lake Ontario basin (Karrow 1967; 1974; Eyles 2002). In light of the progressively-refined, event-stratigraphic model for the ORM area (e.g., regional unconformities, Sharpe et al. 2004; 2011) and improved understanding of depositional processes of ORM sediment (e.g., sub-aqueous fans, Barnett et al. 1998; rapid tunnel channel sedimentation, Russell et al. 2003a), it is necessary to revise the interpretation of paleo-ice-sheet dynamics during deglaciation. Our detailed results fail to support the long-standing paradigm that a lake-bordering drumlinized till surface records late-glacial flow and deposition of Halton Till from the Lake Ontario basin (Fig. 1b; Karrow 1967; Boyce and Eyles 2000). We suggest that deposition of

Halton sediment is primarily related to late ORM meltwater deposition, based on spatial distribution, facies transition, intercalated basal contact with ORM sediment, upward transition from sand to laminated sediment, inter-bedded to massive character, as well as local breccia beds with mud intra-clasts. In contrast, sites away from the focus of glaciofluvial sedimentation appear to have poor Halton sediment records such as along the south shore of Lake Ontario. The basal contact of sedimentary deposits (e.g. abrupt, gradational, intercalated) provides critical information on processes that may have proceeded or be related to the deposition of the overlying unit (e.g. Campbell 1967). The transitional sediment trends, based on logging of continuous cores (e.g., Fig. 7), from ORM sediment to laminated Halton to massive Halton diamicton records a continuum of depositional processes with only minor dis-conformable contacts; that is, the sequence is gradational yet the bed contacts are related to different processes (e.g., underflows) that may be sharp, inter-bedded or gradational.

The surface mapping and isopach maps of Halton formation (Figs. 3, 9a) illustrate key trends that support this interpretation and the development of a new depositional model. The transitional contact from ORM to Halton sediment indicates that Halton sediment was deposited in ice-marginal or sub-glacial, glaciolacustrine setting. An ice-marginal setting allowed space for transitions from sandy ORM to muddy Halton sediment, particularly in deeper western extents of the basin (many 10s of metres, Figs. 9c, 10c). A subaqueous setting is compatible with the westward expanding Halton and ORM geometry and sediment trends, which can be explained by east to west paleoflows in sandy, gravelly esker-like ORM sediment. Hence, predominant ORM sand-gravel grades upward and westward to Halton mud (Figs. 9c, 10c). Ice grounding produced diamicton with re-worked glaciolacustrine sediment (Humber Valley and west; Fig. 3) or as

primary basal sedimentation, till with local striated stone lines (Fig. 6), along the southern margin of ORM.

Halton formation stratigraphic and sediment model

An updated stratigraphic model (Fig. 2) and depositional setting (Fig. 12) for Halton sedimentation provides a process framework to explain Halton sediment facies and architecture. A grounded ice shelf (semi-buoyant) over the Lake Ontario basin controlled the westward flux of sediment along an expanding ORM axis (rather than sediment deposition into Lake Ontario basin), and then reworked these sediments by ice grounding line oscillation, sediment gravity flow, loading and related ice-marginal processes (Fig. 12). The Halton depositional setting was primarily ponded, within pro-glacial and sub-glacial glaciolacustrine settings in deep water supported by the Niagara Escarpment. The sediment model is dominated by subaqueous, gravity-driven debris-flow, underflow, suspension, minor ice-rafting, slope instability and by ice-loading/grounding processes, as supported by common inter-bedding, graded beds, facies transitions, fining-upward sedimentary style, massive grounded-ice deposition and minor deformation structures within Halton sediment (e.g., Figs. 5c, d, g, h; 9c, 10c). However, where Halton sediments are absent, patchy or discontinuous, glacier ice was likely grounded, sediment poor and allowed little if any space for sedimentation marginal to the position of the modern shoreline of Lake Ontario. For example, surface Newmarket Till near Oshawa has a disturbed (overprinted) fabric (Brennand inferred that Newmarket Till clast fabric was re-oriented by Halton ice, personal communication, 2013). Absence of Halton strata eastward of Humber valley is interpreted to define the position of securely grounded ice during westward flushing of fine-grained sediment along the axis of ORM. This is supported by predominant east to west

paleoflow directions in the ORM sediments beneath Halton sediment (Duckworth 1975, 1979; Sharpe and Russell 2005) that also correlate with an east to west fining of mapped ORM sediment from sand and gravel in the east to sand, silt and clay in the west (Fig. 9). Paleoflow indicators explain the east to west sediment geometry and trends in Halton formation sediments as they relate to the down-flow transport and deposition of large amounts of mud by the E-W ORM sediment flux. This is especially noticeable in the westward widening, thickening sediment wedge and fining grains sizes of Halton sediment (Figs. 3, 9).

The depositional model we propose explains why Halton and Oak Ridges Moraine sediments have closely related geometries in their east to west extent, thickness and sediment texture trends (Figs. 3, 9, 12). Previous models (Fig. 1b, c; Eyles 2002) proposed equal sediment influx from the north and south for the ORM with south-north-oriented paleo-flows for Halton sediment, features not observed in this study.

The proposed model explains the link between ORM sedimentation and Halton sedimentation. Stratigraphically, Halton sediment exhibits an upward sand-to-mud facies transition from underlying Oak Ridges Moraine sand and gravel sediments (Figs. 7, 9c, 10b, c). This transition links Halton sediments to the waning stages of glaciofluvial sedimentation that built the ORM (Barnett et al. 1998; Russell et al. 2003a). This interpretation is supported by sand-mud transition visible in cores from east to west (Figs. 7, 9, 10c). Halton sediment architecture is closely linked to ORM features: Halton formation drapes Oak Ridges Moraine ridges, hummocks, and flanks, and, fills depressions, basins and kettles on the moraine with conformable strata (Figs. 2c, d, 4b, 9b, c). Halton debris was also re-sedimented as buried ice blocks melted after being trapped in rapidly-deposited ORM sediment, now represented by kettle

lakes (Fig. 5h). Halton diamicton facies are interbedded upward into Halton glaciolacustrine sediments (Figs. 5 c, d). Hence, widespread inter-bedded, mud-rich, laminated Halton sediment (e.g., Figs. 5e, 7) that occurs conformably across ORM ridges and basins indicate a pervasive standing water body setting for ORM, Halton, and post-Halton sedimentation, perhaps with depths up to 100 m (Gilbert 1997).

