Three-dimensional hydrostratigraphy of the Orangeville Moraine area, Southwestern Ontario, Canada

| Journal: | Canadian Journal of Earth Sciences |
|---------|-----------------------------------|
| Manuscript ID | cjes-2017-0077.R3 |
| Manuscript Type: | Article |
| Date Submitted by the Author: | 22-Nov-2017 |
| Complete List of Authors: | Burt, Abigail K.; Ontario Geological Survey, |
| Is the invited manuscript for consideration in a Special Issue? : | Quaternary Geology of Southern Ontario and Applications to |
| Keyword: | Quaternary, glacial geology, aquifer, glacial history, 3D mapping |
Three-dimensional hydrostratigraphy of the Orangeville Moraine area, Southwestern Ontario, Canada

Abigail Burt, abigail.burt@ontario.ca,

Ontario Geological Survey, 933 Ramsey Lake Road, Sudbury, ON P3E 6B5
tel: 705-670-5958, fax: 705-670-5905
Abstract

Regional-scale three-dimensional modelling of Quaternary sediments in the Orangeville Moraine area of southwestern Ontario has been completed as part of the Ontario Geological Survey groundwater initiative and provides an improved understanding of the glacial history and conceptual hydrostratigraphic framework for that region. Older (Marine Isotope Stage (MIS) 3-5) diamicton, glaciolacustrine, glaciofluvial and rare non-glacial deposits forming regional aquitards and local aquifers are found in the northwestern part of the area. Catfish Creek Till, deposited during the late glacial maximum (LGM) (MIS 2), forms a key aquitard and stratigraphic marker at depth. Diamicton, fine-textured glaciolacustrine sediments, and the gravel, sand and silt conduit and subaqueous fan sediments that comprise the overlying Orangeville Moraine were deposited in an ice walled lake formed between ice lobes during retreat from the LGM. Diamicton deposited during late glacial ice margin fluctuations forms the upper aquitard unit and buries the edges of the moraine. The Orangeville Moraine is the largest aquifer in the area, and is partially confined by the upper tills. Thick fine-textured glaciolacustrine deposits, Catfish Creek Till and older aquitards separate the moraine from bedrock aquifers across most of the area. Depending on hydraulic gradients, buried bedrock valleys with gravel and sand fills have the potential to recharge the bedrock aquifer.

KEY WORDS - glacial geology, Quaternary, aquifer, glacial history, 3D mapping
Introduction

In May 2000, 7 people died and several thousand became ill in Walkerton, Ontario after drinking water from a municipal supply, which had become contaminated by *Escherichia coli*. The impact of the incident was profound and focused the attention of the general public and government on protecting water supplies from pollution. The resulting Public Inquiry made a number of recommendations in order to better protect water quality, including the development of watershed-based source water protection plans (O’Connor 2002). An improved understanding of both regional- and local-scale geology is essential to the implementation of these recommendations.

Since 2002, the Ontario Geological Survey (OGS) has been engaged in regional-scale three-dimensional (3D) sediment modelling in southern Ontario. The first projects focused on large sand and gravel moraine systems (Waterloo Moraine, Oro Moraine) in thick successions of unconsolidated Quaternary sediments in southern Ontario where people are reliant on groundwater for domestic water supply, agriculture and industry (Bajc and Shirota 2007; Burt and Dodge 2011). The importance of understanding and documenting the stratigraphic context and internal sediment characteristics of large moraine systems in order to develop informed groundwater flow models for planning purposes has long been recognized (for example Howard et al. 1995). Of equal importance are buried bedrock valley systems as, depending on the hydrogeological properties of the sediment fill, they have the potential to host producing aquifers (Russell et al. 2004; Meyer and Eyles 2007; Gao 2011; Marich et al. 2011; Huntsman et al. 2012; Hinton et al. 2013; Seyoum and Eckstein 2014; Bajc et al. this volume).
This study demonstrates that the Orangeville Moraine, deposited within the same late glacial interlobate zone as the well-documented Waterloo Moraine (for example Bajc and Karrow 2004; Bajc and Shirota 2007; Bajc et al. 2014; Frind et al. 2014; Meyer et al. 2014), has similar stratigraphic and sediment characteristics and may be expected to have equally complex groundwater flow conditions (Bajc et al. 2014). Buried and partially buried bedrock valleys within the study area contain thick sequences of gravel and sand separated by silt, clay and diamicton (Greenhouse and Karrow 1994; Burt and Rainsford 2010; Burt et al. 2011) that have the potential to form protected producing aquifers similar to those investigated within the Dundas buried bedrock valley (Marich et al. 2011; Bajc et al. this volume). This paper describes regional scale Quaternary sediment packages in the Orangeville Moraine area and interprets their depositional history within the context of aquifer vulnerability and recharge potential.

**Regional Setting**

The Orangeville Moraine 3D study area encompasses approximately 1550 km$^2$ in southern Ontario, extending from the Waterloo Region northeast towards the Niagara Escarpment, located east of the study area (Fig. 1a). Groundwater obtained from both bedrock and Quaternary sediments serves the majority of the population within the area; very few people draw water directly from rivers or reservoirs. There are groundwater-based municipal water systems in the communities of Orangeville, the largest urban centre, as well as in Acton, Alton, Elora, Erin, Fergus, Grand Valley, Hillsburgh and Rockwood (Fig. 1b). People living in smaller villages and hamlets, as well as those in rural locations, are dependent on domestic wells.

Located west of (and above) the prominent north-south trending Niagara Escarpment, the topographically high study area is situated at the southern end of Ontario Island (Fig. 1a; Taylor
and the ground surface declines from 495 m asl in the north to 350 m asl in the south (Fig. 1c). Bedrock valleys, some of which form angular re-entrant notches in the Niagara Escarpment, are incised down to 335 m asl. The Hockley Valley, Alton, Rockwood and Blackwood Creek re-entrants are partially filled, but are clearly visible at surface near the escarpment (Fig. 1c). Further west, the bedrock valleys are completely buried. The Orangeville Moraine extends from the centre to the far northeast of the map area (Fig. 1d), rising to an elevation of 515 m and forming the primary drainage divide between the Nottawasaga Valley watershed in the northeast, the Credit Valley watershed in the east and the Grand River watershed in the west (Fig. 1b). The moraine surface is hummocky in the northeast, becoming more subdued and gently sloping towards the southwest. It was incised by glacial meltwater (Cowan 1976) and post-glacially, prior to the establishment of a protective vegetation cover. A large, irregularly shaped depression in the southern portion of the moraine (Fig. 1c) is interpreted as the product of a large, stranded block of ice melting following construction of the moraine (Burt and Dodge 2016).

Northwest of the Orangeville Moraine, the Dundalk and Stratford till plains (Fig. 1d; Chapman and Putnam 1984), exhibit a very gently rolling topography with localized southeast-trending low flutes and drumlins (Fig. 1c). These gently rolling plains comprise the fine-textured Tavistock Till (Cowan 1976), which was deposited by the southeast flowing Huron-Georgian Bay ice lobe. Shallow depressions in the till surface are partially infilled with fine-textured glaciolacustrine and organic deposits whereas wetlands and ponds occupy modern topographic lows (Fig. 1d). Southeast of the Orangeville Moraine, coarse-textured Port Stanley Till (Cowan 1976), deposited by the northwestward advancing Lake Ontario ice lobe, is characterized by the typically 1 – 6 km long, < 100 – 550 m wide and 5 – 15 m high northwest oriented streamlined landforms of the Guelph drumlin field (Cowan 1976; Chapman and Putnam 1984; Ontario
Ministry of Natural Resources and Forestry 2010). The northwest-trending Singhampton Moraine overlies the Orangeville Moraine and Guelph drumlin field in the far northeast (Figs. 1c and 1d; Cowan 1976). The northern part of the hummocky and multi-ridged Paris Moraine, located close to the Niagara Escarpment in the far southeast of the map area (Fig. 1d), is characterized by proximal outwash plains, dissected fans, high frontal hills, kettle depressions, eskers, and steep ice-contact slopes that are primarily composed of diamicton and gravel deposited in a terrestrial setting (Sadura et al. 2006; Russell et al. 2013; Arnaud et al. this volume). The map area is dissected by numerous late-glacial spillways, typically containing outwash gravels (Cowan 1976), post-glacial organic deposits and modern misfit streams.

**Bedrock Geology**

The Orangeville Moraine area is underlain by southwest-dipping bedrock formations as shown on figure 2a (Armstrong and Dodge 2007). Red and green banded shale of the Ordovician Queenston Formation (Figs. 2b, 2c) is overlain with Silurian Cataract Group shale and dolostone and Clinton Group dolostone (Armstrong and Carter 2010; Brunton and Brintnell 2011). These formations subcrop along re-entrant bedrock valleys that extend northwest and southwest from the Niagara Escarpment. The Early Silurian Lockport Group (Fig. 2a) forms the caprock unit of the Niagara Escarpment and underlies the Quaternary sediments throughout the Orangeville region (Brunton et al. 2012). Basal Gasport Formation dolostone (Fig. 2d) and overlying Goat Island Formation crinoidal grainstone and dolostone, formerly part of the unsubdivided Amabel Formation, outcrop and subcrop in the east. Bituminous dolostone of the Eramosa Formation (Figs. 2e and 2f) also outcrops and subcrops in the east, whereas Guelph Formation dolostone
(Figs. 2g and 2h) subcrops and crops out in some river valleys in the centre and west of the study area.

An extensive buried bedrock valley network was identified in southern Ontario as early as 1890 (Spencer). Subsequent mapping has refined the location and geometry of these valleys (e.g. Karrow 1973; Flint and Lolcama 1985; Gao et al. 2006), their formation (e.g. Straw 1968; Eyles et al. 1997; Gao 2011) and the nature of the fill (e.g. Greenhouse and Karrow 1994; Meyer and Eyles 2007; Marich et al. 2011). The mechanism of valley formation continues to be controversial and current thought ranges from subglacial meltwater erosion during the Last Glacial Maximum (LGM) (Gao 2011) to the long-term modification of an existing preglacial network by the combined effects of glacial and meltwater erosion (e.g. Kunert et al. 1998; Bajc et al. this volume). Further, it is thought that valley geometry may be influenced by stress release fractures and faults in the Paleozoic bedrock (Sandford and McFall 1984) based on valley trend orientations and joint orientation (Eyles et al. 1997; Kunert et al. 1998).

Quaternary Geology

There have been multiple cycles of glacial advance and retreat across Ontario throughout the late Pleistocene, resulting in a complex stratigraphic record of glacial and nonglacial deposits. Sediments predating the LGM do not outcrop within the Orangeville Moraine area; however a series of tills and stratified sediments overlying bedrock have been described from sites extending southwest towards Lake Erie (Fig. 1a) and may be present here at depth. The oldest deposits are Lake Erie shore bluff Bradtville tills and Erie lobe Till A and Till B described from a series of exposures within the Zorra Township quarry located northeast of London (Fig. 1a) (Westgate and Dreimanis 1967; Dreimanis 1982; Dreimanis 1992; Dreimanis and Gibbard
More recent Canning Till and associated glaciolacustrine sediments have been identified in river sections and continuously cored boreholes as far north as the Waterloo area (Karrow 1987; Dreimanis 1992; Bajc and Shirota 2007; Bajc and Dodge 2011). Typically stone-poor, fine-textured Canning Till often has a red or purple to mauve matrix and frequently contains red shale clasts, both of which are long-assumed to be derived from Queenston Formation shales, reflecting an Erie–Ontario lobe source (Krzyszkowski and Karrow 2001). However, the identification of red shale beds in the Salina Group (Armstrong and Carter 2010) raises the possibility of a northern (Bajc and Dodge 2011) to northwestern source area.

Precise dating of these older deposits is not yet available; however, there is a growing database of radiocarbon dates and paleoecological information from overlying organic-rich sediments in Ontario (Bajc et al. 2009; Bajc et al. 2015). Dates range from >50 ka BP to 23.5 ka BP suggesting widespread non-glacial conditions that may have spanned the Early and Middle Wisconsin (Bajc et al. 2009).

Late Wisconsin sediments relating to the LGM (MIS2) are classified as Catfish Creek Till, an important marker horizon across much of southwestern Ontario (Dreimanis and Gibbard 2005; Bajc et al. 2014;). Ice flow directions, established by striated flat-iron boulders, till fabrics, pebble lithologies and heavy mineral assemblages, record the initial advance of ice lobes out of the Huron–Georgian Bay and Erie–Ontario basins into proglacial lakes followed by regional ice flow towards the south (e.g. Dreimanis 1982; Hicock 1992; Bajc and Shirota 2007; Bajc and Dodge 2011). A return to lobate flow during regional deglaciation (Hicock 1992) initiated the formation of an interlobate zone extending from Orangeville to southwest of London as ice continued to thin and retreat (Bajc and Dodge 2011). Ice lobes effectively blocked drainage during the initial breakup so that meltwater and sediments flowed into the interlobate zone
forming a complex sequence of interbedded diamictons and stratified deposits that comprise the Dorchester, Waterloo and Orangeville moraines (Fig 1a; Karrow and Paloschi 1996; Bajc and Shirota 2007; Burt 2011; Bajc et al. 2015; Burt and Dodge 2016).

The Waterloo Moraine forms an important aquifer and groundwater recharge area comprising fining-upwards sequences of gravel to mud deposited within a series of coalescing subaqueous fans supplied by sediment laden meltwater delivered by channels within and under the ice (Russell et al. 2007; Bajc et al. 2014;). The fan sediments are separated by muddy glaciolacustrine sediments and debris flow diamicton (Bajc et al. 2014). While the Orangeville Moraine has yet to receive the same level of attention as the Waterloo Moraine, it has been discussed in the literature for over a century and been the subject of surficial mapping (Cowan 1976) and reconnaissance sedimentological reports (for example Cummings and Russell 2008). It has been described as an Ontario ice lobe terminal moraine (Taylor 1910, 1913), and as an interlobate moraine with the bulk of sediments deposited during either the initial formation of the interlobate zone (Chapman and Putnam, 1984) or during the subsequent advance of ice lobes during the Port Bruce Phase (Cowan 1976; Gwyn and Cowan 1978). More recently, an esker-subaqueous fan depositional setting has been proposed (Cummings and Russell 2008; Russell et al. 2008).

During the late glacial Port Bruce Phase, lobate ice deposited coarse- and fine-textured tills, including Tavistock, Port Stanley and Newmarket tills, and subaqueous debris flow deposits that variably overlie or are interfingered with the interlobate sand and gravel Waterloo and Orangeville moraines (Cowan 1976; Bajc and Shirota 2007; Bajc et al. 2014; Burt and Dodge 2016). Thick sand and gravel outwash was deposited in meltwater channels incised into the Orangeville Moraine and till surface as the ice retreated (Cowan 1976; 1984; Bajc and Shirota...
Late glacial fluctuations of Simcoe lobe ice deposited the Singhampton Moraine over portions of the Orangeville Moraine and the Guelph drumlin field (Cowan 1976), whereas Ontario lobe ice deposited the Paris and Galt moraines east of the interlobate Orangeville, Waterloo and Dorchester moraines (Fig. 1a).

**Development of the 3D Model**

The development of a 3D model for the Orangeville Moraine area was undertaken in 4 stages: 1) compilation and standardization of legacy data sets; 2) acquisition of new high quality geophysical and geological data; 3) development of a conceptual framework; 4) data analysis and model creation following the methodological approach of Bajc and Shirota (2007).

