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STRATIGRAPHIC ANALYSIS OF LATE WISCONSIN AND HOLOCENE GLACIOLACUSTRINE DEPOSITS EXPOSED ALONG THE NOTTAWASAGA RIVER, SOUTHERN ONTARIO, CANADA

SUBMITTED BY

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Abstract

Analysis of 56 outcrop exposures in cut banks along the Nottawasaga River in southern Simcoe County, Ontario, Canada, has led to the identification of eight stratigraphic units (SU1-8) that represent a record of changing environmental conditions during deglaciation and exhibit strong controls on shallow groundwater flow in the region. The stratigraphic succession is floored by the Late Wisconsin Newmarket Till (SU1) which is locally overlain by ice-proximal debris flow deposits (SU2). These glacial sediments are overlain by glaciolacustrine silt rhythmtes (SU3) that pass upwards into deltaic sand (SU4) and channelized fluviodeltaic sand and gravel (SU5). Lying above the fluvial deposits are widespread interbedded glaciolacustrine sands and silt (SU6), which coarsen up-section toward the ground surface. The succession is locally capped by fluviodeltaic (SU7) and younger fluvial (SU8) deposits. These stratigraphic units record sedimentary environments that existed during deglaciation of the region and provide insight into the evolution of glacial lakes Schomberg and Algonquin, and the Nipissing phase of the upper Great Lakes. The environmental changes described from sediments along the Nottawasaga River provide insights into basin-scale events that occurred throughout the upper Great Lakes during deglaciation. Qualitative observations of groundwater discharge from sediments at outcrop faces are used to characterize the hydraulic function of the stratigraphic units as well as possible preferential groundwater flow pathways in the shallow subsurface.

KEYWORDS
QUATERNARY GEOLOGY, GLACIAL LAKE ALGONQUIN, STRATIGRAPHY, SOUTHERN ONTARIO, HYDROGEOLOGY
I. INTRODUCTION

Large areas of Canada and the northern United States were covered by glacial lakes at the end of the Late Wisconsin glaciation, as meltwaters draining from retreating ice margins were ponded against the ice front in isostatically-depressed basins (Teller 2001; Fig. 1a). In southern Simcoe County, Ontario (Fig. 1b), thick successions of glaciolacustrine sediment found at surface, particularly within low-lying areas, record the evolution and drainage of a series of Late Wisconsin to Holocene deglacial and postglacial lakes (Chapman and Putnam 1984; Bajc et al. 2014). Glacial lakes Schomberg (>13 $^{14}$C kyr BP (15,700 cal yr BP)), Algonquin (13-10.5 $^{14}$C kyr BP (15,700-12,400 cal yr BP)), and the Nipissing phase of the upper Great Lakes (6-4 $^{14}$C kyr BP (6,900-4,400 cal yr BP)) inundated parts of the study area and deposited sediments that contain a record of environmental changes as ice margins withdrew from the region (Fig. 1b; Deane 1950; Karrow et al. 1975; Lewis et al. 2008) and currently host significant regional and local aquifers (Sibul and Choo-Ying 1971). Detailed sedimentological analysis of these glaciolacustrine deposits will enhance understanding of the three-dimensional (3D) distribution and character of sediments within the shallow subsurface (Anderson 1989), information that is essential for future hydrogeological investigations in the region. Southern Simcoe County has been identified as a region where extensive urban and industrial development is predicted to occur (Ministry of Public Infrastructure and Renewal 2006) and performing this type of investigation is essential for the evaluation, management and protection of the region’s potable groundwater resources.

This paper presents the first sedimentological description and analysis of sediments exposed in cut banks along the Nottawasaga River in southern Simcoe County (Fig. 1b). Outcrop data are used to develop an improved stratigraphic framework and paleoenvironmental reconstruction of deglacial and postglacial events for lowland areas in the region. These data
help to better constrain information obtained from continuously cored boreholes drilled as part of ongoing regional-scale 3D mapping efforts conducted by the Ontario Geological Survey (OGS; Bajc and Rainsford 2011; Bajc et al. 2012, 2014; Fig. 3a), and to further refine and test previous interpretations of glacial and postglacial lake evolution in the region that were based primarily on geomorphological observations (Deane 1950; Chapman and Putnam 1984; Finamore 1985). Furthermore, these data may be used to better evaluate the hydraulic function of shallow subsurface sediments as well as to identify controls on groundwater behavior.

2. GEOLOGIC BACKGROUND

The study area is underlain by Paleozoic strata that, in turn, unconformably overlie Precambrian basement rocks (Armstrong and Carter 2010). Differential erosion of thick successions of soft shales underlying more resistant dolostones created the Niagara Escarpment that stretches across central Ontario and forms the western border of the study area (Fig. 1b). This regional-scale feature is punctuated by a series of northeast-trending re-entrant valleys likely incised by fluvial, glaciofluvial, and glacial erosion during and prior to the Quaternary (Straw 1968; Kor and Cowell 1998; Eyles 2012). Bedrock valleys were also incised into the Paleozoic strata beneath the study area by pre-glacial fluvial erosion (Spencer 1890; Eyles et al. 1985) and later modified by Quaternary subglacial and subglacial meltwater erosion during the Wisconsin Episode (Gao 2011; Mulligan and Bajc, this volume; Sharpe et al., in press).

The Paleozoic bedrock surface is overlain by Quaternary sediments that locally exceed 200 m in thickness (Gao et al. 2006), attributed primarily to the Wisconsin Episode (Mulligan and Bajc this volume). Early to mid-Wisconsin Episode deposits exposed along the Scarborough Bluffs and underlying much of the Greater Toronto Area host important aquifers (Howard et al. 1995; Gerber et al. this volume). Pre-Late Wisconsin sediments have been identified within the
study area, but are commonly deeply buried in the subsurface (Eyles et al. 1985; Bajc et al. 2012, 2014; Mulligan and Bajc this volume).

During the Late Wisconsin (18-21 \(^{14}\)C kyr BP (21,300-25,400 cal yr BP), the Laurentide Ice Sheet (LIS) advanced into the study area from the north and northeast and deposited the Newmarket Till, an extensive subglacial till sheet (Gwyn 1972; Sharpe et al. 1994; Fig. 2a). The Newmarket Till occurs as a distinctive, highly undulating and drumlinized unit across the study area (Sharpe et al. 2002; this volume) and can be observed capping and flanking broad uplands (Fig. 1b) that are separated by a series of narrow valleys previously interpreted as tunnel channels (Barnett 1990; Sharpe et al. 2004; labeled AE, BV, CV, HMV in Fig. 1b). During the early stages of ice recession (after 16 \(^{14}\)C kyr BP (19,500 cal yr BP)), the margin of the LIS thinned and became lobate (Barnett 1992; Fig. 2b). Thick accumulations of glaciofluvial and glaciolacustrine sediment were deposited in an interlobate setting, between the Simcoe ice lobe to the north and the Ontario ice lobe to the south, resulting in the formation of the Oak Ridges Moraine (Howard et al. 1995; Barnett et al. 1998; Fig. 2b).

A succession of shoreline features and associated glaciolacustrine and lacustrine deposits record the presence and evolution of a series of lakes across the area during later phases of deglaciation (after 13 \(^{14}\)C kyr BP (15,700 cal yr BP); Deane 1950; Chapman and Putnam 1984; Lewis et al. 2008; Schaezl et al. 2016; Fig. 2b,c). Glacial Lake Schomberg was the first to develop, forming a stable water plane at 300 m asl, as meltwaters were dammed between the Niagara Escarpment to the west, the Oak Ridges Moraine (and Ontario ice lobe) to the south, and the retreating Simcoe ice lobe to the north (Fig. 2b; Chapman and Putnam 1984; Mulligan 2013; Mulligan et al. 2015). Subsequent retreat of the Simcoe lobe from the Niagara Escarpment in the north allowed waters of Lake Schomberg to partially drain and coalesce with those occupying
the Lake Huron basin forming glacial Lake Algonquin (12.5-10.5 $^{14}$C kyr BP (15,000-12,400 cal yr BP); Fig. 2c; Eschman and Karrow 1985). Several discrete phases of this lake have been identified from shoreline studies across the region and record progressive retreat of ice from the basin and isostatic uplift of outlets (Figs. 1, 2). Early Lake Algonquin (Karrow et al. 1975) developed after the final phase of drainage of glacial Lake Schomberg, as water levels fell to incrementally lower levels (from 300 m to approximately 250 m asl; Fig. 2b,c). A low-water phase (Kirkfield Low; 12-11.4 $^{14}$C kyr BP (14,000-13,300 cal yr BP)) marks the opening of a new outlet to the east near Fenelon Falls (Finamore 1985; Fig. 2c). Isostatic rebound of this lake outlet allowed water levels to rise towards southern outlets and form main Lake Algonquin (11.4-10.5 $^{14}$C kyr BP (13,300-12,400 cal yr BP); Lewis et al. 2005; Fig. 2c). Ice recession beyond isostatically-depressed outlets in the northern parts of Algonquin Park and near North Bay (Fig. 1) after 10.5 $^{14}$C kyr BP (11,700 – 12,800 cal yr BP) resulted in drainage of glacial Lake Algonquin from the study area and led to the establishment of the Stanley Low Phase which was punctuated by multiple short-lived high stands (Lewis et al. 2005; Lewis 2016). Finally, uplift of the North Bay outlet following deglaciation triggered water level rise in Georgian Bay; water levels south and west of the outlet rose towards southern outlets, up to 15 m above modern Lake Huron (192 m asl) within the study area, during the establishment of the Nipissing phase of the upper Great Lakes (6-4 $^{14}$C kyr BP (6,900-4,400 cal yr BP); Eschman and Karrow 1985).

3. METHODS

Fifty six exposures were logged as part of this study (Fig. 3a). Sections were cleaned and logged using standard sedimentological logging techniques, recording grain size, bedding, sedimentary
structures, bed contacts, clast lithologies, unit geometry and continuity of contacts between sediment groups, and paleoccurrent directional indicators (Fig. 3b). Ice flow directions were interpreted from analysis of the long axes of regional subglacial landforms, as well as the orientations of striae on clasts and large boulders with locally well-developed stoss-lee features, Paleocurrent measurements in stratified sediments were obtained by cutting horizontal sections into bedforms and measuring the direction normal to foresets. Qualitative descriptions of groundwater seepage zones were also made. Fossils were isolated from organic bearing sediments by wet sieving to allow for preliminary paleoecological identification of specimens. Material for dating was picked under a binocular microscope to isolate wood, needles, leaves, seeds, molluscs, insect fragments. In rarer cases, larger sticks and logs were sawed and removed from an outcrop, cleaned, then cut into smaller pieces suitable for submission. Wood and leaves of terrestrial plants were sent out to the Illinois State Geological Survey Radiocarbon Dating Laboratory and the University of Ottawa André E. Lalonde AMS Laboratory for radiocarbon age determination by accelerator mass spectrometry (Crann et al. 2016). Wood and leaf samples were subjected to a standard acid-alkali-acid pretreatment prior to combustion to remove any modern contaminants (humic and fulvic acids). Radiocarbon dates are reported as both uncalibrated and calibrated ages (Table 1). Digital data used to create maps include a 5 m digital elevation and hillshade model (DEM; OMNRF 2010) and surficial geology data (OGS 2010).