No sedimentological evidence was observed to support the presence of Mackinaw interstadial beds (Barnett et al. 1998). Mackinaw beds identified in the southern Great Lakes basin have been used as the basis for a proposed climate forcing (re-advance due to cooling; Eyles 2002, equates Mackinaw interstadial with ORM) and inferences in the Lake Ontario basin have been linked to sand inter-beds in Halton sediment. It is commonly inferred that sandy beds within and/or below near-surface diamictons represent Mackinaw inter-stadial deposits (e.g. Meyer and Eyles 2007); however, such bedded sediments, and inter-bedded diamictons (debris flows rather than till beds) are common in glaciolacustrine basins produced by seasonal sedimentation, floods, slumps and dynamic ice-marginal events (e.g., Eyles and Eyles 1983; Hicock and Dremanis 1989). Furthermore, there is no sedimentological support for major ice-marginal retreat and re-advance, or for sediment with predominant grounded, subglacial ice properties (Table 4; sandy inter-beds are basin depositional facies not necessarily climate-forced Mackinaw inter-stadial deposits). Previous Halton models (see Fig. 1c) imply a grounded ice advance from the Lake Ontario basin, however there is no evidence of till deposited across lake-bordering areas. Furthermore, advancing grounded ice would have truncated underlying sediment as it rode up flanks of the ORM (to > 200 m above Lake Ontario levels), rather than leaving transitional sediment trends from ORM to Halton sediment (Figs. 10c, 11a).

The new late-glacial reconstructions explain the three-dimensional Halton sedimentological and stratigraphic data in the GTA (Figs. 7, 9, 10, 11). The tabulated results (Table 4) and re-configured paleo-geographic setting (Fig. 12), related to deposition of Halton sediments, can be related to a plausible succession of events (Table 5) that are compatible with key Halton formation sedimentary data (Table 4).

EVENT SEQUENCE AND PALEOGEOGRAPHIC RECONSTRUCTION

Recent related work has identified a regional unconformity linked to drumlins, tunnel valleys, and Oak Ridges Moraine (e.g., Russell et al. 2003a, 2006a; Sharpe et al. 2004; Brennand et al. 2006) based on a sequence of events for the late glacial landscape that involves a dynamic ice sheet with large-volume, sediment-laden, meltwater discharges (Table 5; Fig. 13). Presented data and the demonstrated relationship between ORM and Halton sediments support the integration of a Halton depositional model into the regional event model. Elements of this event model remain controversial, particularly the role of regional sub-glacial sheet floods (Shaw and Gilbert, 1990). Prior to 1996, it was considered physically impossible to sustain sheet floods; however, the plausibility of such sheet floods was supported by studies of the 1996 Icelandic jökulhlaup (Russell et al. 2007; Burke et al. 2008), and has subsequently been modeled for ice sheets (Flowers et al. 2004). Similarly, early suggestions of subglacial meltwater storage at the scale of Lake Ontario as proposed by Shoemaker (1992) have been supported (Evatt et al. 2006), adopted (Russell et al. 2003a), modelled (Livingston et al. 2013), and, regional events have been linked by dating meltwater discharge events (Lewis and Todd 2015) for eastern areas under the

former Laurentide Ice Sheet. Hence, large amounts of stored meltwater were likely available for ORM and related Halton sedimentation.

Event-sequence reconstruction of late glacial conditions

Key features in the late-glacial history, the revised distribution and sedimentary character of Halton formation (Table 5) are reviewed and illustrated in an event-sequence narrative and sketch (Fig. 13).

Prior to formation of the ORM, regional Newmarket Till was deposited subglacially during the maximum advance of the Laurentide Ice Sheet (Boyce and Eyles 2000; Sharpe et al. 2002). As this extensive late-glacial, ice cover started to thin and melt back /down, warming conditions produced excess meltwater that accumulated on and in depressions beneath the ice. As subglacial and supra-glacial storage increased, the opportunity for meltwater discharge increased (Shoemaker 1992). Analogues for both subglacial reservoirs and subglacial meltwater discharge between reservoirs are documented from Antarctica (e.g., Seigert et al. 2005; Fricker and Scambos 2009). Similarly, information regarding meltwater storage and drainage from supra-glacial sites to the glacial sole is documented from Greenland (Zwalley et al. 2002).

Formation of a regional unconformity and channel network

Stored meltwater was released as subglacial floods that eroded rock forms, sediment drumlins, and tunnel channels (Shaw and Sharpe 1987; Brennand and Shaw 1994; Sharpe et al. 2004). Of note, Shaw and Gilbert (1990) inferred a two-stage flow event; ~NS sheet-channel flow (Algonquin) event followed quickly by a lower-stage ~EW sheet-channel flow (Ontarian) event along the axis of Lake Ontario. Each flood quickly evolved to channel flow, based on theory (Shoemaker 1992) and field evidence (Sharpe et al. 2004), resulting in a channel network

(Fig. 13a) that focused discharge into larger and deeper channels (e.g. Russell et al. 2003a, b; Brennand et al. 2006), before eskers later formed in many of the widespread subglacial corridors or tunnel channels.

a) Tunnel channel sedimentation, lower Oak Ridges Moraine formation

Widespread, gravel and sand deposits in north-south-oriented ORM tunnel channels record rapid subglacial deposition of thick coarse-grained sediments (Russell et al. 2003a; Brennand et al. 2006; Fig. 13a). Subglacial water ponded in unfilled channels as the overlying ice lid sagged to upland surfaces and post-flood seasonal melt cycles deposited banded silt-clay couplets (rhythmites) as upper channel fill (Sharpe and Russell 2005).

b) Construction of the Oak Ridges Moraine Ridge

A re-profiled ice sheet, following reservoir draining and N-S channel cutting, then reservoir refilling, led to EW flow conditions that formed the ORM. A thinner ice sheet profile, in part induced by discharge along the axis of Lake Ontario (Lewis and Todd, 2015) and by a sub-glacial lake in the Lake Ontario basin (e.g. Shoemaker, 1992), resulted in an east to west ice sheet gradient. Floating ice across Lake Ontario basin with a grounding line north of the modern day Lake Ontario created a zone of weakness along the axis of Oak Ridges Moraine. Following reservoir filling, renewed rapid meltwater drainage produced confined high-energy, east-west flow that eroded a wide (kms) corridor and deposited gravel, sand, and mud along the central ORM ridge, overtopping Niagara Escarpment as outlet channels (Fig. 13b; Barnett et al. 1998; Russell et al. 2005). This large flood episode, dated at about ~16 cal ka (Lewis and Todd 2015), may have been similar to an Icelandic esker flood event (Burke et al. 2008) and in general, coarse sediment was deposited in the east and finer sediment (mud) in the west, as subglacial flow

entered deep water to form overlapping subaqueous fans (Russell et al. 2003a, 2006). As the flow waned, large amounts of mud settled predominately in the western ORM and in upper strata, trapped by grounded ice (Figs. 12, 13c). Gravel beds deposited at the base of a deep continuous stratified fining-upward sequence in Dundas valley (Marich et al. 2012) may be the downflow equivalent of the ORM E-W discharge event. Sand and gravel was observed in association with moraines on the southern side of Lake Ontario near Buffalo, correlated to ORM- Halton-age events (Calkin 1970).