**COMPILATION AND STANDARDIZATION OF LEGACY DATA SETS**

Legacy subsurface data sets were gathered for a variety of purposes, and therefore are of highly variable resolution and quality (Fig. 3a). These data sets include: 1) Ministry of the Environment and Climate Change water well database (10,343 records); 2) Ministry of Transportation GEOCRES geotechnical drilling database (98 records); 3) a geotechnical database for Waterloo Region (WAGAIS) (7 records); 4) overburden drill logs from private consultants, conservation authorities and gravel pit operators (383 records); and 5) OGS archived field descriptions and data points obtained from the seamless surficial geology map (258 records). Cored boreholes, described by a geologist or trained technologist, are considered high quality records. Sediment descriptions that are based on cuttings, drilling speeds, and fluid gains or losses, such as those found on water well records, are considered low quality. The geological information contained in these data sets was standardized (Burt and Bajc 2005; Burt and Dodge 2007; Burt and Dodge 2016).
2016) into 17 primary material types (Table 1) and merged creating a database of 11 074 legacy records with 42 267 geological layers.

**ACQUISITION OF NEW HIGH QUALITY GEOPHYSICAL AND GEOLOGICAL DATA**

Ground gravity surveys were conducted in order to refine the locations and broad geometry of buried bedrock valleys in the study area that were identified from water well records. Between 2010 and 2012, 6868 stations along 54 lines totalling 723 line kilometres were surveyed along roads selected to cross predicted thalwegs (Fig. 3b; Burt and Rainsford 2010; Ontario Geological Survey 2013a; 2013b; 2013c; Burt and Dodge 2016;). A 100 m station spacing was used in the central part of the lines (near the predicted thalwegs) and a 200 m spacing was used near the ends of the survey lines. The gravity surveys were performed using a LaCoste & Romberg gravimeter and high-precision elevation data, with an absolute accuracy of ±2 cm, was obtained using a Leica GS15 RTK Rover GPS unit linked to Leica Geosystem’s SmartNet real-time differential correction service (Ontario Geological Survey 2013a; Burt and Dodge 2016). Standard data reduction procedures, including terrain correction, were applied to the gravity results and the Bouguer gravity anomaly was calculated using a density of 2.1 g/cm$^3$. A regional field was subtracted from the Bouger gravity in order to isolate the part of the gravity signal most likely to be associated with buried-bedrock valleys.

Drilling targets were selected within each physiographic region to refine the stratigraphic relationships of tills and associated stratified sediments, establish sediment-landform associations and determine the nature of bedrock valley fills in the Orangeville Moraine and surrounding area (Burt 2008; 2009). Forty-three PQ (8.5 cm diameter) continuously cored boreholes, totalling 1918.5 m in length, were drilled between 2008 and 2010 using mud rotary drills with modified
Christiansen core barrels retrievable by wireline (Burt and Webb 2013; Burt and Chartrand 2014). The core was visually logged and photographed in the field and representative intervals were sampled for clast lithology, grain size, carbonate and heavy mineral analysis. Wood obtained from organic-rich sediment in BH40 was submitted to the Illinois State Geological Survey for AMS radiocarbon dating and organic-rich sediment from the same interval was submitted to the University of Toronto for pollen analysis. Approximately 3 m of fractured and/or competent bedrock was cored at each location to confirm the top of bedrock. Additional field work was undertaken to document natural and man-made exposures of Quaternary deposits (Fig. 1b). These exposures were typically limited to surficial and near-surface sand and gravels deposits within the Orangeville Moraine and outwash channels (see Fig. 1d).

DEVELOPMENT OF A CONCEPTUAL FRAMEWORK

Due to the limited number of exposures, depositional environments have been interpreted based on 43 continuously cored boreholes resulting in limited information on landform – sediment associations and the geometry of sediment units. Furthermore, the preponderance of low quality records limited the ability to provide detailed sedimentological descriptions and ultimately detailed reconstructions of depositional conditions. As a result, analysis focused on identifying major changes in depositional conditions based on the sequence of sediments encountered in cores and the established regional stratigraphic framework (Bajc and Shirota 2007; Bajc and Dodge 2011). Hydrostratigraphic units were then identified based on predominant textures (lumping water-bearing stratified sediments and typically combining tills and fine-textured proglacial lake deposits into a single unit).

A conceptual framework of 17 units (Burt and Dodge 2016), developed for modelling purposes, has been condensed here into 12 regionally significant Quaternary sediment units and
1 bedrock unit (Fig. 4, Table 2). The hydrostratigraphic units and codes developed for the Waterloo Region and Brantford–Woodstock 3D projects have been extended to the current map area (Bajc and Shirota 2007, Bajc and Dodge 2011, Burt 2012). The three areas have a similar glacial history and are located within the same late glacial interlobate zone, so it is often possible to trace hydrostratigraphic units across all 3 areas. However, local oscillations in ice margins and different relative positions within sedimentary basins have resulted in considerable variations in unit thickness, lateral continuity and internal characteristics (Bajc and Shirota 2007, Bajc and Dodge 2011, Burt and Dodge 2016).

DATA ANALYSIS AND MODEL CREATION

The 3D model was created using Datamine Studio® software. Three-dimensional points identifying the top of a given hydrostratigraphic unit were manually digitized onto the new and legacy borehole traces, guided by the conceptual framework developed from the 43 high-quality continuously cored boreholes drilled for this study (Burt and Dodge 2016). The number of “picks” made on an individual borehole trace was dependent on the number of hydrostratigraphic units that could be interpreted from the primary material types. Additional points were digitized adjacent to, or below, the borehole traces in order to refine the geometry of the modelled surfaces and reduce potential effects of clustered data points.

Once a preliminary set of picks had been made on the new and legacy borehole traces, scripted routines were used to generate interpolated wireframe surfaces representing the tops of each hydrostratigraphic unit using the picks and a surface geology file. The interpolation method used for OGS 3D modelling is isotropic inverse power of distance cubed (Bajc and Shirota 2007). First, the picks were validated by the modelling software to ensure that the hydrostratigraphic units were in the correct sequence. Out of order picks were flagged for
correction and then ignored by the software during the current run. In order to reduce problems with crossing wireframe surfaces, especially in data sparse areas, hydrostratigraphic unit elevations were interpolated from the borehole trace and off-trace picks onto a 100 X 100 m grid of columns covering the entire model area. During this process, each hydrostratigraphic unit was considered individually. A search radius, defined by the geologist to reflect the perceived extent of the unit, was drawn around each column in turn. Generally, larger search radii were used for units that were considered to be more continuous, such as bedrock, tills and regional aquitards, whereas smaller search radii were used for aquifers (Table 2). An interpolated elevation was assigned to the column when a minimum of one high-quality, two medium-quality, or three low-quality picks were found within the given search radius. If there were insufficient picks, the unit in question was considered to be absent and the elevation was automatically set as equal to the underlying unit. This process resulted in all 17 hydrostratigraphic units being represented in each column even though some units had the same elevation. Finally, a continuous set of wireframes were generated from the interpolated elevations using scripted software routines to remove any crossing wireframe surfaces. Pinch-outs were accommodated by draping units on top of each other. A set of discontinuous wireframes with true pinchouts were also created and these more accurately represent the spatial extent of the units. The final 3D block model was generated by filling in the spaces between the wireframe surfaces using 100 X 100 m blocks of variable thickness.

Once a model run was complete, the results were visually compared with the original borehole traces. Early model runs typically resulted in unrealistic pinch-outs, bulls-eye’s around clustered or high quality data points and wavy or rolling surfaces. Out of order picks were corrected, interpretations refined and additional off-trace picks added before the model was re-
run, a process that continued until the modelled surfaces reflected unit distributions and geometries that are realistic considering depositional models for these glaciated settings and that are consistent with the regional stratigraphic framework. In the absence of statistical assessment of surface fidelity, paired maps showing the distribution and thickness of each unit and the quality (low, medium, high, off-trace) of picks used to generate the modelled surface were released as part of the groundwater study allowing for a qualitative assessment of the data (Burt and Dodge 2016).

**Modelled Units**

**PALEOZOIC BEDROCK SURFACE**

The bedrock surface dips from 480 m asl in the north to 305 m asl in the southwest (Fig. 5a). The upper few metres of bedrock, observed in exposures and cored boreholes, ranges from glacially polished, striated and highly competent to fractured (Fig. 6a) and/or highly weathered. In the northwest and central portions of the map area, the bedrock topography is characterized by broad lows and resistant bedrock highs or knobs (Site 3, Fig 5a). The eastern side of the map area is characterised by a series of wide, deeply incised valleys that form angular re-entrants in the Niagara Escarpment (located to the east of the study area) and are partially infilled with Quaternary sediments (Figs. 1a and 5a). These valleys extend southwest and northwest from the escarpment, becoming completely buried and undetectable at surface. The 2010 ground gravity survey recorded increasing widths and amplitudes of the negative residual anomalies towards the escarpment in both the Alton and Rockwood valleys suggesting that the valleys widen and deepen as they approach the escarpment (Fig. 3b; Burt and Rainsford 2010). The valleys are incised to depths of as much as 200 m below the surrounding bedrock at the Hockley re-entrant,
145 m at the Alton–Rockwood re-entrant and 70 m at the Black Creek re-entrant. Headward erosion of the Hockley and Alton valleys formed an incised headwater area east of Orangeville (Site 1, Fig. 5a). The Alton valley has a short tributary and water well data suggests a plunge pool formed at the confluence of the 2 streams (Site 2, Fig. 5a). The northern extent of the narrow Rockwood Valley contains a ledge of resistant rock, informally named the Erin sill, (Site 4, Fig 5a) that was first encountered during drilling and later confirmed by a wide, low amplitude ground gravity negative residual anomaly (Fig. 3b, Burt et al. 2011; OGS 2013a, 2013b, 2013c).

There are several additional southwest-trending buried-bedrock valleys in the southern portion of the map area such as the 45 to 55 m deep Elora buried valley (e.g. Arai 1975; Jensen 1975; Lee 1975; Chaitan 1976; Greenhouse and Karrow 1994) and the 30 m deep Cumnock valley. These valleys are typically less than 400 m wide, and have steep, if not vertical, sides similar to the modern Elora Gorge (Figure 5a, Burt and Dodge 2016). The Elora buried-bedrock valley, east of Belwood Lake, appears to terminate abruptly before reappearing several kilometers to the northeast (Site 5, Fig. 5a). The cross-sectional shape of the valley floors could not be resolved with the information available; however, it is suspected that repeated glaciations will have eroded the bedrock valleys into u-shaped profiles rather than the v-shaped profile typically associated with fluvial valleys.

In this paper, the term re-entrant will be used to refer to the wide, partially infilled notches in the escarpment, buried bedrock valleys will be used to refer to the narrow valleys that are not visible at surface, and bedrock valleys will be used as a collective term referring to all valleys in the area.
QUATERNARY SUCCESSION

The sediment cover in the Orangeville Moraine area is highly variable (Fig. 5b). The thickest sediments are located centrally in a band dominated by the Orangeville Moraine (up to 75 m thick) and in bedrock valleys (50 to 145 m thick). The sediments are thinner in the north, south and east, frequently pinching out at the brow of the Niagara Escarpment. Isolated outwash and kames, the large streamlined landforms of the Guelph drumlin field and the hummocky Paris and Singhampton end moraines add local variability in sediment thickness in the southern and eastern parts of the map area.

Pre-Late Wisconsin Deposits

OLDEST TILLS (ATG1)

Hydrostratigraphic unit ATG1 is composed of two distinct diamictons and stratified sediments overlying bedrock. Although clearly distinguishable in the cored boreholes, the sediments were modeled together as it was not possible to differentiate between them in the legacy datasets. The unit is thickest and most continuous in the west-central part of the map area, thinning to the north and becoming thin and discontinuous to the east and south (Figs. 7a, 8a, 9a to 9c).

A thin, overconsolidated, massive, stony, sandy silt diamicton (Fig. 6b) was observed overlying bedrock in three boreholes in the north-central portion of the study area. From the limited data available, the diamicton is interpreted as subglacial till. Red shale clasts and a distinct reddish coloured matrix may be attributed to red shales located to the east (Queenston or Cabot Head formations) or localized red shale beds to the west (Salina Formation) (Armstrong and Carter 2010).
More widespread is a typically yellowish brown (Fig. 6c) stony, sandy silt diamicton (Table 3) with rare beds of slightly silty sand and/or gravel. Cobbles in the diamicton caused recovery problems in several boreholes and the core often had a washed appearance. Where intact, the diamicton was typically firm to hard. These widespread sediments may have been deposited subglacially, however the borehole data is not definitive. The diamicton was observed overlying either bedrock or the older reddish diamicton. High average matrix carbonate content of 59% and low average calcite to dolomite ratios of 0.5 (Table 3) reflect erosion and incorporation of the underlying Guelph Formation dolostone bedrock. In some locations, the sediment overlying permeable bedrock is highly oxidized as a result of subsequent infiltration of oxygenated groundwater (Fig. 6d).

Beds of coarse- and fine-textured diamicton, possibly debris flow deposits based on associated interbeds of gravel or rhythmically bedded (laminated) glaciolacustrine silt and clay, were observed in centrally located boreholes. These deposits suggest fluctuating depositional conditions.

Strong yellow brown staining was observed at the top of the unit in several boreholes and is interpreted as a weathering profile formed during prolonged subaerial exposure. Precise dating was not possible; however, wood fragments obtained from the overlying Pre-Catfish Aquifer (AFD1) (see below) were radiocarbon dated at >52.2 and 54.5±2.9 $^{14}$C ka BP suggesting the deep weathering may have occurred during widespread Sangamon-age glacial retreat (Bajc et al. 2015).

**OLDER AQUIFER (AFF1)**
Aquifer AFF1 (Figs. 7b and 8b, Table 2) is composed of two distinctly different deposits that were grouped into one hydrostratigraphic unit for modelling purposes based on their stratigraphic position overlying the oldest tills (unit ATG1) and underlying Canning sediments (unit ATE1). In the centre of the study area (Figs. 7b, 8b and 9c BH16), there is up to 15 m of interbedded gravel, sand and diamicton overlain by fining-upwards gravelly sand, rhythmically bedded sand and silty sand (Figs. 6e and 6f) whereas to the southwest (Figs. 7b, 8b and 9b BH02), similar thicknesses of sand were observed. This centrally located fining upwards sequence, similar to sequences found within the Waterloo Moraine (Bajc et al. 2014), is interpreted as a large subaqueous fan (Table 2). The thicker sediment accumulations and interbedded gravel and diamicton may represent either an esker that fed the growing fan or deposition at the fan apex (Benn and Evans 1998) and suggest a northern to eastern source. The deposits have a fragmented distribution, likely due to post-depositional erosion.