4. RESULTS

Exposures along the Nottawasaga River are composed of eight distinct stratigraphic units (SU1-8) that can be traced consistently along the valley (Figs. 3b, 4, 5). SUs are distinguished based on an integrated analysis of individual sediment types and genetically-related sediment associations, stratigraphic context, geomorphologic setting and sediment-landform associations.
identified through regional surficial mapping, and chronostratigraphic information from local and regional radiocarbon age determinations.

4.1 SU 1: Sand-rich diamict

Silt to sand-rich diamict (SU1) is observed at many locations at the base of cut bank exposures along the Nottawasaga, River (Fig. 3a). The observed thickness of SU1 in outcrops ranges from 1 to 15 m (Fig. 4) and its occurrence is discontinuous along the river due to a highly undulating upper surface. The lower bounding surface of this unit is not exposed in the study area. The diamict is poorly sorted and appears massive at most locations (Fig. 6a,b), but crude interstratification with sandy and gravelly interbeds (up to 1 m thick) and stacked alternating beds of massive sand- and silt-rich matrix textures (up to 4 m thick) is observed at some outcrops (Fig. 6c,d). The diamict matrix is moderately to highly consolidated, and displays well-developed fissility at several sites (Fig. 6c). Clasts comprise less than 5-10% of the diamict and are dominantly sub-angular to sub-rounded, composed primarily of locally-derived carbonate lithologies. Clast size ranges from granules to boulders over 3 m in diameter. Carbonate clasts are often striated and faceted with flattened tops or bullet shapes (Fig. 6b). Long axes of the clasts tend to be sub-horizontal and show a preferred northeast-southwest orientation (Fig. 6b). A few horizontal to undulating silt to gravel lenses and interbeds, ranging from 10 cm to 2 m thick, are locally observed (Fig. 6c). Groundwater is commonly observed discharging from the outcrop faces at the upper surface of the diamict unit or along the base of interbeds composed of sand or gravel (Fig. 6d).

The characteristics of SU1 suggest it is a subglacial till. The presence of striated clasts with a preferred parallel and sub-horizontal orientation, poor textural sorting, and high consolidation and fissility of the diamict matrix, are all consistent with subglacial transport and
deposition (e.g. Boulton and Deynoux 1981). Although no detailed clast fabric analyses were performed, the crude preferential long-axis alignment, development of stoss-lee features on boulders, and strong parallelism of striae indicate widespread deposition by lodgement processes, consistent with a well-drained and strongly coupled ice-bed interface (Evans et al., 2006). Coarse-grained interbeds within the diamict probably record meltwater flow that created local bed separation events during emplacement of the till (Boyce and Eyles 2000). The physical characteristics of SU1 are similar to those reported for the Newmarket Till (Gwyn 1972; Russell and Dumas 1997; Mulligan 2017), as are its surface topography, and stratigraphic position (Todd et al. 2008; Baje et al. 2012; 2014) (Fig. 13b). Outcrops of SU1 are typically found close to areas where Newmarket Till has been mapped at surface near the margins of streamlined, drumlinized upland terrain (Mulligan and Baje 2012; Mulligan 2017) and adjacent to individual drumlins rising above the floor of the paleolake plain within lowland areas (Figs. 1, 3a; Mulligan 2013). The highly variable surface elevation of SU1 along the Nottawasaga River may reflect drumlinization of the till surface underlying lowland areas, as reported in water borne seismic investigations by Todd et al. (2008) in the nearby Lake Simcoe basin (Fig. 1b).

4.2 SU2: Interbedded sand and sand-rich diamict

Interbedded, crudely stratified sand-rich diamict and variably textured sorted beds directly overlie SU1 at two locations along the Nottawasaga River (SU2; Fig. 7). Interbedded planar-laminated silt, asymmetrical ripple-scale cross-laminated very fine- to fine-grained sand, planar-laminated fine- to coarse-grained sand, and massive to crudely-stratified gravel with till intraclasts (derived from SU1) comprise the sorted beds, which are up to 0.75 m thick. Sedimentary structures within sorted beds are often highly deformed by shearing, folding and
faulting (with common low-angle reverse faults) when overlain by diamict beds (Fig. 7b,c).

Diamict beds vary from stratified, stone-poor, silt-rich diamict to structureless, well-consolidated, clast- and sand-rich. Individual diamict beds in SU2 are up to 1 m thick. Clasts range up to 30 cm in diameter, and lack the preferential long-axis orientation observed in SU1. Contacts between individual beds comprising SU2 are typically sharp, highly deformed, and irregular (Fig. 7). SU2 is 1.2 - 3 m thick and is only observed locally, directly overlying SU1, in areas where the surface of SU1 is highly irregular, commonly near the flanks of isolated ridges of Newmarket Till (drumlins) mapped at surface (Figs. 1b, 4; Mulligan and Bajc 2012).

Sharp bed contacts, rapid transitions in sediment texture, poor sorting, and pervasive deformation features throughout SU2 suggest a chaotic depositional environment, characterized by rapid fluctuations in sediment deposition rates and processes (Evenson et al. 1977; Glasser et al. 2009). The localized distribution of SU2 on the flanks of highs on the upper surface of SU1 suggests that its formation has been controlled in part by the topography of the underlying sediment. Interbedding of well-sorted sand and silt in SU2 records low-energy sedimentation into an ice-marginal lake by density underflows (Smith and Ashley 1985). Gravelly beds with till intraclasts record higher-energy meltwater activity and erosion of the underlying SU1. SU2 is interpreted to record slumping from the ice front and/or local topographic highs during the earliest phases of deglaciation (Fig. 13d-f; Mills 1983; Benn 1989; Mulligan 2013). Some diamict beds may be attributed to minor readvances of the ice front, which could promote subglacial till deposition and lead to glaciotectonization (shearing and faulting) of the bed (White 1975; Mulligan 2013; Mulligan et al. 2017). SU2 is interpreted to record early deglacial sedimentation into an ice-marginal lake, along steep slopes on the surface of SU1 and a retreating ice margin with possible minor readvances.
Silt and clay rhythmites abruptly overlie and drape the upper surfaces of both SU1 and SU2 and typically grade upward into sand- and silt-rich sediments of SU4 (Figs. 3b, 4, 8, 9). SU3 is observed in all sections logged along the Nottawasaga River (Fig. 4) and forms a unit locally exceeding 12 m thick. SU3 consists primarily of a succession of rhythmites composed of silt and clay couplets ranging from a few mm up to 4-cm thick (Fig. 8). The silt fraction forms the base of the rhythmites, is sharp-based and usually thicker and lighter coloured than the finer-grained clayey silt caps, although there are variations in layer thickness within the unit and between sections. Horizontal laminae are present within both the silt and clay portions of the rhythmites, but are more common in the coarser silt portions. These laminae often consist of small (cm-scale) starved ripples and small-scale soft sediment deformation features less than 0.5 cm in amplitude. The transition between silt and overlying clay fractions of the rhythmites is commonly gradational, but in places a thin (mm-scale) lamination of coarse silt or fine sand forms an abrupt division within the couplet. The clays generally appear massive at the outcrop, but fine planar laminations are commonly visible once a sample is broken and dried.

Silt-rich diamict beds and scattered clast horizons are common within the basal part of SU3. Diamict beds are crudely stratified to laminated, with individual clasts commonly deforming underlying rhythmites (Fig. 8a,c,d). Diamict beds are typically 0.5 - 10 cm thick and grade upward into rhythmically laminated silt and clayey silt with scattered clasts. Diamict beds and clast horizons within SU3 decrease in thickness and abundance up-section, and are only observed in the lower 1-3 m of the unit, where they are observed in both the fine and coarse fraction of the rhythmites. In the upper part of SU3, thin, planar beds of very fine to fine-grained
sand become increasingly prevalent and thicken upwards (Figs. 3b, 5, 8b). These sand beds range from 0.5 cm to 10 cm in thickness and are massive to laminated, or ripple-scale cross-stratified (Type A; Jopling and Walker 1968; see SU4 descriptions); the latter typically exhibits northward paleoflow directions, ranging from NNW to NNE. The sand beds are laterally continuous, can be traced along entire outcrop faces (>30 m Figs. 8b), and are typically sub-horizontal, except at the base where SU3 drapes the irregular upper surface of SU1 or SU2. Sand beds increase in thickness and abundance upward. Groundwater is commonly discharged at their contact with underlying fine-grained units as well as at small circular groundwater piping conduits.

The overall fine-grained texture of SU3 suggests a low-energy, subaqueous (glaciolacustrine) depositional environment, consistent with an ice-marginal lake. Clay and silt beds were likely deposited from suspension settling whereas coarser-grained sediments were delivered via density underflows entering the lake from subglacial meltwater streams (Van Der Meer and Warren 1997). Seasonal ice cover and precipitation patterns associated with summer melting were probably important controls on sedimentation (e.g. Gilbert 1975). Rhythmites may record a combination of annual (Breckenridge et al. 2004) or diurnal (Schneider and Bronge, 1996) cycles of sedimentation, storms, or rapid snow melt events (Lamoureux 2000), sediment gravity flows in a prodeltaic environment (Harrison 1975), or distal subaquatic fan sedimentation (Gravenor and Coyle 1985). Small deformation structures are likely caused by loading and dewatering of sediments during discrete sedimentation events. Interbedded diamict horizons may record deposition of coarse-grained debris by rainout of ice-rafted material or by slumping along oversteepened slopes of SU1 and SU2 (e.g. Bennett et al. 2002). Isolated scattered clasts higher up-section within rhythmites of SU3 are interpreted as more distal ice-rafted debris from icebergs calved off a retreating ice margin (Dowdeswell and Dowdeswell 1989; Condon et al. 2002),
possibly recording reduced glacial influence on the succession as ice retreated northward. Alternatively they may record the break-up of seasonal shore ice (Martini et al. 1993).

Gradational up-section textural changes combined with the consistency of northward paleocurrent directional indicators in sands within SU3 suggests continuous sedimentation patterns, consistent with gradual ice retreat from the study area.

4.4 SU4: Ripple-scale cross-laminated fine-grained sand

There is a gradual transition from the silt and clay rhythmites with sand interbeds of SU3 into a thick unit of rippled, cross-stratified very fine- to fine-grained sand with silt interbeds comprising SU4 (Figs. 3b, 9a). SU4 is between 4 and 10 m thick, generally thins northward, and is not observed north of log 39 (Figs. 3-5, 9). Both stoss-erosional (Type A) and stoss-depositional (Type B) ripple-scale cross-lamination with amplitudes of between 2-5 cm are common (Fig. 9b; Jopling and Walker 1968). Bed-sets of ripple-scale cross-laminated sand reach thicknesses of up to 1.5 m and may be separated by silt drapes up to 10 cm thick (Fig. 9a). Both types of ripple-scale cross-lamination are commonly associated with horizons of large-scale soft sediment deformation characterized by ball and pillow and/or flame structures up to 2 m in amplitude (Fig. 9a). Paleocurrent measurements from ripple-scale cross-laminations show consistent paleoflow directions towards the north (NNW-NNE). Silt-rich interbeds are massive to finely laminated. Groundwater typically discharges along the contact between the base of rippled sand bed-sets and the tops of silt drapes.