c) Grounded ice on lake-bordering upland and deposition of Halton

Late-stage, fine-grained Oak Ridges Moraine sediments were deposited in transition to Halton sediments such as silty clay diamicton and inter-bedded with sand, silt, and clay (Fig. 7, 12). North of Lake Ontario basin, Halton sediment consists of deformed diamicton and glaciolacustrine mud disturbed during ice re-grounding episodes (Fig. 12); grounded ice also stressed the upper portion of the Newmarket till plain and its primary sediment fabric (Brennand personal communication, 2013). Grounded ice controlled formation of the short Brampton esker (Saunderson and Jopling 1980). Proglacial lacustrine sedimentation, including deformed clayey diamicton slumps (Brennand 1997) and minor ice-rafted sediments were deposited beyond the grounded-ice zone (Figs. 12, 13c). Glaciolacustrine sediment with dropstones is more common in the Lake Ontario basin (Lewis and Todd 2015).

d) Collapse of glacial ice in the Lake Ontario basin

Halton sedimentation ended when grounded ice lifted (Fig. 13d). The ice seal for the perched ORM basin water (Figs. 12, 13c) was removed and ponded water drained to equilibrate with the floating ice tongue over the Lake Ontario basin (Fig. 13d). Ice stagnated over the adjacent

landscape composed of drumlins, tunnel channels, and till plains, and, meltwater became trapped in small, shallow, ice marginal lakes (e.g. Peel Ponds, White 1975). Minor crevasse-fill ridges record sediment squeezed between stagnant ice masses on inter-channel till uplands (e.g. Barnett 1992). The fact that esker sediment was not deformed by this late glacial cover or by deposition of the draped Halton sediment (Saunderson and Jopling 1980; Brennand 1997) supports the event sequence model presented here.

DISCUSSION

Mechanism to explain lake-bordering flow patterns and sediments

Glacial landscapes adjacent to the large lakes in the Great Lakes basins have been affected by ice moving along the axis of lake basins and onto the adjoining land surface (e.g. Dreimanis and Karrow 1972; Fullerton 1980; Clayton et al. 1985). On land ice movement has long been considered to be related to the notion that depressions retained thicker ice masses, and accordingly, ice flowed upward and landward under this apparent gradient (see Fig. 1c). These same lake depressions, such as Lake Ontario however, have recently been considered to have stored water in sub-glacial reservoirs, particularly in late-glacial times (e.g., Shoemaker 1992; Evatt et al. 2006). Modelling results indicate that during deglaciation the ice sheet was likely to have more subglacial lakes than advancing ice-sheets (Livingstone et al. 2013). Such subglacial water bodies eliminate basal shear stress at the ice-bed interface and thus produce a flat, ‘floating’ ice surface profile over the sub-glacial lake as demonstrated with recent mapping in Antarctica (Siegert et al. 2005; Bell et al. 2007; Fricker and Scambos 2009).

650

651 A variety of mechanisms have been proposed to explain lake-bordering flow patterns; for
652 example, climate-induced stadial grounded ice advance-inter-stadial ice retreat (e.g., Barnett
653 1992), surging (Clayton et al. 1985; Colgan et al. 2003), ice streaming (Ross et al. 2006; Eyles et
654 al. 2015), subglacial floods (Shaw and Gilbert 1990; Shoemaker 1992; Cutler et al. 2002; Lewis
655 and Todd 2015), and grounded ice bed deformation (Eyles et al. 2010; Maclachan and Eyles
656 2011). Each mechanism and related process model was developed to explain lake-margin flow
657 patterns and sediments.

658

659 Rapid flow (surging), followed by ice stagnation, has been inferred to account for late glacial
660 flow along basin troughs in the Great Lakes region (Clayton, et al. 1985; Colgan et al. 2003). The
661 presence of low topographic relief, large, shallow, lake-basins and fine-grained sediment near
662 basin margins helped de-stabilize ice lobes as climates warmed and pro-glacial and sub-glacial
663 water accumulated. Such models cite the role of high, pro-glacial lake levels and the presence of
664 glaciolacustrine muds to enhance (lubricate) lake marginal ice movement. Thus, ice lobes are
665 inferred to have re-advanced, perhaps rapidly, over previously deposited fine-grained lacustrine
666 sediment to produce mud-rich subglacial tills (e.g., Halton Till, Karrow 1974; Meyer and Eyles
667 2007; Maclachan and Eyles 2011) and till moraines (White 1975; Karrow 1974; Eyles et al.
668 2010) and elsewhere in the Great Lakes basin (e.g. Michelson et al. 1981).

669 **Deformable beds**

670 A variant of the re-worked glaciolacustrine bed model and the deforming bed process model has
671 been suggested to explain deposition of Halton Till and formation of small moraines marginal to
672 the western end of Lake Ontario (Eyles et al. 2010; Maclachan and Eyles 2011). They suggest

that surging and /or ice stream flow along the axis of the Lake Ontario basin, resulted in the repeated incremental deposition of fine-grained debris as a deforming bed (Eyles et al. 2010) or that glaciolacustrine conditions prevailed, followed by deformation and deposition from over-riding Halton ice (MacLachlan and Eyles 2011). Massive diamicton could have been formed by a deforming bed process under elevated porewater pressure conditions (Iverson 2010) such as within Halton diamicton. While such conditions were likely common over much of the Great Lake basin (Alley 1991), rapid movement was probably not accompanied by wide-spread pervasive deformation of sub-ice sediment because stratigraphic sequences are generally intact, or, would only have occurred within till that did not contain lenses, inter-beds and clasts of unlithified bedded sand that would have been destroyed by pervasive shearing (Clayton et al. 1989). According to recent findings (e.g., Engelhardt and Kamb 1998; Iverson et al. 2007), such pore-water induced deformation is most likely to occur as thin beds (< 1m thick). While inferred metre-thick deforming beds (e.g., Eyles et al. 2010) may not be representative of true conditions from Antarctic ice stream beds (Alley 2000), others suggest that deformation found in tills is a cumulative effect of strain within relatively thin, deforming spots under the ice sole which accrete during ice over-riding (Piotrowski et al. 2004).