The Rockwood buried-bedrock valley contains discontinuous coarse-textured stratified AFF1 deposits that, in places, reach thicknesses of over 10 m (Figs. 7b, 8b and 9f). Over 5 m of boulders (Fig. 6g) and gravel overlain by slightly silty sand and gravel were observed in the southern-most valley borehole (Fig. 9f BH26). The drilling conditions encountered caused a loss of return circulation and large volumes of drilling mud were required to stabilize the hole, which often occurs in coarse-grained, water-bearing units (Don Grant personal communication 2009). In the northeastern valley fill, the deposits become discontinuous and the water-bearing boulders, cobbles and gravel are replaced by slightly silty gravel and cobbles with some diamicton. The unit was only observed within the bedrock valley and is interpreted as fluvial or glaciofluvial sediments confined to the bedrock valley similar to those observed in buried bedrock valleys below the escarpment (Meyer and Eyles 2007) and in Waterloo Region to the southwest (Bajc et
al. 2014). Boulders greater than 1m were observed at the bottom of borehole BH26 and these may represent rock falls associated with the headwards erosion of the valley similar to those observed below waterfalls and interpreted in bedrock valley borehole records (Ontario Hydro 1989; Burt 2017).

**CANNING EQUIVALENT SEDIMENTS (ATE1)**

A thin, discontinuous fine-textured unit (unit ATE1), rarely more than 6 m thick, is located in the west-central to northwest and far southwest of the map area (Figs. 7c, 8c, 9a-9c and 9e; Burt and Dodge 2016) and is interpreted to be equivalent to the Canning aquitard mapped in the Waterloo Region and Brantford–Woodstock 3D areas based on stratigraphic position as well as textural and colour similarities (Bajc and Karrow 2004; Bajc and Shirota 2007; Bajc and Dodge 2011).

Less than 2 m of rhythmically bedded glaciolacustrine silt and clay overlain by a typically thin, stone-poor, silty diamicton (Fig. 6h) with occasional silty lenses and rarely, coarser textured sandy silt diamicton (Table 3) was observed in several boreholes (Table 2). With an average matrix composition of 15% sand, 70% silt and 15% clay, total carbonate of 44% and a calcite to dolomite ratio of 2 (Table 3), the Canning-equivalent diamicton is distinctly different from the underlying coarser diamicton associated with unit ATG1. This is most apparent in boreholes where glaciolacustrine sediments were absent and Canning-equivalent diamicton was observed overlying the older diamicton (Fig. 6i). In places the diamicton appears massive and overconsolidated, suggesting deposition as a subglacial till. In other boreholes textural variations and stratified sediments within the diamicton are more suggestive of waterlain deposits. It is envisioned that the glaciolacustrine sediments were deposited in an ice-supported
proglacial lake based on the association of fine-textured sediments and diamicton. Recent research (Livingstone et al. 2015) raises the possibility that a subglacial lake depositional environment should be considered where subglacial till is observed overlying glaciolacustrine sediments; however distinguishing between these environments is problematic (Livingstone et al. 2015), particularly in the absence of exposures.

In the northwest corner of the study area, the Canning-equivalent diamicton is overlain by rhythmically bedded glaciolacustrine clay coarsening upwards to silt and clay and finally silt and sand (unit AFD1) as shown on borehole BH09 (Fig. 9a). The lower portion of these glaciolacustrine sediments is frequently deformed and often contains rare beds of silty and sandy silt diamicton that may be attributed to debris flows or ice rafted debris.

Near the western edge of the map area, abundant red and green shale clasts were observed and the matrix has a distinct reddish tinge (Fig. 6j) that is often associated with Canning Till (White and Karrow 1998; Bajc and Dodge 2011) and traditionally interpreted as indicative of an Erie–Ontario lobe source area below the escarpment (Kryzszkowski and Karrow 2001). However, younger red shale beds located to the northwest raise the possibility of a Huron–Georgian Bay lobe source as was noted in the Brantford–Woodstock area (Bajc and Dodge 2011). The reddish matrix colour was not observed in more centrally located boreholes and this diamicton may be attributed to a different source area.

A 5 to 20 m thick stratigraphically equivalent diamicton has been mapped within the Rockwood buried-bedrock valley (Figs. 9d and 9f). Southwest of the Erin sill, a greyish brown, stone-poor silty till (Fig. 6k) with an average matrix composition of 28% sand, 58% silt and 14% clay (Table 3) and average total carbonate content of 29% (Table 3) suggests deposition by ice
flowing from the east that had not yet travelled over dolomite-rich bedrock (Figure 2b). A high proportion of small, rounded, black limestone pebbles, sourced from below the escarpment, were observed and may allow further refinements to a northeastern source area. Northeast of the Erin sill, diamicton with a strong red matrix colour and abundant red shale clasts reflects localized incorporation of the underlying Queenston Formation red shale bedrock (Fig. 2).

**PRE-CATFISH AQUIFER (AFD1)**

Typically thin, discontinuous pre-Catfish coarse-textured stratified sediments (Table 2) are located across the map area (unit AFD1; Figs. 7d, 8d, 9a, 9b, 9d and 9e). The Elora buried-bedrock valley, located in the southwestern portion of the map area (Fig. 5a), typically contains up to 40 m, and rarely up to 55 m, of silt and sand (Arai 1975; Jensen 1975; Lee 1975; Chaitan 1976; Greenhouse and Karrow 1994). Greenhouse and Karrow (1994) suggested a lacustrine depositional environment for this AFD1 valley fill, possibly dating back to the last interglacial based on observed pollen assemblages and overlying till stratigraphy. In this study, water well records were used to map these lacustrine sandy stratified sediments filling the bedrock channel and spilling over the banks in its southern reaches (Burt and Dodge 2016); however, no new boreholes were drilled in these deposits. In the west-central portion of the study area, pulses of dominantly fine to very fine sand (Fig. 6l) fining upwards to silty sand and occasionally silt, with rare beds of gravelly sand were observed. These deposits may represent the northern extension of the lacustrine system. Although dateable material was not recovered, organic-rich sandy silt beds (Fig. 6m), are indicative of non-glacial conditions.

Further south, a rare alluvial sequence of slightly silty sand and gravel, pebbly sand and silty sand up to 2.5 m thick was observed in borehole BH40 (Fig. 9a). Wood fragments recovered
from the organic-rich sediments, radiocarbon dated at greater than 52 200 $^{14}$C years BP and 54 500 $^{14}$C yrs BP, provide a minimum age for the unit. Samples submitted to the University of Toronto for pollen analysis contained a common interstadial assemblage dominated by boreal tree pollen, with the highest counts coming from pine and spruce (McAndrews and Turton written communication 2011). Pine- and spruce-rich boreal forest pollen assemblages were also found in organic-rich silt, radiocarbon dated to 50.5 to 42.9 $^{14}$C years BP, at the Zorra township quarry (Bajc et al. 2015).

Interbedded diamicton, slightly silty sand and gravel, gravel and sand observed in several northern and centrally located boreholes (Table 2) have also been included in this model unit based on a stratigraphic position underlying Catfish Creek Till. The context of diamicton and stratified sediments suggests deposition during ice advance.

**Catfish Creek Till (ATC1)**

The main Late Wisconsin (MIS2) ice advance is represented by Catfish Creek Till (unit ATC1), which forms an important stratigraphic marker and regional aquitard in southwestern Ontario (Bajc and Shirota 2007; Bajc and Dodge 2010). The unit is thickest in the west and centre of the map area (typically up to 25 m thick and occasionally up to 37 m thick) and is continuous except where dissected by the modern Grand River valley (Figs. 7e and 8e). It thins, becoming increasingly sporadic and eventually pinches out towards the east and southeast whereas noticeably thicker deposits are occasionally found in protected locations such as the deep re-entrant and buried-bedrock valleys (Figs. 9a to 9e).

In the northwest and centre of the map area, there is a lower stone-poor sandy silt to silt diamicton with an average matrix composition of 26% sand, 61% silt and 13% clay, average
total carbonate of 42% and calcite to dolomite ratios of 1.7 (Table 3) overlying rhythmically bedded glaciolacustrine silt and clay (Fig. 9a BH06, BH04 and BH09). Southwest of the study area, the diamicton has been interpreted as an early Catfish Creek till deposited by lobate ice (Bajc and Dodge 2011). Detailed studies from Lake Erie shore bluffs (Hicock 1992) determined early ice flows were from the northwest (Huron-Georgian Bay lobe). The observed fine-textured matrix of the diamicton in this area may reflect the incorporation of underlying proglacial lake sediments during the early stages of ice advance.

More widespread is an overconsolidated, somewhat stony to stony sandy silt diamicton (Figs. 6n, 6o), interpreted as Catfish Creek Till, deposited subglacially by combined regional ice flows (Dreimanis 1982; Hicock 1992). This till is typically coarser than the underlying diamicton with an average matrix composition of 40% sand, 52% silt and 7% clay (Table 3). In the far south and in the northeast extending to the west-centre, there are often thin, highly deformed laminations of silt and/or clay that have been partially incorporated into the till matrix (Fig. 6p) or thicker beds of in situ and undisturbed to deformed glaciolacustrine silt and clay and occasionally sand and gravel within the till (for example BH25 and BH27 Fig. 9e). These stratified sediments suggest waterlain (Dreimanis 1982) or flow tills (Huntley 1991; Bajc et al 2014) form part of the Catfish Creek Till package. At some locations there is an upper unit comprised of interbedded diamicton, slightly silty sand and gravel, gravel, sand and silt and clay (Table 2) The silt and clay are rhythmically bedded suggesting deposition in a glaciolacustrine setting; whether this was proglacial or subglacial could not be determined from the available borehole records.

Rare occurrences of an upper fine-textured diamicton observed in boreholes (this study) and during surficial mapping (Cowan 1976) may record the return to lobate ice flows, as suggested
by Hicock (1992) based on structural and lithological evidence from the Lake Erie shore bluffs, during the early stages of retreat from the LGM.

**Lower Orangeville Moraine and Valley Fill Aquifer (AFB3)**

In the central portion of the map area, Catfish Creek Till (Unit ATC1) is overlain by a discontinuous southwest-trending band of coarse-textured stratified sediments that forms the lower Orangeville Moraine (unit AFB3; Figs. 7f, 8f, 9b and 9e). Cobble gravel and interbedded gravel and sand fines southward to laminated and ripple cross-laminated sand overlain with rhythmically bedded sand, silt and clay (Table 2). Following the models of the nearby Waterloo Moraine (Bajc et al. 2014) and Oak Ridges Moraine (Paterson and Cheel 1997; Barnett et al. 1998) the cobble gravel beds are interpreted as hyperconcentrated density flow deposits (Mulder and Alexander 2001) reflecting a subglacial conduit to ice proximal setting (Benn and Evans 1998). The horizontally laminated and ripple cross-laminated sand is interpreted as traction deposits from unconfined concentrated flows (Cummings and Russell 2008) representing the interchannel zones of a subaqueous fan while the rhythmically bedded sand and silt record increasing deposition from suspension in more distal subaqueous fan settings. These sediments, deposited during the initial retreat of the regional ice-sheet, may delineate the zone where the ice first separated into distinct lobes.

Sandy sediments within the Hockley Valley and the Mono, Alton and Rockwood bedrock valleys (Fig. 9f) are mapped as 20 to 45 m thick, and locally up to 65 m thick, pinching out towards the valley heads. The Rockwood valley aquifer also pinches out over the Erin sill, forming 2 distinct segments. The fill is characterised by 45 to 55 m of variably bedded cobbles, gravel, sand and silt that form 2 or more distinct fining-upwards cycles (Fig. 9f). The coarsest
sediments (cobbles, gravel and gravelly sand) were observed in the basal section of the most northerly borehole suggesting a northern sediment source. Mid-valley, the basal sediments are dominated by gravelly sand and coarse sand (Figs. 10a and 10b) whereas coarse- and medium-textured sand were observed further south. The valley fill aquifer fines upwards into rhythmically bedded fine-textured sand, silt and clay (unit ATB3) interpreted as glaciolacustrine deposits (Bajc et al. this volume). While the observed sediments may represent bedrock valley controlled fluvial or glaciofluvial deposits (Meyer and Eyles 2007; Bajc et al. 2014,), the stratigraphic context between Catfish Creek Till and unit ATB3 glaciolacustrine sediments provides a strong case for a glaciofluvial interpretation. It is envisioned that the bedrock valley would have formed a preferential drainage path for glacial meltwater, either in a subglacial or proglacial setting.

Maryhill Aquitard (ATB3)

Muddy sediments up to 35 m thick that form the Maryhill Aquitard unit (unit ATB3) are laterally continuous across the central region of the map area (Figs. 7g and 8g), becoming up to 40 m thick near the mouth of the Rockwood and Alton re-entrant valleys, and over 60 m thick within the Hockley Valley re-entrant (Figs. 9a to 9f). The unit consists of typically stone-poor, silt- to clay-rich diamicton, occasional beds of silt and sandy silt diamicton, and glaciolacustrine rhythmically bedded silt and clay with rare beds of silty sand (Figs. 10c to 10e). The diamicton has an average composition of 13% sand, 74% silt and 13% clay (Table 3), an average carbonate content of 41% and calcite to dolomite ratios of 2.2 (Table 3). These deposits are correlated with a stone-free, clay-rich diamicton, formally named Maryhill Till (Karrow 1974; 1993), interbedded with laminated clay and silt, collectively referred to as Maryhill drift (Bajc and
Karrow 2004) and Lower Maryhill Till (Bajc and Dodge 2011; Bajc and Shirota 2007; Bajc et al. 2014), observed to the south and west, based on texture and stratigraphic position overlying sandier Catfish Creek Till. In the Orangeville Moraine area, the Maryhill Aquitard unit has a complex internal stratigraphy, as diamicton was observed overlying, underlying or interbedded with fine-textured glaciolacustrine sediments that were often highly deformed. Deformation likely occurred during deposition of the diamicton, interpreted as slump deposits, debris flows and/or subaqueous flow tills (Fitzsimmons 1992; Bajc and Karrow 2004; Bajc and Dodge 2011). The association of diamicton and fine-textured glaciolacustrine sediment suggest deposition in an ice walled lake, as observed to the southwest within the interlobate zone (Bajc and Dodge 2011). Relatively undisturbed rhythmically bedded silt and clay glaciolacustrine deposits were observed in a centrally located, northeast-southwest-trending line of boreholes (BH12, BH22, BH37 and BH39, Fig. 1b) that probably delineates both the deepest part of the growing lake and the greatest distance from the margins of the supporting Ontario, Huron–Georgian Bay and Simcoe ice lobes.

**Orangeville Moraine Aquifer (AFB1)**

The upper Orangeville Moraine aquifer is comprised of a large central deposit with broad bands of sediment, referred to as limbs (Cowan 1976), extending to the north and northeast as well as isolated deposits located in the southeast (unit AFB1; Figs. 7h and 8h). Previous surficial mapping identified the deposits as glaciolacustrine in origin (Cowan 1976) while sedimentological investigations in the far northeast of the map area suggested a more specific subaqueous fan depositional setting (Cummings and Russell 2008) similar to that of the Waterloo Moraine, located to the southwest (Fig. 1a) (Russell et al. 2007; Bajc et al. 2014). Narrow ridges of sediment terminating in coalescing mound-like deposits are evident both at
surface and on the new isopach map (Fig. 7h). This morphology is consistent with an esker (ridge) and fan (mound) depositional model similar to that of the Waterloo Moraine (Bajc and Shirota 2007).