The gradational up-section increase in sand content from SU3 to SU4, combined with consistent northward paleocurrents in both units is likely a result of sediment supply from the south. Asymmetrical ripples are generated by unidirectional traction currents and the presence of
thick packages of Type-A and -B climbing ripples suggests rapid deposition from flows carrying large quantities of suspended and bedload sediment (Jopling and Walker 1968; Winsemann et al. 2015). The association of climbing ripples with silt-rich horizons characterized by large-scale soft sediment structures records dewatering of saturated sediments and indicates rapid, but fluctuating discharge and rates of sediment deposition (Kelly and Martini 1986; Winsemann et al. 2007). The coarsening-upward succession of fine-grained rhythmites (SU3; Fig. 3b) passing upward into ripple-scale cross-laminated sands with northward paleocurrent directions (SU4; Fig. 3b) is consistent with a prograding deltaic system from the south (e.g. Nutz et al., 2015). Silt drapes within SU4 record suspension settling during quiescent periods, consistent with seasonal decreases in fluvial input, depositional lobe and distributary channel migration, or flow shut off/ponding during sediment progradation (e.g. Kelly and Martini 1986).

4.5 SU5 (FA 5): Partially-channelized fine-grained sand to gravel

SU5 is characterized by trough cross-bedded sandy gravel and gravelly sand in the southern parts of the study area (Figs. 4, 10a,b,c) and exhibits gradational textural fining toward the northern parts of the Nottawasaga River basin where it is composed of fine-grained planar laminated to ripple-scale cross-laminated sand with silt rip-up clasts (Figs. 4,5 10c,d,e). The lower bounding surface of SU5 is either gradational with SU4 (Fig. 9c), or sharp and erosive near the base of channel features (Figs. 4, 5, 10b,c,d); SU5 is always overlain by fine-grained deposits of SU6 (Figs. 4, 5, 10a). SU5 typically forms a planar tabular sheet nearly 2 m thick, but can be thicker where it infills incisions cut into underlying SUs (Figs. 4, 5). Incised channels range in size from 2 to 10 m wide and 1 to 4 m deep (Figs. 5, 10c) and contain stacked smaller-scale channelized elements, each of which generally displays a slight fining-upward trend in grain size.
Silt and clay intraclasts (rip-ups) are common and range up to 10 cm in diameter (Fig. 10e). SU5 commonly contains abundant fossil molluscs, including articulated bivalve shells concentrated along bed foresets (Fig. 10e). Paleocurrent measurements indicate east-northeastward to northward flow in the south and north-northwestward to north-northeastward flow in more northern locations. The occurrence of outcrops of SU5, as well as recorded paleocurrent directions, correspond to sinuous dark-toned lineations (palimpsest channel features) identified on aerial photographs (Mulligan and Bajc 2012; Mulligan 2013). SU5 deposits are locally oxidized and display strong Fe- (orange) and Mn-oxide (black) stained intervals (Fig. 10a,b). Groundwater piping is commonly observed from the base of channel features, especially where they are floored on impermeable sediments.

Gravel cross-beds and coarse-grained sands with large rip-up clasts infilling channelized incisions cut into underlying SUs, record unidirectional flows (e.g. Eynon and Walker 1974) and suggest a high-energy depositional environment, consistent with lowered base levels following deposition of SU3 and SU4 (e.g. Winsemann et al. 2015). The correlation of gravelly sediments infilling shallow incisions observed in near surface outcrops with sinuous features observed on aerial photography permits the delineation of a fluvial channel system that formerly occupied the study area (Mulligan 2013). Consistent northward paleocurrent directions and lateral fining of the grain size in SU5 record fluvial flows from high ground along the Niagara Escarpment toward new, lower elevation lake shorelines to the north (SU5 is floored at 207m asl in log 37; Figs. 3, 4). Oxidation of SU5 deposits could be related to subaerial exposure following deposition, but the strong permeability contrasts between the coarse-grained SU5 sediments and underlying fine-grained deposits (SU1-3) and the influence this has on shallow groundwater flow precludes the interpretation of oxidation as evidence of subaerial weathering.
4.6 SU6: Interbedded sand and silt

SU5 is abruptly overlain by a coarsening-upward succession of laminated silt and very fine-grained sand to interbedded fine to medium-grained sand comprising SU6 (Figs. 4, 5, 11). Thick (up to 20 cm) beds of thinly planar laminated silt are common near the base of SU6 and are commonly disturbed by minor soft sediment deformation features (Fig. 11a). Individual sand interbeds near the base of SU6 are typically less than 5 cm thick (Fig. 11b), but thicken up-section into stacked sand beds up to 4 m thick as silt content decreases (Fig. 11c,d). Sand beds in the upper part of SU6 are characterized by planar laminae, starved asymmetrical ripples, soft sediment deformation structures, symmetrical ripple-scale cross-lamination, and horizontal truncation horizons (Fig. 11). The occurrence of symmetrical ripples and horizons characterized by large-scale soft sediment deformation structures increases up-section as sand packages thicken (Fig. 11c,d); deformation features are commonly truncated by laterally continuous, sub-horizontal erosion surfaces. SU6 also contains abundant gastropods and bivalves. Significant erosion of outcrop faces is observed from groundwater piping along the contact between sand and silt layers in SU6.

The lower part of the coarsening-upward succession that comprises SU6 is interpreted to record inundation of the area by rising lake levels (Karrow et al., 1975) and deposition of interbedded silt and sand by alternating episodes of settling of suspended fines and traction current and/or wave activity (Rosenthal and Walker 1986; Shanmugam et al. 1993). Thicker sand bodies in the upper part of SU6, characterized by symmetrical (wave) ripples, soft sediment deformation structures, and planar erosional disconformities, record decreased accommodation space due to basin infilling and are interpreted to record sediment deposition in a shallow
lacustrine environment between fair-weather and storm wave base (Li et al. 2014). Soft sediment
deformation features and horizontal erosional surfaces likely reflect dewatering caused by rapid
sediment deposition and/or storm wave shock (Molina et al. 1998) and erosion by large waves
during the onset of storm events (Eyles and Clark 1988). The presence of sedimentary structures
attributed to storm wave activity in the upper part of SU6 indicates that the glaciolacustrine
environment in which deposition occurred was extensive with a large fetch allowing significant
(several metres high?) storm waves to develop (Figs. 1, 2c; Li et al. 2014). This assertion is well-
supported by geomorphic and sedimentological data from elsewhere in the paleolake plain (e.g.
Krist and Schaeztl 2001; Schaetzl et al. 2016) and, though we have not performed the wave
theory calculations, is reasonable, given that modern November storms in southern Georgian Bay
commonly produce waves >3 m high (REF) and in extreme cases, have produced waves in
excess of 11 m (‘White Hurricane’ of November 1913; Brown 2002).

4.7 SU7: rippled and deformed fine-grained sand

Near Angus (Fig. 3a), a unit of very fine- to medium-grained sand (SU7) is observed in
several outcrops (Figs. 12, 13). The unit has a gradational lower contact with underlying
laminated silts which coarsen upward into rippled and planar laminated fine-grained sand (Figs.
4, 12, 13b,d). The upper portion of SU7 is interbedded with thick (up to 15 cm), thinly laminated
silt drapes (Fig. 12a) and is highly deformed in places, with large (m- scale) ball and pillow
structures. The bulk of SU7 is characterized by deformed homogenous sand, grading from large-
scale deformation structures (flames, balls and pillows) into small scale structures, which pass
upwards into dish structures, then Type-B and finally Type-A climbing ripple-scale cross
lamination (Figs. 4, 12b). Paleocurrent measurements from ripple-scale cross-laminations
suggest flows towards the north and northwest. Rare detrital plant material is observed, and both fragmented and intact mollusc remains are scattered throughout the upper parts of the unit (Fig. 12c). Locally, the upper part of the succession is truncated and is unconformably overlain by medium- to coarse-grained sand. This truncation surface is marked with signs of subaerial weathering (orange and white colour mottling with humified organic material with charcoal overlying the soil; Fig 13c,d) and is locally overlain by peat (Fig. 4). Large amphitheatre-shaped piping scars are observed in SU7.

SU7 records high sediment accumulation rates in a subaqueous environment. The large scale deformation features that gradually transition upwards into dish structures and ripple-scale cross-lamination suggest rapid deposition, loading and dewatering for the bulk of the unit (Lowe and LoPiccolo 1974; Stárková et al. 2015; Winsemman et al. 2015). Consistent north and northwestward paleoflow directions indicate sediment delivery from the south, and combined with the incorporation of shell fragments and other organic debris, indicate erosion and resedimentation of pre-existing sandy sediments (e.g. SU4-6). The land surface in the vicinity is low relief, with a gentle slope to low-lying wetlands to the north. SU7 is interpreted as fluviodeltaic sediment and shares many similarities with SU4, but can be differentiated on the basis of sediment characteristics, elevation, stratigraphic position, and correlation to local landforms (Figs. 4, 9, 12, 13). Unlike SU4, silt drapes are more common in the upper, rather than the lower part of the unit. The lower stratigraphic elevation and consistent northward paleocurrent directions of SU7 are consistent with a base level fall following deposition of SU6.

4.8 SU8: planar and ripple-scale cross-laminated sand
A unit of highly fossiliferous fine- to medium-grained sand with minor silt (SU8; Fig. 13c,d) overlies the subaerial weathering horizon at the top of SU7. SU8 is predominantly planar laminated and ripple-scale cross-laminated sand with rare, thin (<2 cm), semi-discontinuous silt drapes and contains an abundance of detrital wood and molluscs, including large unionid clams and some bones (logs 51, 52, 53; Figs. 4, 13). Radiocarbon age determination of wood recovered from a massive peat bed underlying SU8 (Fig. 13e) suggests it was deposited after 5,880±25 $^{14}$C yr BP (6,650 – 6,750 cal yr BP; Table 1). In this area, SU8 is found at low elevations (192 m asl; Figs. 4, 13a), overlying accumulations of peat and thin paleosols that overlie SU7 (Fig. 13c-e).

The weathering profile above SU7 records a hiatus caused by lowered base levels prior to deposition of SU8, which is interpreted to record rising water levels in the area (Karrow et al., 1975; Chapman and Putnam, 1984; Fitzgerald, 1985). The sediments of SU8 record deposition in either a low-energy fluviodeltaic or shoreface setting in a lake ponded within the Minesing basin immediately north of Angus (Figs. 1b, 3; Bajc and Rainsford 2010; Mulligan 2017).

5. DISCUSSION

5.1 Paleoenvironmental reconstruction
The sedimentary successions examined along the Nottawasaga River in southern Simcoe County record deposition in glacial, fluvial, and lacustrine environments formed both during and following deglaciation of the region at the end of the Wisconsin Episode. SU1 is interpreted to record Late Wisconsin ice advance into the basin from the northeast and deposition of the Newmarket Till (Figs. 2, 14a, 15). The undulating and drumlinized upper surface of SU1 is similar to the morphology and orientation of regional drumlinized uplands (Sharpe et al. 2004; Maclachlan and Eyles 2013; Mulligan 2013); the elevation of the upper surface of the till sheet ranges by up to 160 m between drumlinized upland areas and the base of lowland successions in
the area (140 m asl in borehole SS-11-07 versus >300 m asl on adjacent uplands to the north; Fig. 3a; Bajc et al. 2015).