Nevertheless, if we assume that till deformation occurred in some Halton sediments (massive diamicton member), sediment associations should be compatible with the basin sedimentary processes presented in this paper. In the Trafalgar Moraine area, Wildfield Till (interpreted to be Halton Till; Table 2) forms a wedge-like till volume (~ 4 x 15 km area, ~ 2-16 m thick), with micro-deformation structures and a dimpled, 'brain-like' surface appearance up flow of weakly fluted terrain (Karrow 2005; Eyles et al. 2010). These characteristics are inferred to relate to a short-lived ice re-advance on a subglacial deforming layer within a proposed ice stream

advancing along and out of the Lake Ontario basin (flow model depicted in figure 1c; Eyles 2002). This process model was inferred to have basin wide implications; however, the till volume (~0.8 cu km) in the Trafalgar Moraine is several orders of magnitude smaller than Halton sediment represented in this study (Fig. 9). It is not clear why moraines would not be present along more of the lake-bordering terrain east from Trafalgar Moraines (Fig. 3), if this were a significant process with basin implications. Across Lake Ontario, small moraines near Buffalo are mainly sand and gravel (Calkin 1970; Cadwell 1988). In addition, Halton sediments draped onto ORM sand and gravel ~50 km onshore from, and ~200 m above Lake Ontario, are not in accord with the inferred significant Ontario lobe re-advance to the position of the Trafalgar moraine just 10 km inland and 20 m above Lake Ontario.

The Trafalgar Moraine (and similar Gooseville, Watertown moraines, Fig. 3) likely represents a grounding line position than a significant ice stream re-advance from the Lake Ontario basin. Karrow (2005), however, calls Trafalgar a minor retreat moraine. The dimpled, brain-like landscape pattern, reported at Trafalgar Moraine, is typical of ice-pressed terrain features observed in ice stagnant or low-flow glacial settings (e.g. Gravenor 1955); such features would be consistent with interpreted deformation structures within wet, fine-grained subglacial sediment. Ice-pressed features are observed in Halton sediment (Fig. 5h) in the Oshawa area (Brennand 1997) and in similar muddy diamicton (St. Joseph Till) sediments along the shores of Lake Huron (Sharpe and Edwards 1979). These interpreted ice-pressed deformed sediments and those associated with the Trafalgar Moraine would be compatible with deformation from a lake-bordering, ice shelf, grounding line as depicted in figure 12. The ice shelf /lid scenario is supported by the likelihood of subglacial lakes in the Ontario basin based on field data (Russell,

2003a; Lewis and Todd, 2015; this study) and inferred from theory (e.g., Shoemaker 1992, 1999; Evatt et al. 2006). Subsequent modeling by Livingstone et al. (2013) highlights the importance of subglacial lakes as a controlling factor on glacial flow, a factor that is not compatible with the inference of predominant grounded ice, deformable glacier bed processes in a surge or ice stream bordering and along the axis of Lake Ontario (e.g., Eyles et al. 2015).

Grounded or floating ice in Lake Ontario basin and beyond

Does the floating or grounded ice model apply beyond the study area? A recent re-construction west of the Lake Ontario basin favoured the advancing, fully-grounded ice model. A model of progressive deformation of over-ridden glaciolacustrine sediment is used to explain formation of Halton strata (MacLachlan and Eyles 2011) above the Niagara Peninsula (Fig. 1a). They infer that thick grounded ice of the Ontario Lobe advanced following the Mackinaw inter-stadial and ponded pro-glacial water against and over the Niagara Escarpment. In contrast, the proposed depositional setting illustrated in Figure 12 emphasizes an ice shelf related to a subglacial lake in the Ontario basin, as meltwater collected in lake depressions during late-glacial conditions (e.g., Shoemaker 1992; Livingstone et al. 2013). Late glacial ice in the Great Lakes area is considered by many to have been thin as well as mobile (e.g., Alley 1991): a thin ice profile would not have the mass nor gradient to prevent subglacial water bodies from developing in depressions of the Great Lake basins (Shoemaker 1992). Hence, it appears unlikely that late-glacial, fully-grounded ice re-advanced from such lake basins.

The floating ice/ grounding line model proposed in this paper adequately accounts for the focused and modest sedimentation reported in late sequences at lake-border settings. The model

accounts for the relatively undeformed sequence reported from the Niagara Peninsula: undeformed silt and clay beneath brecciated silt-clay within a 5 m interval (MacLachlan and Eyles 2011). In this model, deformed silt clasts represent slump breccia, debris flows or ice shelf disturbances. The floating ice model can also explain nearby till moraines as expected grounding line pinning-points focused at escarpment-edge positions such as the Vinemount Moraine, and similar small moraines (e.g., Niagara, Fort Erie, Fenestra 1975). Furthermore, there is no evidence of significant re-advance associated with small Halton till moraines to the north (e.g., Trafalgar, Watertown, Gooseville, Karrow 2005). These till ridges are likely pinning point moraines, perhaps ice shelf 'till deltas' as inferred by Alley et al. 1989. In classic ice shelf models, a floating terminus occurs beyond a debris-rich, grounded, cold to temperate ice flux (Mayerle and Powell, 2015); whereas in Lake Ontario basin, the ice shelf floated across ponded water to a sediment-poor, lake-edge grounding line. Laminated glaciolacustrine sediment with dropstones occurs in Lake Ontario basin on drumlins in Newmarket Till (Lewis and Todd 2015). Thus, the Lake Ontario ice shelf model also accounts for the absence of Halton glacial sediment over considerable lake-border area where distal ORM meltwater mud was not trapped or local sediment reworked. Such areas occur from Toronto eastward beyond Oshawa, and, along the south coast of Lake Ontario where drumlins with Newmarket Till-like properties form the surface sediment (Cadwell 1988).

Analysis of events on the south side of Lake Ontario are hampered due to the lack of high-quality subsurface datasets (e.g., cored boreholes) compared to those on the north side of Lake Ontario. Reports of sand and gravel associated with moraines on the southern side of Lake Ontario near Buffalo (Calkin 1970) may be correlative with ORM- Halton-age meltwater events, due to the

Alden moraine being correlated with Halton Till (Fullerton 1980), based primarily on landform types.