The Orangeville Moraine aquifer deposits were investigated using boreholes and reconnaissance level observations made at aggregate pits (Fig. 1b) and record deposition in northeastern proximal to southwestern distal subaqueous fan settings. Thick, irregular and typically poorly defined beds of cobble gravel, normally graded cobble gravel, crude to well-defined planar and/or trough cross-bedded cobble gravel, gravel and sandy gravel (Fig. 11a-11c) are interpreted as high-density turbulent flow deposits (Winsemann et al. 2009; Ravier et al. 2014) reflecting a proximal subaqueous fan setting (Benn and Evans 1998; Delaney 2002; Thomas and Chiverrell 2006). Irregularly shaped metre-scale ripped-up clasts of fine sand concentrated near the base of a cobble gravel bed (Fig. 11c) may represent meltwater outburst floods following the interpretation of Cummings and Russell (2008) for similar deposits. Thin beds of rippled fine sand and silty sand interbedded with cross-bedded sand (Fig. 11d-11e), and often traceable between gravel and cobble beds, suggest repeated pulses of sediment-laden water rather than a single depositional event (Ravier et al. 2014) providing supporting evidence for discharge into a standing water body (Delaney 2002).

Gravelly sand, sand and silt dominate the sediment record in more distal settings to the southwest. Gently dipping sandy backsets and foresets, sandy sinusoidal waveforms, planar and trough-cross bedded gravelly sand and sand, diffusely stratified sand, and ripple cross-laminated sand with rare beds of cobble gravels (Fig. 12a-12f) are interpreted as interchannel sediments (Benn and Evans 1998) deposited from unconfined concentrated flows (Cummings and Russell 2008) in a mid-subaqueous fan setting. Although detailed facies architecture observations were
not made as part of this study, the range of sedimentary structures present suggests deposition occurred under lower supercritical to subcritical flow conditions (Lang and Winsemann 2013). Multiple overlapping broad channels infilled with sand, and occasionally gravel (Fig. 12g), may represent distributary channels crossing the fan surface, similar to those observed in proximal to mid subaqueous fans that comprise the Oak Ridges moraine (Barnett et al. 1998). Cross-bedded and planar laminated medium to fine sand, ripple cross-laminated sand to silty sand (Fig. 10f-10h) and sand rhythmically bedded with laminated silt and clay (Burt and Webb 2013) reflect increasing deposition from suspension moving towards a distal fan setting (Barnett et al. 1998; Delaney 2002).

Observations made at a cluster of sites (Fig. 1b P5, P6 and BH23) located within a single fan provide further insight into the deposits. In pit P5, cross-bedded coarse-textured sand (Fig. 12b) with southwest paleoflows (230° – 275°, n=16) were observed. The sediments become progressively finer to the south, dominated by medium to fine horizontally laminated and ripple cross-laminated sand. Exposures composed of cross-bedded, ripple cross-laminated and diffusely stratified fine sand with west (Cummings and Russell 2008) and southwest (220° – 280°, n=10) paleoflow directions record a continuation of these textural trends in pit P6 while distinct fining-upwards sequences of sand and silt in borehole BH23 suggest fluctuating flow velocities and sediment loads that may be attributed to multiple discharge events. Collectively, the paleoflow directions and observed textural trends are consistent with an eastern to northeastern meltwater and sediment source for this fan. Although it was not possible to make paleoflow estimations in other parts of the moraine, repeated pulses of sand- and silt-rich sediments (Figs. 9b, 9e BH02, BH14, BH15, BH16) suggest a multi-stage depositional history was common.
The upper portion of pit P5 is characterized by normally graded cobble gravel beds, a bed with 2 m high gravel and coarse sand foresets, relatively thinner beds of cross-bedded gravel and channels infilled with diffusely stratified coarse sand interpreted as proximal high-density turbulent flow deposits (Winsemann et al. 2009; Ravier et al. 2014). Gravel and sand infilling a shallow channel eroded into rippled sand is interpreted as a distributary channel scoured by the high density turbulent flows. The sediments are highly deformed, likely by subglacial shearing during a subsequent ice advance (see unit ATB1 below). This shift to coarse-textured sediments in the upper portions of pit exposures was also observed in the borehole record (Figs. 9b, 9d BH02, BH12, BH21, BH22, BH28, BH39).

Upper Tills (ATB1)

Oscillations of ice lobes from the northwest, northeast and southwest during the Port Bruce Phase (Bajc et al. this volume) deposited up to 45 m of diamicton, typically described and interpreted as till (Cowan 1976, 1979; Karrow 1968, 1974, 1993) that comprise aquitard ATB1 (Figs. 7i, 8i, 9b-9d; Table 3). These sediments partially bury the edges of the Orangeville Moraine (Figs. 7h and 8h). Rhythmically bedded fine-textured glaciolacustrine sediments observed under (Fig. 10i) and overlying the tills (Fig. 1d) are included within the aquitard. Georgian Bay lobe ice (Cowan 1976) deposited typically stone-poor silt to clayey silt Tavistock Till northwest of the Orangeville moraine (Fig. 10j). The till has an average matrix composition of 17% sand, 68% silt and 15% clay (Table 3), calcite to dolomite ratios of 1.4 and total carbonate of 43% (Table 3). A thin sandy silt facies (Fig. 9b) with an average matrix composition of 42% sand, 52% silt and 5% clay was observed in several boreholes in the far northwest of the area (Fig. 9a, Table 3). While this could simply be local variations within Tavistock Till (Cowan 1976), mapping
to the southwest raises the possibility of correlating this coarser facies with Stirton Till (Karrow 1993; Karrow and Paloschi 1996).

The Erie–Ontario ice lobe (Cowan, 1976) deposited Port Stanley Till (Fig. 10k) southeast of the Orangeville Moraine. The till matrix is typically a stony, sandy silt (40% sand, 54% silt and 7% clay) with an average calcite to dolomite ratio of 1.5 and total carbonate of 42% (Table 3).

Previous surficial mapping documented the advance of Simcoe lobe ice to the Singhampton Moraine depositing a small patch of stony, sandy silt Newmarket till (Cowan 1976). Observations of a fissile, stony silty sand to sand till (Fig. 10l), informally referred to as upper sandy till (Burt 2011; Burt and Webb 2013; Burt and Dodge 2016), in boreholes (BH21, BH23) and a pit (P6) located west of the moraine is thought to be an extension of Newmarket Till. The sandier (coarser) texture is a result of the Simcoe ice lobe over-riding sandy Orangeville Moraine sediments.

**Outwash Aquifer (AFA2)**

The outwash aquifer (unit AFA2; Figs. 7j and 8j) is comprised of thin and thick surficial sand and gravel occupying a stratigraphic position overlying the upper till aquitard (unit ATB1). The sediments were mapped by Cowan (1976) as ice-contact stratified, glaciofluvial and coarse-textured glaciolacustrine deposits (Fig. 1d). Thin sheets of gravel, deposited by meltwater flowing from the Erie-Ontario and Georgian Bay ice lobes (Cowan 1976) are scattered throughout the area. As meltwater became channelled (Cowan 1976), up to 25 m and locally up to 45 m, of gravel and sand (Figs. 10m-10n), interpreted as glaciofluvial proglacial outwash was deposited in re-entrant valleys (Figs. 1b, 9f). A recent digital surface model (Ministry of Natural Resources and Forestry 2010) shows the outwash has a flat upper surface that dips gently in the
direction of meltwater flow, typically towards the southwest, and steep, northeast- and east-facing ice-supported slopes that record temporary ice margins. Up to 25 m of sediment was deposited within channels incised into underlying upper tills (unit ATB1) in the south and northwest of the map area. There are additional outwash deposits located south of Orangeville and east of Fergus, which are either perched above the surrounding landscape or incised into broad channels on the flanks of the Orangeville Moraine.

The channel outwash deposits are currently being exploited for aggregate, both above and below the water table and most active pits were visited during the current project. Beds of imbricate cobble and pebble gravel, thin sheet-like beds of gravel and sand as well as gravel and sandy channel fills (Fig. 13a-13c) were deposited as large bars migrated downstream (Cowan 1984; Burt 2011). Occasional beds and lenses of fine sand and laminated silt and clay mark a shift to quiescent conditions as individual channels were abandoned. An overall decrease in grain size occurs in the more distal southern reaches of the outwash channels.

**Paris Moraine (ATA2) and Wentworth Aquifer (AFA1)**

The Paris Moraine (unit ATA2; Figs. 1c-1d, 7k and 8k), deposited by a readvance of the Ontario ice lobe (Arnaud et al. this volume) is characterised by numerous small, steep-sided, closed depressions interrupted by local highs. Soft, stony, sandy silt diamicton (Fig. 10o), interpreted as Wentworth Till (Cowan 1976), with an average matrix composition of 41% sand, 54% silt and 5% clay (Table 3), slightly silty gravel, gravel, sand and rarely silt and clay (Fig. 10p) was observed in boreholes drilled in the moraine (Figs. 9b-9c). A large overturned fold, interpreted as ice push deformation, observed in a pit exposure located northeast of the study area clearly demonstrates the complexity of sediments within the moraine (Fig. 14). East of the Paris
Moraine, the Quaternary sediment cover thins to less than 10 m of typically stony, sandy silt diamicton, interpreted as Wentworth Till, with rare beds of gravel or sand.

The youngest glacial sediments are confined to the extreme southeast of the map area (Figs 7l, 8l), and are associated with and postdate the late glacial readvance of the Ontario lobe (unit AFA1). Legacy data sets indicate that up to 70 m of silt and sand fills the Black Creek re-entrant bedrock valley and extends beyond the confines of the valley to thicknesses of up to 20 m. These sediments were deposited in a glacial lake that formed between the Paris Moraine in the west and the retreating ice front in the east. Occasional gravel and diamicton beds may represent either subaqueous debris flows from the retreating ice (Benn 1989) or mass wasting off the valley walls (Sletten 2003; Meyer and Eyles 2007).

Discussion
The development of an evidence based 3D hydrostratigraphic model has provided the opportunity to refine understanding of the stratigraphy and late Quaternary history of the Orangeville Moraine area. Aquifer vulnerability and recharge potential can now be assessed using the lateral extent, thickness and composition of surficial and buried sediment packages identified through this study.

QUATERNARY HISTORY
Southwestern Ontario has been subjected to ice lobes advancing from the Great Lakes basins as well as combined regional flow from the north (Karrow 1974; Cowan 1976; Barnett 1992; Hicock 1992). Catfish Creek Till, deposited during the LGM, is a key marker horizon in southwestern Ontario (Bajc et al. 2014), effectively separating the sediment record into older (MIS3-5) and younger (MIS2 and younger) deposits.
This study has demonstrated that the sediment cover in the Orangeville Moraine area holds a record of glacial and nonglacial deposits extending from before the LGM. Landforms such as the interlobate Orangeville moraine (Cowan 1976; Burt and Dodge 2016), the Singhampton and Paris end moraines (Cowan 1976; Chapman and Putnam 1984; Arnaud et al. this volume) and the Guelph drumlin field (Cowan 1976; Chapman and Putnam 1984) make it relatively easy to determine the direction and extent of late glacial ice flows. More challenging is to distinguish between sediments derived from the north (combined regional ice flows) and sediments from the northwest (Huron-Georgian Bay ice lobe), northeast (Simcoe ice lobe) and southeast (Ontario ice lobe) during older glaciations. The absence of exposures in pre-LGM deposits means that tools such as landforms, facies architecture and the orientation of striations, clasts and glaciotectonic deformation structures (Hicock 1992) are not available. Instead, a series of diamictons and stratified deposits have been described and interpreted from continuously cored boreholes drilled as part of the OGS groundwater initiative (Table 2; Burt and Dodge 2016).

**Pre-LGM deposits**

Pre-LGM deposits (units ATG1, AFF1, ATE1, AFD1) are concentrated in the northwest of the area (Figs. 7a-7d, 8a-8d and 9a-9c) as well as in protected locations such as buried-bedrock valleys (Fig. 9f). The data distribution is sparse and the likelihood of erosion under subsequent glacial and glaciofluvial conditions is high, making it difficult to reconstruct ice extent or ice flow directions.

A late glacial interlobate zone containing an ice-walled lake has long been recognized in southwestern Ontario (Karrow 1969; Cowan 1976; Chapman and Putnam 1984; Barnett 1992; Bajc and Shirota 2007; Bajc and Dodge 2011) and there is growing evidence that similar zones
existed during older (pre-LGM) glaciations (Krzyszkowski and Karrow 2001; Bajc and Dodge 2011). A reddish coloured fine-textured diamicton (unit ATE1; Fig 8C) was observed along the western edge of the study area, and may represent an extension of Canning Till mapped in Waterloo Region to the southwest (Bajc and Shirota 2007; Bajc et al. 2014). The reddish colour, typically attributed to the incorporation of Queenston Formation red shales (Fig. 2), has been used as supporting evidence for a southeastern source area (Krzyszkowski and Karrow 2001). However, other fine-textured diamicton from unit ATE1 (Fig 8c) observed in centrally located boreholes and in the Rockwood bedrock valley (Fig. 9a BH34, BH33, BH26) does not show a reddish colour, suggesting deposition by a different ice lobe. Recent discovery of localized red shale beds identified in the Salina Group to the west (Armstrong and Carter 2010) raises the possibility of ice flows from the northwest (Huron-Georgian Bay ice lobe) rather than the southeast to explain the red colour in ATE1 deposits along the western edge of the study area. These findings suggest that lobate ice affected the area at this time, resulting in spatially variable ATE1 properties.

Thin glaciolacustrine silt and clay observed underlying and overlying the Canning equivalent diamicton (unit ATE1) suggest the ice lobes advanced into a proglacial lake (Bajc and Dodge 2011). Similar, although typically thicker, packages of rhythmically bedded glaciolacustrine silt and clay separated by clay-rich diamicton have been observed in many of the 99 continuously cored boreholes drilled as part of the on-going Niagara Peninsula 3D project (Burt 2013, 2014, 2015, 2016, 2017) and record an advance into a proglacial lake supported by the ice front (Feenstra 1981; Menzies and Taylor 1998; Burt 2016, 2017; Burt and Mulligan 2017).
Despite a growing database of radiocarbon dated sites in Ontario, determining the age of older glacial deposits is an on-going problem. Dates ranging from >50 ka BP to 23.5 ka BP suggest that in addition to the period of ice retreat during the Sangamon (MIS5), widespread non-glacial conditions spanned the Early and Middle Wisconsin (MIS3) (Bajc et al. 2009; Bajc et al. 2015). Chronological control in the Orangeville Moraine area comes from wood fragments obtained from non-glacial sediments (unit AFD1) overlying the oldest tills (unit ATG1) and Canning equivalent deposits (unit ATE1). These >50 ka BP dates provide a minimum age for deposition of pre-LGM deposits. The weathering profile observed in several boreholes at the top of the oldest till unit (unit ATG1) could have formed during the Sangamon, or possibly during the Early to Middle Wisconsin.

**LGM and post-LGM deposits**

Ice advancing to the LGM deposited Catfish Creek Till (unit ATC1) across the Orangeville Moraine area. The deposits thin and pinch out in the east and southeast towards the Niagara Escarpment (Figs. 7e and 9a-9d). A similar trend was observed in older diamictons (unit ATG1) in the Orangeville Moraine area, as well as in boreholes across the Niagara Peninsula (Burt 2016, 2017), and is likely the result of erosion during subsequent ice margin fluctuations. In the northwestern portion of the area, a fine-textured diamicton (unit ATC1) overlying fine-textured glaciolacustrine sediments (Figs 9a and 9b) and underlying Catfish Creek Till represents deposition during the early stages of glaciation when ice lobes were advancing into a proglacial lake (Bajc and Dodge 2011) prior to coalescing and forming a combined regional ice flow (Hicock 1992).