SU1 (Fig. 14a) was followed by general ice retreat and localized slumping of sediment from both the retreating ice front and local topographic highs within an ice-marginal lake. SU2 probably records the earliest phases of deglaciation in the basin with possible minor readvances (Figs. 4, 14a,b, 15), but due to limited exposures, its spatial extent and origin remain poorly defined. Previous studies (White 1975; Mulligan 2013) have documented till at similar stratigraphic positions within lows on the Newmarket Till sheet to the south, and ongoing drilling investigations have intersected subglacial till that post-dates Newmarket Till within adjacent parts of the paleolake basin (Bajc et al. 2012; Mulligan et al., 2017).

The rhythmically laminated sediments of SU3 are interpreted to record deposition in quiet water environments of glacial lakes Schomberg and early Lake Algonquin (Figs. 14b,c, 15) with multiple sediment sources (glacial meltwater, sediment gravity flows from basin margins and flanks of bathymetric highs, alluvial systems, and shoreline erosion along poorly-vegetated slopes surrounding the basin; Mulligan, 2013; Mulligan et al., 2015; Carrivick and Heckmann 2017). These depositional processes were likely influenced by a wide range of seasonal and/or non-seasonal controls, such as fluctuating glacial meltwater supply, the development and break-up of winter ice cover, major storm events, seismic activity (Deane 1950; Gravenor and Coyle 1985; Doughty et al. 2014). The decreasing thickness and abundances of diamict layers within the basal part of SU3 probably records retreat of ice from the study area. A better understanding of the paleobathymetry of the lake (i.e. topography of SU1) would allow refinement of this interpretation.
SU3 contains no visible organic material for radiocarbon dating, or evidence of unconformities that could be attributed to rapid changes in water level; hence, it is not possible to differentiate between the deposits of glacial Lake Schomberg and early Lake Algonquin within SU3. However, the up-section increase in sand within SU3 may record decreasing accommodation space and/or increasing influence of fluviodeltaic systems prograding northward during gradual or stepwise water level fall from 300 m asl (glacial Lake Schomberg) to below 250 m asl (early Lake Algonquin) as ice withdrew from the study area (Figs. 14b-d, 15; Mulligan et al., 2015). Raised shorelines, which are particularly well-developed west of Lake Simcoe (Fig. 1), reveal the extent of early Lake Algonquin, and indicate an ice-marginal position approximately 60 km to the northeast during deposition of the upper part of SU3 (Mulligan et al. 2015; Fig. 14c,d).

The gradational transition and consistent northward paleoflow indicators from silt-clay rhythmites (SU3) into ripple-scale cross-stratified and deformed fine-grained sands with interbedded silt of SU4 (Figs. 4, 5, 9) are interpreted to record the transition from prodelta to delta front sedimentation in response to decreasing accommodation space in early Lake Algonquin due to a combination of sediment aggradation and lowering of water levels following exposure of a new, lower outlet for the Huron basin at Fenelon Falls (Figs. 1, 14c,d, 15). The thick packages of rippled and deformed sands of SU4 suggest relatively high rates of sediment supply, delivered by sediment-laden streams re-working glacial deposits along elevated ground to the south and west (Figs. 1b, 14c,d; Mulligan and Bajc 2012). Unlike many deltas deposited at the margins of ice-marginal lakes during deglaciation of the Great Lakes region, which formed thick (>30 m), well-defined delta bodies (Vader et al., 2010; Arbogast et al., 2017; Connallon and Schaetzl, 2017; Barnett and Karrow this volume), fluviodeltaic sediments exposed along the
Nottawasaga River are comparatively thinner and no distinct delta morphologies are identified.

Large deltas were constructed into stable lake bodies that pre-date SU4 in the area (Glacial Lake Schomberg and equivalents; Chapman and Putnam 1984; Mulligan and Bajc, 2012; Mulligan et al., 2015). These represent the coarse-grained proximal equivalents to the silt and clay rhythmites (SU3) that forms the bulk of the sedimentary infill within the valleys in the study area. However, during deposition of SU4 and SU5, drastically-lowered water levels (Fig. 15) significantly reduced accommodation space and prevented the construction of classic Gilbert-type deltaic sediment within the Nottawasaga River cut bank exposures.

Unlike many deltas deposited at the margins of ice-marginal lakes during deglaciation of the Great Lakes region, which formed thick (>30 m), well-defined delta bodies (Vader et al., 2010; Arbogast et al., 2017; Connallon and Schaetzl, 2017; Barnett and Karrow this volume), fluviodeltaic sediments exposed along the Nottawasaga River are comparatively thin and no distinct delta morphologies are identified. Large deltas were constructed into stable lake bodies that pre-date SU4 in the area (Glacial Lake Schomberg and equivalents; Chapman and Putnam 1984; Mulligan and Bajc, 2012; Mulligan et al., 2015). These represent the coarse-grained proximal equivalents to the silt and clay rhythmites (SU3) that forms the bulk of the sedimentary infill within the valleys in the study area. However, during deposition of SU4 and SU5, drastically-lowered water levels (Fig. 15) and significantly reduced accommodation space prevented the construction of classic Gilbert-type deltaic sediment within the Nottawasaga River cut bank exposures.

The delta front deposits of SU4 are overlain by sand and gravel of SU5, which also infill incisions into the underlying units (Figs. 4, 5). This erosional phase likely records a drop in regional base level during the Kirkfield low water phase, following the ice retreat beyond an
isostatically-depressed outlet near Fenelon Falls (Figs. 1, 2c 14d, 15; Finamore 1985; Lewis et al. 2005). Water levels are previously interpreted to have fallen by as much as 10-30 m during this time (Fig. 15; Kaszycki 1985; Lewis et al. 2008). Channel incision and infilling with cross-bedded gravels and planar-laminated sands with silt rip-up clasts (SU5) provides the sedimentological record of this drop in water level. The difference in elevations between the lowest early Lake Algonquin shorelines (236 m asl; Mulligan et al. 2015) and the base of SU5 sediments (207 m asl; Fig. 4) is consistent with a fall in water level of up to 29 m during this interval. Compilation of recent shoreline mapping suggests the drop in water levels from early Lake Algonquin to the Kirkfield low phase may have been a rapid event, since no intermediate shorelines have been documented between the early and Main Lake Algonquin water planes (Mulligan 2014; 2017; Mulligan et al. 2015).

Organic-rich sediments found in several outcrops elsewhere in the paleolake basin have been used to date the Kirkfield lowstand to between 12 and 11.2 $^{14}$C kyr BP (approximately 14,615 to 12,973 cal yr BP; Table 1; Fig. 15). Accelerator mass spectrometer radiocarbon dating of Dryas integrifolia leaves found in sand near the top of a coarsening-upward succession interpreted to be correlative with SU4-5 in boreholes SS-11-06 and SS-13-04 (Fig. 3a; Bajc et al., 2014), yielded ages of 12,410±25 $^{14}$C yr BP (14,320-14,640 cal yr BP) and 12,810±40 $^{14}$C yr BP (15,170-15,320 cal yr BP), respectively (Table 1). These dates provide a maximum age for the timing of this low-water event in Simcoe County.

Very fine-grained sand and laminated silt (SU6; Figs. 4, 5) overlying the coarse-grained sediments of SU5, records a lake level rise to the main Lake Algonquin level (225-235 m asl) in response to isostatic uplift of the depressed Fenelon Falls outlet (Figs. 1, 2c, 14e, 15; Finamore 1985). The difference between the elevations of the maximum depth of incision of SU5 deposits
(207 m asl) and the local elevation of the main Lake Algonquin bluff (233 m asl) provides an upper limit for local water level rise and subsequent water depths of approximately 26 m (Fig. 15). The Main Lake Algonquin shoreline forms strongly developed wave-cut bluffs in Simcoe County (up to 30 m high) and there is evidence of large spit growth at this time in the region (Bajc and Rainsford 2010; Mulligan 2011; 2014; Schaetzl et al. 2016). The highest bluffs in the study area are observed on northwest-facing slopes, and spits (up to 3 km long and 1 km wide) composed of sand to coarse gravel, commonly grew toward the south and east from the flanks of regional uplands. Together, these features suggest prevailing winds from the northwest (Deane 1950; To et al. 2015Fig. 14e). These interpreted paleowind directions are supported by sediments from the main Lake Algonquin phase (SU6) in the study area, which are derived from wave erosion of bluffs marking the main Lake Algonquin shoreline and contain a record of frequent storm activity (soft sediment deformation, and horizontal truncation surfaces; Fig. 11) which would have required large (several metres high?) storm waves and a significant fetch. However, data from areas to the north and west, on the lower peninsula of Michigan, show strong evidence for contemporaneous easterly winds (Krist and Schaetzl 2001; Vader et al 2010; Schaetzl et al., 2016). These differences likely reflect proximity to the retreating ice margin – easterly winds in northern Michigan were sustained by katabatic gradients near the ice sheet, while westerly winds dominated further south, where the influence of the ice was lessened (Schaetzl et al., 2016; Arbogast et al. 2017).

At Angus, a younger package of fluviodeltaic sediment (SU7) is observed (Figs. 4, 12, 13), recording declining water plane elevations of post-Algonquin lakes (Fitzgerald 1985; Fig. 15). The lower, sand-rich part of SU7 is consistent with high sedimentation rates (possibly a single depositional event), while interbedded sand and silt in the upper part of the unit (Fig. 12a)
likely represent more sluggish accumulation rates, with fewer and smaller sediment pulses. The upper surface of SU7 grades to the Wyebridge phase shoreline mapped in the vicinity (Fitzgerald 1985; Mulligan et al., 2015; Mulligan 2017 Fig. 14f). Together, these form a sediment-landform assemblage consistent with a rapid drop in water levels from the upper Orillia to Wyebridge phases (likely recording the opening of a new low outlet in the north), followed by a period of stable water levels. Organic material (plant debris) sampled from SU7 provides a maximum age of 9,950±490 14C yr BP (10,800-12,200 cal yr BP) for the Wyebridge phase (Fitzgerald, 1985; Table 1).

Truncation of SU7 by an unconformity surface marked by a paleosol and associated terrestrial organic deposits records lowered water levels in the region following construction of the delta (Figs. 13, 14g, 15). A similar succession of sediments was exposed in a borehole drilled 3.5 km north of Angus within the Minesing basin (Fig. 1b; Fitzgerald 1982). A likely correlative paleosol is identified in fine- to medium-grained sand beneath the surficial lacustrine silty clay and peat deposits at approximately 178 m asl (9 m lower than in log 52; Figs. 4, 13; Fitzgerald 1982).

Radiocarbon dating of wood retrieved from peat and detrital wood overlying the unconformity and paleosol separating SU7 and SU8 at Angus has produced dates of between 5,880±25 and 7,510±70 14C yr BP (6,650 – 6,950 and 8,200 – 8,400 cal yr BP, respectively) and records the latter part of a lake level rise during the mid-Holocene (Bajc and Rainsford 2010; Table 1; Fig. 14g). No sediments that could be attributed to early- mid-Holocene Mattawa high stands were observed in this study due to separation of the study area and from the rest of the Lake Huron by the Edenvale Moraine (Fitzgerald 1982). SU8 deposits grading to 191 m asl are
interpreted to record sedimentation in Lake Edenvale during the Nipissing phase high stand in the study area (Figs. 12, 14h, 15; Fitzgerald 1985).