West of Lake Ontario in Dundas Valley, the Copeland borehole records ~200 m of sediment, with the top 60 m identified as Halton sediment (Marich et al. 2011). Here, the Halton interval comprises an interbedded sequence of sand, silt, clay and diamicton that is analogous to sequences of Halton formation described in this study. The continuous Halton interval only has syn-depositional disturbance and diamictons occur as inter-bedded debris flows. Marich et al. (2011) report ~120 m of rhythmically-bedded silt, clay and fine sand, which combined with the upper 60 m, is comparable to the 180 m thick Halton formation-ORM sequence at Caledon East (Fig. 9c, 1). Both sequences fine upwards from 10-25 m of gravel at the base of uninterrupted, conformable cored sequences. Hence, the lower 140 m of the Copeland sequence could be considered distal ORM equivalent meltwater sediments (Ontarian flood event?). Meltwater activity of the ORM flood events may not be recorded on the south side of the Lake Ontario; yet, the Ontarian event eroded sediments along the axis of Lake Ontario and into Lake Erie (Lewis and Todd 2015) and likely deposited a Halton formation sequence at the western end of the lake basin at Copeland. Thus, it appears that the sedimentary record is not in support of a late-glacial, grounded-ice, re-advanced from the Lake Ontario basin.

The floating ice (shelf)/ grounding line model proposed here may not be suitable to explain lake-bordering sediment sequences in all Great Lakes basins. Ice shelves are often associated with cold ice, although temperate ice shelves can not be ruled out (Alley et al. 1989; Mayerle and Powell 2015). Shoemaker (1992, 1999) in his detailed analysis of subglacial lakes in Great

Lakes basin refers to ice lids over water-filled depressions. In order to exclude late glacial ORM sedimentation (at ~300 m asl) from being deposited in the Lake Ontario basin (~75 m asl), a grounding line is required. Detailed sedimentary evidence observed in the GTA has assisted in identifying conditions that apply beyond the study area. These include large depressions to store sub-glacial and or proglacial water and glaciofluvial sedimentation events that introduce large amounts of fine-grained sediment to ice-marginal settings (Hicock and Dreimanis 1992). Further, depressions need to be deep enough to lead to ice shelf /ice lid conditions. Sediments deposited as a result of these conditions occur in a narrow belt of muddy sediment (St. Joseph Till), observed along the eastern shores of Lake Huron (Fig. 1). At this location, Sharpe and Edwards (1979) reported a 10-30 m thick gravel sequence overlain conformably by 20-30 m of laminated to massive mud with rare dropstones. St Joseph's Till is similar to Halton formation sediment with inter-bedded clay-silt and fine sand with intercalated diamicton (till and debris flows) in the upper 5-10 m of the sequences.

When tested against the sedimentary record the grounded-ice model of enhanced glacial flow in troughs and re-worked mud at the glacier bed requires considerable revision that takes account of trapped water bodies and ice shelf processes more than grounded ice processes.

CONCLUSIONS

We propose that Halton Till and associated sediments be renamed, Halton formation. A revised depositional model for Halton formation explains its regional context, stratigraphic setting,

reduced extent, sediment thickness trends, variable lithology and predominant glaciolacustrine character. This revised model also explains both form and facies trends such as upward transition from, and inter-bedding with, underlying sandy Oak Ridges Moraine sediment which was derived from high-energy meltwater discharge events. The glaciolacustrine sedimentation and stratigraphic model provides a predictive framework for assessing lake-bordering sequences in the Lake Ontario basin. Our depositional model, which accounts for deposition of Halton formation, is the result of our interpretative paleo-geographic setting that includes a sub-glacial lake with a floating ice lid over Lake Ontario and grounded ice along the basin margin. Significant east to west meltwater flow associated with ORM delivered mud to western regions of Halton sedimentation during late stages of construction of Oak Ridges Moraine, at about ~16 cal ka. Mud deposited from waning Oak Ridges Moraine (suspension) sedimentation was partially reworked by grounded Halton ice, debris-flow, and other ice shelf and ice marginal processes.

Halton formation sediment is absent from significant portions of terrain bordering Lake Ontario. Previously mapped Halton Till in some of the area is recognized to be older Newmarket Till. Hence, the classical concept of re-advance of thick, grounded glacier ice and deposition of drumlins from the Lake Ontario basin cannot explain the sedimentary character and distribution of Halton sediments. However, a glaciolacustrine-focused depositional model including debris-flow and inter-bedded, fining-upward, and fine-textured character of Halton formation sediment does explain observed sedimentary facies. Recently inferred regional bed deformation models in the Ontario basin (e.g., Eyles et al. 2010; MacLachlan and Eyles 2011) do not explain the extent, facies, facies trends, architecture and distribution of Halton sediment. In addition, models of late-

glacial subglacial lakes in the Lake Ontario basin (Shoemaker 1999; Livingstone et al. 2013) provide important theoretical and contextual support for the glacio-dynamic setting for the depositional model derived from a wealth of high-quality field observations and data.

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- 1197

1198 **Table captions**

1199

1200 **Table 1.** Simple Quaternary stratigraphy of southern Ontario.

1201 **Table 2.** Tills of the Greater Toronto Area.

1202 **Table 3.** Grain-size data for Halton Till.

1203 **Table 4.** Summary of sedimentary attributes and implications regarding Halton (Till) sediment.

1204 **Table 5.** Regional event sequence for Halton Till sedimentation.

1205 **Figure captions**

1206 **Figure 1. a)** Location map and general geology of southern Ontario. Halton, St. Joseph, and
1207 Allenwood mud-rich diamictons (tills) and ice and/or lake marginal muddy strata rest on regional
1208 sandy tills (Catfish Creek, Elma, Newmarket; *after* Barnett et al. 1991). Paleozoic bedrock (2)
1209 and Canadian Shield (1) have little glacial sediment; **b)** Traditional stratigraphic-depositional
1210 model of the Greater Toronto Area (*after* Eyles 2002); **c)** Flow lines depict the traditional
1211 inferred re-advance of Ontario lobe ice to deposit drumlinized Halton Till across the area south
1212 of Oak Ridges Moraine (*after* Boyce and Eyles 2000). Compare conceptual Halton Till
1213 distribution in figure 2b with that from detailed mapping in figure 3.

1214 **Figure 2.** Stratigraphy in the Greater Toronto Area: **a)** Conceptual geological model of Late
1215 Wisconsinan strata, Newmarket Till, tunnel channels (yellow) and Oak Ridges Moraine (ORM)
1216 sediments, and Halton Till (formation), which overlie older strata (not shown), and Paleozoic
1217 shale and carbonate. **b)** Location of N-S section. Section extends from north of ORM to Lake
1218 Ontario east of Scarborough Bluffs. **c)** North-south cross-section (Sharpe et al. 1994; *see also*

1219 Barnett et al. 1998) of regional distribution of Newmarket Till from Lake Ontario bluffs north,
1220 beneath the Oak Ridges Moraine, to the drumlinized uplands of the Peterborough drumlin field.
1221 Halton Till (formation) occurs as thin sediments on the south flank of the Oak Ridges Moraine;
1222 thin glaciolacustrine sediments occur on Halton Till (formation) and the Newmarket Till plain to
1223 the south, above the glacial Lake Iroquois shoreline.