Sediments deposited during retreat from the LGM (unit AFB3) are found in dispersed patches extending from the northeast to southwest of the area where they form the lower
Orangeville Moraine (Figs. 7f, 8f, 9b and 9e). The borehole record suggests fining upwards conduit to ice-proximal (Benn and Evans 1998) and mid (Cummings and Russell 2008) and distal subaqueous fan depositional environments (unit AFB3). In the central portion of the study area, the coarsest sediments were observed in BH38, and become finer textured in boreholes BH15 and BH39 to the south and southeast suggesting a northern to northwestern sediment source. Fining upwards textural trends imply an overall reduction in meltwater velocity delivering sediment to the central portion of the area (Knighton 1984), culminating with deposition of up to 60 m of diamicton and fine-textured glaciolacustrine sediments (unit ATB3).

A thick valley fill sequence of gravel and sand (unit AFB3) fining upwards to fine-textured sand, silt and clay (unit ATB3) was observed within the Rockwood re-entrant (Figs. 9d and 9f BH35) and buried bedrock valley (Figs. 9b and 9f BH33 and BH26). These deposits were observed overlying Catfish Creek Till (unit ATC1) in the southern portion of the valley. Legacy datasets were used to identify similar deposits within the Alton and Hockley Valley re-entrants. The fining upwards valley fill suggests a shift in sedimentation from glaciofluvial deposits confined to the bedrock valley to glaciolacustrine deposits. The aquifer distribution, shown on figure 8f, implies the eastern valleys continued to act as drainage routes after the western Cumnock and Elora valleys were infilled with pre-LGM sediments (Figs. 8a-8d) and buried by Catfish Creek till during the LGM (Fig. 8e). Preferential drainage, recorded in the thick outwash aquifer gravels (unit AFA2; Fig. 8j), continued in the re-entrant valleys during late glacial ice margin fluctuations.

When considered within the context of other 3D mapping projects in southwestern Ontario (Bajc and Shirota 2007, Bajc and Dodge 2011), the modelled distribution of Maryhill aquitard deposits (unit ATB3; Fig. 8g) can be used to roughly delineate the minimum extent of a vast ice
walled lake that widened from less than 10 km near the Niagara Escarpment in the northeastern portion of the Orangeville Moraine area to at least 60 km wide 90 km to the southwest (Bajc and Dodge 2011). In the southwest of the Orangeville Moraine area there are windows through thin glaciolacustrine sediments (unit ATB3; Figs. 7g and 8g) revealing Catfish Creek Till (unit ATC1) below. In this area, the glaciolacustrine sediments appear to be draping the sides of localized highs and preferentially filling in depressions within the till surface whereas thicker deposits to the northeast bury the till. The glaciolacustrine deposits are mapped at elevations up to 120 m higher 20 km to the northeast and so it is unlikely the localized highs would have formed islands.

There is considerable evidence within the Orangeville Moraine area that ice margins fluctuated during retreat from the LGM. Notwithstanding problems associated with preservation and interpreting a likely incomplete sediment record, the distribution of glaciolacustrine sediments has the potential to provide insight into the position of ice lobe margins during the Erie Phase. The presence of thick glaciolacustrine sediments (Maryhill aquitard, Unit ATB3) within bedrock valleys that drain over the Niagara Escarpment (Figs. 7g, 9d and 9f) suggests grounded ice remained at the escarpment for a considerable period supporting the lake on its eastern margin. Boreholes in the far south of the area had little compositional difference between Catfish Creek Till and overlying Port Stanley Till. This, and the lack of stratified sediments, suggests a single deposit resulting from a continuous cover of ice as proposed to the southwest (Bajc and Dodge 2011). Similarly, no evidence was found for ice retreat in the far northwest of the area (Figs. 9a and 9e). Previous mapping (Cowan et al. 1978) suggested that Huron–Georgian Bay lobe ice retreated to Holstein, located 25 km west northwest of the Orangeville Moraine area, prior to readvancing in order to explain textural changes between fine-textured Georgian Bay lobe Tavistock Till and older, sandy silty Catfish Creek Till. It is
possible, however, that the textural changes simply reflect a different sediment source resulting from changing ice flow directions or the incorporation of localized older muddy sediments.

A Port Bruce Phase ice-margin adjustment may have increased meltwater velocities and sediment loads initiating deposition of the upper Orangeville Moraine (Figs. 9b, 9d, 9e), recorded by the transition from rhythmically bedded glaciolacustrine silt and clay to silt and sand subaqueous fan deposits (unit AFB1, Fig 9b). Textural trends (Fig. 9e), consistent southwest trending paleoflow measurements, sand mineralogy consistent with a source below the Niagara Escarpment (Cowan 1976), and esker ridges on the eastern side of the moraine provide convincing evidence of a predominantly Simcoe or Simcoe-Ontario lobe (Cowan 1976) source. Continued ice advance is recorded in pit exposures and boreholes by an overall coarsening upward trend in moraine sediments (Fig. 9b) as well as deposition of upper tills (unit ATB1) over the outer portions of the moraine (Figs. 8i, 9a-9e). A similar succession was observed in the Oak Ridges Moraine Bloomington complex (Paterson and Cheel 1997). Unit ATB1 records lobate flow from various directions: the Georgian Bay Lobe advanced from the northwest depositing Tavistock Till; the Simcoe Lobe advanced from the northeast depositing an upper sandy facies of Newmarket Till; and the Ontario Lobe advanced from the southeast depositing stony sandy silt Port Stanley Till. Outwash deposits (Fig. 8j) and deposition of the Paris Moraine in the far southeast of the area (Fig. 8k, 9b, 9c) record the final fluctuations of the Ontario lobe within the Orangeville Moraine area.

**IMPLICATIONS FOR AQUIFER VULNERABILITY AND RECHARGE**

The thick, centrally located Orangeville Moraine (unit AFB1; Fig. 7h, 8h) is the largest sediment aquifer in the map area, and is largely unconfined. Groundwater management and protection studies prepared for the Town of Erin (Blackport Hydrogeology Inc. 2005) and Wellington
County (MHBC Planning Limited, Golder Associates and SRG Soil Resources Group 2005) describe the Orangeville Moraine as a significant recharge area. It is anticipated that the greatest recharge potential is in the hummocky and sand and gravel dominated northeastern and central portions of the moraine. However, fine sand, silt and clay beds will complicate groundwater flow paths through the sediment package (Bajc et al. 2014). Fine-textured sediments were observed throughout the moraine, but are most prevalent in the southwest. Current modelling suggests that while the upper moraine aquifer may be recharged, thick fine-textured glaciolacustrine sediments and multiple tills (units ATB3, ATC1, ATE1, ATG1) beneath the moraine limit potential for recharging both lower (older) local sediment aquifers (units AFB3, AFD1, AFF1) and bedrock aquifers (Figs. 9a-9e; Table 2).

A refined bedrock elevation map delineates broad and deeply incised re-entrant notches extending back from the Niagara Escarpment and an extensive buried-bedrock valley system throughout the study area. Buried-bedrock valleys have been a source of considerable attention in recent years (Greenhouse and Karrow 1994; Russell et al. 2004; Hackley et al. 2010; Burt et al. 2011; Seyoum and Eckstein 2014; Bajc et al. this volume) as they have the potential to host significant aquifers capable of meeting the needs of municipalities (Samuelson 2006; Russell and Sharpe 2009; Huntsman et al. 2012; Hinton et al. 2013). They also form preferential flow pathways where there can be significant groundwater gains or losses for a watershed. A ground-based gravity survey and four continuously cored boreholes were used to investigate the Rockwood bedrock valley system and revealed the presence of both buried and surface hydrostratigraphic units composed of varying thicknesses of stratified gravel and sand (Fig. 9f).

Thick gravels forming the outwash aquifer unit (AFA2) are located at surface in well-defined channels within the valley (Figs. 8j and 9f). The low elevation, compared to surrounding
till covered uplands, means that there is the potential for recharge directly by rain and meltwater as well as by runoff from less permeable uplands and by streams. This runoff exacerbates the ongoing surface contamination problems and is likely part of the reason the Town of Erin (Fig 1b), located adjacent to the Rockwood buried bedrock valley in the east central study area, decommissioned wells screened in the outwash aquifer unit (AFA2). These effects may, in part, be reduced where surficial outwash aquifer deposits are discharge points in the groundwater flow system as documented in some parts of the region (MHBC Planning Limited, Golder Associates and SRG Soil Resources Group 2005).

Although not investigated in detail, the Hockley, Alton, Mono and Black Creek re-entrant valleys also contain thick surficial outwash deposits (units AFA2 and AFA1) and can be expected to have similar recharge and contamination potential. Outwash deposits located in narrow channels in the northern and southern portions of the map area, as well as in the Black Creek re-entrant, overlie both older tills and bedrock. Although not typically used for domestic water supply, these deposits are significant as direct connection with bedrock may increase the vulnerability of the bedrock aquifer as was found in the Salem–Elora–Fergus area (Fig. 1b) (Blackport Hydrogeology Inc. and Waterloo Hydrogeologic 2002).

The sandy valley fill aquifer (unit AFB3) in the Rockwood buried bedrock valley has the greatest resource potential as it is both thick and buried beneath interlobate lake deposits (unit ATB3) and upper tills (unit ATB1). These fine-textured sediments provide separation between the valley fill unit below, and surficial outwash unit above. Similarly, a groundwater management study prepared for the Township of Centre Wellington identified the Elora buried bedrock valley fill (Pre-Catfish aquifer unit AFD1) as a locally important aquifer. However, the story is not a simple one. Postglacial and modern streams have cut through the overlying tills and...
interlobate lake deposits; these in turn can create hydraulic connections that allow for aquifer recharge, as documented elsewhere, (Hackley et al. 2010; Huntsman et al. 2012; Bajc et al. this volume), but also increasing vulnerability to contamination. The Centre Wellington study alludes to this in the suggestion that water from a dammed section of the Grand River, the man-made Belwood Lake, recharges the Elora buried bedrock valley aquifer system (Blackport Hydrogeology Inc. and Waterloo Hydrogeologic 2002). Variations in hydraulic gradients, due to changing river levels and groundwater pumping rates (Hackley et al. 2010), may allow the windows to act as both recharge and discharge points for the valley fill aquifer (unit AFB3).

There are other complicating factors. The valley walls allow for direct connections between the valley fill and one or more bedrock formations. This means that, depending on the hydraulic gradients, the valley fill may be recharging the bedrock aquifer or vice versa (Huntsman et al. 2012; Seyoum and Eckstein 2014). The valley fill may also be acting as a mixing zone for water from multiple bedrock formations. The Rockwood valley fill is separated into two distinct basins at the informally named Erin sill (Fig. 5a; BH34 Fig. 9f). The northern basin, and other re-entrant valley aquifers, may be draining groundwater eastward over the Niagara Escarpment. Management of groundwater in these areas will require higher resolution geological modeling and hydrogeological testing to ensure sustainable use and protection of the groundwater resource.

Acknowledgements

The author acknowledges the support and contributions made to this project by Ryan Post (Nottawasaga Valley Conservation Authority), Greg Zwiers and Sonja Strynatka (Grand River Conservation Authority) and Dan Banks (Credit Valley Conservation). Drilling services were
provided by All-Terrain Drilling Ltd and Procore Drilling. Desmond Rainsford (OGS) coordinated geophysical surveys, field support was provided by student assistants Cameron MacDougall, Riley Mulligan, Justin Vanslingerland and Andrea Hanson and Rebecca Lee drafted earlier versions of the cross sections. Local aggregate producers, township, county and municipal staff allowed access to pits and drill sites. The manuscript has been improved by the suggestions of Emmanuelle Arnaud, Nigel Atkinson and an anonymous reviewer. Andy Bajc (OGS) and Hazen Russell (GSC) reviewed earlier versions of this manuscript. The project was funded by the Ontario Geological Survey Groundwater Initiative. This manuscript is published with permission of the Ontario Geological Survey.

References

Arai, Y. 1975. Geophysical investigations of a buried valley south of Belwood Lake, Ontario; BSc thesis, University of Waterloo, Waterloo, Ontario, 63p.

Arnaud, E., McGill, M., Trapp, A. and Smith, J.E. Subsurface heterogeneity in the geological and hydraulic properties of the hummocky Paris Moraine, Guelph, Ontario; Canadian Journal of Earth Sciences: 00, 1–18 dx.doi.org/10.1139/cjes-2016-0161. (This volume).

Armstrong, D.K. and Carter, T.R. 2010. The subsurface Paleozoic stratigraphy of southern Ontario; Ontario Geological Survey, Special Volume 7, 301p.

Armstrong, D.K. and Dodge, J.E.P. 2007. Paleozoic geology of southern Ontario. Ontario Geological Survey, Miscellaneous Release—Data 219.

Bajc, A.F. and Dodge, J.E.P. 2011. Three-dimensional mapping of surficial deposits in the Brantford-Woodstock area, southwestern Ontario. Ontario Geological Survey, Groundwater Resources Study 10, 77 p.
Bajc, A.F. and Karrow, P.F. 2004. 3-Dimensional mapping of Quaternary deposits in the Regional Municipality of Waterloo, southwestern Ontario: Geological Association of Canada Fieldtrip Guidebook FT-7, 72 p.

Bajc, A.F. and Shirota, J. 2007. Three-dimensional mapping of surficial deposits in the Regional Municipality of Waterloo, southwestern Ontario. Ontario Geological Survey, Groundwater Resources Study 3, 42 p.

Bajc, A.F., Karrow, P.F., Jasinski, P. and Warner, B.G. 2009. New occurrences of sub-till organic deposits in southwestern Ontario: are they really all that rare? Eos, Transactions, American Geophysical Union, 90: GA71A-02.

Bajc, A.F., Russell, H.A.J. and Sharpe, D.R. 2014. A three-dimensional hydrostratigraphic model of the Waterloo Moraine area, southern Ontario, Canada. Canadian Water Resources Journal, 39(2): 95-119. doi:10.1080/07011784.2014.914794.

Bajc, A.F., Karrow, P.F., Yansa, C.H., Curry, B.B., Nekola, J.C., Seymour, K.L. and Mackie, G.L. 2015. Geology and paleoecology of a Middle Wisconsin fossil occurrence in Zorra Township, southwestern Ontario, Canada. Canadian Journal of Earth Sciences 52: 386-404.

Bajc, A.F., Marich, A.S., Priebe, E.H. and Rainsford, D.R.B. Evaluating the groundwater resource potential of the Dundas buried bedrock valley, southwestern Ontario; An integrated geological and hydrogeological case study. Canadian Journal of Earth Sciences (This volume).

Barnett, P.J. 1992. Quaternary geology of Ontario; in Geology of Ontario. Ontario Geological Survey, Special Volume 4, Part 2, p. 1011-1090.
Barnett, P.J., Sharpe, D.R., Russell, H.A.J., Brennand, T.A., Gorrell, G., Kenny, F. and Pugin, A. 1998. On the origin of the Oak Ridges Moraine. Canadian Journal of Earth Sciences 35: 1152-1167.