The stratigraphic units appear to host an exceptional record of changing depositional environments following deglaciation of the region. The paleogeography of the local area was likely a strong control in determining the style of sedimentation and the deep, elongate valleys excavated during Late Wisconsin ice cover provided the necessary accommodation space for the deposition of sediments associated with each lake stage described herein, despite several tens of meters of water level rises and falls (Fig. 15).

5.2 Groundwater applications

Sedimentological data gathered from exposures along the Nottawasaga River valley provide new insights into the hydrostratigraphic framework and potential for groundwater flow and contaminant transport within the southern Simcoe County region, but the detailed three-dimensional (3D) distribution of stratigraphic units cannot be determined from this study alone.

Groundwater sapping horizons observed in outcrops along the Nottawasaga River indicate that the majority of water escaping from the outcrop faces is travelling through SU4-8 (Figs. 4, 16, 17). Based on their sedimentological characteristics, stratigraphic position, and spatial distribution, these units are interpreted to be correlative with the ‘Lake Algonquin Sand Aquifer’ of Sibul and Choo-Ying (1971). Variability in the thickness of the unconfined aquifer (0-14 m) results from the high relief (up to 75 m) on the surface of underlying SU1 deposits that controls the geometry of overlying units (Figs. 4, 17).

Past hydrogeological investigations in the study area report groundwater flow in the Lake Algonquin Sand Aquifer from the valley margins toward the Nottawasaga River and downstream
toward the north (Sibul and Choo-Ying 1971; Hill 1982; Fig. 17). Hill (1982) noted marked
decreases in nitrate concentration with increasing depth in the Lake Algonquin sand aquifer
(SU4-8), which may reflect widespread distribution of the thicker fine-grained lower portion of
SU6 (Figs. 4, 5, 11, 16, 17) that impedes downward migration of the surface contaminants.
Spoelstra et al. (2017) showed that water extracted from many domestic wells penetrating the
Lake Algonquin sand aquifer, and groundwater seeps along the river, contain artificial
sweeteners, likely derived from rural septic systems in the sand plain. Further testing of water
chemistry in shallow and more deeply-buried aquifers may assist in determining the potential
connection between aquifer systems in the region.

Although no outcrops were analyzed within the Canadian Forces Base Borden property
(Fig. 3a), it is likely that the unconfined aquifer complex represented by SU4-8 extends into the
Base Borden property and may share similar hydrogeologic properties with unconfined aquifer
units identified on the base that have been subjected to intense local hydrogeological and
geochemical study (McFarlane et al. 1983; Sudicky and Illman 2011). The ‘Borden aquifer’ is
described as a heterogeneous unconfined aquifer hosted in a deglacial glaciolacustrine or
fluviodeltaic unit consisting of fine- to coarse-grained sand and pebbly sand between 6 and 10 m
thick that rests on a thick unit of sandy silt and clay (Sudicky and Illman 2011; Weissmann et al.
2015). The unconfined Borden aquifer is stratigraphically correlative with SU4-8 (Kirkfield to
post-Algonquin phase deposits), and the silt and clay deposits underlying it are interpreted here
to represent glacial Lake Schomberg and early Lake Algonquin sediments (SU3; Figs. 4, 17).

Groundwater flow directions and unconfined aquifer thickness within the Nottawasaga
River valley appear to be controlled by the topography of the underlying SU1 and SU3 aquitards.
These units are considered as a regional hydraulic barrier through which surface water has
difficulties penetrating (Fig. 16). However, textural heterogeneities and/or erosion or non-deposition of SU1 and SU3 (Figs. 4, 6, 8, 17) led to significant groundwater discharge though discrete coarse-grained interbeds within these aquitard units elsewhere in the region (Fig. 16, 17; Gerber and Howard 1996; Gerber et al. 2001; Sharpe et al. 2002). These interbeds form localized conduits for groundwater flow, which may create hydraulic windows connecting surficial and deeply buried aquifer units (Boyce et al. 1995; Gerber and Howard 1996; Desbarats et al. 2001).

Assessing the risk of contamination of deep aquifers in the region as a result of surface activities remains problematic due to uncertainties with the distribution and potential connectivity of coarse-grained interbeds within the aquitards (SU1 and SU3; Figs. 16, 17). Based on observations of groundwater flow discharging from shallow stratigraphic units within the Nottawasaga River basin, it seems that deep aquifers are reasonably well protected against contamination from surface sources in the former lake plain (Fig. 17). However, the 3D distribution and potential connection of coarse-grained layers within the aquitard units is unclear and should be a focus of future research within the study area. Geochemical analysis of the water in underlying aquifers has revealed a mixing of old (13-25 $^{14}$C ka BP) and modern water (Aravena and Waassenaar 1993), although the recharge areas remain uncertain. Previous reports and recent sediment drilling by the OGS have revealed that many aquifers underlying the Newmarket Till (SU1) beneath the paleolake Algonquin plain display upward hydraulic gradients, and artesian conditions are encountered beneath many low-lying areas within the lowlands (Sibul and Choo-Ying 1971; Fig. 17). Future geochemical investigations using tracers (i.e. artificial sweeteners, nitrates and/or tritium) as a proxy for quantification of infiltration of surface water into the deep groundwater system and/or in-situ hydrogeologic testing and monitoring may help to assess potential hydraulic connections between surficial and buried
aquifer units on a more regional scale. Improving our understanding of the stratigraphic
framework and controls on groundwater flow in southern Simcoe County is essential, as this
rural area is dominated by heavy agricultural use and is slated for major urban expansion in the
near future (Ministry of Public Infrastructure and Renewal 2006).

6. CONCLUSIONS

Developing a better understanding of the depositional history of formerly glaciated basins
is essential for the reconstruction of past environmental changes and the evaluation and
preservation of modern groundwater resources. Detailed logging and sedimentological analysis
of cut bank exposures along the Nottawasaga River allowed identification of eight stratigraphic
units that help establish the major controls on changing sedimentation patterns during the Late
Wisconsin. The sediments exposed along the Nottawasaga River provide the local signature of
regional-scale events that contributed to environmental changes during the deglacial and
postglacial period and give valuable insights into the nature of potentially correlative subsurface
successions elsewhere in the Lake Algonquin basin. The data presented here suggest a high level
of glacial Lake Schomberg developed early during ice retreat (300 m asl). Water levels began to
incrementally fall to early Lake Algonquin levels (240-250 m asl), followed by a rapid base level
fall (to approximately 207 m asl) during the Kirkfield Low Phase following exposure of the
Fenelon Falls outlet. Uplift at Fenelon Falls led to rising water levels and the development of
main Lake Algonquin (225-235 m asl). Main Lake Algonquin drained to incrementally lower
stages during continued uplift at Fenelon Falls, and experienced rapid drops in water levels
following exposure of northern outlets in the North Bay area. The Stanley Low phase is marked
by a paleosol recording a depositional hiatus in the study area, and the entire succession is
capped by organic-bearing sediments recording the Nipissing phase high stand (191 m asl) in the
study area. Detailed sedimentological analysis, together with the collection of organic material and radiocarbon age determination, permits refinement of the timing and magnitude of lake level fluctuations in the study area, which have important implications for investigations elsewhere in the Lake Huron basin.

Qualitative observations of groundwater flow exiting outcrop faces suggest that shallow groundwater is preferentially discharged into the Nottawasaga River, rather than infiltrating into deeply buried aquifers. However the potential connection between surficial and more deeply-buried aquifer units is unclear. Further research into the quantification and monitoring of groundwater flow and chemistry across the former lake plain is warranted. Integration of geophysical, hydrogeological, and hydrochemical data sets with the sedimentological work presented here would aid in the development of an enhanced stratigraphic framework for the sediments underlying the former Lake Algonquin plain and may assist in improving understanding of groundwater flow and contaminant transport pathways in other glaciolacustrine basins across North America.

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## List of Tables:

| lake / stage | Location | Coordinate(s) | Lab number | Material | Elevati(°C yr BP) | Age (±4°C yr BP) | Age Cal yr BP | Reference |
|--------------|----------|---------------|------------|----------|------------------|-----------------|---------------|-----------|
| Kirkfield phase | Baxter | 44°14.2'N 79°48.9'W | A2060 | Dryas leaves | 193-197 | 12,410±25 | 14,321-14,635 | Bajc et al., 2014 |
| | | | A2446 | | | 12,455±40 | 14,396-14,774 | |
| | Hockley | 44°5.8'N 79°53.2'W | A3041 | Dryas leaves | 12,805±40 | 15,172-15,316 | Bajc et al., 2014 |
| | Orillia | 44°34.6'N 79°26.3'W | UOC-3284 | Grizzly | 249 | 11,700±250 | 13,264-13,784 | Tovell and Deane, 1966 |
| | Beaver River | 44°31.4'N 80°28.7'W | UOC-3299 | wood | 225 | 11,776±40 | 13,546-13,712 | This study |
| | | | UOC-3300 | | | 11,863±34 | 13,611-13,741 | |
| | | | | | | 11,828±34 | 13,600-13,711 | |
| Western Erie | Penetangor e River | 44°10.0'N 81°38.0'W | GSC-1842 | Picea/Larix wood | 191 | 11,300±140 | 13,039-13,302 | Anderson, 1979 |
| | Kincardine Bog | 44°09.0'N 81°39.0'W | GSC-1374 | Plant detritus, roots | 194 | 11,200±170 | 12,860-13,213 | Karrow et al., 1975 |
| | multiple sites | multiple samples | GSC-1366 | Plant detritus | 195 | 10,600±150 | 12,247-12,711 | Lewis and Anderson, 1989 |
| | Eighteen Mile River | 44°01.3'N 81°43.6'W | GSC-1127 | Picea wood | 188 | 10,600±160 | 12,241-12,322 | Karrow, 1986 |
| | | | GSC-1126 | | 10,500±150 | 12,161-12,626 | |
| | Clarksburg | 44°31.3'N 80°27.8'W | GSC-2688 | Plant detritus | 225 | 11,200±90 | 12,825-13,248 | Karrow et al., 1995 |
| | | | GSC-2700 | | 11,150±90 | 12,784-13,180 | |
| | Greenbush Swamp | 45°56.0'N 82°00.5'W | WAT-579 | basal gyttja | 307.5 | 9,930±90 | 11,236-11,494 | Warner et al. 1984 |
| | Everett | 44°12.2'N 80°57.0'W | WAT-493 | wood | 225 | 10,280±100 | 11,825-12,301 | Fitzgerald, 1982 |
| | Cookstown | 44°13.3'N 79°37.3'W | GSC-1111 | Basal peat | 229 | 10,200±150 | 11,412-12,159 | Karrow et al., 1975 |
| | Cookstown | 44°13.5'N 79°38.0'W | A3046 | Basal peat | 229 | 10,030±40 | 11,398-11,620 | Bajc et al., 2014 |
| Lower Orillia | Osler Bluff | 44°28.8'N 80°16.7'W | UOC-3303 | wood | 226 | 9,531±30 | 10,731-11,065 | This study |
| | | | UOC-3304 | | 8,912±38 | 9,938-10,172 | |
| Wyebridge | Angus | 44°19.5'N 79°55.0'W | UOC-3297 | wood | 186 | 10,093±48 | 11,412-11,838 | This study |
| | | | UOC-3296 | | 10,109±59 | 11,420-11,990 | |
| | | | UOC-3300 | | 10,557±37 | 12,429-12,588 | |
| Location                  | Coordinates          | Sample Code | Type               | Age         | Depth Range | Reference                |
|---------------------------|----------------------|-------------|--------------------|-------------|-------------|--------------------------|
| Angus                     | 44°18.9’N 79°52.2’W  | WAT-788     | plant debris       | 195         | 9,950±490   | Fitzgerald, 1982         |
| Sheguianda Bog H Bog      | 45°53.7’N 81°55.4’W  | W-345       | basal peat         | 219         | 9,130±350   | Lee, 1957                |
| Tehkumma Lake             | 45°36.0’N 81°59.9’W  | GSC-1108    | basal gyttja       | 184.2       | 10,150±190  | Lewis, 1969              |
| Morel Lake                | 46°16.3’N 78°48.0’W  | GSC-1275    | basal gyttja       | 180.2       | 10,100±240  | Harrison, 1972           |
| Straits of Mackinac       | 45°49.1’N 84°43.8’W  | M-2337      | roots and stumps   | 138.5       | 8,150±1300  | Crane and Griffin, 1970  |
| Bruce Mines Bog           | 46°17.8’N 83°42.8’W  | GSC-1359    | plant detritus     | 180.3       | 8,160±220   | Lewis and Anderson, 1989 |
| Hope Bay                  | 44°55.0’N 81°07.1’W  | I-7858      | wood               | 147         | 8,785±145   | Lewis and Anderson, 1989 |
| SW Lake Huron             | 44°30.3’N 83°08.0’W  | GSC-1966    | woody peat         | 124.3-125.3 | 9,680±110   | Lewis and Anderson, 1989 |
| Nipissing phase           |                      |             |                    |             |             |                          |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | A3329       | logs in alluvium   | 178-182     | 6,895±25    | 7,682-7,741              |
| Picotte’s Creek           | 44°49.5’N 79°55.9’W  | A3328       | logs in alluvium   | 178-182     | 6,370±25    | 7,316-7,267              |
| Waubashen e               | 44°46.7’N 79°41.4’W  | A3325       | logs in alluvium   | 178-182     | 6,195±25    | 7,026-7,162              |
| Angus                     | 44°19.0’N 79°51.6’W  | BGS-1508    | wood               | 190         | 5,725±100   | Bajc, 1994               |
| Blooms                    | 44°19.0’N 79°51.6’W  | BGS-1504    | wood               | 190         | 5,920±90    | Bajc, 1994               |
| Waubashen e               | 44°46.7’N 79°41.4’W  | BGS-1511    | wood               | 186-190     | 6,440±90    | 7,173-7,506              |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | BGS-1512    | wood               | 186-190     | 6,440±90    | 7,173-7,506              |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | BGS-1506    | wood               | 186-190     | 6,440±90    | 7,173-7,506              |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | BGS-1510    | wood               | 186-190     | 6,440±90    | 7,173-7,506              |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | BGS-1505    | wood               | 186-190     | 6,440±90    | 7,173-7,506              |
| Angus                     | 44°19.0’N 79°51.6’W  | A6688       | wood               | 190         | 5,900±70    | Bajc and Rainsford, 2010 |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | A6689       | wood               | 190         | 5,900±70    | Bajc and Rainsford, 2010 |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | A6690       | wood               | 190         | 5,900±70    | Bajc and Rainsford, 2010 |
| Wasaga Beach              | 44°28.9’N 80°02.6’W  | A6684       | wood               | 190         | 5,880±25    | Bajc and Rainsford, 2010 |
| Nipissing phase           |                      |             | peat               | 190         | 5,336±162   | Martini and Hoffman, 1976|
| Minesing                  |                      | WAT-507     | Wood               | 190         | 4,642±60    | FitzGerald, 1982         |
| Wasaga Beach              | 44°28.2’N 80°02.9’W  | BGS-224     | Peat (2 distinct beds) | 186 | 6,670±100 | Terasmae, 1979          |
| Wasaga Beach              | 44°28.2’N 80°02.9’W  | BGS-378     | Peat (2 distinct beds) | 192 | 4,390±90 | Terasmae, 1979          |
| Wasaga Beach              | 44°28.2’N 80°02.9’W  | A3330       | wood in sand       | 181         | 6,570±25    | This study               |
| Location          | Latitude      | Longitude   | Site Code | Age (cal BP) | Date Range  | Comment               |
|-------------------|---------------|-------------|-----------|--------------|--------------|-----------------------|
| Wasaga Beach      | 44°28.2'N     | 80°02.8'W   | A3423     | 5,915±15     | 6,679-6,775  | This study            |
|                   |               |             | A3422     | 5,685±20     | 6,442-6,489  |                       |
|                   |               |             | A3327     | 5,000±20     | 5,663-5,745  |                       |
| Post-Nipissing    |               |             |           |              |              |                       |
| Collingwood       | 44°31.2'N     | 80°16.5'W   | UOC-3301  | 1,450±27     | 982-1170     | This study            |
|                   |               |             | UOC-3302  | 1,197±27     | 1,081-1,175  |                       |
| Wasaga Beach      | 44°28.9'N     | 80°02.6'W   | UOC-3305  | 748±27       | 669-692      |                       |

*local elevations, no isostatic adjustment

**converted using intCal13 (Reimer et al. 2013), 2σ , present defined as 1950

Table 1: radiocarbon dates from Simcoe County and other selected sites from the Lake Huron basin

List of Figs.:

**Fig. 1:** a) Maximum extent of proglacial lake and postglacial marine deposits in central Canada and northern United States during deglaciation. Lake outlets identified by black arrows; C=Chicago outlet, PH=Port Huron outlet, R=Rome outlet, FF=Fenelon Falls outlet, NB=North Bay outlet. Red line identifies southermmost extent of Late Wisconsin glacial ice. Location of Fig. 1b shown in black rectangle. Modified from Barnett (1992); b) DEM of central Ontario showing prominent physiographic features, including drunlinized uplands (U), the Barrie (BV), Cookstown (CV) and Holland Marsh (HMV) valleys, Alliston embayment (AE), and Minesing Basin (MB). Abandoned shorelines of glacial lakes Iroquois and Algonquin shown in black, Nipissing phase shoreline shown in blue. Fenelon Falls (FF) outlet shown with black star. Simcoe County outlined in red. Location of Fig. 3a shown in black rectangle.

**Fig. 2:** Glacial history and paleogeography of southern Ontario during the Late Wisconsin, showing a) regional ice flow from the northeast during the last glacial maximum; b) lobate flow during early deglacial period, development of glacial lakes Schomberg (GLS) and early Algonquin following formation of Oak Ridges Moraine (ORM); c) maximum extents of glacial lakes Algonquin and Iroquois during deglaciation. Fenelon Falls (FF) and Port Huron (PH) outlets shown with black star, red arrows show lake drainage pathways, Fig. 3a shown in yellow rectangle. Modified from Chapman and Putnam (1984).

**Fig. 3:** a) DEM of study area showing location of measured sections (green dots) and OGS boreholes (white dots). See Figs. 1, 2 for location. Location of Fig. 13 shown in dashed black rectangle. Outcrop sections used to construct Fig. 4 shown by red dots and outcrops shown in Fig. 5 marked with arrows; b) idealized stratigraphic log summarizing the overall stratigraphy of the Nottawasaga River valley. Sediments are grouped into stratigraphic units (SU1-8) see text.
for detailed descriptions, SU7 and SU8 not shown, see Fig. 4 for relationships). Legend for sediment logs (Figs. 4, 5 and 13) shown at right.

**Fig. 4:** S-N cross-sectional profile showing distribution of SUs exposed along the Nottawasaga River. Refer to Fig. 3a for log locations. Note the truncation/non-deposition of units where SU1 is exposed at higher elevations and thickening of units when SU1 is at lower elevations. No horizontal scale, but distances between logs shown above. Elevations reported in meters above sea level and have not been corrected for glacial isostatic adjustment.

**Fig. 5:** Annotated photomosaics of a) cut bank exposure of log 37 (Figs. 3, 4; 594382 mE, 4899076 mN). SU3-6 are well exposed and have planar tabular unit geometry; section is 14 m high; b) cut bank exposure of log 19 (Figs. 3, 4; 594341 mE, 4887003 mN). SU4 and SU5 have a consistent planar tabular geometry except where SU5 is incised into SU4 at left; channel feature is 4 m deep and 10-12 m wide, section is 11 m high.

**Fig. 6:** SU1: a) massive diamict (lower half) directly overlain by silt rhythmites (upper half, SU3). Contact shown with black arrow at left; shovel is 50 cm long; b) large striated boulder with well-developed stoss and lee ends indicating ice flow to the southwest. Clast long axis and striae are parallel (orientation 230 degrees N); compass is 12 cm long; c) crude stratification showing massive, blocky texture at base, fissile beds and silt-rich beds near top; contacts between beds shown with red dashed lines, ice flow was into page; d) coarse-grained pebbly sand interbed within SU1. Shovel handle is 4 cm wide.

**Fig. 7:** SU2: a) interbedded coarse-grained sand and silt-rich diamict; b) deformed and faulted medium to coarse-grained sand and sand-rich diamict beds. Diamict beds have textural similarities to SU1; c) deformed (folded and faulted) unit of silt and very fine-grained sand.

**Fig. 8:** SU3: a) scattered clasts within SU3; beds dipping gently to the right in response to underlying topography of SU1; selected clasts circled in black, knife is 30 cm long; b) silt rhythmites and sand interbeds within SU3. Note continuity of sand bed (light coloured bed at knife tip) along entire outcrop face; knife is 30 cm long; c) dipping beds and a clast-rich horizon (pebble band) within silt and clay rhythmites (knife is 25 cm long); d) rounded limestone clast deforming underlying beds, while overlying beds drape clast surface, and are truncated by planar sandy laminae approximately 2 cm above the clast. Knife blade is 3 cm wide.

**Fig. 9:** SU4: a) large-scale soft sediment deformation structures involving thick silt beds that both underlie and drape the sand body. Compass is 12 cm long; b) Type-A climbing ripples passing upward into Type-B ripples with increasing climb angle, fingertip for scale; c) gradational transition from planar and ripple-scale cross-laminated land (SU4) into highly fossiliferous trough cross-bedded medium to coarse-grained sand (SU5). Shovel handle is 50 cm long.

**Fig. 10:** SU5: a) cross-bedded gravel and sand sharply overlain by massive and faintly laminated silt with fine-grained sand interbeds (SU6). The concave-up feature at left (dashed white line) likely represents the last stage of active channel that was subsequently infilled by SU6, shovel is 50 cm long; b) cross-bedded pebble gravel directly overlying silt rhythmites (SU3); c) small (1 m
Fig. 11: SU6: a) thinly bedded silt with fine-grained sand interbeds near the base of SU6. Sand beds contain starved asymmetrical ripples and have sharp upper and lower contacts; b) sand intraclasts (arrowed) within laminated silt-rich sediments near base of SU6; c) Fine- to medium-grained sand in upper part of SU6; sands display soft sediment deformation structures that are truncated along sub-horizontal erosion horizons (arrowed); grub hoe blade is approx. 25 cm long; d) symmetrical (wave) ripples and small-scale (3cm) soft-sediment deformation structures, fingertip is 2 cm wide.