1224 **Figure 3.** Simplified geology of the Greater Toronto Area from Sharpe et al. 1998); note
1225 distribution of Halton Till and its relationship with (older) Newmarket Till and Oak Ridges
1226 Moraine (ORM) sediments, with cored borehole locations. Note also, northeast-southwest
1227 drumlin orientation north and south of Oak Ridges Moraine along its eastern flanks. These
1228 drumlins are part of the Peterborough drumlin field. Northwest-southeast-oriented forms, south
1229 of Oak Ridges Moraine, occur on the same till surface (Newmarket) east of the Humber River
1230 valley (HV). Locations mentioned in the text are identified in letters: NE = Niagara Escarpment,
1231 GM = Gooseville Moraine, TM = Trafalgar Moraine (includes Waterdown Moraine, not shown
1232 separately), VM= Vinemount Moraine, B = Bolton, Br = Brampton, C= Caledon, CV= Credit
1233 Valley, DV= Dundas Valley, G = Glasglow, K = Kleinburg, M = Markham, MS = Maple Spur of
1234 ORM, Ma= Maple, RH = Richmond Hill, SB = Scarborough Bluffs, Bb = Bowmanville bluffs, P
1235 = Peterborough; Po=Pontypool, V=Vaughan, W = Woodbridge. Note that sections in Figure 9
1236 are located at: a) 1 km east of RH, b) 5 km north RH, c) 3–5 km northwest of Maple (Ma). Sites
1237 of images Figs. 6a, 6b are also shown. Note that glaciofluvial sediment outside ORM is orange
1238 with no red outline.

1239 **Figure 4. a)** Newmarket Till: massive, stony sandy diamicton (trowel is about 10 cm);
1240 photograph by D. Sharpe; GSC-2012–140A; **b)** Halton Till (HT) rests conformably (dashed line)

1241 on Oak Ridges Moraine cross-bedded sand; S = spoil; a = soil (section is about 8 m high);
1242 photograph by D. Sharpe; GSC-2012–140B.

1243 **Figure 5.** Photographs of Halton Till sediment facies and terrain: **a)** massive, stone-poor, silty
1244 diamicton; photograph by H. Russell; GSC-2012–141A; scale bar is 30 cm across; **b)** massive,
1245 silt diamicton; 1–2% clasts; photograph by D. Sharpe; GSC-2012–141B; scale bar is 6 cm
1246 across; **c)** diamicton, inter-bedded silt, fine sand (knife, *see* arrow, is about 8 cm); photograph
1247 by D. Sharpe; GSC-2012–141C; **d)** laminated silt; transition to diamicton, d (hammer about
1248 15 cm); photograph by D. Sharpe; GSC-2012–141D; **e)** banded silt and minor clay; photograph
1249 by H. Russell; GSC-2012–141E; scale bar is 3 cm across; **f)** Halton Till (d) with large sand inter-
1250 bed (s); photograph by D. Sharpe; GSC-2012–141H; sand lens is ~4 m across; **g)** Halton Till (d)
1251 with interbedded sand (s) over stony Newmarket Till (n); photograph by D. Sharpe; GSC 2012–
1252 141G; staff is 2 m high; **h)** hummocky terrain with a kettle lake near Oak Ridges; dark-light
1253 areas in fields indicate moisture differences; lake is approximately 400 m wide; photograph by
1254 F. Johnson; GSC-2012–141F.

1255 **Figure 6.** **a)** Halton Till, stone-poor, silt diamicton (*see* person at top) rests abruptly on sandy,
1256 stony diamicton (ds), massive diamicton (d) resting on carbonate-shale bedrock (b); Etobicoke
1257 Creek, south Humber River valley; photograph by D. Sharpe; GSC- 2012–143; **b)** Measured
1258 section 10 km to the north, on Etobicoke Creek, south Humber River valley of Halton Till and
1259 related formation sediments over dense, stony Humber till; this local till is correlated with
1260 Newmarket Till (NT). Locations shown on Fig. 3.

1261 **Figure 7.** Kleinberg continuous core and photographs; sediment log is upper 44 m, extending
1262 from Oak Ridges Moraine (ORM) sand and silt, upward to inter-bedded Halton formation

1263 diamicton and laminated sediment. Photographs illustrate key sediment facies; 1= massive sandy
 1264 diamicton, 2= diamicton breccia, 3= deformed mud diamicton, 4= deformed sand, silt
 1265 rhythmites, 5= massive clay-silt diamicton, 6= stratified sand; photographs by C. Logan, GSC-
 1266 2012–142.

1267 **Figure 8.** Comparative grain-size plot of Halton and Newmarket tills: **a)** matrix grain-size plots
 1268 with stratigraphic correction and adjustment for gravel fraction. The plot generalizes Halton
 1269 (>275) and Newmarket (>700) till analyses; **b)** grain-size plot of Halton Till with samples re-
 1270 classified as Newmarket Till (black dots), N= average Newmarket Till. Literature sources of data
 1271 for figure 8a: a) Markham (N=10; J.A. Westgate unpub. map, 1980); b) Markham (N=9; Sibul et
 1272 al.1977), c) Oshawa (Singer, 1974); d) Scarborough (N=11; Karrow, 1967); e) Markham (N=7;
 1273 Sharpe, et al. 1994); f) Brampton (N=2; Karrow 1991); g) Hamilton (N=1; Karrow 1989); i)
 1274 Oshawa (N=8; Brennand unpublished). Literature sources in Figure 8b: 6, Vaughan (Interim
 1275 Waste Authority, 1994a, b); 5, Carville (Maple spur, MS); 4, Thornhill (Karrow 1970); 3, Bolton
 1276 (White 1975). See figure 3 for site locations.

1277 **Figure 9.** **a)** Isopach map of Halton sediments based on regional stratigraphic data (Logan et al.
 1278 2002, 2005); note distribution of thickness is similar to Oak Ridges Moraine extent (Fig. 3),
 1279 except for the southwest. Note that thickness map shows light tones (<30 m) and dark tones (up
 1280 to 75 m). **b)** North-south section A-A' shows Halton draped on Oak Ridges Moraine (ORM)
 1281 sediment in the north and on bedrock in the south. LS = lower sediment. **c)** Continuous cores
 1282 from Credit Valley (1), Vaughan (2), and Glasglow (3) intercept thick sediment sequence
 1283 transitions from Oak Ridges Moraine to Halton sediments; HT = Halton Till, ORM = Oak
 1284 Ridges Moraine, NT = Newmarket Till, TF = Thorncliffe Formation. Note that ~ 80 m of mud

comprises the upper ORM sediments below Halton formation at site 1, Credit Valley. This provided fine-grained sediment for Halton formation. Cores locations are shown in figure 9 a.