Benn, D.I. 1989. Controls on sedimentation in a late Devensian ice-dammed lake, Achnasheen, Scotland. Boreas 18: 31-42.

Benn, D.I. and Evans, D.J.A. 1998. Glaciers & glaciation. Arnold, London, England.

Blackport Hydrogeology Inc. 2005. Groundwater management and protection strategies: Groundwater management study: Town of Erin; Unpublished report, 53p.

Blackport Hydrogeology Inc. and Waterloo Hydrogeologic 2002. Water Resources Characterization Groundwater Management Study, Township of Centre Wellington; unpublished report, 101p.

Brunton, F.R. and Brintnell, C. 2011. Final update of Early Silurian stratigraphy of the Niagara Escarpment and correlation with subsurface units across southwestern Ontario and the Great Lakes Basin; in Summary of Field Work and Other Activities 2011; Ontario Geological Survey, Open File Report 6270, pp.30-1 to 30-11.

Brunton, F.R., Brintnell, C., Jin, J. and Bancroft, A.M. 2012. Stratigraphic architecture of the Lockport Group in Ontario and Michigan – A new interpretation of Early Silurian “Basin Geometries” & “Guelph Pinnacle Reefs”; Technical Paper No. 8; in 51st Annual Conference – Ontario–New York Oil & Gas Conference, October 23 to 25, 2012, Niagara Falls, Ontario, p.1-37.
Burt, A.K. 2008. The Orangeville Moraine study: A new three-dimensional Quaternary mapping project; in Summary of Field Work and Other Activities 2008, Ontario Geological Survey, Open File Report 6226, pp.30-1 to 30-9.

Burt, A.K. 2009. The Orangeville Moraine project: An update of field activities; in Summary of Field Work and Other Activities 2009, Ontario Geological Survey, Open File Report 6240, pp.22-1 to 22-3.

Burt, A.K. 2011. The Orangeville Moraine project: Preliminary results of drilling and section work; in Summary of Field Work and Other Activities 2011, Ontario Geological Survey, Open File Report 6270, pp.28-1 to 28-34.

Burt, A.K. 2012. Conceptual geologic model for the Orangeville Moraine three-dimensional project; in Summary of Field Work and Other Activities 2012, Ontario Geological Survey, Open File Report 6280, p.32-1 to 32-6.

Burt, A.K. 2013. The Niagara Peninsula study: A new three-dimensional Quaternary geology mapping project; in Summary of Field Work and Other Activities, 2013, Ontario Geological Survey, Open File Report 6290, p.38-1 to 38-21.

Burt, A.K. 2014. Penetrating Niagara with three-dimensional mapping; in Summary of Field Work and Other Activities, 2014, Ontario Geological Survey, Open File Report 6300, p.32-1 to 32-18.

Burt, A.K. 2015. Quaternary stratigraphy of the Niagara Peninsula revealed with three-dimensional mapping; in Summary of Field Work and Other Activities, 2015, Ontario Geological Survey, Open File Report 6313, p.35-1 to 35-17.
Burt, A.K. 2016. The Niagara Peninsula in three dimensions: a drilling update; in Summary of Field Work and Other Activities 2016, Ontario Geological Survey, Open File Report 6323, p. 30-1 to 30-13.

Burt, A.K. 2017. Digging deep on the Niagara Peninsula: A drilling update; article 24 in Summary of Field Work and Other Activities 2017, Ontario Geological Survey, Open File Report 6333.

Burt, A.K. and Bajc, A.F. 2005. Three-dimensional groundwater mapping in complex moraine sediments: Current projects in Ontario, Canada; abstract in Geological Society of America, Abstracts with Program, v.37, no.7, p.144.

Burt, A.K. and Chartrand, J.E. 2014. Interactive graphic borehole logs and hydrostratigraphic correlations, Orangeville–Fergus three-dimensional study area; Ontario Geological Survey, Miscellaneous Release—Data 313.

Burt, A.K. and Dodge, J.E.P. 2011. Three-dimensional modelling of surficial deposits in the Barrie–Oro moraine area of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 11. 125 p.

Burt, A.K. and Dodge, J.E.P. 2016. Three-dimensional modelling of surficial deposits in the Orangeville–Fergus area of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 15, 155 p.

Burt, A.K. and Mulligan, R.P. 2017. Late glacial Ontario lobe ice on the Niagara Peninsula: how far did it go? Geological Society of America Abstracts with Programs. Vol. 49, No. 2 doi: 10.1130/abs/2017NE-290335
Burt, A.K. and Rainsford, D.R.B. 2010. The Orangeville Moraine Project: Buried valley targeted gravity study; in Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6220, pp.31-1 to 31-6.

Burt, A.K. and Webb, J.L. 2013. Results of the 2008, 2009 and 2010 drilling programs in the Orangeville–Fergus area of southwestern Ontario; Ontario Geological Survey, Miscellaneous Release—Data 303.

Burt, A.K, Rainsford, D.R.B. and Bajc, A.F. 2011. Aquifer or drain? The southern Ontario Rockwood buried-bedrock valley; 2011 Geological Society of America Annual Meeting, Paper No. 62-4, Minneapolis, Minnesota.

Chaitan, W.B. 1976. An investigation of bedrock topography using gravity and resistivity methods in Eramosa Township, Ontario, Canada; BSc thesis, University of Waterloo, Waterloo, Ontario.

Chapman, L.J. and Putnam, D.F. 1984. The physiography of southern Ontario; Ontario Geological Survey, Special Volume 2, 270p.

Cowan, W.R. 1976. Quaternary geology of the Orangeville area, southern Ontario; Ontario Division of Mines, Report 141, 98p.

Cowan, W.R. 1979. Quaternary geology of the Palmerston area, southern Ontario; Ontario Division of Mines, Report 187, 64p.

Cowan, W.R. 1984. Geology of the Caledon outwash, Ontario; in The geology of industrial minerals in Canada, Canadian Institute of Mining and Metallurgy, Special Volume 29, pp.137-142.
Cowan, W.R., Sharpe, D.R., Feenstra, B.H. and Gwyn, Q.H.J. 1978. Glacial geology of the Toronto – Owen Sound area; in Toronto 1978 Fieldtrips: Guidebook, p.1-16.

Cummings, D.I. and Russell, H.A.J. 2008. Sedimentology of aggregate pits in the Alliston–Orangeville area, southern Ontario: A reconnaissance survey for groundwater application; Geological Survey of Canada, Open File 5693, 78p.

Delaney, C. 2002. Sedimentology of a glaciofluvial landsystem, Lough Ree area, Central Ireland: implications for ice margin characteristic during Devensian deglaciation. Sedimentary Geology, 149: 111-126.

Dreimanis, A. 1982. Two origins of the stratified Catfish Creek Till at Plum Point, Ontario, Canada. Boreas, 11: 173-180.

Dreimanis, A. 1992. Early Wisconsinan in the north-central part of the Lake Erie basin: A new interpretation; in The last interglacial-glacial transition in North America, Geological Society of America Special Paper 270, pp.109-118.

Dreimanis, A. and Gibbard, P. 2005. Stratigraphy and sedimentation of the stratotype sections of the Catfish Creek Drift Formation between Bradtville and Plum Point, north shore, Lake Erie, southwestern Ontario, Canada. Boreas, 34: 101-122.

Eyles, N., Arnaud, E., Scheidegger, A.E. and Eyles, C.H. 1997. Bedrock jointing and geomorphology in southwestern Ontario, Canada: an example of tectonic predesign. Geomorphology, 19: 17-34.

Feenstra, B.H. 1981. Quaternary geology and industrial minerals of the Niagara–Welland area, southern Ontario; Ontario Geological Survey, Open File Report 5361, 260p.
Flint, J.J., and Lolcama, J. 1985. Buried ancestral drainage between Lakes Erie and Ontario. Geological Society of America Bulletin 97: 75-84.

Fitzsimmons, S.J. 1992. Sedimentology and depositional model for glaciolacustrine deposits in an ice-dammed tributary valley, western Tasmania, Australia. Sedimentology, 39: 393-410.

Frind, E.O., Russell, H.A.J., Rudolph, D.L. and Sharpe, D.R. 2014. Preface to the special issue The Waterloo Moraine: Water, science and policy. Canadian Water Resources Journal, 39(2): 85-87. doi:10.1080/07011784.2014.914793.

Gao, C. 2011. Buried bedrock valleys and glacial and subglacial meltwater erosion in southern Ontario. Canadian Journal of Earth Sciences, 48: 801-818. doi:10.1139/E10-104

Gao, C., Shirotta, J., Kelly, R.I., Brunton, F.R., and van Haaften, S. 2006. Bedrock topography and overburden thickness mapping, Southern Ontario. Ontario Geological Survey, Miscellaneous Release—Data 207.

Greenhouse, J.P., and Karrow, P.F. 1994. Geological and geophysical studies of buried valleys and their fills near Elora and Rockwood, Ontario. Canadian Journal of Earth Sciences, 31: 110-114.

Gwyn, Q.H.J. and Cowan, W.R. 1978. The origin of the Oak Ridges and Orangeville Moraines of Southern Ontario. Canadian Geographer: XXII(4): 345-352.

Hackley, K.C., Panno, S.V. and Anderson T.F. 2010. Chemical and isotopic indicators of groundwater evolution in the basal sands of a buried bedrock valley in the Midwestern United States: Implications for recharge, rock-water interactions, and mixing. GSA Bulletin, 122 (7/8) 1047-1066.
Hicock, S.R. 1992. Lobal interactions and rheologic superposition in subglacial till near Bradtville, Ontario, Canada. Boreas, 21: 73-88.

Hinton, M.J., Logan, C.E., Calderhead, A.I., Oldenborger, G.A., Sharpe, D.R., Russell, H.A.J. and Pugin, A.J.-M. 2013. Conceptual, geological and numerical groundwater flow models of the Spiritwood buried valley aquifer in southwest Manitoba. Geological Society of America Abstracts with Programs 45 (7): 697.

Howard, K.W.F., Eyles, N., Smart, P.J., Boyce, J.I., Gerber, R.E., Salvatori, S.L., Doughty, M. 1995. The Oak Ridges moraine of southern Ontario; a ground-water resource at risk. Geoscience Canada, B: 101-120.

Huntley, D.H. 1991. Lithofacies analysis of the Catfish Creek till: Bradtville, Ontario; Atlantic Geology, 27: 213-220.

Huntsman, B.E., Smith, K.C. and Wagel, D.J. 2012. The upper Little Miami River basin buried valley aquifer: a sustainable groundwater resource. Geological Society of America Abstracts with Programs 44 (5): 4.

Jensen, K.A. 1975. A geophysical investigation for buried valleys in the Bellwood Lake area; BSc thesis, University of Waterloo, Waterloo, Ontario, 106p.

Karrow, P.F. 1968. Pleistocene geology of the Guelph area; Ontario Geological Survey, Report 61, 38p.

Karrow, P.F. 1969. Character and variations in multiple-till sequences in the Waterloo interlobate area of Ontario; Abstracts with Programs - Geological Society of America, 25 (Part 6).
Karrow, P.F. 1973. Bedrock topography in southwestern Ontario. A progress report; Geological Association of Canada, Proceedings, 25: 67-77.

Karrow, P.F. 1974. Till stratigraphy in parts of southwestern Ontario; Geological Society of America Bulletin, 85 (5): 761-768.

Karrow, P.F. 1987. Quaternary geology of the Hamilton–Cambridge area, southern Ontario; Ontario Geological Survey, Report 255, 94p.

Karrow, P.F. 1993. Quaternary geology of the Stratford-Conestogo area, southern Ontario; Ontario Geological Survey, Report 283, 104p.

Karrow, P.F. and Paloschi, G.V.R. 1996. The Waterloo kame moraine revisited: new light on the origin of some Great Lake region interlobate moraines. Zeitschrift für Geomorphologie, 40: 305-315.

Knighton, D. 1984. Fluvial forms and processes; Edward Arnold, London 218 p.

Krzyszkowski, D. and Karrow, P.F. 2001. Wisconsinan inter-lobal stratigraphy in three quarries near Woodstock, Ontario. Geographie physique et Quaternaire 55 (1): 3-22.

Kunert, M., Coniglio, M. and Jowett, E.C. 1998. Controls and age of cavernous porosity in Middle Silurian dolomite, southern Ontario. Canadian Journal of Earth Sciences 35: 1044-1053.

Lang, J. and Winsemann, J. 2013. Lateral and vertical facies relationships of bedforms deposited by aggrading supercritical flows: From cyclic steps to humpback dunes. Sedimentary Geology, 296: 36-54.

Lee, P.F.Y. 1975. Geophysical studies of a buried-bedrock channel in the Elora–Fergus regions, southwestern Ontario; MSc thesis, University of Waterloo, Waterloo, Ontario, 73p.
Livingstone, S.J., Piotrowski, J.A., Bateman, M.D., Ely, J.C., and Clark, C.D. 2015. Discriminating between subglacial and proglacial lake sediments: an example from the Danischer Wohld Peninsula, northern Germany. Quaternary Science Reviews, 112, 86-108.

Marich, A.S., Priebe, E.H., Bajc, A.F., Rainsford, D.R.B. and Zwiers, W.G. 2011. A geological and hydrological investigation of the Dundas buried bedrock valley, southern Ontario. Ontario Geological Survey, Groundwater Resources Study 12.

Menzies, J. and Taylor, E.M. 1998. Urban geology of St. Catharines–Niagara Falls, Region Niagara; in Urban geology of Canadian cities, Geological Association of Canada, Special Paper 42, p.287-321.

Meyer, P.A., and Eyles, C.H. 2007. Nature and origin of sediments infilling poorly defined buried bedrock valleys adjacent to the Niagara Escarpment, southern Ontario, Canada. Canadian Journal of Earth Sciences, 44 (1): 89–105. doi:10.1139/E06-085.

Meyer, P.A., Brouwers, M. and Martin, P.J. 2014. A three-dimensional groundwater flow model of the Waterloo Moraine for water resource management. Canadian Water Resources Journal, 39(2): 167-180. doi:10.1080/07011784.2014.914800.

MHBC Planning Limited, Golder Associates and SRG Soil Resources Group. 2005. Preliminary draft report: County of Wellington Groundwater Protection Study; unpublished report submitted to County of Wellington Planning and Development Department, 66p.

Mulder, T. and Alexander, J. 2001. The physical character of subaqueous sedimentary density flows and their deposits. Sedimentology, 48: 269-299.
Mulligan, R.P.M. 2016. Subsurface data collection for three-dimensional mapping of Quaternary deposits in the central part of the County of Simcoe, southern Ontario; *In* Summary of Field Work and Other Activities 2016, Ontario Geological Survey, Open File Report 6323, pp. 31-1 to 31-10.

O’Connor, D.R. 2002. Report of the Walkerton Inquiry. The events of May 2000 and related issues. Parts 1 and 2. Toronto, Ontario: Ontario Ministry of the Attorney General.

Ontario Geological Survey 2010. Surficial geology of southern Ontario. Ontario Geological Survey, Miscellaneous Release—Data 128–Revised.

Ontario Geological Survey 2013a. Ontario geophysical surveys, ground gravity data, grid and point data (ASCII and Geosoft® formats) and vector data, Orangeville area. Ontario Geological Survey, Geophysical Data Set 1072.

Ontario Geological Survey 2013b. Ground gravity survey, residual of the Bouguer anomaly, Orangeville area. Ontario Geological Survey, Map 82 589, scale 1:50 000.