Fig. 12: SU7: a) upper part of SU7 at Angus (see Figs. 3, 13 for location), showing Type-A climbing ripples (NW paleoflow directions) in fine-grained sand draped by thick (up to 15 cm) beds of laminated silt with thin stringers of very fine-grained sand; b) gradational transition passing upward from large-scale (>1m) deformation structures (i) into dish structures (ii) and ripple-scale cross-laminated sand (iii). Black rectangle shows location of photo in c; c) close-up view of dish structures. Two small fragments of mollusc shells are highlighted by white arrows. Knife is 30 cm long; d) thick packages of amalgamated beds of ripple-scale cross-laminated fine-grained sand in the lower part of SU7. Locations of a and b shown with white arrows.

Fig. 13: a) DEM showing surface morphology and location of logged sections 51 and 52 near Angus (see also Fig. 3a), and location of wood sample used for radiocarbon dating shown in e); b) photo of cutbank exposure showing location of log 52, two post-Algonquin terrace levels (white arrows), unconformity surface (Stanley low phase; dashed red line) and location of photomosaic (white box) shown in c); c) photomosaic of lower terrace sediments. White arrows point to large (5-10cm) unionid clam fossils. d) line sketch of exposure shown in c) with corresponding sediment log. Buried unconformity surface and paleosol shown in red; e) buried organic-rich horizon beneath fluviodeltaic sands of SU8; R’s shows location and age of wood samples collected for radiocarbon dating, reported in cal yr BP.

Fig. 14: Late Wisconsin – Holocene paleogeographic reconstructions of central Ontario overlain onto regional DEM viewed obliquely from the south (study area outlined in black): a) separation of ice lobes during deglaciation and formation of Oak Ridges Moraine (ORM) and kame terrace deposits along Niagara Escarpment to the west; b) extent of glacial Lake Schomberg following ice retreat; c-f) extent of glacial Lake Algonquin during several distinct phases; g) Stanley low phase; h) Nipissing phase high stand in the Lake Huron basin. Data for water plane elevations and dates from multiple sources (Fig. 15; Table 1); shorelines were mapped by the author, compared to elevations reported by previous workers, then lake extents were manually digitized onto the hillshaded relief map.

Fig. 15: Lake level curve for the study area. Local water plane elevations were calculated based on regional shoreline mapping, timing of lake level fluctuations based on correlation of dated organic material within the Huron basin. Elevation data have not been corrected for isostatic
effects. The curve is tied to ice margin positions during deglaciation, changing drainage outlets, and the Stratigraphic Units identified in this study. Note that no signature of Mattawa high stand(s) were observed in this study, but were added to the curve to assist in correlating events from the study area with regions across the paleolake basins. Refer to Table 1 for radiocarbon data.

Fig. 16: a) surface seepage zones identify preferential flow paths of groundwater through coarser-grained interbeds within SU1 (dark tones shown with red arrows); b) small piping feature within silt rhythmites of SU3; c) photo of northern portion of section 37, showing planar tabular geometry of SU3-6 and continuity of seepage horizons (dark coloured areas) along entire outcrop face; section is 14 m high, location of d shown with black rectangle; d) groundwater seepage horizons (arrowed) within SU4 sediments, section 37 (see Fig. 4a for location); e) active erosion of outcrop from groundwater sapping within SU6. Note large blocks of sediment that have fallen from undercutting due to seepage of water along the upper contact on fine-grained sediments beneath; f) large amphitheatre-shaped piping scar within deltaic sediments of SU7 southeast of Angus.

Fig. 17: Conceptual model of groundwater flow through shallow subsurface sediments identified in this study. High flow rates are interpreted for SU4-8 (large blue arrows). SU1 and SU3 are interpreted to form hydraulic barriers (thick black arrows) that impede downward flow of groundwater. Note that coarse-grained interbeds within SU1 and SU3 may create thin, highly conductive flow paths (blue arrows) that may provide hydraulic connection between surface and buried aquifers. SU2 not shown. Depending on elevation within the lowlands and proximity to elevated recharge areas, shallow groundwater may infiltrate downward into deeper confined aquifers. Elsewhere, strong upward gradients exist, which create artesian conditions in many areas.
| lake / stage | Location | Coordinates | Lab number | Material | Elevation (masl) | Age (14C yr BP) | Age Cal yr BP | Reference |
|-------------|----------|-------------|------------|----------|-----------------|----------------|--------------|-----------|
| Kirkfield phase | Baxter | 44°14.2'N 79°48.9'W | A2060 | Dryas leaves | 193-197 | 12,410±25 | 14,321-14,635 | Bajc et al., 2014 |
| | Hockley | 44°5.8'N 79°53.2'W | A2446 | Dryas leaves | 12,805±40 | 15,172-15,316 | Bajc et al., 2014 |
| | Orillia | 44°34.6'N 79°26.3'W | UOC-3284 | Grizzly bear skull | 249 | 11,700±250 | 13,264-13,784 | Tovell and Deane, 1966 |
| | Beaver River | 44°31.4'N 80°28.7'W | UOC-3299 | wood | 225 | 11,863±34 | 13,611-13,741 | This study |
| | Penetangore River | 44°10.0'N 81°38.0'W | GSC-1842 | Picea/Larix wood | 191 | 11,300±140 | 13,039-13,302 | Anderson, 1979 |
| | Kincardine Bog | 44°09.0'N 81°39.0'W | GSC-1374 | Plant detritus, roots | 194 | 11,200±170 | 12,860-13,213 | Karrow et al., 1975 |
| | | | GSC-1366 | Plant detritus | 195 | 10,600±150 | 12,247-12,711 | |
| Western Erie multiple sites | Eighteen Mile River | 44°01.3'N 81°43.6'W | GSC-1127 | Picea wood | 188 | 10,600±160 | 12,241-12,322 | Karrow, 1986 |
| | | | GSC-1126 | Picea wood | 190 | 10,500±150 | 12,161-12,626 | |
| | Clarksburg | 44°31.3'N 80°27.8'W | WAT-2688 | Plant detritus | 225 | 11,200±90 | 12,825-13,248 | Karrow et al., 1995 |
| | | | WAT-2700 | | | 11,150±90 | 12,784-13,180 | |
| | Greenbush Swamp | 45°56.0'N 82°00.5'W | WAT-579 | basal gyttja | 307.5 | 9,930±90 | 11,236-11,494 | Warner et al. 1984 |
| | Everett | 44°12.2'N 80°57.0'W | WAT-493 | wood | 225 | 10,280±100* | 11,825-12,301 | Fitzgerald, 1982 |
| | Cookstown | 44°13.3'N 79°37.3'W | GSC-1111 | Basal peat | 229 | 10,200±150 | 11,412-12,159 | Karrow et al., 1975 |
| | Cookstown | 44°13.5'N 79°38.0'W | A3046 | Basal peat | 229 | 10,030±40 | 11,398-11,620 | Bajc et al., 2014 |
| Main Algonquin | Osler Bluff | 44°28.8'N 80°16.7'W | UOC-3303 | wood | 266 | 9,531±30 | 10,731-11,065 | This study |
| | | | UOC-3304 | | | 8,912±38 | 9,938-10,172 | |
| Lower Orillia | Angus | 44°19.5'N 79°55.0'W | UOC-3297 | | | 10,093±48 | 11,412-11,838 | This study |
| | | | UOC-3296 | wood | 186 | 10,109±59 | 11,420-11,990 | |
| | | | UOC-3298 | | | 10,557±37 | 12,429-12,588 | |
| Wyebridge | Angus | 44°18.9'N 79°52.2'W | WAT-788 | Plant debris | 195 | 9,950±490 | 10,756-12,165 | Fitzgerald, 1982 |
| Stanley Low | Sheguiandah Bog | 45°53.7'N 81°55.4'W | W-345 | basal peat | 219 | 9,130±350 | 9,744-10,720 | Lee, 1957 |
| | Tekkummah Lake | 45°36.0'N 81°59.9'W | GSC-1108 | basal gyttja | 184.2 | 10,150±190 | 11,393-12,090 | Lewis 1969 |
| | Morel Lake | 46°16.3'N 78°48.0'W | GSC-1275 | basal gyttja | 180.2 | 10,100±240 | 11,269-12,052 | Harrison, 1972 |
| | Straits of Mackinac | 45°49.1'N 84°43.8'W | M-2337 | roots and stumps | 138.5 | 8,150±300 | 8,663-9,435 | Crane and Griffin 1970 |
| | | | M-1996 | | | 9,780±330 | 10,696-11,754 | |
| | Bruce Mines Bog | 46°17.8'N 83°42.8'W | GSC-1359 | Plant detritus | 180.3 | 8,160±220 | 8,780-9,420 | Lewis and Anderson, 1989 |
| | | | GSC-1360 | | | 9,560±160 | 10,697-11,144 | |
| | Hope Bay | 44°55.0'N 81°07.1'W | I-7858 | wood | 147 | 9,930±250 | 11,129-11,963 | Lewis and Anderson, 1989 |
| | | | I-7857 | | | 8,785±145 | 9,599-10,128 | |
| Location                  | Latitude | Elevation | Type          | Age (8±14 C) | Error | References                                      |
|---------------------------|----------|-----------|---------------|--------------|-------|------------------------------------------------|
| SW Lake Huron             | 44°30.3'N 83°08.0'W | 9,680±110 | woody peat    | 124.3 - 125.3 | 10,794-11,214 | Lewis and Anderson, 1989 |
| BGS-1983                  | 44°49.5'N 79°55.9'W | 8,460±180 | logs in alluvium | 178-182 | 6,095-6,730 | Bajc, 1994 |
| BGS-1508                  | 44°46.7'N 79°41.4'W | 6,895±25  | wood          | 5,725± 100  | 6,312-6,730 | Bajc, 1994 |
| BGS-1504                  | 44°19.0'N 79°51.6'W | 6,960±90  | peat          | 5,900±70    | 6,534-6,898 | Bajc and Rainsford, 2010 |
| UOC-3301                  | 44°31.2'N 80°16.5'W | 1,450±127 | wood in peat  | 179  | 982-1170 | This study |
| UOC-3302                  | 44°28.9'N 80°02.6'W | 1,197±127 | wood in peat  | 192 | 1,081-1,175 | This study |
| UOC-3305                  | 44°28.9'N 80°02.6'W | 748±27   | charcoal      | 195 | 669-692 | This study |
| Minesing                  | 44°28.9'N 80°02.6'W | 6,670±100 | peat (2 distinct beds) | 186  | 7,461-7,614 | Terasmae, 1979 |
| Collingwood               | 44°31.2'N 80°16.5'W | 6,670±100 | peat (2 distinct beds) | 192 | 4,852-5,261 | Terasmae, 1979 |
| Collingwood               | 44°28.9'N 80°02.6'W | 6,570±125 | wood in sand  | 181 | 7,435-7,480 | This study |
| Collingwood               | 44°28.9'N 80°02.6'W | 5,915±15  | wood in peat(1) | 185-186 | 6,679-6,775 | This study |
| Collingwood               | 44°28.9'N 80°02.6'W | 5,685±20  | Wood in peat(2) | 192 | 6,442-6,489 | This study |