Figure 10. Stratigraphic cross-sections based on boreholes of stratigraphic relationship of Halton sediment (*see* Fig. 3 for locations, or 10c, inset): **a)** Eight borehole cores up to 60 m deep across a ~ 500 m long WE transect southeast of Richmond Hill on the flank of the ORM intercept an undulating Newmarket Till surface, Oak Ridges Moraine sediment and Halton formation (inter-bedded stratified sediments not shown). **b)** Fifty cored boreholes northwest of Richmond Hill intercepts 2–20 m thick inter-bedded Halton sediment. Inter-bedded stratified sediments consist of multiple units of sand, silt and diamicton, which conformably overlie thick (<40 m) Oak Ridges Moraine sand and silt (dashed line), and, Newmarket Till (NT). Note that colours in Figures 10b and 10c indicate lithology illustrated on the map below (Fig. 10c). **c)** Four cored boreholes in the Humber River watershed with sandy Oak Ridges Moraine sediment transitional upward to inter-bedded Halton formation diamicton and silt and sand; strata thicken westward with a basin-fill geometry (*after* Russell et al. 2005, Fig. 7). Note that g= gravel.

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 (undeformed silt beds) to Halton Till (OGS-92-19: P.J. Barnett unpub. data, 1993). The Glasgow reference site occurs north of Newmarket Till plain (*see* 11b), exposed in section nearby (*see* Fig. 4a). **b)** North-south stratigraphic section provides context for reference site OGS-92-19 with a N-S transect from Glasglow to Whitevale (*see* Fig. 3 and inset location map). Halton formation was mapped as a stone-poor, silt till with laminated silt, clay, and fine sand inter-beds at tens of field sites along this transect (*see* Barnett and Dodge 1996). **c)** Highway 407 at Markham (Rouge

1307 River): portion of about 15 km transect across Newmarket Till is shown at the surface of the
1308 former Halton Till plain of Karrow 1970; Boyce and Eyles 2000; Fig. 2b, d), now identified as a
1309 drumlinized Newmarket Till surface. Section displays stratigraphic sequence to bedrock: top
1310 down; Newmarket Till, Thorncliffe sand, Sunnybrook Till, York Till, Whitby shale.

1311 **Figure 12.** Halton depositional setting: **a)** Oak Ridges Moraine (ORM) paleo-geographic setting
1312 with buoyant Lake Ontario ice shelf grounded along the lake margin; east to west flow (white
1313 arrow) transported mud to western regions during formation of Oak Ridges Moraine; H is margin
1314 of Halton sedimentation; gL marks position of grounding line; **b)** cross-section of the Halton
1315 grounded-ice position as buoyant forces suspend the floating ice shelf to minimum contact on
1316 marginal Oak Ridges Moraine sediments but remains grounded inboard toward Lake Ontario
1317 basin on Newmarket Till as water levels fluctuated (vertical black arrow). Suspended mud (S)
1318 from waning Oak Ridges Moraine sedimentation is reworked by grounded Halton ice, debris-
1319 flow (white arrow), and other ice-marginal processes. The section is oriented approximately east-
1320 west. PL = pro-glacial lake, SL = subglacial lake; H = Halton, NT = Newmarket Till,
1321 NE = Niagara Escarpment.

1322 **Figure 13.** Simplified event sequence reconstruction:
1323 **a)** high-energy Oak Ridges Moraine (ORM) north-south, sub-glacial channel sedimentation
1324 (orange unit) into subglacial lake (SL);
1325 **b)** formation of the Oak Ridges Moraine ridge sediment (yellow) with east to west flow;
1326 grounding line at margin of subglacial lake (SL) to south prevents sedimentation into Lake
1327 Ontario basin.

1328 **c)** mud (blue) transport and deposition at end of Oak Ridges Moraine sedimentation and prior to
1329 Halton formation reworking; and,

1330 **d)** collapse of Lake Ontario ice lid; formation of ice marginal lakes. H and the green areas
1331 represent Halton formation; PL = pro-glacial lake, SL = sub-glacial lake.

1332 This event sequence is linked to more details in Table 5, Regional event sequence for Halton
1333 sedimentation.

Draft

figure 6

figure 9

figure 10

figure 11

figure 12

Table 1 Simple Quaternary stratigraphy of southern Ontario

<i>Unit</i>	<i>Age</i>	<i>Description</i>	<i>Lithology</i>
6	Modern	alluvium/ organics	sand, silt, organics
5	Late glacial	basin sand (glaciolacustrine)	sand, silt (lake plain)
4	Late glacial	basin mud/ till	mud, diamicton (lake plain)
3	Late glacial (channels)	glaciofluvial sediment	sand and gravel
2	Late Wisconsinan (drumlinized)	regional till (e.g. Catfish Creek)	stone, sand-silt till
1	Pre-Late Wisconsinan	pre-regional till sediment	till, mud, sand-gravel (buried)

Draft

Table 2 Tills of the Greater Toronto Area

Name -type area, (reference)	Lithofacies	Reported association	Correlation
Kettleby -Bolton, (White, 1975)	<i>silt, clay, mud diamicton</i>	-mainly mud and mud-rich diamicton with < 1 % clasts -inferred Halton equivalent north of the ORM	Halton
Halton¹ -near Hamilton, (Karrow, 1959)	<i>silt, clay, mud diamicton; local inter- bedded sand-silt diamicton (Fig. 5)</i>	-silty with < 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 (Westgate, unpublished field notes and map). -this mapping gap left no designed main late-glacial till (~25 to 12 Ka) in GTA (e.g. lower Leaside).	Halton
Wentworth -near Hamilton (Karrow, 1959)	<i>dense, stony sand-silt till</i>	- from Hamilton to Brampton, Halton Till is distinguished from underlying Wentworth Till	Newmarket
Leaside Upper and Lower (Scarborough Karrow, 1967)	<i>dense, stony sand-silt till</i>	-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 (IWA, 1994), or, Halton and northern tills (Boyce et al., 1995; 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)	<i>dense, stony sand-silt till (Fig. 6b)</i>	-at Brampton, Karrow, 1991 correlated a dense, stony, sand till (Humber till); identified by Dreimanis, 1964; Sharpe, 1980 below Halton Till	Newmarket
Newmarket Till (Newmarket Gwyn and DiLabio, 1973)	<i>dense, stony sand till (Fig. 4a)</i>	-sandy silt, stone-rich drumlinized till -mapped north of ORM (Gwyn 1976), southward beneath ORM (e.g. Bowmanville Till, east of Scarborough (Fig. 3). -north of Scarborough, former Leaside Till was traced (Fig. 2b) beneath ORM (Sharpe and Barnett, 1997) and correlated with Newmarket Till (Fig. 3; Sharpe et al., 1994)	Newmarket
Bowmanville Till , -Bowmanville (Brookfield et al. 1982)	<i>dense, stony sand till</i>	-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	<i>stony sand- silt till (Fig. 6a)</i>	-dense, sandy till resting on bedrock (west of Toronto) with no overlying sediment can be interpreted as any age -Fig. 6a may be older stoney till, with overlying Halton	Newmarket, or 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 ORM region.