Ontario Geological Survey 2013c. Ground gravity survey, residual of the Bouguer anomaly, Orangeville area, Ontario Geological Survey, Map 82 588, scale 1:50 000.

Ontario Hydro. 1989. Niagara River hydroelectric development: St. Davids gorge geotechnical investigation and evaluation; Ontario Hydro Civil Engineering and Architecture Department, Report No. 89333, 129p.

Ontario Ministry of Natural Resources and Forestry. 2010. Southwestern Ontario Orthophotography Project (2010) – Digital Surface Model; Ontario Ministry of Natural Resources and Forestry, Land Information Ontario, Peterborough, Ontario.
Paterson, J.T. and Cheel, R.J. 1997. The depositional history of the Bloomington complex, an ice-contact deposit in the oak ridges moraine, southern Ontario, Canada. Quaternary Science Review 16: 705-719.

Ravier, E., Buoncristiani, J-F., Clerc, S., Guiraud, M., Menzies, J., and Portier, E. 2014. Sedimentological and deformational criteria for discriminating subglaciofluvial deposits from subaqueous ice-contact fan deposits: A Pleistocene example (Ireland). Sedimentology 61: 1382-1410.

Russell, H.A.J. and Sharpe, D.R. 2009. Mapping buried escarpment valley aquifers in southern Ontario. Geological Society of America Abstracts with Programs 41 (7): 214.

Russell, H.A.J., Hinton, M.J., van der Kamp, G., and D.R. Sharpe. 2004. An overview of the architecture, sedimentology and hydrogeology of buried-valley aquifers in Canada, in, Proceedings of the 57th Canadian Geotechnical Conference and 5th joint CGS-IAH Conference, pp. 26-33.

Russell, H.A.F., Sharpe, D.R., and Bajc, A. 2007. Sedimentary signatures of the Waterloo Moraine: Emerging insights. In Glacial sedimentary processes and products, ESS Cont.#2005701, Special Publication No. 39, Hambrey, M.J., Christoffersen, P., Glasser, N.F., Hubbard, B., and Montanez, I. (eds.), Oxford, UK: International Association of Sedimentologists: 85-108.

Russell, H.A.J., Cummings, D.I., Sharpe, D.R., Slattery, S., 2008. Elements of aquifer heterogeneity, Orangeville Moraine, southern Ontario, Geological Survey of Canada, Open File 5979, 1 poster: doi:10.4095/226088
Russell, H.A.F., Bajc, A., Sharpe, D.R., and Cummings, D.I. 2013. Paris and Galt Moraines Southern Ontario: depositional elements, paleoglacial implications, and hydrogeology applications; Geological Survey of Canada, Open File 7135, 1 poster: doi:10.4095/292705.

Sadura, S., Martini, I.P., Endres, A.L. and Wolf, K. 2006. Morphology and GPR stratigraphy of a frontal part of an end moraine of the Laurentide Ice Sheet: Paris Moraine near Guelph, ON, Canada. Geomorphology, 75: 212-225.

Samuelson, A.C. 2006. Groundwater productivity in glacial aquifers as influenced by variation in glacial geology and bedrock topography in east central Indiana. Geological Society of America Abstracts with Programs. 38 (7) 223.

Sanford, B.V. and McFall, G.H. 1984. Fracture framework – a controlling factor in the accumulation of hydrocarbons in southwestern Ontario. Geological Survey of Canada, Open File 964, 13p.

Seyoum, W.M. and Echstein, Y. 2014. Hydraulic relationships between buried valley sediments of the glacial drift and adjacent bedrock formations in northeastern Ohio, USA. Hydrogeology Journal 22: 1193-1206.

Sletten, K., Bilkra, L.H., Ballantyne, C.K., Nesje, A., Dahl, S.O. 2003. Holocene debris flows recognized in a lacustrine sedimentary succession: sedimentology, chronostratigraphy and cause of triggering. The Holocene 13 (6): 907-920.

Spencer, J.W. 1890. Origin of the basins of the Great Lakes of America. Journal of the Geological Society of London, 46: 523-533.

Straw, A. 1968. Late Pleistocene glacial erosion along the Niagara Escarpment of southern Ontario. Geological Society of America Bulletin, 79: 889-910.
Taylor, F.B. 1910. Field studies of the Pleistocene deposits of southwestern Ontario; Geological Survey of Canada, Summary Report 1909, p.164-167.

Taylor, F.B. 1913. The moraine systems of southwestern Ontario. Royal Canadian Institute Transactions, 10, 1-23.

Thomas, G.S.P and Chiverrell, R.C. 2006. A model of subaqueous sedimentation at the margin of the Late Midlandian Irish Ice Sheet, Connemara, Ireland, and its implications for regionally high isostatic sea-levels. Quaternary Science Reviews, 25: 2868-2893.

Westgate, J.A. and Dreimanis, A. 1967. The Pleistocene sequence at Zorra, southwestern Ontario. Canadian Journal of Earth Sciences, 4: 1127-1144.

White, O.L. and Karrow, P.F. 1998. Urban and engineering geology of the Kitchener-Waterloo Area, Ontario; in Urban geology of Canadian cities, Geological Association of Canada, Special Paper 42, p.261-277.

Winsemann, J., Hornung, J.J., Meinsen, J., Asprion, U., Polom, U., Brandes, C., Bußmann, M., and Weber, C. 2009. Anatomy of a subaqueous ice-contact fan and delta complex, Middle Pleistocene, North-west Germany. Sedimentology 56: 1041-1076.
Table 1. List of primary geologic materials used for 3D modelling (Burt and Dodge 2016).

| Primary Material               | Number of Occurrences | Type                      |
|--------------------------------|-----------------------|---------------------------|
| Fill                           | 712                   |                           |
| No recovery                    | 99                    | Unknown Descriptors       |
| Previously drilled             | 376                   |                           |
| Unknown                        | 2546                  |                           |
| Clay                           | 3211                  |                           |
| Silt                           | 1237                  |                           |
| Silt and sand                  | 3028                  |                           |
| Sand                           | 4182                  |                           |
| Sand and gravel                | 252                   |                           |
| Gravel                         | 3979                  | Material Descriptors     |
| Diamicton                      | 745                   |                           |
| Diamicton: clay silt           | 9016                  |                           |
| Diamicton: silt sand           | 2955                  |                           |
| Slightly silty Gravel          | 1019                  |                           |
| Organic                        | 167                   |                           |
| Water                          | 1                     |                           |
| Paleozoic Rock                 | 15587                 | Rock Descriptors         |
Table 2. Summary characteristics of the hydrostratigraphic units modelled in the Orangeville Moraine area.

| Hydrostratigraphic Unit       | OGS code | Thickness (m) | Sediment description                                                                 | Interpretation                                                                                     | Search Radius (m) |
|-------------------------------|----------|---------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|-------------------|
| Wentworth Aquifer             | AFA1     | <74           | *1. Sand, silty sand, some silt  
*2. Rare gravel beds  
*3. Rare diamicton beds  
*4. Peat, organic-rich sediments, perennially wet areas (OGS 2010) | 1-2. Glaciolacustrine deposits  
3. Debris flows  
4. Alluvium, post glacial to modern wetlands                                                        | 500                             |
| Paris Moraine                 | ATA2     | <55           | 1. Somewhat stony to stony silty sand to sand diamicton  
2. Slightly silty sand and gravel  
3. Occasional beds of gravel and sand  
4. Occasional beds of sand, silty sand and rhythmically bedded silt and clay, slightly to highly deformed | 1. Wentworth till (Cowan 1976)  
2. Debris flows  
3. Outwash  
4. Glaciolacustrine deposits                                                              | 750                             |
| Outwash Aquifer               | AFA2     | <41           | 1. Thick beds of imbricate cobble gravel  
2. Sheet-like beds of gravel and sand  
3. Planar and cross-bedded gravel and sand in broad, shallow channels  
4. Laminated to rippled fine sand and laminated silt and clay  
*5. Peat, organic-rich sediments, perennially wet areas | 1-3. Proglacial gravel rivers with migrating bars, channel fills (Cowan 1984; Burt 2011)  
4. Channel abandonment: shift from fluvial to lacustrine setting  
5. Post glacial to modern wetlands                                                        | 750                             |
| Upper Tills                   | ATB1     | <45           | 1. Stone-poor to slightly stony, clayey silt to silt diamicton  
2. Sandy silt diamicton  
3. Stony sandy silt diamicton  
4. Fissile, stony silty sand to sand diamicton  
5. Interbedded diamicton, slightly silty sand and gravel, minor sand, rhythmically bedded silt and clay.  
6. Silty sand, silt, laminated silt and clay  
7. Silt and clay (deformed) with some thin beds of diamicton | 1. Georgian Bay lobe Tavistock Till (Cowan 1976)  
2. Georgian Bay lobe Tavistock Till or Stirton Till (Karrow 1993; Karrow and Paloschi 1996)  
3. Erie-Ontario lobe Port Stanley Till (Cowan 1976)  
4. Simcoe lobe upper sandy till (extension of Newmarket Till)  
5. Debris flows, outwash and glaciolacustrine deposits in an ice marginal setting  
6. Glaciolacustrine deposits  
7. Basinal glaciolacustrine deposits with debris flows                                                                 | 1500                           |
| Orangeville Moraine Aquifer   | AFB1     | <74           | 1. Crude beds of cobble gravel, crude to well-defined cross-bedded cobble gravel, gravel and sandy gravel.  
2. Irregularly shaped blocks of fine sand within beds of cobble gravel  
3. Beds of cobbles and gravel interbedded with thin beds of rippled fine sand and silty sand  
4. Broad sheets of planar and trough cross-bedded gravelly sand and sand, sandy backsets and foresets; diffusely stratified sand and rippled sand.  
5. Broad channels infilled with sand and occasionally gravel.  
6. Rhythmically bedded laminated and rippled sand, rippled silty sand and rarely silty clay. | 1. Dense turbulent flow ice proximal deposits in a subaqueous fan setting (Benn and Evans 1998; Delaney 2002; Ravier et al. 2014; Thomas and Chiverrell 2006; Winseman et al. 2009).  
2. Ripped-up clasts (Cummins and Russell 2008)  
3. Repeated discharge events into a standing water body (Ravier et al 2014; Delaney 2002)  
4. Traction deposits from unconfined concentrated flows on interchannel zones of subaqueous fans (Benn and Evans 1998; Cummings and Russell 2008).  
5. Distributary channels crossing subaqueous fan surface (Barnett et al. 1998).  
6. Traction deposits with increasing deposition from suspension in distal subaqueous fan settings (Barnett et al. 1998; Delaney 2002). | 1000                           |
| Maryhill Aquitard             | ATB3     | <70           | 1. Silt, rhythmically bedded silt and clay, rare beds of silty sand; in places deformed  
2. Stone-poor, silty to clayey diamicton  
3. Silt and sandy silt diamicton | 1. Basinal glaciolacustrine sediments  
2-3. Till  
4. Basinal glaciolacustrine sediments with slump deposits / debris flows / flow tills (Bajc and Dodge 2011; Bajc and Karrow 2004; | 2000                           |
| Aquifer Type                  | Code  | Age (ka) | Sediments                                                                 |
|------------------------------|-------|----------|---------------------------------------------------------------------------|
| Valley Fill Aquifer          | AFB3  | <67      | 1. Cobble gravel, interbedded gravel and sand, sandy gravel               |
|                              |       |          | 2. Slightly gravelly sand, cross-bedded, laminated and rippled sand       |
|                              |       |          | 3. Rhythmically bedded laminated and rippled sand, silt and minor clay    |
|                              |       |          | 4. Rockwood valley: 2 or more fining-upwards cycles of cobbles, gravel,  |
|                              |       |          | sand and minor silt.                                                     |
| Catfish Creek Till           | ATC1  | <37      | 1. Stone-poor sandy silt to silt diamicton.                              |
|                              |       |          | 2. Overconsolidated somewhat stony to stony sandy silt diamicton.        |
|                              |       |          | 3. Overconsolidated somewhat stony to stony sandy silt diamicton with     |
|                              |       |          | highly deformed laminations of silt and clay and/or beds of silt and    |
|                              |       |          | clay and occasionally sand and gravel.                                   |
|                              |       |          | 4. Interbedded diamicton, slightly silty sand and gravel, gravel, sand.   |
|                              |       |          | 5. Rhythmically bedded silt and clay.                                    |
| Pre-Catfish Aquifer          | AFD1  | <60      | 1. Sand, silt (Greenhouse and Karrow 1994),                              |
|                              |       |          | 2. Rhythmically bedded laminated and rippled sand fining upwards to      |
|                              |       |          | silty sand and silt, rare organic-rich sandy silt beds.                  |
|                              |       |          | 3. Slightly silty sand and gravel, pebbly sand, organic-rich silty sand.  |
|                              |       |          | 4. Interbedded diamicton, slightly silty sand and gravel, gravel, sand.   |
|                              |       |          | 5. Gravel and sand.                                                     |
| Canning Equivalent Sediments | ATE1  | <20      | 1. reddish stone-poor to slightly reddish silty to clayey silt diamicton  |
|                              |       |          | with occasional silty lenses.                                            |
|                              |       |          | 2. Greyish brown stone-poor silty diamicton.                             |
|                              |       |          | 3. Rare sandy silt diamicton.                                            |
|                              |       |          | 4. Strong red diamicton with abundant red shale clasts.                   |
|                              |       |          | 5. Silt, rhythmically bedded silt and clay, minor diamicton, in places   |
|                              |       |          | variably slightly to highly deformed.                                    |
| Older Aquifer                | AFF1  | <20      | 1. Interbedded gravel, sand and diamicton.                               |
|                              |       |          | 2. Fining-upwards gravelly sand, laminated and rippled sand, rhythmically|
|                              |       |          | bedded sand and silty sand.                                              |
|                              |       |          | 3. Rockwood valley: gravel, slightly silty sand and gravel, diamicton in  |
|                              |       |          | northern boreholes.                                                     |
|                              |       |          | 4. Rockwood valley: large boulders.                                      |
| Oldest Tills                 | ATG1  | <38      | 1. Reddish overconsolidated, massive, stony sandy silt diamicton.        |
|                              |       |          | 2. Yellowish brown stony sandy silt diamicton, rare beds of slightly     |
|                              |       |          | silt sand and/or gravel.                                                |
|                              |       |          | 3. Coarse- and fine-textured diamicton with gravel and rarely             |
|                              |       |          | rhythmically bedded silt and clay interbeds.                             |
|                              |       |          | 4. Oxidized (stained) stony sandy silt diamicton.                        |
|                              |       |          | 1. Subglacial till.                                                     |
|                              |       |          | 2. Till with minor waterlain deposits.                                   |
|                              |       |          | 3. Debris flow, glaciolacustrine sediments deposited in an ice marginal  |
|                              |       |          | setting.                                                                 |
|                              |       |          | 4. Weathering profile.                                                  |