1 local elevations, no isostatic adjustment
2 converted using intCal13 (Reimer et al. 2013), 2σ, present defined as 1950

A= Illinois State Geological Survey Radiocarbon Dating Laboratory
BGS= Brock University Geological Sciences
GSC= Geological Survey of Canada
UOC= University of Ottawa A.E. Lalonde AMS lab
WAT= University of Waterloo
Fig. 1: a) Maximum extent of proglacial lake and postglacial marine deposits in central Canada and northern United States during deglaciation. Lake outlets identified by black arrows; C=Chicago outlet, PH=Port Huron outlet, R=Rome outlet, FF=Fenelon Falls outlet, NB=North Bay outlet. Red line identifies southernmost extent of Late Wisconsin glacial ice. Location of Fig. 1b shown in black rectangle. Modified from Barnett (1992); b) DEM of central Ontario showing prominent physiographic features, including drumlinized uplands (U), the Barrie (BV), Cookstown (CV) and Holland Marsh (HMV) valleys, Alliston embayment (AE), and Minesing Basin (MB). Abandoned shorelines of glacial lakes Iroquois and Algonquin shown in black, Nipissing phase shoreline shown in blue. Fenelon Falls (FF) outlet shown with black star. Simcoe County outlined in red. Location of Fig. 3a shown in black rectangle.
Fig. 2: Glacial history and paleogeography of southern Ontario during the Late Wisconsin, showing a) regional ice flow from the northeast during the last glacial maximum; b) lobate flow during early deglacial period, development of glacial lakes Schomberg (GLS) and early Algonquin following formation of Oak Ridges Moraine (ORM); c) maximum extents of glacial lakes Algonquin and Iroquois during deglaciation. Fenelon Falls (FF) and Port Huron (PH) outlets shown with black star, red arrows show lake drainage pathways, Fig. 3a shown in yellow rectangle. Modified from Chapman and Putnam (1984).
Fig. 3: a) DEM of study area showing location of measured sections (green dots) and OGS boreholes (white dots). See Figs. 1, 2 for location. Location of Fig. 13 shown in dashed black rectangle. Outcrop sections used to construct Fig. 4 shown by red dots and outcrops shown in Fig. 5 marked with arrows; b) idealized stratigraphic log summarizing the overall stratigraphy of the Nottawasaga River valley. Facies are grouped into stratigraphic units (SU1-8) see text for detailed descriptions, SU7 and SU8 not shown, see Fig. 4 for relationships). Legend for sediment logs (Figs. 4, 5 and 13) shown at right.
Fig. 4: S-N cross-sectional profile showing distribution of SUs exposed along the Nottawasaga River. Refer to Fig. 3a for log locations. Note the truncation/non-deposition of units where SU1 is exposed at higher elevations and thickening of units when SU1 is at lower elevations. No horizontal scale, but distances between logs shown above. Elevations reported in meters above sea level and have not been corrected for glacial isostatic adjustment.

237x157mm (300 x 300 DPI)
Fig. 5: Annotated photomosaics of a) cutbank exposure of log 37 (Figs. 3, 4; 594382 mE, 4899076 mN). SU3-6 are well exposed and have planar tabular unit geometry; section is 14 m high; b) cutbank exposure of log 19 (Figs. 3, 4; 594341 mE, 4887003 mN). SU4 and SU5 have a consistent planar tabular geometry except where SU5 is incised into SU4 at left; channel feature is 4 m deep and 10-12 m wide, section is 11 m high.

721x542mm (96 x 96 DPI)
Fig. 6: SU1: a) massive diamict (lower half) directly overlain by silt rhythmites (upper half, SU3). Contact shown with black arrow at left; shovel is 50 cm long; b) large striated boulder with well-developed stoss and lee ends indicating ice flow to the southwest. Clast long axis and striae are parallel (orientation 230 degrees N); compass is 12 cm long; c) crude stratification showing massive, blocky texture at base, fissile beds and silt-rich beds near top; contacts between beds shown with red dashed lines, ice flow was into page; d) coarse-grained pebbly sand interbed within SU1. Shovel handle is 4 cm wide.

658x737mm (96 x 96 DPI)
Fig. 7: SU2: a) interbedded coarse-grained sand and silt-rich diamict; b) deformed and faulted medium to coarse-grained sand and sand-rich diamict beds. Diamict beds have textural similarities to SU1; c) deformed (folded and faulted) unit of silt and very fine-grained sand.
Fig. 8: SU3: a) scattered clasts within SU3; beds dipping gently to the right in response to underlying topography of SU1; selected clasts circled in black, knife is 30 cm long; b) silt rhythmites and sand interbeds within SU3. Note continuity of sand bed (light coloured bed at knife tip) along entire outcrop face; knife is 30 cm long; c) dipping beds and a clast-rich horizon (pebble band) within silt and clay rhythmites (knife is 25 cm long); d) rounded limestone clast deforming underlying beds, while overlying beds drape clast surface, and are truncated by planar sandy lamine approximately 2 cm above the clast. Knife blade is 3 cm wide.

573x542mm (96 x 96 DPI)
Fig. 9: SU4: a) large-scale soft sediment deformation structures involving thick silt beds that both underlie and drape the sand body. Compass is 12 cm long; b) Type-A climbing ripples passing upward into Type-B ripples with increasing climb angle, fingertip for scale; c) gradational transition from planar and ripple-scale cross-laminated land (SU4) into highly fossiliferous trough cross-bedded medium to coarse-grained sand (SU5). Shovel handle is 50 cm long.

269x735mm (96 x 96 DPI)
Fig. 10: SU5: a) cross-bedded gravel and sand sharply overlain by massive and faintly laminated silt with fine-grained sand interbeds (SU6). The concave-up feature at left (dashed white line) likely represents the last stage of active channel that was subsequently infilled by SU6, shovel is 50 cm long; b) cross-bedded pebble gravel directly overlying silt rhythmites (SU3); c) small (1 m deep x 4 m wide) channel/scour feature (black dashed outline) infilled with planar-laminated fine-grained sand with large silt rip-up clasts, shovel (50 cm long) placed at right margin of channel; d) base of larger channel/scour feature (2.5 m deep x 8 m wide) showing truncation of underlying strata and rip-up clasts (up to 12 cm diameter; arrowed), compass is 12 cm long; e) high concentrations of bivalve and mollusk shells along sandy NNE-dipping foresets.
Fig. 11: SU6: a) thinly bedded silt with fine-grained sand interbeds near the base of SU6. Sand beds contain starved asymmetrical ripples and have sharp upper and lower contacts; b) sand intraclasts (arrowed) within laminated silt-rich sediments near base of SU6; c) Fine- to medium-grained sand in upper part of SU6; sands display soft sediment deformation structures that are truncated along sub-horizontal erosion horizons (arrowed); grub hoe blade is approx. 25 cm long d) symmetrical (wave) ripples and small-scale (3cm) soft-sediment deformation structures, fingertip is 2 cm wide.

272x665mm (96 x 96 DPI)
Fig. 12: SU7: a) upper part of SU7 at Angus (see Figs. 3, 13 for location), showing Type-A climbing ripples (NW paleoflow directions) in fine-grained sand draped by thick (up to 15 cm) beds of laminated silt with thin stringers of very fine-grained sand; b) gradational transition passing upward from large-scale (>1m) deformation structures (i) into dish structures (ii) and ripple-scale cross-laminated sand (iii). Black rectangle shows location of photo in c; c) close-up view of dish structures. Two small fragments of mollusc shells are highlighted by white arrows. Knife is 30 cm long; d) thick packages of amalgamated beds of ripple-scale cross-laminated fine-grained sand in the lower part of SU7. Locations of a and b shown with white arrows.
Fig. 13: a) DEM showing surface morphology and location of logged sections 51 and 52 near Angus (see also Fig. 3a), and location of wood sample used for radiocarbon dating shown in e); b) photo of cutbank exposure showing location of log 52, two post-Algonquin terrace levels (white arrows), unconformity surface (Stanley low phase; dashed red line) and location of photomosaic (white box) shown in c); c) photomosaic of lower terrace sediments. White arrows point to large (5-10cm) unionid clam fossils. d) line sketch of exposure shown in c) with corresponding sediment log. Buried unconformity surface and paleosol shown in red; e) buried organic-rich horizon beneath fluviodeltaic sands of SU8; R’s shows location and age of wood samples collected for radiocarbon dating, reported in cal yr BP.
Fig. 14: Late Wisconsin – Holocene paleogeographic reconstructions of central Ontario overlain onto regional DEM viewed obliquely from the south (study area outlined in black): a) separation of ice lobes during deglaciation and formation of Oak Ridges Moraine (ORM) and kame terrace deposits along Niagara Escarpment to the west; b) extent of glacial Lake Schomberg following ice retreat; c-f) extent of glacial Lake Algonquin during several distinct phases; g) Stanley low phase; h) Nipissing phase high stand in the Lake Huron basin. Data for water plane elevations and dates from multiple sources (Fig. 15; Table 1); shorelines were mapped by the author, compared to elevations reported by previous workers, then lake extents were manually digitized onto the hillshaded relief map; see references within text.
Fig. 15: Lake level curve for the study area. Local water plane elevations were calculated based on regional shoreline mapping, timing of lake level fluctuations based on correlation of dated organic material within the Huron basin. Elevation data have not been corrected for isostatic effects. The curve is tied to ice margin positions during deglaciation, changing drainage outlets, and the Stratigraphic Units identified in this study. Note that no signature of Mattawa high stand(s) were observed in this study, but were added to the curve to assist in correlating events from the study area with regions across the paleolake basins. Refer to Table 1 for radiocarbon data.
Fig. 16: a) surface seepage zones identify preferential flow paths of groundwater through coarser-grained interbeds within SU1 (dark tones shown with red arrows); b) small piping feature within silt rhythmtes of SU3; c) photo of northern portion of section 37, showing planar tabular geometry of SU3-6 and continuity of seepage horizons (dark coloured areas) along entire outcrop face; section is 14 m high, location of d shown with black rectangle; d) groundwater seepage horizons (arrowed) within SU4 sediments, section 37 (see Fig. 4a for location); e) active erosion of outcrop from groundwater sapping within SU6. Note large blocks of sediment that have fallen from undercutting due to seepage of water along the upper contact on fine-grained sediments beneath; f) large amphitheatre-shaped piping scar within deltaic sediments of SU7 southeast of Angus.

565x723mm (96 x 96 DPI)
Fig. 17: Conceptual model of groundwater flow through shallow subsurface sediments identified in this study. High flow rates are interpreted for SU4-8 (large blue arrows). SU1 and SU3 are interpreted to form hydraulic barriers (thick black arrows) that impede downward flow of groundwater. Note that coarse-grained interbeds within SU1 and SU3 may create thin, highly conductive flow paths (blue arrows) that may provide hydraulic connection between surface and buried aquifers. SU2 not shown. Depending on elevation within the lowlands and proximity to elevated recharge areas, shallow groundwater may infiltrate downward into deeper confined aquifers. Elsewhere, strong upward gradients exist, which create artesian conditions in many areas.