Table 3 Grain size data for Halton Till¹

Area	Author	Samples N #	Sand	Silt	Clay	Gravel (est)	Comments		
1. Hamilton	(Karrow, 1987)	39	20	49	31				
2. Brampton	(Karrow, 1991)	40	25	53	22	1-3			
3. Bolton	(White, 1975)	98	30	50	20				
4. Thornhill	(Karrow, 1970)	7	18	44	38				
5. Carville	(consult.)	11	18	44	38				
6. Vaughan	(IWA, 1994)	50	20	50	30	5			
7. Markham	(Sharpe, et al., 1994)	12	19	53	28	1-3			
8. Bolton-Oshawa (GSC, 1994)		<u>24</u>	<u>17</u>	<u>76</u>	<u>7</u>		<u>-silt facies - Humber R.</u>		
9. Markham	(Sibul, 1977)	9	34	45	21		<i>-mixed samples below this line</i>		
10. Markham	(Westgate, 1980)	43	40	44	16		unpublished data		
11. Scarborough	(Karrow, 1967)	16	50	31	19	-	-upper Leaside		
Newmarket Till									
Highway 407 (Markham)		300	52	37	11	5-15	N=50-100; W is <10%		

1. Percentages should be assessed with +/- 3% because some of the early studies (<1987) used a 3.9 micron silt/clay boundary (Wentworth classification), whereas later ones used a 2 micron (USDA) boundary.

Table 4. Summary of sedimentary attributes and inferences regarding Halton sediment

1. Halton is discontinuous south of ORM and east of Humber River; extent closely matches extent of underlying ORM sediments (**Fig. 3**)
2. Halton has a conformable, fining-upward, inter-bedded and transitional relationship with underlying rapidly-deposited, east to west-trending sandy ORM sediments (**Fig. 8c; 9c**)
3. Halton sediment mainly reflects passive, subaqueous underflow/ debris flow deposition; not ice-moulded, drumlin-forming, re-advance deposition (Karrow 1967; 1974; 1987; 1991)
4. Dense, stoney till, not muddy Halton till, is found in drumlinized till plains, south of ORM. (**Fig. 2d, 3**)
5. Drumlins /fluting south of ORM are not depositional landforms¹ composed of Halton formation; they are erosional landforms cut into Newmarket Till¹, and form part of Peterborough drumlin field (Sharpe et al., 2004)
6. Newmarket Till, mapped as Halton Till by some, underlies and is stratigraphically older than ORM (**Fig. 2d, 3**)
7. Halton formation partially fills drumlin swales and tunnel channels cut into Newmarket Till² (**Fig. 11**)
8. A major re-advance of grounded, 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**), or late bottom features (Lewis and Todd, 2015).
9. Due to the transitional facies relationship between ORM and Halton sediment, prominent sandy inter-beds are readily explained as basin depositional facies (drainage events; basin sedimentation) not linked to climate forcing; thus, it is not reasonable to infer inter-beds as Mackinaw inter-stadial deposits.

1. Area 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) and crescentic scours eroded on upflow ends of drumlins in the Peterborough field and around drumlins in Lake Ontario (Lewis and Todd, 2015).

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

Table 5. Regional event sequence for Halton sedimentation**Pre- Halton events*****Formation of a regional unconformity and channel network***

Subglacial meltwater accumulated in lake basins under late glacial melting (e.g. Shoemaker, 1992; Evatt et al., 2006; Livingston et al., 2013), during and following events that formed ORM channels and ridges

a) *Tunnel channel sedimentation, lower Oak Ridges Moraine formation*

A network of ~N-S channels were eroded and filled with a thick-bedded sequence (~60 m) of gravel, sand and silt-clay deposited within a subglacial lake ponded to ~200 m asl (Fig. 13a).

b) *Construction of the Oak Ridges Moraine Ridge*

ORM ridges formed during a rapidly-deposited sequence of high-energy, west-flowing meltwater events (e.g. Russell et al. 2003); this included meltwater channels that drained westward above Niagara Escarpment (Fig. 13b; see Barnett et al. 1998)

Ice closure and grounding following east-west meltwater events (Shaw and Gilbert 1990; Lewis and Todd 2015) prevented northward sediment flux on land from the Ontario basin.

During this interval, renewed/ continued meltwater ponding in Lake Ontario basin floated the glacier and effectively ended glacier shear stress and ice flow from the lake basin.

Halton events

Transitional deposition from ORM to Halton sediment occurred (e.g. Fig. 10), coinciding with east to west sediment dispersal during ORM ridge formation.

c) *Grounded ice on lake-bordering upland and deposition of Halton Till*

As ORM high-energy sedimentation waned, suspended sediment (mainly mud) was transported westward, deposited across an ice-constrained lake bottom prior to being reworked by Halton ice-marginal processes (Fig. 13c).

Ice closure and re-activation following meltwater events, led to grounded ice deposits on the south flanks of ORM, in part incorporating mud from east-west drainage events.

Sedimentary features indicate upward coarse-to-fine trends /interbeds in deep water during transition to Halton sediment (Gilbert 1997; Russell et al. 2005); grounded ice deformed thin sediments on land north of Lake Ontario.

Eskers mainly supplied sediment from the east (Gorrell and Brennand 1997); a late, rare northwest-trending, low-energy, esker formed near Brampton with overlying conformable Halton sediment (Saunderson and Jopling 1980). Laminated dropstone mud overlies Newkarket Till drumlins on the floor of Lake Ontario (Lewis and Todd 2015).

d) *Collapse of glacial ice in the Lake Ontario basin*

Halton sedimentation ended when grounded ice lifted and ponded water drained to a smaller subglacial reservoir in Lake Ontario basin (Fig. 13d).

Ice stagnated over drumlins, channels, till plains, trapping meltwater in late marginal lakes. Minor ridges may record crevasse-fill sediment squeezed between stagnant ice masses on till uplands. Ice-marginal lakes drained during final ice melting.