Fitzsimmons 1992.  
Benn and Evans 1998; Mulder and Alexander 2001  
Cummings and Russell 2008  
Bajc et al. 2014  
Bajc et al. 2011; Hicock 1992.  
Cowan 1976; Dreimanis 1982; Hicock 1992.  
Huntley 1991.  
Bajc et. al. 2014.  
Bajc and Dodge 2011, Hicock 1992.  
Greenhouse and Karrow 1994  
Meyer and Eyles 2007  
Burt 2017; Ontario Hydro Civil Engineering and Architecture Department 1989.
| Bedrock          | BR | 1. Shale       | 2. Dolostone | 1. Ordovician bedrock | 2. Silurian bedrock | 5000 |
|------------------|----|---------------|--------------|-----------------------|---------------------|------|

Note that sediments marked with an asterisk (*) are described from legacy datasets and surficial maps (OGS 2010), whereas others are from outcrops or cores recovered as part of this study.
Table 3. Results of grain size and carbonate analysis for Orangeville Moraine area tills.

| Formation                        | No. of Samples | No. of Samples | No. of Samples | No. of Samples | Calcite (%) | Dolomite (%) | Total Carbonate (%) | Calcite to Dolomite (ratio) |
|----------------------------------|----------------|----------------|----------------|----------------|-------------|--------------|---------------------|-----------------------------|
| ATA2 Wentworth Till              | 43             | 54 (36-74)     | 5 (<1-8)       | 39             | 21 (3-30)   | 26 (3-39)    | 47 (19-57)          | 1.2 (0.1-6)                 |
| ATB1 Port Stanley Till          | 108            | 54 (27-73)     | 7 (<1-16)      | 105            | 23 (5-28)   | 19 (7-45)    | 42 (26-63)          | 1.5 (0.2-4)                 |
| ATB1 Tavistock Till             | 63             | 69 (53-87)     | 15 (4-26)      | 59             | 25 (7-52)   | 18 (8-44)    | 42 (23-63)          | 1.7 (0.4-3.7)               |
| ATB1 Tavistock Till (coarse)    | 23             | 52 (37-62)     | 5 (2-11)       | 23             | 22 (18-25)  | 19 (10-43)   | 41 (34-62)          | 1.3 (0.4-2.3)               |
| ATB1 Upper Sandy till           | 20             | 31 (8-53)      | 3 (0-7)        | 17             | 22 (12-26)  | 23 (17-40)   | 45 (39-52)          | 1.1 (0.3-1.5)               |
| ATB3 till and diamicton         | 37             | 76 (54-88)     | 13 (4-26)      | 33             | 27 (21-35)  | 15 (6-26)    | 42 (35-51)          | 2.1 (0.9-6)                 |
| ATC1 Catfish Creek regional till| 232            | 52 (31-75)     | 7 (2-22)       | 233            | 21 (13-29)  | 29 (8-56)    | 51 (29-80)          | 0.9 (0.2-2.7)               |
| ATC1 Catfish Creek lobate till  | 52             | 61 (47-81)     | 13 (2-37)      | 51             | 25 (18-31)  | 17 (8-48)    | 42 (20-61)          | 1.7 (0.4-4)                 |
| ATE1 Canning equivalent: Rockwood valley | 25 | 58 (48-64) | 14 (8-18) | 26 | 20 (19-22) | 8 (7-14) | 29 (27-35) | 2 (1.6-3) |
| ATE1 Canning equivalent         | 19             | 70 (43-87)     | 15 (6-32)      | 19             | 25 (18-32)  | 19 (7-43)    | 44 (37-61)          | 2 (0.4-4.4)                 |
| ATG1 Older till 1               | 73             | 51 (32-75)     | 8 (1-16)       | 73             | 20 (13-26)  | 40 (16-59)   | 59 (36-77)          | 0.5 (0.2-1.4)               |
| ATG1 Older till 2 (BH07)        | 3              | 61 (60-63)     | 14 (12-15)     | 3              | 21 (19-23)  | 30 (29-33)   | 51 (49-53)          | 0.7 (0.6-0.8)               |
| ATG1 Older till 3 (BH20)        | 3              | 56 (54-57)     | 8 (<8)         | 3              | 20 (17-22)  | 30 (28-32)   | 50 (49-51)          | 0.7 (0.6-0.8)               |

Average results are shown in bold and the range of values are shown in parentheses. Note that calcite has leached from the upper metre of surface tills (ATA2 and ATB1) and several obvious outlier results were not included in this compilation. Grain-size and carbonate data plots are shown on supplementary figures S1 and S2.
Fig. 1. A) Regional topography and location of the Orangeville Moraine project area in southwestern Ontario. The interlobate Orangeville, Waterloo and Dorchester moraines are shown in orange. The Niagara Escarpment is shown in black. B) Orangeville Moraine study area with communities, municipal boundaries, roads and conservation authority boundaries. The locations of continuously cored boreholes and aggregate operations visited are marked. The Orangeville Moraine Aquifer (unit AFB1) is shown in orange. Note that portions of this unit are buried. C) Digital surface model of the Orangeville Moraine area draped over a hillshade (Ontario Ministry of Natural Resources, 2010). D) Surficial geology of the Orangeville Moraine area (Ontario Geological Survey, 2010). Key physiographic features are marked on maps c) and d). Map coordinates for c) and d) are the same as those in Fig. 1b.
Fig. 2. A) Bedrock geology map. Devonian formations are shown in green, Silurian formations are shown in yellow and Ordovician units are shown in purple and blue. (Armstrong and Dodge 2007). B) Primary lithology map. (Armstrong and Dodge 2007). C-H) Examples of Paleozoic bedrock units. Each pictured core is 40 cm long and the top is to the left. C) Queenston Formation red and green shale, BH35. D) Gasport Formation fossiliferous dolostone, BH41. E) Eramosa Formation bituminous dolostone, BH23. F) Eramosa Formation dolostone, BH34. G) Guelph Formation vuggy and fractured dolostone, BH24. H) Guelph Formation dolostone, BH17.
Fig. 3. A) Locations of continuously cored and other high quality data (green), medium quality data (orange) and low quality data (blue) (modified from Burt and Dodge 2016). B) Location of 2010, 2011 and 2012 ground gravity survey lines, gravity profiles and negative residual Bouger gravity anomaly (OGS 2013a). The base map is the southern Ontario bedrock topography surface (Gao et al. 2006). Map coordinates for a) and b) are the same as those in Fig. 1b.
Fig. 4. Idealized conceptual stratigraphic framework for the Orangeville Moraine area (modified from Burt 2012). The sketch extends from the northwest to the southeast of the study area, covering 55 km. Overall sediment thicknesses range from 0 to 145 m. Individual unit thicknesses and geometry may not be exactly as shown.
Fig. 5. A) Topographic map of the bedrock surface draped over a hillshade generated from the modelled bedrock surface (modified from Burt and Dodge 2016). The roughly north-south trending Niagara Escarpment is located to the east of the study area. Buried-bedrock valleys (BBV) and the modern Elora gorge are labelled. Note that the Hockley, Mono, Alton, Rockwood and Black Creek valleys form re-entrant notches in the escarpment. 1) Headwater. 2) Plunge pool. 3) Hillsburgh high. 4) Erin sill. 5) Disappearing valley. B) Sediment thickness map. The thickest sediment is found in the Orangeville Moraine and bedrock valleys. Map coordinates for a) and b) are the same as those in Fig. 1b.
Fig. 6. Examples of continuously cored sediments. Each pictured core is 40 cm long and the top is to the left. A) Oldest tills (ATG1): Sand and gravel over vuggy and fractured bedrock, BH03. B) ATG1: Older finer-textured till, BH07. C) ATG1: Oxidized stony sandy till, BH04. D) ATG1: Stony sandy till oxidized by infiltration of groundwater, BH24. E) Older aquifer (AFF1): Rhythmically bedded, fining-upwards sand with heavy mineral laminations and ripple-cross laminations, BH16. A pebble is at the base of a fining-upward sequence. F) AFF1: Poorly sorted sand, gravel and cobbles with a thin sandy bed, BH16. G) AFF1: Part of a large boulder overlying bedrock, BH26. Notice the steeply dipping stylolites. H) Canning equivalent sediment (ATE1): Silty till (left) overlying highly deformed glaciolacustrine sediments (right), BH01. The contact is sharp, but deformed. I) ATE1, ATG1: Canning equivalent silty till (left) overlying older stony, sandy silt till (right), BH04. J) ATE1: Clayey, silty till with a reddish matrix colour that is derived from red shale, BH32. K) ATE1: Stone-poor silty till from the Rockwood buried valley that lacks the red matrix colour shown in (J), BH33. L) Pre-Catfish aquifer (AFD1): Ripple-cross-laminated fine sand, BH27. M) Catfish Creek Till (ATC1), AFD1: Catfish Creek Till (left) overlying highly deformed silty sand and organic-rich silty sand BH10. N) ATC1: Typical overconsolidated, slightly stony, sandy silt Catfish Creek Till, BH10. O) ATC1: Stony, sandy silt Catfish Creek Till with dolostone cobbles and an erratic granite cobble (centre of image), BH06. P) ATC1: Debris flows of Catfish Creek diamicton with abundant highly deformed silt laminations, BH10. Note that the silt laminations appear white because the core has started to dry out.
Fig. 7. Isopach maps for hydrostratigraphic units in the Orangeville Moraine area (modified from Burt and Dodge 2016). The municipal boundaries are shown in light grey and the modern river network in blue. Map coordinates are the same as those in Fig. 1b. A) Oldest Tills. B) Older Aquifer. C) Canning Equivalent Sediment. D) Pre-Catfish Aquifer. E) Catfish Creek Till. F) Valley Fill Aquifer. G) Maryhill Aquitard. H) Orangeville Moraine Aquifer. Prominent esker ridges are marked with black arrows. I) Upper Tills. J) Outwash Aquifer. K) Paris Moraine. L) Wentworth Aquifer.
Fig. 8. Location maps for hydrostratigraphic units in the Orangeville Moraine area (modified from Burt and Dodge 2016). Each unit is shown overlying older units, such that each panel represents the surficial geology at the time of deposition of that unit. The sequence of maps also gives a visual sense of the stratigraphic sequence at any one location within the study area. The bedrock surface has been used as a base. The municipal boundaries are shown in light grey and the modern river network in blue. Map coordinates are the same as those in Fig. 1b. A) Oldest Tills. B) Older Aquifer. C) Canning Equivalent Sediment. D) Pre-Catfish Aquifer. E) Catfish Creek Till. F) Valley Fill Aquifer. G) Maryhill Aquitard. H) Orangeville Moraine Aquifer. I) Upper Tills. J) Outwash Aquifer. K) Paris Moraine. L) Wentworth Aquifer.
Fig. 9. Geologic cross-sections constructed from cored holes along transects perpendicular and parallel to the Orangeville Moraine and parallel to the Rockwood buried-bedrock valley bottom. The location of the Erin sill is shown on e). Inset surficial geology map and legend from seamless surficial geology map (OGS 2010). Map coordinates are the same as those in Fig. 1b.
Fig. 10. Examples of continuously cored sediments. Each pictured core is 40 cm long and the top is to the left. A) Valley fill aquifer (AFB3): Ripple-cross-laminated sand, BH33. B) AFB3: Gravel with a sandy matrix, BH33. C) Maryhill aquitard (ATB3): Stone-poor, silty clay diamicton, BH09. D) ATB3: Faulted and offset rhythmically bedded and laminated silt, silty clay and clay with diamicton stringers (left side and centre of image) overlying silty clay diamicton (right side of image), BH09. The reddish colour in the silty clay and clay is likely derived from the Queenston shale, which subcrops below the Niagara Escarpment in the Orangeville Moraine area. E) ATB3: Rhythmically bedded couplets of laminated silt with thin clay caps, BH31. F) Orangeville Moraine aquifer (AFB1): Laminated, very fine sand and silt, BH12. G) AFB1: Ripple-cross-laminated medium sand, BH15. H) AFB1: Planar-bedded sand BH15. The structure is highlighted by heavy minerals (left of image) and coarse sand (centre and right of image). I) Upper tills (ATB1): Rhythmically bedded and laminated silt and silty clay with rare sandy laminations, BH38. Note the pebble dropstone (marked with an arrow). J) ATB1: Slightly stony, silty Tavistock Till, BH24. K) ATB1: Oxidized, somewhat stony, sandy silt Port Stanley Till, BH33. L) ATB1: Slightly stony, sandy till (informally named upper sandy till), BH23. M) Outwash aquifer (AFA2): Beds of coarse sand, gravelly (granular) sand and sandy gravel, BH34. N) AFA2: Gravel, BH35. Note that the matrix was washed away during drilling and drilling mud is visible between the clasts. O) Paris Moraine (ATA2): Soft, stony, sandy diamicton, BH29. P) ATA2: Bed of slightly deformed, rhythmically bedded silt and clay (left) in stony, sandy diamicton (right), BH30.
Fig. 11. Examples of Orangeville Moraine (AFB1) sediments exposed in aggregate pits. The red and white scale is 1 m long and is divided into 10 cm sections. A) Cobble gravel overlain by cross-bedded gravel, pit P9. B) Thick cross-bedded sand and gravel, pit P10. C) Coarse gravel with large ripped-up sand clast (arrow), pit P5. D) Cross-beded coarse sand interbedded with ripple cross-laminated fine sand, pit P10. Face is approximately 5 m high. E) Close up of ripple cross-laminated sand bed, approximately 10 cm thick, pit P10.
Fig. 12. Examples of Orangeville Moraine (AFB1) sediments exposed in aggregate pits. The red and white scale is 1 m long and is divided into 10 cm sections. A) Beds of coarse gravel and diffusely stratified sand (P11). B) Cross-bedded sand, pit P5. C) Trough cross-bedded sand (P11). D) Diffusely stratified sand (antidune?) (P7). Face is approximately 2 m high. E) Climbing dunes in sand, pit P6. F) Rhythmically bedded ripple cross-laminated medium- to fine sand, climbing ripple cross-laminated sand and wavy laminated sand and silt (P11). G) Multiple inset channels highlighted by dashed white lines, (P11). Face is approximately 8 m high.
Fig. 13. Examples of outwash aquifer (AFA2) sediments exposed in aggregate pit P12. The red and white scale is 1 m long and is divided into 10 cm sections. **A)** Imbricate cobble gravel. Flow was from right to left. **B)** Bar front avalanche faces. Flow was from right to left. **C)** Planar- and cross-bedded gravelly (granular) sand and sand in a broad, shallow channel incised into imbricate cobble gravel highlighted by a dashed white line. Channel flow was out of the face.
Fig. 14. Paris Moraine aquitard diamicton, sand and gravel (ATA2) overlying outwash aquifer (AFA2) gravel (below dashed line) exposed in aggregate pit P12. The red and white scale is 1 m long and is divided into 10 cm sections.

cjes-2017-0077suppla

Grain-size data plotted on ternary diagrams. A) Older tills (ATG1). B) Canning-equivalent tills (ATE1). C) Catfish Creek Tills (ATC1). D) Maryhill aquitard (ATB3). E) Tavistock Tills (ATB1). F) Port Stanley Till (ATB1), Upper sandy till (ATB1), and Wentworth Till and associated diamicton (ATA2).

cjes-2017-0077supplb

Total carbonate (%) plotted against calcite dolomite ratio. A) Older tills (ATG1). B) Canning-equivalent tills (ATE1). C) Catfish Creek Tills (ATC1). D) Maryhill aquitard (ATB3). E) Tavistock Tills (ATB1). F) Port Stanley Till (ATB1). G) Upper sandy till (ATB1). H) Wentworth Till and associated diamicton (ATA2).
